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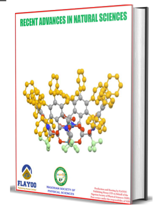

Diurnal solar energy and temperature changes over Nigeria using satellite data

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A R T I C L E I N F O

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A B S T R A C T

This study investigated the diurnal variability of global horizontal irradiance (GHI) and surface temperature across Nigeria's major climatic zones. Daily all-sky surface shortwave downward irradiance and 2-m air temperature data spanning 2001–2023 were obtained from the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). The daily datasets were aggregated into monthly means and analyzed across four climatological seasons. Daily variability was quantified using standard deviation, while long-term trends were assessed using simple linear regression, with statistical significance evaluated at $p < 0.05$. The relationship between GHI and surface temperature was examined using Pearson's correlation coefficient. Results show that daily GHI variability was highest in the southern tropical monsoon and tropical rainforest zones, whereas daily temperature variability was greatest in the northern warm desert and warm semi-arid regions. Monthly analysis revealed that GHI peaked in April over northern zones but reached maximum values in February across other regions. Surface temperature was highest between March and May, but lowest in August for the tropical monsoon, tropical rainforest, and Mediterranean climates; January for the warm semi-arid and warm desert climates; and December for the tropical savanna climate. Correlation analysis indicated very weak to moderate relationships between GHI and surface temperature. Regression results revealed a very weak to weak positive relationship, with significant differences across all locations examined ($p < 0.0001$). Long-term trends showed a slight increase in GHI across all climatic zones, while surface temperature increased marginally in most regions except the northern warm semi-arid and warm desert zones.

1. INTRODUCTION

Diffused horizontal irradiance (DHI) and direct normal irradiance (DNI) incident on the earth's surface in the form of shortwave radiation add up to the all-sky surface shortwave downward irradiance, also known as global horizontal irradiance (GHI). It is the main energy source that propels the hydrological cycle and a measure of the amount of solar energy that reaches the Earth's surface under various atmospheric conditions and is useful for environmental, physical, and biological processes (like photosynthesis, soil and air warming, moisture evaporation, and evap-

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otranspiration) [1, 2].

The intensity of insolation received at a location on the earth's surface is typically influenced by a number of factors, including the time of day, season, cloud cover, atmospheric gas molecules, aerosols, temperature, atmospheric and geographic features, as well as the conditions and types of the surface (bare, vegetated, water, etc.) [3]. It is essential to understand incoming irradiation since it affects land-surface processes, photovoltaic solar applications, validation of crop growth simulation models and surface radiation energy balance. Because of these, many studies on incoming solar radiation have been carried out worldwide, but there is scanty research for the entirety of the tropical region of Nigeria, where a sizable amount of solar radiative flux is received each year [4].

Few researchers have undertaken studies on Nigeria radiative flux; Jegede et al. 2006 found significant differences in net radiation parameterizations from Ile-Ife, Nigeria, indicating cloudiness's impact on tropical atmosphere radiative balance, with good correlations between the schemes [5]. Falodun and Ogolo, 2007 found maximum solar radiation varying between 512 W/m^2 and 543 W/m^2 over two years, and a 2-hour lag between air temperature and radiation courses in Akure, Nigeria [6]. And Ogolo et al. 2009 study on surface radiation balance components during NIMEX-1 revealed a shift in heat fluxes, with peak radiation values occurring two hours after noon [7].

Additionally, Adeniyi et al. 2012 analyzed total solar radiation in Ibadan, Nigeria from 1997 to 2001, and found maximum radiation in March/April/May and October/November, and positive annual trend indicating global brightening, with significant intra-annual cycles [8]. Oladosu et al. 2012 found a daily mean of 143.66 ± 11.79 W/m^2/day, with a maximum of 653.42 ± 32.33 W/m^2/day, and fluctuations during the wet season for global solar radiation flux in Iju, Nigeria for 2008 [9].

Examination of diurnal and seasonal variations on global solar radiation in Akure, Nigeria, revealed increases from dawn to 14:00 hours, then decreases in the late afternoon and evening, with maximum values during February and April; and minimum values between June and October [10]. In the same vein, Ayoola et al. 2014 assessment of net all-wave radiation at Obafemi Awolowo University in Nigeria revealed hourly maxima at 14:00 LT, significant increases in the wet season, strong intra/inter-seasonal variation, and a net radiative heating at the surface, with bimodal annual trend [3]. Furthermore, diurnal and seasonal variations on incoming solar radiation flux in Ile-Ife, Nigeria found maximum flux between 13:00-14:00 local time, with varying intensity in the wet and dry months, also a double peak in March/May/October/November and a minimum in July/August [2].

Accordingly, diurnal and seasonal variations in solar radiation at Anyigba, Nigeria varied across four seasons, with surface temperature influenced by atmospheric response to solar radiation and not directly dependent on sun temperature, with year 2012 exhibiting lower radiation due to higher rainfall [11]. Chiemeka, 2008 used the Hargreaves equation on temperature data from October 5th to 31st, 2007 to estimate solar radiation at Uturu, Nigeria and found a mean global radiation of 1.89 ± 0.82 kWh per day [12].

The reviewed studies are all one location based, hence the need for a broader coverage of the nation. The objectives of this article are to (a) quantify the diurnal patterns of GHI in various Nigerian regions, (b) examine the daily variability of all-sky surface shortwave downward irradiance in relation to surface temperature, and (c) determine the spatial and temporal distribution of solar energy potential over Nigeria. By achieving the mentioned objectives, the study will bring about increase in understanding of Nigeria's solar radiation patterns, growth in solar energy projects and enhance resource management strategies. Furthermore, the study's findings will serve as a helpful tool for future research on the region's climate unpredictability and solar energy potential.

2. METHODOLOGY

2.1. THE STUDY AREA

Nigeria, located in West Africa, is notable for its varied climate and geographical features. The country is positioned between 4^o North and 14^o North of the equator and between 3^o East and 15^o East of the Greenwich meridian, covering a total area of 923,768 square kilometers. It shares its southern border with the Gulf of Guinea alongside Benin and Cameroon, while Chad and Niger border the north. In the southern region, Nigeria experiences constant humidity, extensive cloud cover, and minimal solar exposure, whereas the northern region endures a drier climate with distinct wet and dry seasons. Different areas across the nation receive vastly different levels of rainfall. The northern Sahel region relies on irrigation due to its more pronounced dry season, marked by high solar radiation and aerosols, while the Niger Delta in the south flourishes with dense vegetation thanks to its abundant cloud cover and rainfall. The landscape features plains, plateaus, and mountains, with the Jos Plateau in the center and the Adamawa Plateau in the northeast being particularly prominent. The coastal plains and mangrove swamps in the southwest enhance the nation's rich biodiversity. Climate patterns are shaped by interactions between the Atlantic Ocean, the Gulf of Guinea, and Nigeria's southern coastline, influencing the country's ecology, agriculture, and lifestyle. Nigeria is divided into thirty-six states and the Federal Capital Territory, Abuja.

The study area is shown in Fig. 1 with partitions displaying Koppen climate classifications Af, Am, Aw, BSh, BWh, and Csb, which stand for Tropical Rainforest, Tropical Monsoon, Tropical Savanna, Hot Semi-Arid Climate (Steppe), Hot Desert, and Mild Temperature with Dry/Warm Summer Climates [13].

2.2. SOURCES OF DATA

To examine the connection between daily global horizontal irradiation (GHI) and surface temperature over Nigeria, daily all sky surface shortwave downward irradiance measured in kW-hr/m^2/day and daily temperature at 2 Meters measured in ^{o}C datasets between 2001 and 2023 were acquired from the archives of the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) obtained from https://power.larc.nasa.gov/data-access-viewer/. The GHI data was converted to W/m^2, and along with temperature obtained at 0.5^o × 0.625^o resolution were sampled to 0.038^o × 0.038^o. Additionally, Beck et al. 2023 provided a qualitative framework for characterizing the climates of particular regions within the study area by integrating the Koppen climate classification [14]. This was accessed at https://www.gloh2o.org/koppen/, at 0.01^o × 0.01^o res-

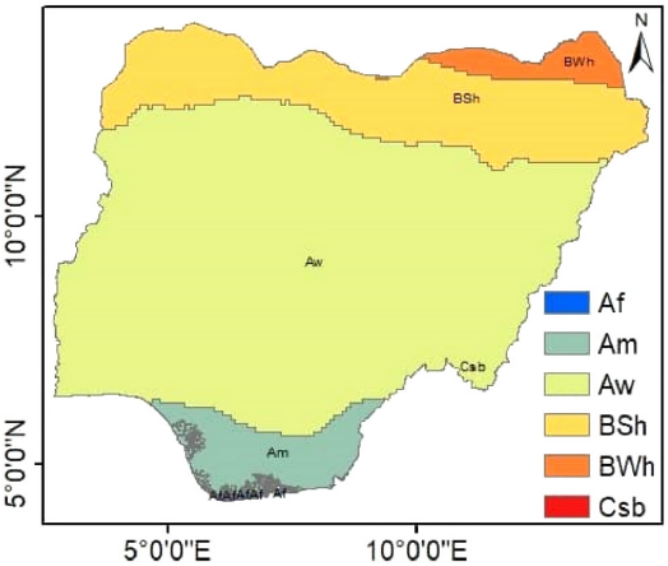

Figure 1. The study area with partitions displaying Koppen climate classifications: Af, Am, Aw, BSh, BWh, and Csb [13].

olution.

2.3. DATA PROCESSING AND ANALYSIS

2.3.1. Monthly and seasonal variations of daily GHI and temperature

To understand the monthly and seasonal changes in GHI and temperature, the daily datasets were grouped into monthly and divided into four seasons: dry [December–January–February (DJF)], pre-wet [March–April–May (MAM)], wet [June–July–August (JJA)] and pre-dry [September–October–November (SON)]. Variability was determined by means of standard deviation (equation (1)) from the daily, monthly, and seasonal mean for both GHI and temperature. This is in line with a number of earlier researches that employed standard deviation to study variability [15, 16].

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(GHI_i - \overline{GHI}\right)^2}, \tag{1}$$

where σ is the variability, N is the number of data points, GHI_i is each individual value in the dataset, and $\overline{GHI}$ is the population mean. GHI in equation (1) was subsequently replaced with temperature values and mean for the estimation of variability in daily surface temperature.

2.3.2. Long-term trend analysis

Long-term trends were calculated using the simple linear regression (equation (2)) of the datasets, with $p < 0.05$ values taken to be statistically significant. In this study, GHI was the independent and temperature the dependent variable. Likewise, GHI and Temperature as the dependent and time (year) as the independent variable for the computation of long-term GHI and temperature trends. Journée, et al. 2012 used a similar technique to calculate trends in surface irradiance over Benelux [17].

$$GHI = \varepsilon + Temp.\beta, \tag{2}$$

where Temp is the dependent variable, GHI is the independent variable, ε is the intercept, and β is the slope.

The slope β was determined using equation (3).

$$\beta = \frac{\sum (GHI_i - \overline{GHI})(Temp_i - \overline{Temp})}{\sum (GHI_i - \overline{GHI})^2}. \tag{3}$$

2.3.3. Correlation of GHI and temperature

Pearson's correlation coefficient (equation (4)) was used to estimate the magnitude and direction of the linear connection between GHI and temperature over the study period. The daily GHI and surface temperature data were re-gridded using linear interpolation to match the dataset resolutions.

$$r = \frac{\sum_{i=1}^{n} (Temp_i - \overline{Temp})(GHI_i - \overline{GHI})}{\sqrt{\sum_{i=1}^{n} (Temp_i - \overline{Temp})^2}.\sqrt{\sum_{i=1}^{n} (GHI_i - \overline{GHI})^2}}, \tag{4}$$

where n is number of observations.

3. RESULTS ANALYSIS AND DISCUSSION

3.1. DAILY GHI CHANGES

Daily changes in GHI reveal the cumulative effects of atmospheric conditions, the solar angle, and local weather patterns on solar radiation at the surface. Understanding these variations is essential for evaluating short-term solar energy potential, particularly in enhancing the efficiency of photovoltaic systems and predicting daily energy production. Fig. 2 illustrates the spatial and temporal variations in daily GHI across various regions of Nigeria.

Fig. 2 show that variations in daily GHI had significant differences across Nigeria's Köppen climate zones. The tropical monsoon (Am) zone displayed the highest variability of 103.37 W/m^2, indicating considerable daily fluctuations driven by cycles of heavy cloud cover and clear skies typical of monsoon climates. In a similar vein, the tropical rainforest (Af) zone, followed closely with a high variability of 103.24 W/m^2. The tropical savanna (Aw) and semi-arid (BSh) zones demonstrated moderate to high average variability (up to 89.66 and 83.27 W/m^2, respectively), reflecting significant impacts on solar radiation trends. On the other hand, the hot desert (BWh) zone exhibited relatively lower variability (maximum of 75.41 W/m^2), which may be linked to clearer skies, although occasional dust haze could cause short-term variations. The warm-summer Mediterranean (Csb) zone, likely representing elevated regions, showed the most stable conditions, with an average variability of 85.06 W/m^2, indicating minimal atmospheric disruptions. These variations in GHI directly affect the design and efficiency of solar energy systems, particularly in aligning energy output reliability with local climatic conditions.

3.2. DAILY TEMPERATURE CHANGES

Evaluating daily temperature changes offers understanding of the impact of solar energy on thermal conditions in various climatic regions. Fig. 3 illustrates the spatial and temporal variations in daily surface temperature across various regions of Nigeria.

Fig. 3 shows that the examination of daily surface temperature changes across Nigeria's Köppen climate zones uncovers

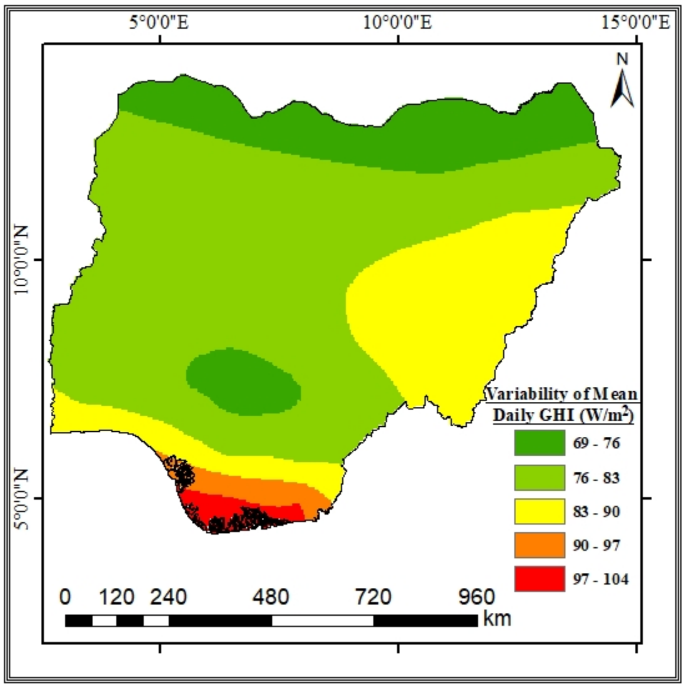

Figure 2. Variability (standard deviation) of mean daily global horizontal irradiance (W/m^2) over Nigeria. Data span from 2001 to 2023.

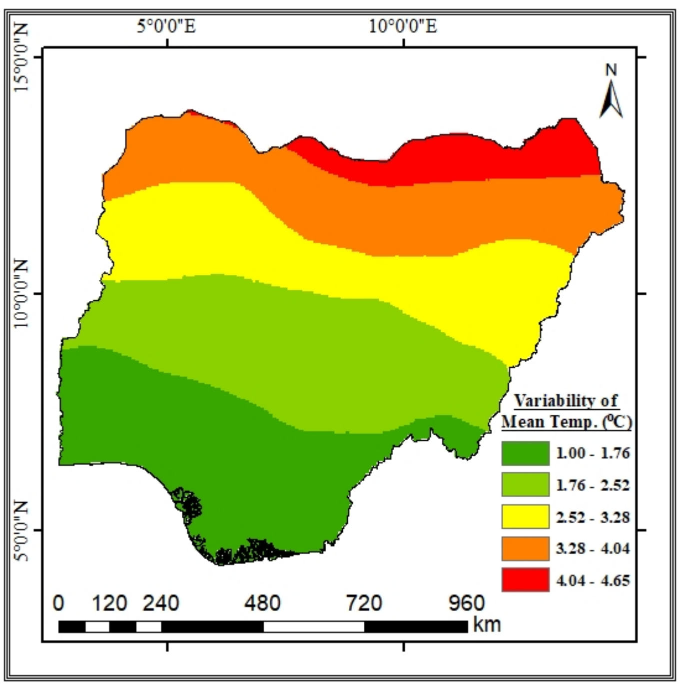

Figure 3. Variability (standard deviation) of mean daily surface temperature (°C) over Nigeria. Data span from 2001 to 2023.

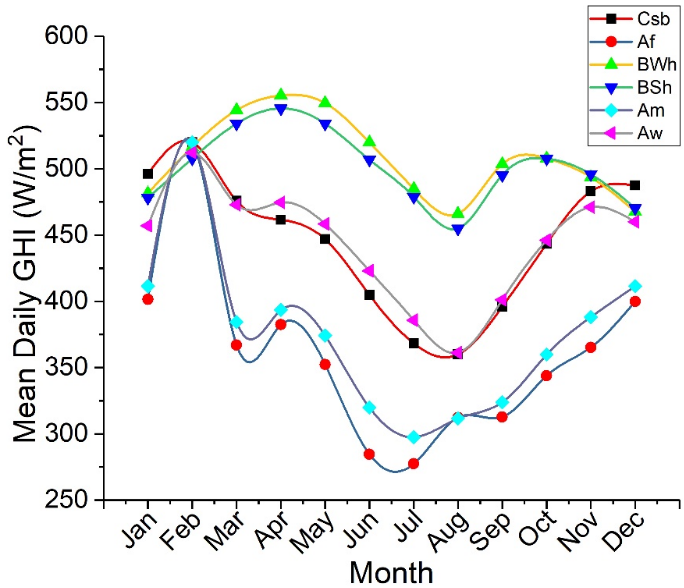

Figure 4. Mean monthly GHI over Nigeria's Koppen climate zones. The data extend from 2001 – 2023.

significant spatial trends in temperature consistency. The BWh displayed the highest variability, recording a standard deviation of 4.65°C. This is indicative of a typical arid environment characteristics, where clear skies and low humidity lead to extreme daytime warmth and rapid cooling at night. The BSh followed closely with variability up to 4.46°C, suggesting pronounced changes in temperature stability—likely influenced by alternating dry and wet seasons. On the contrary, the Af revealed the least variability of 1.04°C, illustrating humid, and cloudy conditions that lessen temperature excesses all year round. The Am and Csb zones also demonstrated relatively low variability, with maximum values of 1.40°C and 1.58°C respectively, aligning with areas that experience moderate climatic effects and oceanic moisture influences. Interestingly, the Aw zone showed a moderate variability (ranging between 1.12 and 3.79°C), reflecting notable diversity in surface temperature trends.

3.3. MEAN MONTHLY CHANGES OF GHI OVER NIGERIA

The mean monthly changes of GHI across Nigeria's Koppen climates, showing trends and variations, critical for comprehending the nation's solar energy potential through the years is in Fig. 4.

Fig. 4 shows that between 2001 and 2023, the mean monthly changes of GHI across Köppen climate zones in Nigeria are significant and vary across the regions. The northern BWh and BSh regions consistently showed the highest and most consistent GHI values, with BWh reaching a peak of 555.45 W/m^2 in April and dropping to 466.11 W/m^2 in August, while BSh varied from 545.67 W/m^2 in April to 454.78 W/m^2 in August, offering ideal conditions for solar energy production throughout the year. On the contrary, the southern Af and Am zones experienced sharp seasonal declines, both peaking at 520.11 W/m^2 in February but dropping to 277.44 W/m^2 and 297.50 W/m^2 in July, respectively, likely due to continuous cloud coverage. The Csb and Aw regions displayed moderate GHI values with wieldy seasonal fluctuations, Csb varied from 520.11 W/m^2 in February to 359.93 W/m^2 in August, and Aw from 512.24 W/m^2 in February to 361.26 W/m^2 in August, making these areas suitable for effectively designed solar systems. In summary, the data indicates that the northern regions are the most advantageous for solar energy implementation, while the southern areas may need storage or hybrid solutions for consistent energy supply. Adeniyi, et al. 2012 made similar observations for Ibadan, Nigeria [8].

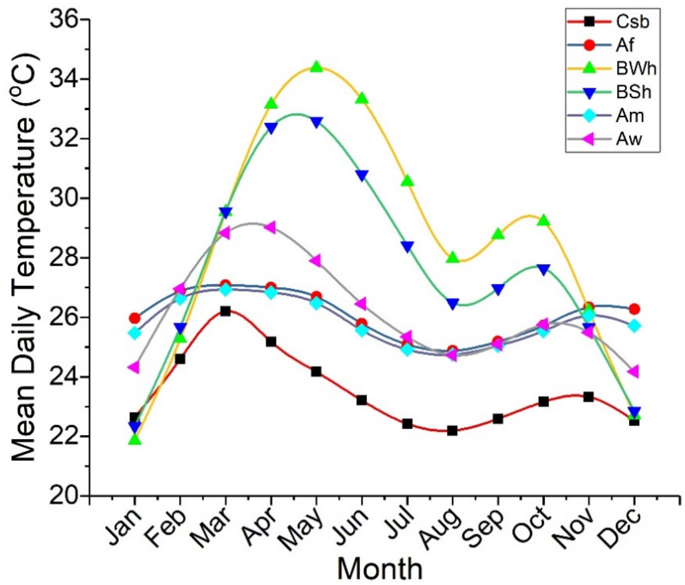

Figure 5. Mean monthly surface temperature over Nigeria's Koppen climate zones. The data extend from 2001 – 2023.

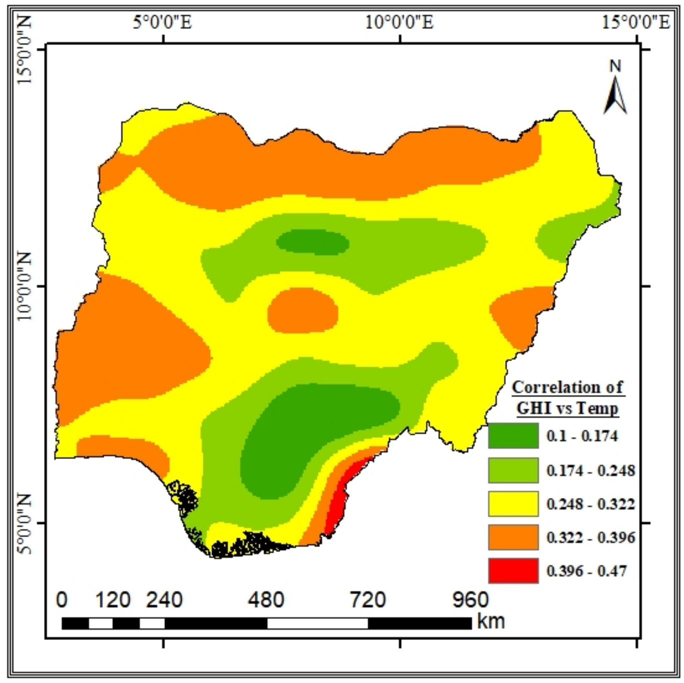

Figure 6. Correlation between GHI and surface temperature over Nigeria. The data cover from 2001 – 2023.

3.4. MEAN MONTHLY CHANGES OF SURFACE TEMPERATURE OVER NIGERIA

Temperature changes are connected to solar radiation patterns, especially GHI, which dictates surface warming during the day. Examining surface temperature variations offers understanding of how solar energy affects thermal conditions in various climate regions. Fig. 5 is the monthly change in surface temperature.

Fig. 5 shows that between 2001 and 2023, the average monthly temperature data across the Köppen climate zones in Nigeria exhibited distinct spatial and periodic trends. The northern BWh and BSh zones consistently recorded the highest temperatures, with BWh hitting a peak of 34.39°C in May and BSh reaching 32.59°C in the same month, reflecting the intense solar heating and low humidity characteristic of these arid areas. In contrast, the Csb zone experienced the lowest temperatures throughout the year due to its elevation, ranging from 22.19°C in August to a peak of 26.20°C in March, indicating a cooler and more temperate climate. The Af and Am zones exhibited relatively stable temperatures year-round, with Af ranging from 24.88°C in August to 27.08°C in March, and Am from 24.74°C to 26.93°C in the same months, attributed to constant cloud cover and high humidity that lessen temperature variations. The Aw zone, which is the distinctive of central Nigeria, displayed moderate temperature values with a wider range, rising from 24.18°C in December to 29.02°C in April, reflecting a transitional climatic position between the wetter southern regions and the drier northern ones. Notably, the warmest months in most of these regions transpired from March to May, preceding the onset of the rainy season, whereas the coldest months were observed in August for the southern Am and Af climates, as well as the Csb (aligning with maximum precipitation and extensive cloud cover), and in January for the northern BWh and BSh climates, along with the Aw climate in December (coinciding with the arid harmattan season).

3.5. CORRELATION BETWEEN GHI AND SURFACE TEMPERATURE OVER NIGERIA

The spatial distribution of the correlation between daily GHI and surface temperature over Nigeria is presented in Fig. 6.

Fig. 6 shows that the southern part of the country, where tropical rainforest (Af) and monsoon (Am) climates prevail, moderate correlations are noted along the southeast coast, with coefficient of correlation (r-values) reaching up to 0.45. This finding is to some extent surprising, as these areas typically have substantial cloud cover and rainfall, which would usually diminish solar irradiance; however, clearer skies during dry intervals may strengthen the correlation between GHI and temperature. The central region of Nigeria, characterized by a tropical savanna (Aw) climate, shows a range of weak correlation with r-values between 0.22 to 0.35. This inconsistency may be due to seasonal changes, higher humidity in the atmosphere, and variations in local elevation that impact irradiance and temperature. In the northern BSh and BWh climates, weak correlations with r values up to 0.33 are found. In this area, the generally dry and clear conditions allow solar radiation to directly affect surface temperature. The Csb region also exhibited a weak positive correlation with r values up to 0.31, indicating a consistent relationship between solar input and temperature, despite the cooling effects of altitude. This agrees favourably with Adedoja et al. 2015, who also observed that surface temperature was influenced by atmospheric response to solar radiation and not directly dependent on sun temperature [11].

3.6. REGRESSION SLOPE OF DAILY GHI AND SURFACE TEMPERATURE OVER NIGERIA

The regression slope of GHI and temperature over Nigeria (Fig. 7) illustrates the influence of global irradiance variations

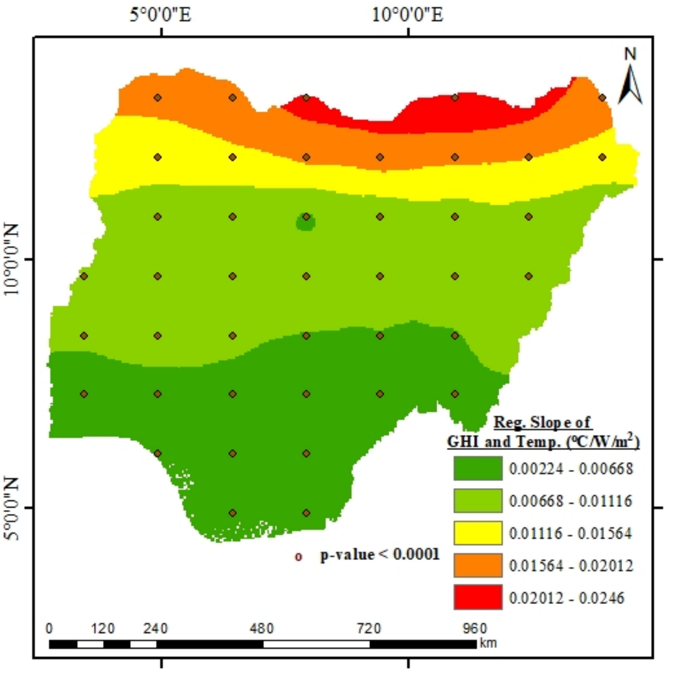

Figure 7. Spatial distribution of GHI versus temperature regression slopes over Nigeria. The data span from 2001 to 2023.

on surface temperature across various climatic zones.

The regression slope data of GHI and temperature across Nigeria's Köppen climate zones shows significant spatial differences in the intensity of their correlation. The BWh zone recorded the highest slope, ranging from 0.0154 to 0.0246°C/W/m^2, which indicates a consistent positive correlation between solar radiation and temperature. Similarly, the BSh zone presented a maximum slope of 0.023°C/W/m^2, suggesting effects of GHI on temperature. The Aw zone revealed slopes ranging from 0.0028 to 0.017°C/W/m^2, with good variability, implying that temperature responses to solar radiation differ within this transitional climate zone. In contrast, the Csb zone showed a relatively low, yet stable mean slope of 0.0055°C/W/m^2, indicating a very weak correlation, probably influenced by elevation and cooler temperatures. The Am and Af zones recorded the lowest slopes (ranging from 0.0022 to 0.0066 °C/W/m^2), indicating very weak correlations between GHI and temperature. These low values can be attributed to constant cloud cover, high humidity, and frequent rainfall, which restrict the direct effect of solar radiation on surface temperatures. Stippling shows significant differences ($p < 0.0001$) in all the points examined. The exceptionally low p-values reveal clearly that the independent variable (GHI) in each point significantly affects the dependent variable (temperature).

3.7. SEASONAL GHI AND TEMPERATURE TREND

Seasonal trends in GHI and surface temperature are crucial indicators of solar energy potential and climatic behavior. These trends are shaped by the Earth's axial tilt, atmospheric conditions, and local climate patterns that influence both the strength of incoming solar radiation and surface's thermal response. Table 1 shows the changes in GHI and temperature over the seasons, emphasizing trends unique to Nigeria's various climate zones, and offers insights into how these patterns can aid in renewable energy planning and climate-sensitive strategies.

Table 1. Seasonal GHI trend (W/m^2/month).

Koppen	DJF			MAM			JJA			SON			Av
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	
Csb	0.232	0.236	0.234	-0.087	-0.082	-0.084	-0.526	-0.512	-0.519	-0.138	-0.127	-0.132	-0.125
Af	0.075	0.125	0.098	0.196	0.230	0.208	0.552	0.635	0.617	-0.525	-0.441	-0.501	0.105
BWh	-0.051	0.493	0.224	-0.024	0.751	0.327	-1.078	0.522	-0.565	0.159	1.343	0.522	0.127
BSh	-0.051	0.462	0.225	-0.092	0.541	0.219	-1.171	0.026	-0.892	-0.131	0.638	0.219	-0.057
Am	0.077	0.263	0.138	0.047	0.389	0.247	-0.057	0.631	0.305	-0.530	-0.151	-0.371	0.080
Aw	0.090	0.423	0.281	-0.391	0.496	0.030	-1.194	0.476	-0.501	-0.422	0.419	-0.016	-0.052

Table 2. Seasonal temperature trend (°C/month).

Koppen	DJF			MAM			JJA			SON			Av
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	
Csb	0.043	0.047	0.045	0.013	0.015	0.014	0.009	0.010	0.009	0.043	0.047	0.045	0.028
Af	0.024	0.043	0.032	0.014	0.019	0.015	0.019	0.023	0.021	0.024	0.043	0.032	0.025
BWh	-0.050	-0.028	-0.037	0.011	0.015	0.013	-0.076	-0.046	-0.061	-0.050	-0.028	-0.037	-0.030
BSh	-0.063	-0.014	-0.043	0.005	0.016	0.011	-0.068	0.008	-0.044	-0.063	-0.014	-0.043	-0.030
Am	0.014	0.096	0.045	0.004	0.031	0.016	0.009	0.029	0.021	0.014	0.096	0.045	0.032
Aw	-0.087	0.117	-0.006	-0.008	0.034	0.012	-0.078	0.029	-0.011	-0.087	0.117	-0.006	-0.003

Table 1 shows that the seasonal trends of GHI across Nigeria's climate zones demonstrate diverse patterns of changes over time. The BWh and Af zones exhibited the most pronounced net increases in GHI, averaging +0.127 W/m^2/month and +0.105 W/m^2/month respectively. In the BWh zone, the most significant gains were observed during the SON season (up to 1.343 W/m^2/month), while the MAM season followed with a maximum trend of 0.751 W/m^2/month. In the Af region, GHI consistently raised from DJF (maximum of 0.125) to JJA (0.635 W/m^2/month), then a sharp decline in SON (mean -0.501 W/m^2/month), indicating possible increase in cloud cover, or other atmospheric parameters. The Am zone also showed a positive mean trend (+0.080), particularly high in JJA (up to 0.631 W/m^2/month), whereas the Csb, BSh, and Aw zones displayed negative trends of -0.125, -0.057, and -0.052 W/m^2/month, respectively although BSh and Aw recorded positive trends especially in the MAM and SON seasons. These downward trends are largely attributed to considerable reductions in GHI during the JJA and DJF seasons, especially within the Aw zone, where the decline reached -0.501 W/m^2/month during JJA. This analysis indicates that while certain zones witnessed increases in solar

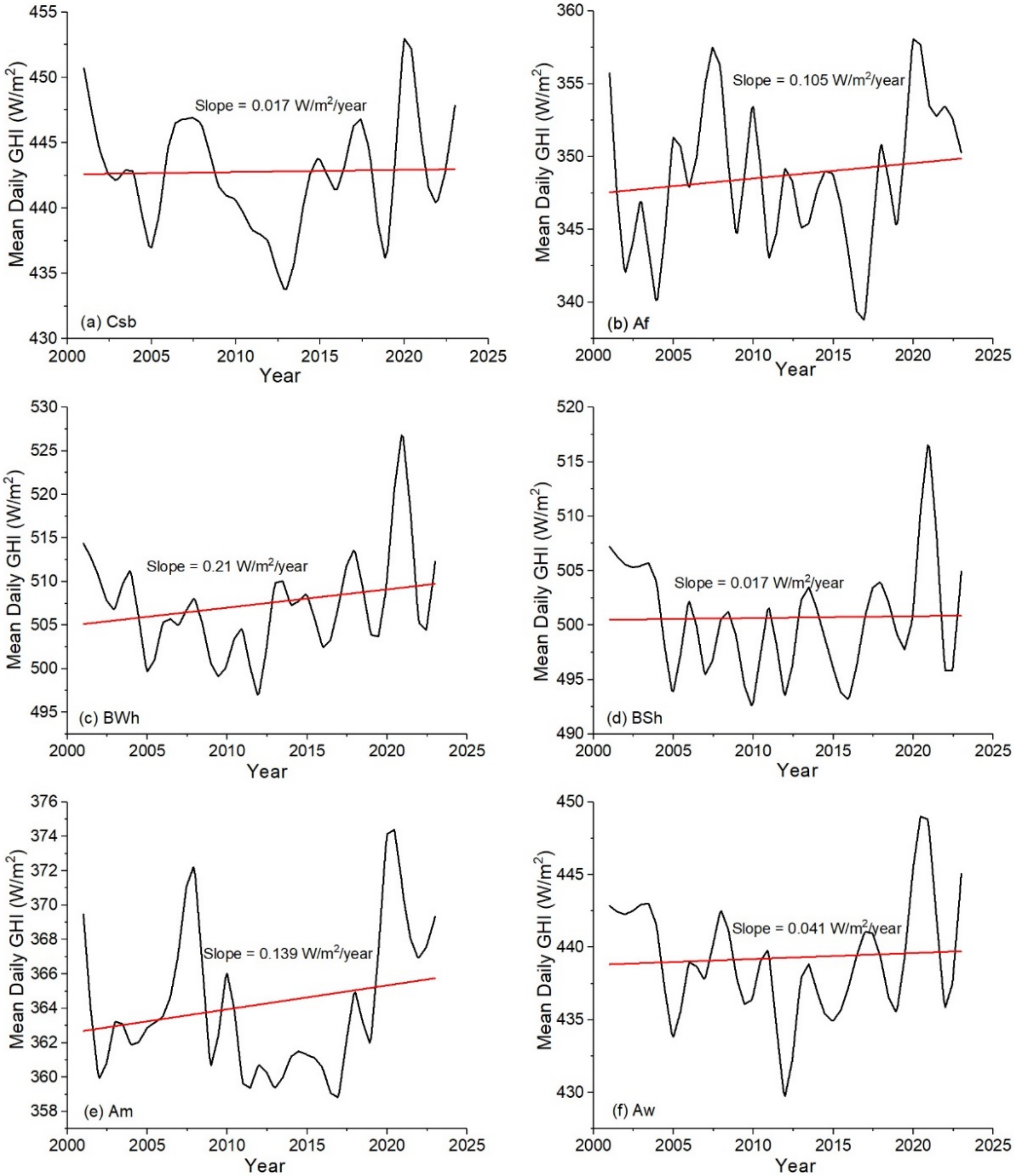

Figure 8. Mean daily GHI vs time series plots over Nigeria's Koppen climate zones. Data span from 2001 – 2023.

energy accessibility, particularly in the dry seasons, others experienced reduced solar radiation during some seasons—thereby stressing the necessity for tailored solar energy planning and adaptation approaches.

According to Table 2, the temperature trends throughout Nigeria's various climatic regions revealed a complex pattern of

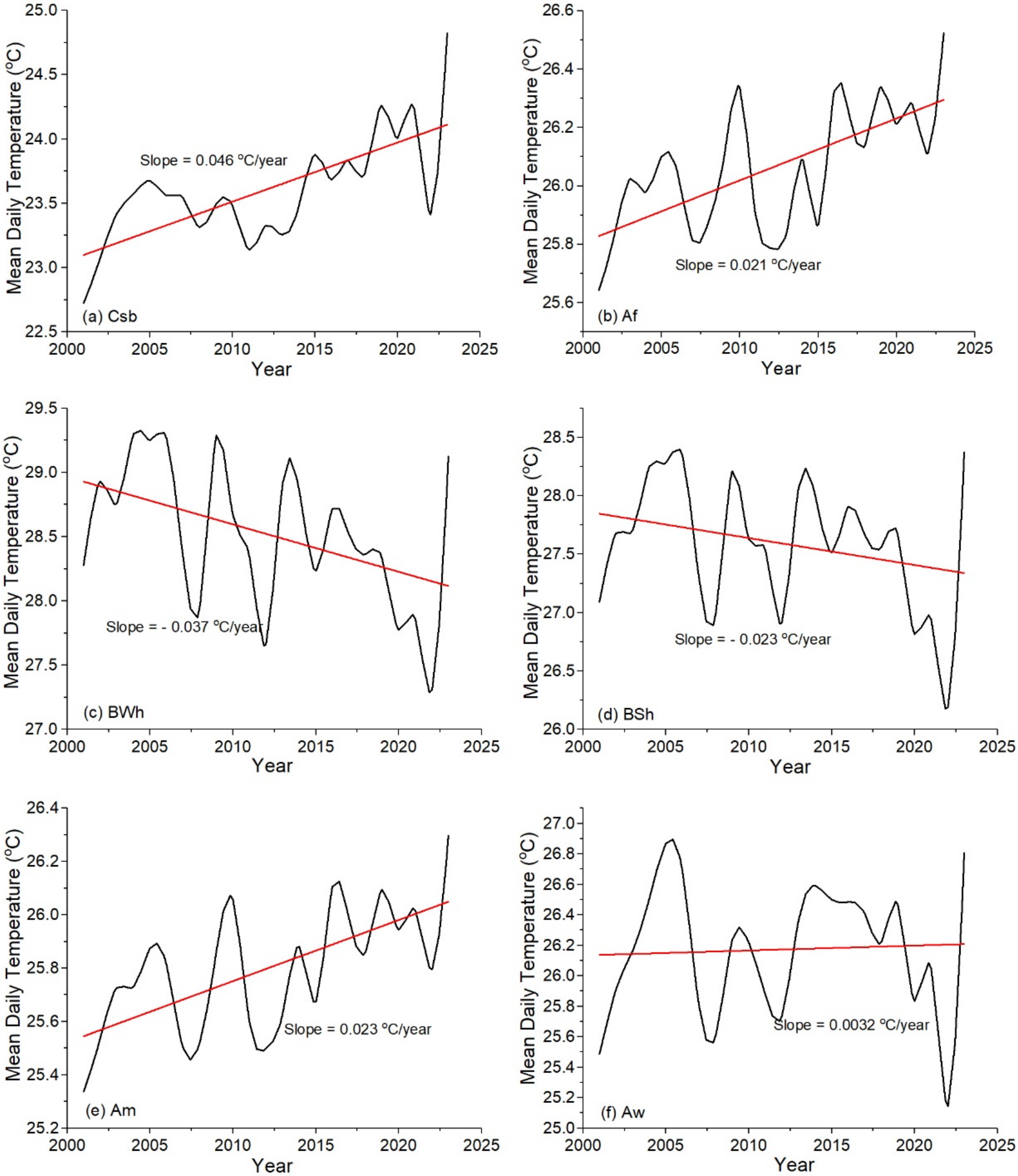

Figure 9. Mean daily temperature vs time series plots over Nigeria's Koppen climate zones. Data span from 2001–2023.

both warming and cooling, shaped by geographical and atmospheric parameters. The Am and Csb regions demonstrated the most consistent increases in temperature, with average rates of +0.032°C/month and +0.028°C/month, respectively. The Am zone experienced the greatest seasonal warming during DJF and SON with maximum value of +0.096 °C/month, likely credited to variations in surface energy patterns. Furthermore, the Af zone showed a marginal increase in temperature at +0.025°C/month at average, maintaining relatively consistent growth throughout the year. On the contrary, the BWh and BSh regions reflected a cooling trend of -0.030°C/month each, producing marginal positive trend only in the MAM season, potentially owing to transition from the dry to the wet season. The Aw zone exhibited nearly neutral average trend (-0.003°C/month), fluctuating between marginal warming (+0.117°C/month) and cooling (-0.087°C/month) throughout the seasons. These results imply that while the southern regions are gradually warming, certain areas in northern Nigeria are undergoing cooling or stabilizing temperatures, which could have mixed effects on agriculture, public health, and the efficiency of solar photovoltaic systems.

3.8. MEAN DAILY GHI VS TIME SERIES OVER NIGERIA

The time series of mean daily GHI in Nigeria (Fig. 8) demonstrates the temporal trends and long-term variability vital for assessing the stability and dependability of solar energy potential nationwide.

Figure 8 depicts the trends over time of mean daily GHI across the six different Köppen climate zones in Nigeria from 2000 to 2023. In general, all zones show a positive trend, reflecting an increase in GHI throughout the country. The BWh zone recorded the highest values over the years, ranging from 497.1 W/m^2 in 2012 to a maximum of 526.6 W/m^2 in 2021, and experienced the most pronounced increase of 0.21 W/m^2 annually, pointing to a significant growth in solar energy potential in northern Nigeria. Similarly, the BSh zone maintained high values ranging from 490 to 510 W/m^2, but featured a slight upward trend of 0.017 W/m^2 each year, likely due to prolonged dry seasons and diminished cloud coverage. The Aw and Csb zones demonstrated moderate GHI values, generally ranging from 430 to 450 W/m^2, with trends of 0.041 and 0.017 W/m^2 per year, respectively. Year-to-year fluctuations, and significant declines in 2005 and 2012 may be linked to increased atmospheric aerosols or rainfall. [11] also reported lower radiations in 2012. The Am zone also exhibited relatively high GHI values, with a noteworthy trend rise of 0.139 W/m^2 annually, suggesting rising solar irradiance despite typically damp conditions. In contrast, the lowest GHI values were observed in the Af zone, fluctuating between 342.1 and 358.1 W/m^2. This is consistent with its high cloud cover and atmospheric moisture, yet it showed a considerable upward trend of 0.105 W/m^2 annually. These observations agree favourably with [11].

4. MEAN DAILY TEMPERATURE VS TIME SERIES OVER NIGERIA

Understanding the temporal variations in surface temperature is crucial for evaluating climate trends and their effects on energy needs, and environmental stability. Figure 9 is a time series analysis of the average daily surface temperature in Nigeria.

Figure 9 shows the trends over time of mean daily surface temperature across the six different Köppen climate zones in Nigeria from 2000 to 2023, revealing notable spatial and temporal trends. The Csb zone with the lowest temperature values experienced the most significant warming pattern, with temperatures rising from 22.72°C in 2001 to 24.82°C in 2023, leading to a positive slope of +0.046°C per year. This indicates a considerable warming likely driven by reduced rainfall, changes in land use, or urban development. In the humid southern areas, both the Af and Am zones with temperature values ranging between 25.34 and 26.52°C exhibited moderate warming, with slopes of +0.021°C and +0.023°C per year, respectively, suggesting that regions typically covered by clouds are seeing temperature rises, possibly due to deforestation and heightened heat retention. On the contrary, the arid BWh and semi-arid BSh zones with the highest daily mean temperatures (26.19 to 29.30°C) revealed cooling trends, with slopes of –0.037°C and –0.023°C per year, respectively. These negative trends could be associated with increasing aerosol levels, changes in vegetation, or localized climatic variations. The Aw zone maintained relative stability (25.15 to 26.87°C), with a minor warming rate of +0.0032°C per year, signifying nearly constant temperature conditions over the past two decades. Generally, year-to-year variability was observed across all zones, including notable drops in 2008 and 2012, and a temperature spike in 2023.

5. CONCLUSION

This research offers important insights into the daily variations of solar energy and surface temperature throughout Nigeria's various climatic zones using satellite-obtained data. The findings indicate considerable spatial and temporal differences in the availability of solar energy and temperature, influenced by regional atmospheric conditions such as cloud cover, precipitation, aerosols, and seasonal changes. Diurnal trends in GHI showed slight elevated irradiance and surface temperature in all regions of the country except in the northern areas where temperature experienced slight decline. These results point again to the necessity of localized assessments of solar resources for effective energy planning and system design.

By emphasizing daily changes in solar irradiance and temperature, the findings of this research can aid in making more informed decisions regarding the placement, sizing, and performance predictions of photovoltaic systems. The results are also expected to support national initiatives geared at expanding renewable energy resources and adapting to climate change. Future investigations should focus on integrating additional satellite data, such as aerosol and cloud optical characteristics, and using high-resolution models to improve on the accuracy of site-specific solar energy predictions across Nigeria's diverse landscapes.

DATA AVAILABILITY STATEMENT

The data used in this study was sourced from the archives of the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), provided by the National Aeronautics and Space Administration's (NASA) Global Modeling and Assimilation Office (GMAO). The datasets are publicly available and can be accessed from https://power.larc.nasa.gov/data-access-viewer/.

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