Universal Thermal Climate Index (UTCI) based physiological stress assessment in Nigeria using ERA5 data

Évaluation du stress physiologique au Nigéria, basée sur l'indice thermique universel (UTCI), à l'aide des données ERA5

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ABSTRACT: Global warming increases understanding of human stress from heat, notably in tropical countries like Nigeria. Research examines mean physiological thermal stress in Nigeria with UTCI. ERA5 data from ECMWF for 84-year period (1940-2024) analyzed alomg with1940, 1970, 2000 and 2024 .The study shows a notable and clear spatial variation in thermal stress throughout Nigeria, with the most severe stress observed in Anambra state reaching 32°C in 2024, and the mildest in Katsina state at 25°C during the same year. The results suggest a range of Universal Thermal Climate Index (UTCI) from 26 to 32°C in Nigeria, indicating moderate heat stress. These findings have implications for public health, agricultural output, and occupational safety. This paper underscores the necessity of incorporating advanced bioclimatic indices like UTCI into national climate adaptation and public health policies to develop targeted interventions for the most at-risk populations.

KEY WORDS: Heat stress, UTCI, ERA5, climate change, Nigeria, public health.

RÉSUMÉ : Le réchauffement climatique permet de mieux comprendre le stress thermique humain, notamment dans les pays tropicaux comme le Nigéria. Une étude examine le stress thermique physiologique au Nigéria à l'aide de l'UTCI. Les données ERA5 du CEPMMT sur une période de 84 ans (1940-2024) ont été analysées. L'étude révèle une variation spatiale notable et nette du stress thermique à travers le Nigéria, le stress le plus intense ayant atteint 32 °C en 2024 dans l'État d'Anambra, et le plus doux dans l'État de Katsina, avec 25 °C la même année. Les résultats suggèrent une fourchette d'indices de climat thermique universel (UTCI) comprise entre 26 et 32 °C au Nigéria, indiquant un stress thermique modéré. Ces résultats ont des implications pour la santé publique, la production agricole et la sécurité au travail. Cet article souligne la nécessité d'intégrer des indices bioclimatiques avancés comme l'UTCI dans les politiques nationales d'adaptation au changement climatique et de santé publique afin de développer des interventions ciblées pour les populations les plus à risque.

MOTS CLÉS : Stress thermique, UTCI, ERA5, changement climatique, Nigéria, santé publique.

1. Introduction

Climate change is unequivocally increasing the frequency, intensity, and duration of heatwaves globally (IPCC, 2021). For nations situated in the tropics, such as Nigeria, the impacts of rising temperatures are particularly acute. Nigeria, Africa's most populous country, is characterized by a rapidly growing population, high dependence on climate-sensitive sectors like agriculture, and significant developmental challenges that heighten its vulnerability to climatic stressors (Ebele & Emodi, 2016). While rising mean and extreme temperatures are well-documented, their direct impact on human well-being is often assessed using simple metrics like air temperature alone. However, human thermal perception and physiological response are complex phenomena influenced by the interplay of temperature, humidity, wind speed, and solar radiation.

Błazejczyk, has been pivotal. Błazejczyk and colleagues provided the seminal validation studies for UTCI in Central European conditions, mapping thermal stress across the continent (Błazejczyk et al., 2013). ERA5 is produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) on behalf of the Copernicus Climate Change Service (C3S), funded by the European Union.

To provide a more holistic assessment of environmental thermal load on the human body, advanced bioclimatic indices have been developed. Among these, the Universal Thermal Climate Index (UTCI) has emerged as a state-of-the-art standard (Jendritzky et al., 2012; Błażejczyk et al., 2013). UTCI is based on a multi-node model of human thermoregulation and is designed for applications across all climates, seasons, and scales. It translates the combined effect of the four key meteorological variables into a single equivalent temperature, which represents the physiological stress experienced by the human body.

In the Nigerian context, research on heat stress has often focused on specific urban areas or relied solely on temperature and humidity data (the heat index). A comprehensive, nationwide assessment using an integrated index like UTCI is largely absent from the literature. This gap is significant, as Nigeria's diverse climatic zones—from the humid tropical coast in the south to the hot, arid Sahel in the north—suggest that thermal stress is likely to be highly variable both spatially and temporally.

This study aims to fill this gap by conducting a nationwide assessment of mean physiological thermal stress in Nigeria. Using the high-resolution ERA5 reanalysis dataset, we calculate and map the mean UTCI across the country for a recent 84-year climatological period (1940-2024). The primary objectives are: to quantify the spatial distribution of mean UTCI across Nigeria's diverse climatic zones and Statistical Analysis categorize different regions of the country based on the internationally recognized UTCI thermal stress scale.

The findings from this research are intended to provide a crucial evidence base for policymakers, public health officials, urban planners, and disaster management agencies to develop effective, geographically-targeted strategies to mitigate the adverse effects of heat stress.

1.1. Literature Review

The study of human thermal comfort and stress has evolved significantly over the past century, moving from simple indices to complex biometeorological models. Early approaches often relied on single meteorological variables like air temperature, or simple combinations such as the Heat Index or Humidex, which primarily considered temperature and humidity (Steadman, 1984). While useful for general guidance, these indices often fail to fully capture the complexity of human physiological responses to the thermal environment, neglecting factors like wind speed, radiation, and clothing insulation.

1.1.1. Thermal Stress in Central Europe

AtioCentral Europe, characterized by a transitional climate between oceanic and continental, is particularly sensitive to thermal fluctuations. Romania, situated in the southeastern part of this region, exhibits a diverse climate influenced by the Carpathian Mountains and the proximity of the Black Sea, making it an interesting case study for UTCI application. This paper investigates the utilization of the UTCI in Central Europe and specifically in Romania, identifying the primary researchers and institutions, and synthesizing the results regarding thermal stress trends. By synthesizing data from major meteorological studies, urban climate research groups, and specific case studies in cities such as Bucharest, Cluj-Napoca, and Timișoara, this review identifies the key researchers and institutions utilizing the index. The results indicate that the UTCI is extensively applied in Central Europe to analyze heat stress events and urban heat islands (UHI). In Romania, studies consistently demonstrate a significant increase in heat stress days (UTCI > 32°C) during summer months and a notable reduction in cold stress during winter, correlating with recent climate change trends.

1.1.2. Climate Change and Thermal Stress in Nigeria

Nigeria's climate is predominantly tropical, characterized by high temperatures and significant humidity for much of the year, especially in the south. The north experiences a more pronounced dry season with higher diurnal temperature variations. Recent climate change assessments indicate a clear warming trend across Nigeria, with observed increases in mean annual temperatures over the past decades (NiMET, 2021; Odekunle et al., 2020). Projections suggest that these trends will continue, leading to more frequent and intense heatwaves.

The implications of increased thermal stress for Nigeria are profound. Heat stress impacts human health, leading to increased incidence of heat stroke, cardiovascular stress, and respiratory problems, particularly among vulnerable groups like outdoor workers, the elderly, children, and those with pre-existing health conditions (WHO, 2018). Beyond health, high temperatures can reduce labor productivity, particularly in agricultural and construction sectors crucial to Nigeria's economy (Dasgupta et al., 2021). Furthermore, increased demand for cooling (air conditioning) could strain the already challenged energy infrastructure and exacerbate greenhouse gas emissions.

While some studies have examined general climatic trends in Nigeria (Odekunle et al., 2020; Enete & Alabi, 2020), a detailed, country-wide assessment of physiological stress using an advanced index like UTCI, leveraging the high-resolution and consistent data from ERA5, remains largely unexplored. Previous research often relied on limited ground station data or simpler thermal indices, which may not capture the full extent and spatial variability of thermal stress. This study addresses this critical gap by providing a comprehensive and physiologically relevant assessment of thermal stress dynamics across Nigeria, contributing to a better understanding of climate change impacts and informing targeted adaptation strategies.

2. Study area

Nigeria is located in West Africa, between latitudes 4°N and 14°N, and longitudes 2°E and 15°E. Its climate is governed primarily by the interaction of the moist, maritime Tropical Maritime (mT) air mass from the Atlantic Ocean and the dry, continental Tropical Continental (cT) air mass from the Sahara Desert.

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Figure 1 Map of Nigeria with location of Africa.

3. Methods

3.1. Data Source: ERA5

This study utilizes the ERA5 atmospheric reanalysis dataset, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5 provides a globally complete and consistent hourly record of the global atmosphere, land surface, and ocean waves from 1940 onwards (Hersbach et al., 2020). Its high spatial resolution (≈31 km) and temporal resolution make it an excellent resource for regional climate studies where dense observational networks are sparse.

For this analysis, we extracted four key variables required for UTCI calculation for the period 1991-2020:

- 2-metre air temperature (T_a)
- 2-metre dewpoint temperature (T_d), used to calculate relative humidity (RH)
- 10-metre U and V components of wind, used to calculate wind speed (v_a)
- Mean radiant temperature (MRT), which was approximated using surface solar and thermal radiation fluxes available in ERA5, following methods established in the literature (Di Napoli et al., 2021).

The European Centre for Medium-Range Weather Forecasts (ECMWF) produces the ERA5 reanalysis dataset, which represents a significant advancement in atmospheric data for climate research (Hersbach et al., 2020). ERA5 provides hourly estimates of a wide range of atmospheric, land-surface, and sea-state parameters on a global grid at a horizontal resolution of approximately 31 km (0.25° x 0.25°), from 1940 to the present with continuous updates. It is generated using a state-of-the-art 4D-Var data assimilation system and the ECMWF Integrated Forecast System (IFS) Cycle 41r2, which integrates billions of observations from satellites, weather stations, buoys, and other sources (Hersbach et al., 2020).

The high spatial and temporal resolution, coupled with the long temporal coverage and consistency, makes ERA5 an invaluable resource for climate studies, particularly in regions with sparse observational networks, such as many parts of Africa. ERA5 has been widely validated and utilized in numerous climate-related research areas, including studies on extreme weather events, climate variability, and climate change detection (Otu & Mbaka, 2020), for precipitation in Nigeria. Its comprehensive set of variables, including 2m air temperature, 2m dewpoint temperature (from which relative humidity can be derived), 10m wind speed, and various radiation components, provides the necessary input parameters for calculating sophisticated biometeorological indices like UTCI. While some variables, like mean radiant temperature, require derivation from other ERA5 outputs (surface solar radiation and thermal radiation), the dataset offers sufficient detail for robust UTCI computation.

3.2. UTCI Calculation and Stress Classification

The UTCI is defined as the air temperature of a reference condition that would cause the same physiological strain response as the actual environment (Jendritzky et al., 2012). It is calculated using a sixth-order polynomial regression equation that takes T_a, MRT, v_a, and water vapor pressure (derived from T_d) as inputs. Due to its complexity, the UTCI was computed for each grid point across Nigeria using established computational packages designed for bioclimatological analysis.

Once calculated, the UTCI values were categorized according to the established thermal stress assessment scale (Table 1), which defines ten categories ranging from 'Extreme cold stress' to 'Extreme heat stress'. For this study, the focus is on the categories indicating heat stress.

Recognizing the limitations of simpler indices, the International Society for Biometeorology (ISB) launched the COST Action 730 "Climate Change and Adaptation of Human Biometeology" project, which led to the development of the Universal Thermal Climate Index (UTCI) (Blazejczyk et al., 2012). UTCI is defined as the air temperature (in °C) of a reference outdoor environment that would produce the same dynamic physiological response (e.g., skin temperature, core temperature, sweating rate) as the actual environment (Jendritzky et al., 2012). It is derived from a sophisticated multi-node human heat balance model (Fiala et al., 2012), which considers the complex interactions between the human body and its surroundings.

This study utilized the ERA5 reanalysis dataset from the ECMWF, which provides global climate data at a spatial resolution of approximately 31 km and a temporal resolution of one hour (Hersbach et al., 2019). The dataset covers various variables, including air temperature, relative humidity, and wind speed, which are necessary for calculating UTCI.

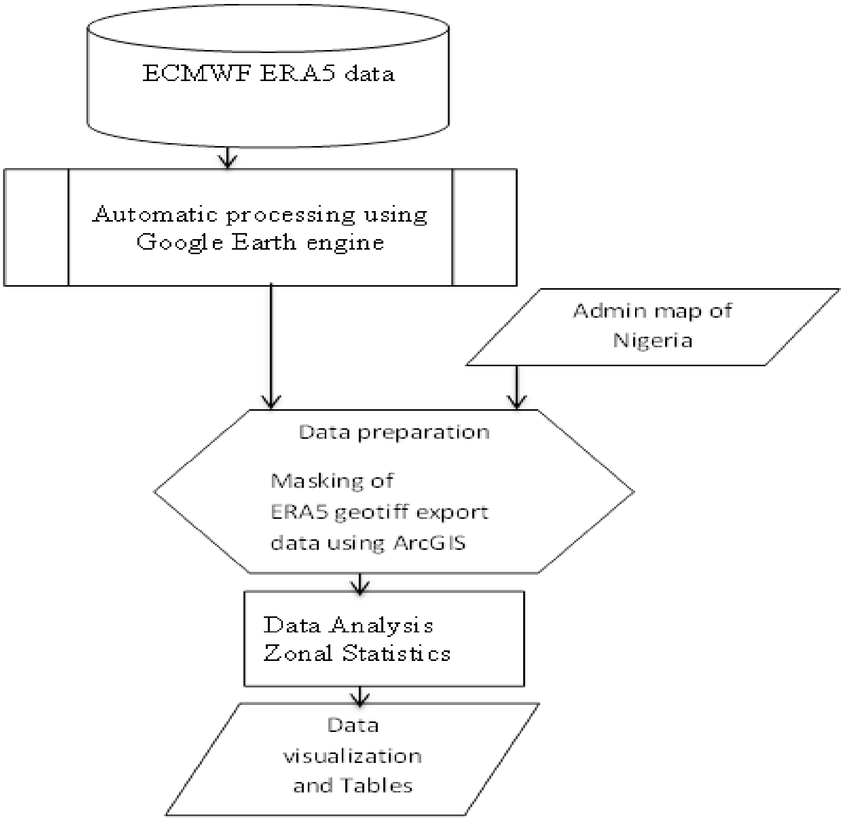

Figure 2 UTCI methodology workflow chart.

Calculation of UTCI

The UTCI is calculated using a complex formula that accounts for air temperature, mean radiant temperature, relative humidity, wind speed, and clothing insulation (Bröde et al., 2012). The specific equation is as follows:

[UTCI = f(T_a, T_r, RH, V, Clo)]

Where:

- (T_a) = air temperature (°C)
- (T_r) = mean radiant temperature (°C)
- (RH) = relative humidity (%)
- (V) = wind speed (m/s)
- (Clo) = clothing insulation (clo)

For this study, values of clothing insulation were assumed to be constant at 1.0 clo, representing standard clothing.

The input parameters for UTCI calculation are air temperature (°C), relative humidity (%), wind speed (m/s at 10m height), and mean radiant temperature (°C). UTCI provides a continuous scale of thermal perception, which is then categorized into ten physiological stress levels, ranging from extreme cold stress to extreme heat stress (Bröde et al., 2012). This comprehensive approach, its global applicability, and its direct physiological basis make UTCI a superior index for assessing human thermal comfort and stress under varying climatic conditions (Blazejczyk et al., 2012).

Studies have successfully applied UTCI across diverse regions, from Europe (Buzasi et al., 2015) to Asia (Hofman et al., 2019) and other parts of Africa (Ngaruye & Ndarana, 2023), confirming its robustness and utility in biometeorological research and climate change impact assessments.

Table 1 UTCI Thermal Stress Classification Scale.

UTCI Range (°C)	Stress Category	Physiological Response / Implications
46	Extreme Heat Stress	Very high level of heat strain
40 – 46	Very Strong Heat Stress	Strongly hot environment
32 – 40	Strong Heat Stress	Hot environment.
26 – 32	Moderate Heat Stress	Warm environment
9 – 26	No Thermal Stress	Thermally neutral
0 – 9	Slight Cold Stress	Slightly cool.
-13 – 0	Moderate Cold Stress	Cool to cold
-27 – -13	Strong Cold Stress	Cold environment
-40 – -27	Very Strong Cold Stress	Very cold
< -40	Extreme Cold Stress	Extremely cold

3.3. Data Analysis

Hourly ERA5 data were downloaded for the entire study area. UTCI was calculated on an hourly basis and then aggregated to produce long-term monthly and annual means for the 1940, 1970, 2000 and 2024 period. Spatial maps were generated using ArcGIS 10.8 Geographic Information System (GIS) software to visualize the distribution of mean UTCI and the corresponding physiological stress categories.

4. Results and discussion

4.1. Spatial Distribution of Mean Annual UTCI

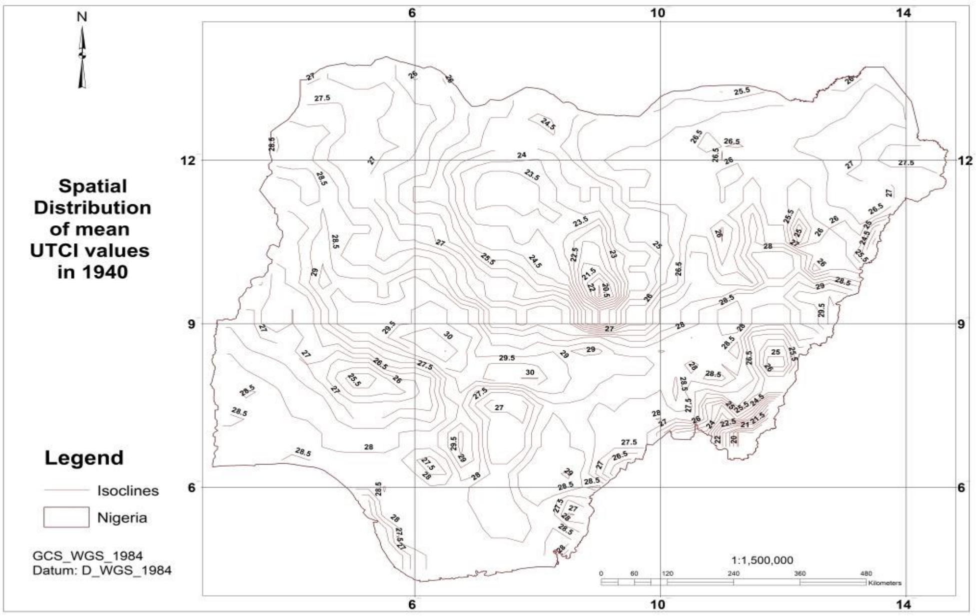

Figure 3 Map of Nigeria showing the spatial distribution of mean UTCI values in 1940.

The analysis reveals a distinct and strong north-south gradient in mean annual physiological stress across Nigeria (Figure 2-5).

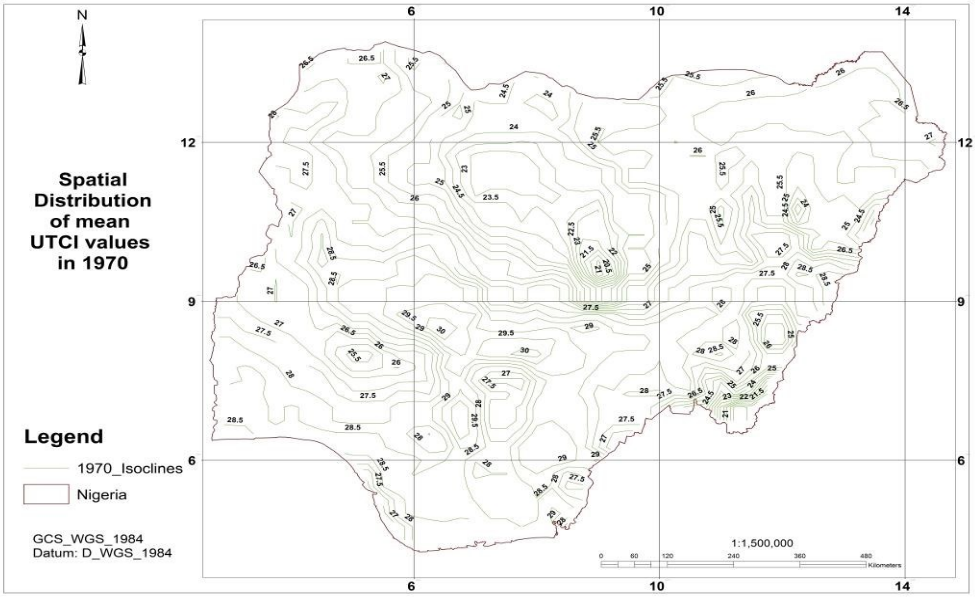

Figure 4 Map of Nigeria showing the spatial distribution of mean UTCI values in 1970.

The highest mean UTCI values are found in state, such as Anambra, Ogun and Rivers. In these regions, the mean annual UTCI consistently exceeds 32°C in 2024, placing them firmly within the 'Strong Heat Stress' category on an average day.

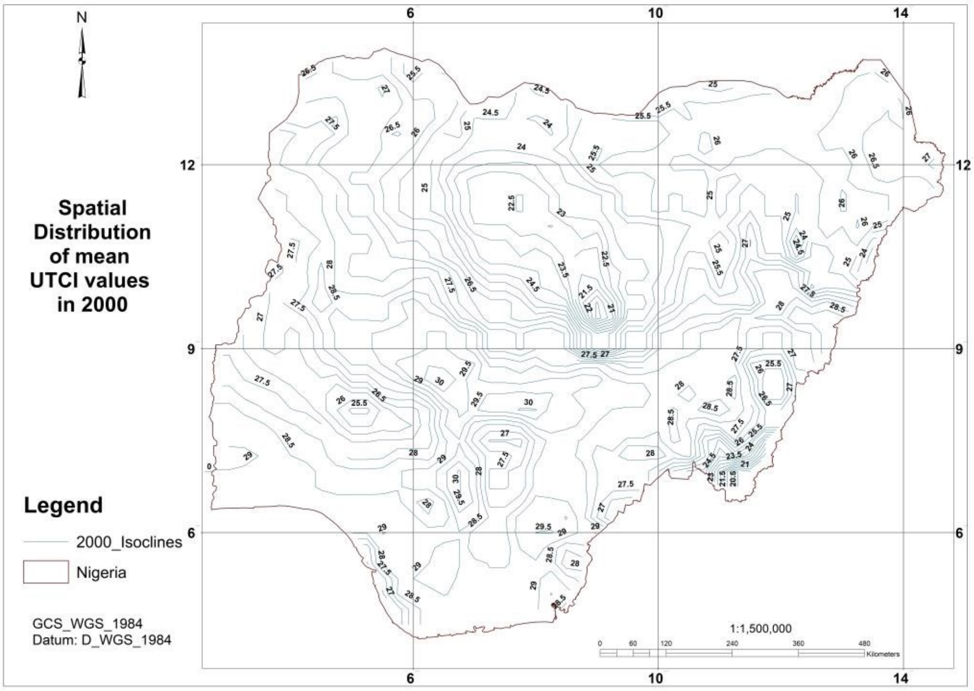

Figure 5 Map of Nigeria showing the spatial distribution of mean UTCI values in 2000.

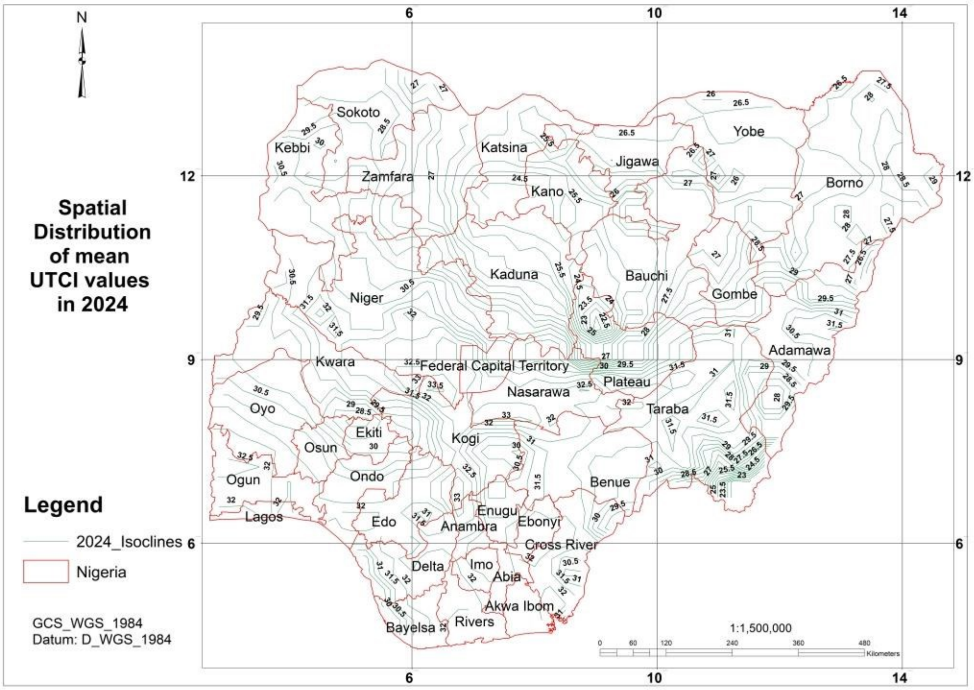

Figure 6 Map of Nigeria showing the spatial distribution of mean UTCI values in 2024.

Conversely, the northern part of the country, particularly the Katsina state, exhibits the lowest mean annual UTCI values, generally falling between 24°C and 35°C. These values correspond to the 'Moderate Heat Stress' category. The central belt of Nigeria, including the Federal Capital Territory, acts as a transition zone, with mean UTCI values typically ranging from 28°C to 31°C.

4.2. Statistical Analysis

Basic descriptive statistics (means, maximums, minimums) computed for UTCI values across Nigeria and different regions (see Table 2-3).

Table 2 Descriptive statistics computed for UTCI values for Nigeria.

Year	Min	Max	Mean	Mean Changes	1940-2024_ change
1940	19.95321	30.51568	26.94857		
1970	20.08596	30.46136	26.69376	-0.25	
2000	20.23043	30.42144	26.77555	0.08	
2024	22.03539	33.5472	29.20467	2.43	2.26

Table 3 Descriptive statistics computed for UTCI values for Nigeria various States.

States	MIN_1940	MAX_1940	MEAN_1940	MIN_2024	MAX_2024	MEAN_2024
Abia	27.65	28.38	27.92	31.07	32.01	31.56
Adamawa	23.74	29.59	27.29	25.50	31.63	29.49
Akwa Ibom	27.81	28.74	28.15	31.54	32.13	31.83
Anambra	27.68	29.46	28.50	31.28	33.21	32.17
Bauchi	21.88	27.16	25.32	23.77	29.30	26.33
Bayelsa	26.52	28.35	27.73	29.96	32.26	31.46
Benue	26.40	29.10	28.17	29.28	32.24	31.26
Borno	24.12	28.47	26.70	26.05	30.03	27.76
Cross River	26.21	29.07	28.09	29.10	32.46	31.41

States	MIN_1940	MAX_1940	MEAN_1940	MIN_2024	MAX_2024	MEAN_2024
Delta	26.68	28.47	27.99	30.12	32.35	31.67
Ebonyi	27.98	28.92	28.69	31.05	32.21	31.92
Edo	26.83	28.89	28.04	29.90	32.58	31.63
Ekiti	25.66	26.77	26.14	28.84	29.97	29.36
Enugu	27.01	28.74	27.51	30.49	32.39	30.99
FCT	27.21	29.45	28.32	30.28	32.73	31.49
Gombe	25.44	28.33	26.71	26.57	30.22	28.02
Imo	27.51	28.37	27.94	31.01	32.08	31.60
Jigawa	24.52	26.42	25.82	25.16	27.41	26.58
Kaduna	22.31	27.32	24.53	24.03	30.38	26.62
Kano	23.27	25.92	24.57	24.38	27.14	25.55
Katsina	23.34	25.20	24.40	24.19	26.23	25.40
Kebbi	25.44	28.68	27.89	27.54	30.68	29.78
Kogi	26.27	30.29	28.00	29.39	33.53	31.38
Kwara	25.13	30.34	27.62	28.30	32.97	30.47
Lagos	28.02	28.58	28.32	31.77	32.05	31.93
Nassarawa	23.44	30.02	28.34	25.59	33.10	31.39
Niger	25.42	30.52	28.21	27.62	33.55	30.75
Ogun	27.98	28.64	28.32	31.48	32.88	32.12
Ondo	26.79	28.46	27.76	29.96	32.09	31.21
Osun	25.13	27.97	27.13	28.30	31.54	30.46
Oyo	26.70	28.56	27.70	29.52	32.19	30.85
Plateau	20.39	29.14	25.74	22.04	32.47	28.15
Rivers	28.02	28.32	28.21	31.79	32.33	32.01
Sokoto	25.96	27.69	26.90	26.48	29.97	28.43
Taraba	19.95	28.77	26.94	22.53	32.09	29.88
Yobe	24.99	26.88	26.09	25.77	28.16	26.60
Zamfara	23.95	27.22	25.86	25.11	29.66	27.44

Table 4 Mean Changes computed for UTCI values for Nigeria various States.

States	Mean 1940	Mean 2024	Mean Changes
Abia	27.92	31.56	3.64
Adamawa	27.29	29.49	2.19
Akwa Ibom	28.15	31.83	3.68
Anambra	28.50	32.17	3.67
Bauchi	25.32	26.33	1.01
Bayelsa	27.73	31.46	3.73
Benue	28.17	31.26	3.09
Borno	26.70	27.76	1.06
Cross River	28.09	31.41	3.31
Delta	27.99	31.67	3.68
Ebonyi	28.69	31.92	3.23
Edo	28.04	31.63	3.60
Ekiti	26.14	29.36	3.21
Enugu	27.51	30.99	3.48
Federal Capital Territory	28.32	31.49	3.17
Gombe	26.71	28.02	1.32
Imo	27.94	31.60	3.66
Jigawa	25.82	26.58	0.76
Kaduna	24.53	26.62	2.09
Kano	24.57	25.55	0.98
Katsina	24.40	25.40	1.00

States	Mean 1940	Mean 2024	Mean Changes
Kebbi	27.89	29.78	1.89
Kogi	28.00	31.38	3.39
Kwara	27.62	30.47	2.85
Lagos	28.32	31.93	3.62
Nassarawa	28.34	31.39	3.04
Niger	28.21	30.75	2.54
Ogun	28.32	32.12	3.80
Ondo	27.76	31.21	3.45
Osun	27.13	30.46	3.33
Oyo	27.70	30.85	3.15
Plateau	25.74	28.15	2.40
Rivers	28.21	32.01	3.80
Sokoto	26.90	28.43	1.53
Taraba	26.94	29.88	2.95
Yobe	26.09	26.60	0.51
Zamfara	25.86	27.44	1.58

4.3. Discussion

The results of this study quantitatively confirm that a significant portion of Nigeria's population is exposed to chronic physiological heat stress. The clear north-south gradient is directly linked to Nigeria's macro-climatic controls. The southern states has higher thermal stress is a function of its lower latitude (closer to the equator), continental position, and dominance by the dry cT air mass, leading to higher solar insolation and air temperatures. In contrast, the prevalence of the moist mT air mass leads to more cloud cover and atmospheric moisture, which moderates temperature but maintains high humidity, resulting in persistent 'Moderate Heat Stress' in some states.

These findings have profound implications. For the million people living in southern and northern Nigeria, conditions of 'Strong' to 'Very Strong Heat Stress' for several months of the year pose a serious threat to public health. This increases the risk of heat-related illnesses such as heat exhaustion and heatstroke, particularly for vulnerable populations including children, the elderly, and outdoor workers in agriculture and construction (UNDP, 2021).

The reliance on advanced indices like UTCI over simple temperature is critical. A day with 25°C in dry, windy Katsina will generate a different physiological response than a 32°C day in humid, calm Port Harcourt. UTCI captures this nuance, providing a more accurate tool for risk assessment. For instance, the high humidity in the south means that even at lower air temperatures, the body's ability to cool itself through sweating is compromised, leading to sustained moderate stress.

Limitations of this study include the use of reanalysis data, which, despite its high quality, is still a model-based approximation of reality and may not capture fine-scale microclimatic variations within cities (the Urban Heat Island effect). Furthermore, this study focuses on climatological means, while extreme heat events are often the most dangerous.

ERA5-Land offers improved representation of surface variables such as soil moisture and snow depth due to its higher resolution and offline land surface forcing, whereas ERA5 provides essential atmospheric variables.

5. Conclusion

This research offers the initial thorough evaluation of physiological thermal strain across Nigeria, utilizing UTCI and ERA5 data on a national scale. The main discovery indicates that the UTCI values in Nigeria range from 26 to 32 degrees Celsius, indicating a moderate level of heat stress that presents notable risks to both human health and economic output.

Based on these findings, we recommend the following:

1. Integration into Public Health Systems: Nigerian health agencies should incorporate UTCI-based forecasts into public heat-health warning systems to issue timely and location-specific advisories.

2. Urban and Regional Planning: Planners must prioritize heat-mitigation strategies, such as increasing green infrastructure, promoting reflective building materials, and ensuring access to cooling centers, especially in northern cities.

3. Occupational Safety Standards: Guidelines for work-rest cycles and hydration for outdoor laborers in sectors like agriculture and construction need to be established and enforced, particularly during the high-risk pre-monsoon season.

Future research should focus on projecting future heat stress under different climate change scenarios (e.g., using CMIP6 models), conducting micro-scale analysis of urban areas, and integrating socio-economic vulnerability data to create comprehensive heat risk maps for Nigeria.The main conclusions of the study must be presented here.

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