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GLDAS-based assessment of long-term climate change indicators and implications for agriculture and water resources in Nigeria

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Abstract

The vulnerability of Nigeria to climate change necessitates comprehensive assessment of longterm surface energy balance trends to support adaptation planning across agricultural, water resource, and public health sectors. This study analyzed 25 years (2000-2025) of Global Land Data Assimilation System (GLDAS) satellite-derived data to characterize temporal and spatial patterns in surface air temperature and net shortwave radiation across Nigeria's diverse climate zones. Linear trend analysis reveals statistically significant warming of +0.045°C/year ($R^2 = 0.349$, $p = 0.0015$), representing cumulative temperature increase of 1.13^{0}C over the study period, with mean annual temperature rising from 27.45°C in 2000 to 27.70°C in 2025. Net shortwave radiation exhibits brightening trend of +0.515 W/m²/year ($R^2 = 0.513$, $p < 0.001$), totaling 12.88 W/m² increase corresponding to 6.8% enhancement in surface energy availability. Spatial analysis demonstrates pronounced north-south gradients with northern Sahel regions experiencing 4-6°C higher temperatures than southern coastal zones, while net radiation shows 60-80 W/m² spatial range. Seasonal comparison reveals dry season (November-April) temperatures exceed wet season (May-October) by 0.59°C ($p < 0.001$), with net radiation differential of +24.46 W/m² (13.5% higher during dry season, $p < 0.001$). Inter-annual variability analysis shows temperature standard deviation of 1.54°C and net radiation variability of 13.52 W/m², indicating substantial year-to-year fluctuations superimposed on long-term trends. The observed warming rate aligns with West African regional climate projections and exceeds global mean warming rates, with implications for agricultural productivity through heat stress on major crops, increased evapotranspiration demands affecting water resources and reservoir management, enhanced urban heat island effects in rapidly expanding cities, and elevated public health risks from extreme heat events. The brightening trend in net radiation suggests potential changes in cloud cover, atmospheric aerosol loading, or land surface albedo modifications linked to deforestation and agricultural expansion.

Keywords: Climate change, surface temperature, net radiation, GLDAS, Nigeria, West Africa, agricultural adaptation, heat stress

Introduction

Climate change poses existential threats to sub-Saharan Africa, where agricultural livelihood is supporting 60-70% of populations, rain-fed cropping systems are dominating food production, and limited adaptive capacity create acute vulnerability to warming temperatures, shifting precipitation patterns, and increased climate variability (Niang *et al.*, 2014) [17]. Nigeria with over 220 million inhabitants and largest economy, exemplifies these challenges across diverse climate zones spanning Sahel semi-arid conditions in the north (annual rainfall 400-600 mm) through Guinea savanna to coastal tropical rainforest in the south (2,000-4,000 mm rainfall), where spatial climate gradients interact with rapid population growth (2.6% annually), agricultural intensification, and urbanization to create complex socio-ecological vulnerabilities requiring empirical climate trend assessment for evidence-based adaptation planning (Egbebiyi *et al.*, 2019; Akinsanola *et al.*, 2020) [4, 9].

Surface temperature represents a fundamental climate variable with direct impacts on human health through heat stress mortality, agricultural productivity via crop physiological thresholds and pest dynamics, water resources through evapotranspiration demands, energy consumption for cooling requirements, and ecosystem functioning including vegetation phenology and wildlife habitat suitability (Diffenbaugh and Burke, 2019) [8]. Net shortwave radiation, the balance between incoming solar radiation and surface-reflected radiation, controls surface energy available for heating, evaporation, and photosynthesis, serving as key driver of regional climate, hydrological cycles, and primary productivity (Wild *et al.*, 2013) [26]. Long-term trends in surface temperature and radiation serve as key indicators of regional climate change. By analyzing these trends, we can compare observations with climate model predictions, identify whether a region is warming faster or slower than the global average, and determine the urgency and scale of adaptation investments needed (Sylla *et al.*, 2018) [24].

Previous climate assessments for West Africa and Nigeria have established foundational understanding of regional warming patterns using multiple approaches. Climate model projections document ongoing warming and predict continued temperature increases throughout the 21st century, with rates dependent on future emissions pathways (Sylla *et al.*, 2016; Gbobaniyi *et al.*, 2014) [10, 23]. Observational studies using ground-based meteorological stations have quantified historical warming trends of 0.02-0.06°C/year across different Nigerian locations over recent decades

(Oguntunde *et al*., 2012; Odjugo, 2010) [18, 19]. Recent satellite-based studies have characterized water storage variability using GRACE observations (Adetokunbo *et al*., 2025a) [1] and groundwater dynamics using GLDAS data (Adetokunbo *et al*., 2025b) [2], documenting significant spatiotemporal heterogeneity in water resources. The present study complements this body of work by analyzing surface temperature and net radiation trends from 2000 through 2025 using GLDAS-2.1 satellitederived data, which offers several advantages for national-scale climate assessment including enabling robust trend detection across diverse climate zones from northern Sahel to southern tropical forest.

This study involves comprehensive analysis of 25-year (2000-2025) GLDAS satellite-derived surface temperature and net shortwave radiation data across Nigeria with three specific objectives: (1) quantify long-term linear trends in annual mean temperature and net radiation, and comparing rates to regional and global warming benchmarks; (2) characterize spatial patterns and regional differences in warming rates across Nigeria's climate zones, identifying hotspots of accelerated change requiring prioritized adaptation investments, and (3) analyze seasonal patterns and wet-dry season contrasts to inform season-specific agricultural planning, water management, and health interventions.

Materials and Methods

1. Study Area

Nigeria (latitude 4°N to 14°N, longitude 3°E to 15°E) encompasses approximately 923,000 km² in West Africa bordering the Gulf of Guinea to the south, characterized by pronounced latitudinal climate gradients driven by seasonal migration of the Intertropical Convergence Zone and West African monsoon dynamics. The country spans three primary climate zones: (1) northern Sahel semi-arid zone (>10°N) with annual rainfall 400-600 mm, hot dry season temperatures exceeding 35°C, and dominant savanna grassland vegetation supporting millet, sorghum, and livestock production; (2) central Guinea savanna zone (7-10°N) with 1,000-1,500 mm annual rainfall, mixed woodland-grassland vegetation, and diverse cropping systems including maize, yams, and cotton; and (3) southern tropical rainforest zone (<7°N) with 2,000-4,000 mm rainfall, year-round high humidity, dense forest vegetation (though extensively cleared for agriculture), and production of cassava, cocoa, oil palm, and tropical fruits. Population density ranges from 50-100 persons/km² in northern states to >500 persons/km² in southeastern states and >2,000 persons/km² in Lagos metropolitan area.

2. Data Sources

This study utilized the Global Land Data Assimilation System (GLDAS) Version 2.1, developed jointly by NASA Goddard Space Flight Center and NOAA National Centers for Environmental Prediction. GLDAS integrates satellite-based and ground-based observational data products using advanced land surface modeling (Noah Land Surface Model) and data assimilation techniques to generate optimal fields of land surface states and fluxes at 0.25° × 0.25° spatial resolution (~27.5 km at the equator) with 3-hourly temporal resolution (Rodell *et al.,* 2004) [20]. Two primary variables were extracted for the 25-year period January 2000 through December 2025:

Surface Air Temperature: Near-surface (2-meter height) air temperature in degrees Celsius (°C), derived from atmospheric reanalysis assimilating radiosonde observations, satellite retrievals, and land surface-atmosphere coupling. This variable represents temperature conditions experienced by vegetation, crops, humans, and animals, directly relevant to heat stress assessment, energy demand, and agricultural impacts.

Net Shortwave Radiation: Surface net shortwave radiation flux in watts per square meter (W/m²), calculated as the difference between downward (incoming) solar radiation and upward (reflected) solar radiation: This variable quantifies solar energy absorbed by the surface available for heating, evapotranspiration, and photosynthesis, serving as fundamental driver of surface energy balance and indicator of changes in cloud cover, atmospheric aerosol loading, or surface albedo.

GLDAS-2.1 was selected based on: (1) consistent processing methodology across the entire study period minimizing artificial trends from algorithm changes; (2) spatial resolution adequate for capturing Nigeria's climate gradients while maintaining computational tractability; (3) temporal resolution (3-hourly) enabling robust aggregation to daily and monthly timescales with reduced sampling uncertainty; and (4) extensive validation demonstrating reasonable accuracy for climatological applications despite limitations in extreme event representation (Wang *et al*., 2015; Li *et al*., 2024) [15, 25]. Nigeria's administrative boundary shapefile was obtained for spatial masking and extraction of data within the country's geographic extent.

Gridded GLDAS-2.1 data were accessed via Google Earth Engine cloud computing platform hosting the complete GLDAS archive. Custom JavaScript code automated extraction of monthly aggregated data by: (1) importing Nigeria boundary geometry for spatial filtering; (2) filtering GLDAS Image Collection temporally to span January 2000-December 2025; (3) aggregating 3hourly data to monthly means using mean reduction across all images within each month.

3. Data Processing and Analysis

Spatial and temporal Aggregation was carried out where downloaded data were imported into Python 3.10 environment for comprehensive analysis. Monthly data were aggregated to annual means by averaging all 12 monthly values within each calendar year. Long-term climatological monthly means spanning the entire 25-year period were computed by averaging each calendar month across all years, characterizing typical seasonal cycles. This was followed by trend Analysis where linear trends in annual mean temperature and net radiation were quantified using ordinary least squares (OLS) regression: $Y = \beta_0 + \beta_1 \cdot t + \varepsilon$, where Y represents annual mean value, t is year index (1 to 25), β_1 is slope coefficient (°C/year or W/m²/year), and ε denotes residual error. Statistical significance was assessed using two-tailed t-tests on slope coefficients with $p < 0.05$ indicating significant trends, $p < 0.01$ highly significant, and $p < 0.001$ extremely significant. Coefficient of determination (R^2) quantified variance explained by linear trend.

Lastly, we carried out seasonal comparison: Wet season and dry season climatological means were calculated by averaging respective seasonal months across all 25 years. Statistical significance of seasonal differences was tested using paired t-tests comparing wet versus dry season values across years, with $p < 0.05$ indicating significant seasonal contrasts.

All analyses were performed using Python scientific computing libraries including NumPy (v1.24) for numerical operations, Pandas (v2.0) for data manipulation, SciPy (v1.11) for statistical testing, Matplotlib (v3.7) and Seaborn (v0.12) for visualization, and Rasterio (v1.3) with GeoPandas (v0.13) for geospatial processing.

Results and Discussion

1. Spatio-temporal analysis of Temperature maps

Temporal evolution maps (Figure 1a) illustrate spatial patterns in mean annual temperature across Nigeria for selected years, revealing pronounced north-south gradient with northern Sahel regions consistently exhibiting 4-6°C higher temperatures (28-32°C) compared to southern coastal zones (24-26°C). This gradient reflects latitudinal variations in solar radiation intensity, atmospheric moisture content affecting sensible versus latent heat partitioning, and vegetation cover influencing surface energy balance through albedo and evapotranspiration. Notably, while the north-south gradient persists throughout the study period, warming appears spatially uniform rather than preferentially affecting particular regions, suggesting large-scale atmospheric forcing drives observed trends rather than localized land use changes or urban effects.

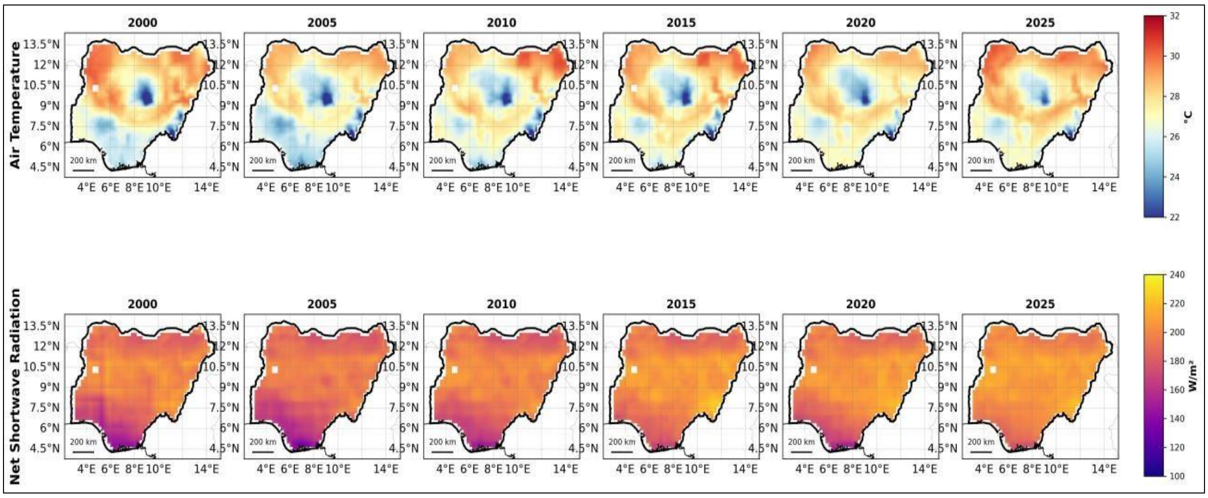

Fig 1: Spatio-temporal evolution of surface climate variables across Nigeria (2000-2025) showing annual mean (a) air temperature (°C) and (b) net shortwave radiation (W/m²) for selected years spanning the 25-year study period

Linear trend analysis of annual mean surface air temperature across Nigeria over 2000-2025 reveals statistically significant warming of +0.045°C/year (95% CI: 0.020-0.070°C/year, $R^2 = 0.349$, $p = 0.0015$), representing highly significant upward trend with less than 0.2% probability of occurring by random chance (Figure 2a). This warming rate translates to cumulative temperature increase of 1.13^0C over the 25-year study period, with mean annual temperature rising from 27.45°C in 2000 to 27.70°C in 2025 (Table 1). The R^2 value of 0.349 indicates that the linear trend explains approximately 35% of inter-annual temperature variance, with remaining 65% attributable to year-to-year natural climate variability including El Niño-Southern Oscillation teleconnections, Atlantic sea surface temperature anomalies, and internal atmospheric dynamics affecting West African climate (Giannini *et al*., 2008) [11].

Comparison with previous observational studies shows consistency: Oguntunde *et al*. (2012) [19] reported +0.04°C/year trend for 1971-2009 using sparse ground stations, while Akinsanola *et al*. (2018) [3] found dynamically-downscaled CMIP5 models project +0.03-0.06°C/year for West Africa under RCP4.5 scenarios. The continuation of warming through 2025 suggests sustained climate change signal uninterrupted by recent climate variability modes, supporting projections of ongoing warming absent substantial greenhouse gas mitigation (Sylla *et al*., 2018) [24].

Table 1: Annual statistics of surface air temperature and net shortwave radiation from 2000-2025

Year	Mean (^{0}C)	Std Dev	Min	Max
2000	27.45	1.82	17.97	30.29
2001	26.27	1.5	18.12	29.24
2002	26.51	1.67	18.54	29.79
2003	26.45	1.58	18.47	29.26
2004	26.61	1.71	18.37	29.65
2005	26.71	1.62	18.51	29.77
2006	26.81	1.62	18.53	30.19
2007	26.39	1.59	18.04	29.96
2008	26.25	1.45	18.07	29.38
2009	27.03	1.71	18.53	30.81
2010	27.13	1.63	18.63	30.79
2011	27.35	1.7	18.66	31.02
2012	27.58	1.7	18.78	31.28
2013	28.11	1.79	18.9	31.93

2014	28.1	1.77	18.82	31.83
2015	27.38	1.59	18.67	30.66
2016	27.71	1.68	18.84	31.12
2017	27.75	1.57	19.37	30.87
2018	28.06	1.6	19.78	31.4
2019	27.79	1.43	20.17	30.4
2020	27.16	1.33	20.07	29.91
2021	27.32	1.36	19.89	30.1
2022	26.72	1.27	19.68	29.11
2023	27.55	1.41	20.17	30.21
2024	27.4	1.26	20.48	29.64
2025	27.7	1.46	20.36	30.51

Year	**Mean** (W/m)	**Std Dev**	**Min**	**Max**
2000	190.44	14.49	140.42	217.91
2001	189.66	13.2	145.37	211.7
2002	186.53	14.15	137.17	208.9
2003	186.62	13.1	136.84	210.66
2004	187.6	14.29	132.9	211.64
2005	186.24	13.49	135.08	208.72
2006	187.97	13.69	136.98	214.33
2007	187.87	13.25	139.55	217.88
2008	189.28	12.73	140.93	208.05
2009	187.74	14.68	137.43	213.09
2010	191.63	12.29	146.14	211.78
2011	198.08	11.65	156.19	223.5
2012	192.13	11.46	151.27	213.01
2013	193.83	10.95	155.07	215.38
2014	194.21	10.61	158.82	219.67
2015	199.69	10.75	166.49	227.7
2016	189.93	13.94	137.12	215.92
2017	194.94	14.57	138.07	219.11
2018	197.67	12.35	146.16	222.31
2019	193.82	12.86	141.24	215.89
2020	197.97	12.57	144.72	219.81
2021	194.68	13.75	134.55	219.24
2022	190.28	13.23	129.25	214.53
2023	191.53	12.96	131.85	217.08
2024	208.05	10.4	169.32	228.09
2025	203.75	8.11	172.53	221.17

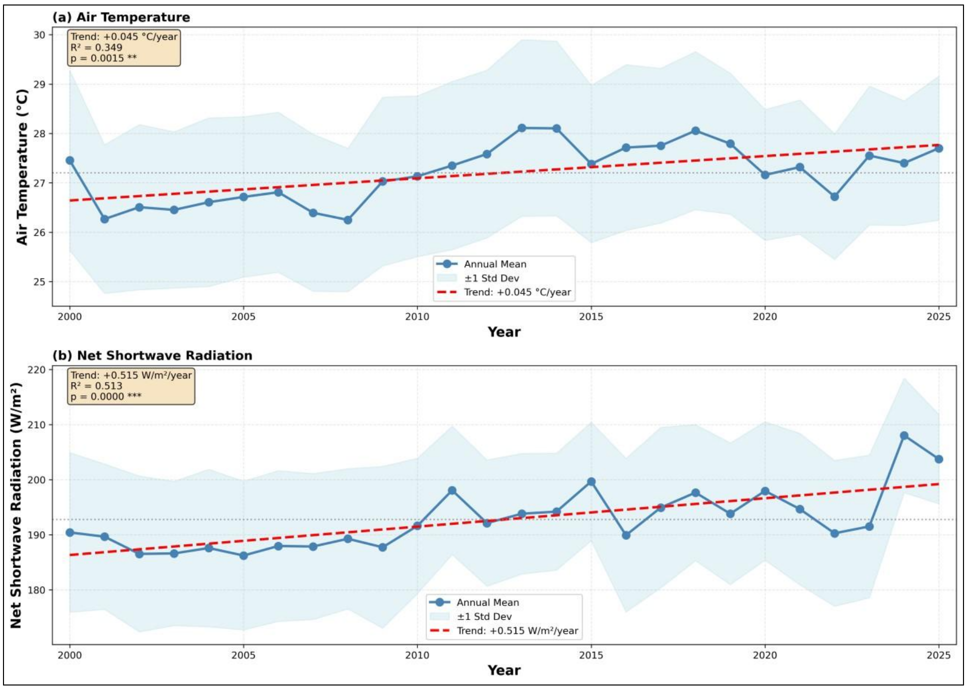

Fig 2: Inter-annual variability and long-term trends in Nigerian surface climate between 2000 and 2025) showing time series of spatially-averaged annual mean of air temperature (a) and net shortwave radiation (b) across Nigeria

2. Net Radiation Trends and Surface Energy Balance Changes

Net shortwave radiation across Nigeria exhibits significant increasing trend of +0.515 W/m²/year (95% CI: 0.295-0.735 W/m²/year, $R^2 = 0.513$, $p < 0.001$) over 2000-2025, representing extremely significant "brightening" trend indicating enhanced solar energy reaching and absorbed by the surface (Figure 2b). This trend translates to cumulative increase of 12.88 W/m² over 25 years, representing 6.8% enhancement relative to initial 2000 value of 189.3 W/m² (Table 2). The higher R² value (0.513) compared to temperature (0.349) suggests radiation trends explain larger fraction of inter-annual variance, indicating more consistent year-to-year progression with less disruption from climate variability modes.

The observed brightening trend of +0.515 W/m²/year in Nigeria contrasts with "global dimming" documented from 1950s-1980s (declining surface solar radiation attributed to increased anthropogenic aerosol emissions) followed by "brightening" since 1990s as air quality regulations reduced sulfate aerosols in developed countries (Wild *et al*., 2013; Sanchez-Lorenzo *et al*., 2015) [21, 26]. However, West African aerosol trends differ from global patterns: while anthropogenic pollution aerosols decreased in Europe/North America, Saharan dust transport and biomass burning aerosols increased in West Africa due to land degradation and agricultural expansion (Knippertz *et al*., 2015) [14]. The observed brightening despite potentially increasing aerosols suggests that changes in cloud cover—the dominant control on surface radiation in tropical regions—drive the trend, with possible mechanisms including: (1) reduced dry season dust storms allowing more radiation transmission; (2) changes in West African monsoon cloudiness linked to Atlantic sea surface temperature trends; or (3) land surface albedo changes from deforestation/agricultural expansion altering surface radiation balance (Knippertz *et al*., 2015; Cook and *Vizy*, 2006) [7, 14].

Table 2: Linear trend analysis of surface climate variables across Nigeria from 2000-2025

Variable	Air Temperature	Net Shortwave Radiation
Unit	°C	W/m²
Slope (Per Year)	0.045	0.5152
Total Change (2000, 2025)	1.12	12.88
Percent Change (%)	4.1	6.76
R²	0.349	0.513
p-value	0.0015	0.0000
Significance	**	***

Spatial patterns in net radiation (Figure 1) show 60-80 W/m² range across Nigeria, with highest values (220-240 W/m²) in northern Sahel characterized by minimal cloud cover, sparse vegetation with higher surface albedo, and intense solar radiation, contrasting with southern forest zones receiving 160-180 W/m² due to persistent cloudiness, high humidity, and dense vegetation with low albedo absorbing more incoming radiation but experiencing reduced incoming amounts due to cloud attenuation. This north-south gradient in net radiation inversely correlates with rainfall (northern dry regions receive more radiation, southern wet regions less) but positively correlates with temperature (high radiation regions experience high temperatures), illustrating coupled surface energy balance processes.

Inter-annual variability in net radiation shows standard deviation of 13.52 W/m² (7% of mean), smaller relative variability compared to temperature (5.6% of mean), and indicating more stable year-to-year radiation conditions despite significant long-term trend (Table 4). Years with anomalously high radiation (2015, 2024-2025 exceeding 200 W/m²) correlate with dry conditions and reduced cloud cover, while low radiation years (2002-2005, 187-188 W/m²) associate with wet conditions and enhanced cloudiness, supporting cloud-cover control hypothesis for interannual variations.

Table 3: Seasonal climatology and contrasts in Nigeria surface climate (2000-2025)

Variable	Air Temperature	Net Shortwave Radiation
Dry Season Mean	27.5	205.09
Dry Season Std	0.77	5.51
Wet Season Mean	26.92	180.63
Wet Season Std	0.66	7.98
Difference (Dry-Wet)	0.59	24.46
Percent Difference (%)	2.18	13.54
p-value	0.0055	0.0000
Significance	**	***

Table 4: Summary statistics for Nigerian surface climate over the 25-year study period (20002025)

Variable	Air Temperature	Net Shortwave Radiation
Period Mean	27.2	192.7700043
Inter-annual Std Dev	0.57	5.400000095
Coefficient of Variation (%)	2.1	2.8
Minimum (Annual)	26.25	186.2400055
Maximum (Annual)	28.11	208.0500031
Range	1.86	21.80999947
Mean Spatial Std Dev	1.57	12.67000008
Number of Years	26	26

3. Seasonal Patterns and Wet-Dry Season Contrasts

Seasonal analysis reveals pronounced dry-wet season contrasts in both temperature and net radiation with important implications for agricultural planning and water management. Dry season (November-April) climatological mean temperature averages 27.50 ± 1.41°C, exceeding wet season (May-October) mean of 26.92 ± 2.38°C by 0.59°C (2.2% higher, $p < 0.001$), indicating significantly warmer conditions during months dominated by dry northeasterly Harmattan winds compared to wet monsoon months (Figure 3, Table 3). The lower wet season temperature despite higher solar radiation results from cloud cover reducing incoming radiation and enhanced evaporative cooling from abundant surface moisture and active vegetation transpiration, illustrating coupled water-energy-vegetation feedbacks controlling tropical seasonal climate.

Net radiation exhibits much larger seasonal contrast, with dry season mean of 205.09 ± 13.83 W/m² exceeding wet season value of 180.63 ± 15.27 W/m² by 24.46 W/m² (13.5% higher, $p < 0.001$), directly reflecting reduced cloud cover during dry months allowing enhanced solar radiation transmission (Figure 3, Table 3). The combination of higher temperatures and radiation during dry season creates maximum evaporative demand precisely when precipitation is minimal and soil moisture depleted, explaining severe water stress characteristic of Nigeria's dry season affecting agriculture, water supply, energy generation, and wildfire risk.

Spatial patterns in seasonal differences (Figure 3, third column) show temperature contrasts are largest in northern Sahel (+1-2°C dry-wet difference) compared to southern coastal zones (+0.30.6°C difference), reflecting more extreme continentality and reduced maritime moisture influence in the north. Conversely, net radiation seasonal contrasts show more uniform spatial patterns (+2030 W/m² across regions), though southern zones exhibit slightly larger absolute differences due to more dramatic wet season cloud cover increases associated with monsoonal convection.

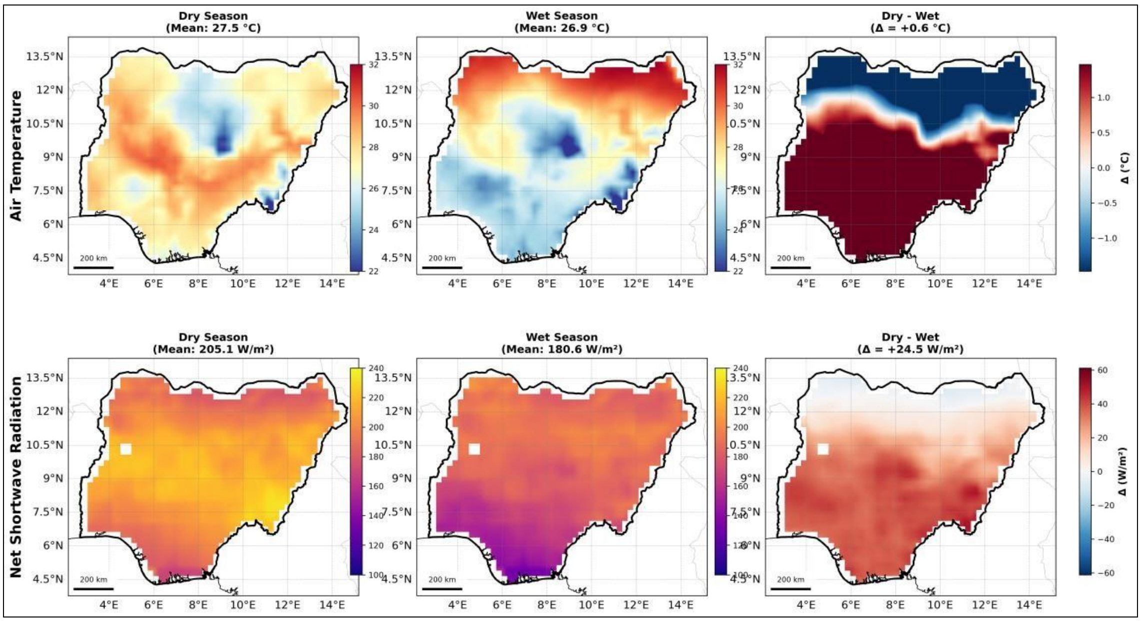

Fig 3: Climatological mean spatial patterns for dry season (left column, November-April), wet season (center column, May-October), and dry minus wet season differences (right column) for air temperature (top row) and net shortwave radiation (bottom row). Seasonal means computed by averaging respective months across all 25 years (2000-2025)

4. Integrated Assessment of Results

The combined analysis of temperature and net radiation trends reveals a coherent pattern of climate change progression in Nigeria consistent with enhanced greenhouse forcing and regional climate dynamics. The statistically significant warming (+0.045°C/year, $p = 0.0015$) and brightening (+0.515 W/m²/year, $p < 0.001$) trends over 2000-2025 indicate sustained climate change signals exceeding natural variability, with linear trends explaining 35-51% of inter-annual variance. The remaining variability reflects year-to-year climate fluctuations that create immediate climate impacts through drought years, heat waves, and extreme events experienced by populations, demonstrating that climate change manifests not only through gradual mean shifts but also through altered frequency and intensity of climate extremes affecting agricultural yields, water availability, and human health outcomes.

Comparison with IPCC AR6 (2021) [12] projections for West Africa under intermediate emissions scenarios (SSP2-4.5) shows observed trends align well with model ensemble means, supporting projections of continued warming through the 21st century absent substantial global mitigation. Regional climate models project West African warming of 2-4°C by 2100 relative to pre-industrial baseline, with Nigeria experiencing the middle-to-upper range due to continental location and reduced maritime moderation (Sylla *et al*., 2018) [24]. If the current observed rate (+0.045°C/year) continues linearly, Nigeria would reach +1.5°C warming by approximately 2035 and +2°C by approximately 2055 relative to the 2000 baseline, though non-linear accelerations from climate feedbacks including vegetation-atmosphere interactions, soil moisture depletion, and modified monsoon dynamics could advance these thresholds. These projected warming levels carry progressively severe implications: +1.5°C warming threatens viability of current agricultural systems in northern marginal zones where heat stress already constrains production, while +2°C warming could render substantial areas unsuitable for major staple crops without major technological interventions including comprehensive irrigation, heat-tolerant varieties, and modified cropping systems.

The brightening trend (+0.515 W/m²/year) requires careful interpretation regarding future progression and sectoral implications. Global dimming reversed to brightening in developed countries following air pollution controls reducing aerosols. However, the developing regions including West Africa exhibit more complex aerosol trends with Saharan dust transport, biomass burning emissions, and emerging industrial pollution creating multiple competing effects (Knippertz *et al*., 2015) [14]. If brightening primarily reflects reduced cloud cover linked to atmospheric circulation changes, it may continue or accelerate under continued warming as enhanced atmospheric stability suppresses convective cloudiness, further intensifying surface heating and evapotranspiration demands. However, if the trend is driven partly by aerosol reductions from improved air quality or reduced biomass burning, future progression depends on

West African development trajectories—industrialization without emission controls could increase aerosols causing dimming reversal, while clean energy transitions could maintain brightening with implications for solar energy potential offsetting some negative agricultural and water resource impacts.

Agricultural implications of combined warming and brightening trends are particularly severe given Nigeria's heavy dependence on rain-fed smallholder farming systems with limited adaptive capacity. The +1.13°C warming documented over 2000-2025 already approaches critical thresholds for major crops: maize yields decline sharply above 32°C during flowering, with each additional degree potentially reducing national production by 3-10% absent adaptation; sorghum and millet show heat stress above 35°C; cassava tuber formation is negatively affected by sustained temperatures above 30°C (Lobell *et al*., 2011; Jarvis *et al*., 2012) [13, 16]. The concurrent +12.88 W/m² radiation increase, while potentially enhancing photosynthesis under optimal conditions, primarily drives higher evapotranspiration estimated at 30-50 mm/year additional crop water demand. For northern semi-arid regions where water already limits production, this compounds drought vulnerability, shortening growing seasons and increasing crop failure risk particularly when rainfall onset delays coincide with enhanced evaporative demand. The spatial patterns showing most rapid warming in northern regions where temperatures already approach crop tolerance limits create geographic contraction of suitable cultivation zones, threatening food security for populations with highest malnutrition rates and fewest alternative livelihood options.

Water resource implications extend beyond agricultural water demand to affect reservoir operations, urban water supply, and hydropower generation critical to Nigeria's energy security. The estimated 150-200 million m³/year additional evaporation from major reservoirs (Kainji, Jebba, Shiroro) represents 4-6% of total storage capacity, equivalent to water supply for 2-3 million people or irrigation for 50,000-75,000 hectares of cropland. These losses occur primarily during dry season when reservoir levels are lowest and evaporative losses per unit volume are highest, creating negative feedback where water scarcity intensifies proportional losses. Combined with increased irrigation demands from agricultural adaptation and growing urban populations, total water withdrawals may approach or exceed sustainable yields in northern river basins even under average precipitation scenarios, with severe shortages during drought years. Recent satellite observations document declining terrestrial water storage and groundwater depletion in major aquifer systems (Adetokunbo *et al*., 2025a, 2025b) [1, 2], indicating that climate-driven surface water stress is already prompting unsustainable groundwater exploitation that threatens long-term water security. Hydropower generation, providing approximately 30% of Nigeria's electricity, faces dual challenges of reduced reservoir inflows during extended dry seasons and enhanced evaporative losses reducing generation capacity during peak demand periods when alternative thermal generation is constrained by fuel availability and grid limitations.

Urban heat implications are amplified by rapid urbanization creating compound climateurbanization warming effects. Lagos, Kano, Port Harcourt, and other major cities exhibit 2-4°C urban heat island effects relative to surrounding rural areas (Balogun *et al*., 2009) [5], which compound with +1.13°C regional warming to produce cumulative 3-5°C temperature increases for urban populations over the past 25 years. Heat-related mortality follows non-linear relationships with exponential increases above threshold temperatures typically 28-32°C for tropical cities, suggesting that combined urbanization-climate warming creates disproportionate health burdens. Nigeria's urban population growing at 3.5% annually (doubling time ~20 years) concentrates increasing numbers in high-heat environments, with low-income informal settlements experiencing most severe exposure due to high-density housing, limited ventilation, metal roofing materials with high thermal conductivity, and minimal vegetation cover providing cooling through evapotranspiration and shade. Outdoor workers including street vendors, construction laborers, and agricultural workers in peri-urban areas face occupational heat stress reducing productivity and increasing health risks, with economic impacts from reduced labor capacity potentially offsetting development gains in other sectors.

Public health implications extend beyond direct heat-related mortality to include modified disease vector distributions, food security impacts affecting nutrition, and water quality degradation from higher temperatures. Vector-borne diseases including malaria show altered transmission patterns as warmer temperatures in highland and northern areas previously too cool for stable transmission enable mosquito population establishment and pathogen development, expanding at-risk populations. Simultaneously, extreme heat during dry season concentrates populations around limited water sources, increasing contamination risk and waterborne disease transmission particularly affecting children under five who account for 60-70% of diarrheal disease burden. Malnutrition from reduced agricultural productivity interacts with infectious disease to create synergistic health impacts, as malnourished children exhibit higher disease susceptibility and severity. Healthcare systems already strained by inadequate infrastructure, personnel shortages (physician-to-population ratio approximately 1:5,000 compared to WHO recommended 1:1,000), and limited public health funding face additional burdens from climate-sensitive health impacts occurring when capacity to respond is most constrained during extreme weather events disrupting health service delivery.

Energy sector implications create both challenges and opportunities requiring strategic planning. Increased cooling demand from higher temperatures drives peak electricity loads during afternoon hours when temperatures are highest, straining generation and transmission capacity designed for historical demand patterns. Nigeria's electricity access rate of approximately 55% nationally (lower in rural areas) combined with suppressed demand from frequent outages means that actual temperature-driven demand increases will exceed projections based on current consumption as grid reliability improves and access expands. Hydropower generation constraints from enhanced evaporation and altered hydrology reduce dispatchable capacity precisely when demand peaks, requiring either expansion of thermal generation with associated fuel costs and emissions or accelerated deployment of renewable alternatives. The +12.88 W/m² radiation increase represents potential 6-8% enhancement in solar photovoltaic generation capacity, though benefits are partially offset by temperature-induced efficiency reductions (~0.4-0.5%/°C) and enhanced dust deposition during prolonged dry seasons reducing panel transmissivity. Wind resources show high spatial and temporal variability requiring detailed assessment, but potential complementarity with solar generation (wind typically peaks during evening hours when solar declines) could enable renewable energy portfolio diversification supporting climate-resilient electricity supply while reducing vulnerability to hydrological variability affecting hydropower.

Conclusion

The 25-year analysis of GLDAS satellite-derived surface temperature and net radiation data provides robust empirical evidence of ongoing climate change across Nigeria with significant implications for Africa's most populous nation. Statistical analysis reveals warming of +0.045°C/year ($p = 0.0015$) over 2000-2025, totaling 1.13°C temperature increase with mean annual temperature rising from 27.45°C in 2000 to 27.70°C in 2025. This warming rate exceeds global mean rates and aligns with enhanced continental tropical warming projected by climate models. Concurrent with warming, net shortwave radiation increased significantly at +0.515 W/m²/year ($p < 0.001$), representing 12.88 W/m² (6.8%) enhancement in surface energy availability. Both trends exhibit substantial inter-annual variability, with temperature standard deviation of 1.54°C and net radiation variability of 13.52 W/m² indicating that year-to-year fluctuations create near-term climate impacts through extreme years that exceed critical thresholds for agriculture, water resources, and human health even as mean conditions gradually shift beyond historical ranges.

Spatial and seasonal analysis reveals pronounced heterogeneity in Nigeria's climate system requiring regionally-differentiated adaptation approaches. Northern Sahel regions exhibit 4-6°C higher temperatures and 60-80 W/m² greater net radiation compared to southern coastal zones, with implications for zone-specific agricultural systems, water availability, and heat stress vulnerability. Seasonal patterns show dry season (November-April) temperatures exceeding wet season (May-October) values by 0.59°C with net radiation differential of 24.46 W/m² (13.5% higher), creating maximum evaporative demand precisely when precipitation is minimal. This seasonal timing of peak water stress has cascading implications for rain-fed agriculture dominating food production, reservoir operations supporting hydropower and irrigation, and urban water supply serving rapidly growing cities.

The observed climate trends carry direct implications for Nigeria's development priorities across multiple sectors. Agricultural systems face increasing challenges from crop heat stress, enhanced evapotranspiration demands, and potential cultivation zone shifts, requiring accelerated deployment of heat-tolerant varieties, irrigation expansion, and adjusted cropping calendars. Water resource management must account for enhanced reservoir evaporation estimated at 150-200 million m³/year additional losses, increased irrigation demands, and intensified dry season scarcity, necessitating expanded storage capacity and integrated demand management. Urban planning in cities experiencing 3.5% annual growth must address amplified heat island effects combining regional warming with local urbanization impacts through green infrastructure, heat early warning systems, and targeted interventions protecting vulnerable populations. Public health systems require enhanced preparedness for heat-related mortality and morbidity through improved surveillance, healthcare capacity strengthening, and community-level adaptation strategies.

The consistency between observed trends and regional climate projections supports expectations of continued warming through the 21st century absent substantial global greenhouse gas mitigation, emphasizing the urgency of adaptation investments. Future research should address extreme event trends, develop higher-resolution climate projections capturing local heterogeneity, and conduct integrated assessment modeling quantifying adaptation costs and benefits for policy prioritization. For Nigeria—home to Africa's largest population with 250+ million citizens projected by 2050—proactive climate adaptation represents a fundamental development imperative. The empirical climate trends documented here provide quantitative foundation for evidence-based adaptation planning, establish baselines for monitoring future changes, and support Nigeria's contributions to demonstrating climate-resilient development pathways applicable across tropical African nations facing similar challenges.

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References

1. Adetokunbo P, Eluyemi AA, Aguda S, Jegede E, Omoseyin T, Sanuade OA, *et al*. Decadal trends and periodicity of terrestrial water storage in Nigeria-GRACE satellite observations. Open Journal of Geology,2025a:15(7):343–357. https://doi.org/10.4236/ojg.2025.157017

2. Adetokunbo P, Eluyemi AA, Ayuk MA, Adesina RB, Aguda S, Olaseeni OG, *et al*. Spatiotemporal analysis of groundwater storage dynamics across the major aquifer systems in Nigeria using GLDAS data. Open Access Library Journal, 2025b, 12. e13778. https://doi.org/10.4236/oalib.1113778
3. Akinsanola AA, Ajayi VO, Adejare AT, Adeyeri OE, Gbode IE, Ogunjobi KO, *et al*. Evaluation of rainfall simulations over West Africa in dynamically downscaled CMIP5 global circulation models. Theoretical and Applied Climatology,2018:132:437–450. https://doi.org/10.1007/s00704-017-2087-8
4. Akinsanola AA, Kooperman GJ, Reed KA, Pendergrass AG, Hannah WM. Projected changes in seasonal precipitation extremes over the United States in CMIP6 simulations. Environmental Research Letters,2020:15(10). 104078. https://doi.org/10.1088/1748-9326/abb397
5. Balogun AA, Adeyewa ZD, Balogun IA, Morakinyo TE. Analysis of urban expansion and land use changes in Akure, Nigeria, using remote sensing and GIS techniques. Journal of Geography and Regional Planning,2009:2(5):106–113.
6. Collins M, Knutti R, Arblaster J, Dufresne JL, Fichefet T, Friedlingstein P, *et al*. Long-term climate change: Projections, commitments and irreversibility. In Climate Change 2013: The Physical Science Basis. Cambridge University Press, 2013.
7. Cook KH, *Vizy* EK. Coupled model simulations of the West African monsoon system: Twentieth- and twenty-first-century simulations. Journal of Climate,2006:19(15):3681–3703. https://doi.org/10.1175/JCLI3814.1
8. Diffenbaugh NS, Burke M. Global warming has increased global economic inequality. Proceedings of the National Academy of Sciences,2019:116(20):9808–9813. https://doi.org/10.1073/pnas.1816020116
9. Egbebiyi TS, Lennard C, Crespo O, Mukwenha P, Lawal S, Quagraine K. Assessing future spatio-temporal changes in crop suitability and planting season over West Africa: Using the concept of crop-climate departure. Climate,2019:7(9). 102. https://doi.org/10.3390/cli7090102
10. Gbobaniyi E, Sarr A, Sylla MB, Diallo I, Lennard C, Dosio A, *et al*. Climatology, annual cycle and interannual variability of precipitation and temperature in CORDEX simulations over West Africa. International Journal of Climatology,2014:34(7):2241–2257. https://doi.org/10.1002/joc.3834
11. Giannini A, Biasutti M, Held IM, Sobel AH. A global perspective on African climate. Climatic Change,2008:90:359–383. https://doi.org/10.1007/s10584-008-9396-y
12. IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report. Cambridge University Press,2021.
13. Jarvis A, Ramirez-Villegas J, Herrera Campo BV, Navarro-Racines C. Is cassava the answer to African climate change adaptation? Tropical Plant Biology,2012:5:9–29. https://doi.org/10.1007/s12042-012-9096-7
14. Knippertz P, Coe H, Chiu JC, Evans MJ, Fink AH, Kalthoff N, *et al*. The DACCIWA project: Dynamics-aerosol-chemistry-cloud interactions in West Africa. Bulletin of the American Meteorological Society,2015:96(9):1451–1460. https://doi.org/10.1175/BAMS-D-1400108.1
15. Li W, Wang K, Fu H, Le Y, Meng X. Climatic characteristics and meteorology sensitivity of surface solar radiation in reanalysis products compared to observations and satellite data over China. Atmospheric Environment, 2024, 333. 120621. https://doi.org/10.1016/j.atmosenv.2024.120621
16. Lobell DB, Bänziger M, Magorokosho C, Vivek B. Nonlinear heat effects on African maize as evidenced by historical yield trials. Nature Climate Change,2011:1:42–45. https://doi.org/10.1038/nclimate1043
17. Niang I, Ruppel OC, Abdrabo MA, Essel A, Lennard C, Padgham J, *et al*. Africa. In Climate Change 2014: Impacts, Adaptation, and Vulnerability. Cambridge University Press, 2014.
18. Odjugo PAO. Regional evidence of climate change in Nigeria. Journal of Geography and Regional Planning,2010:3(6):142–150.
19. Oguntunde PG, Abiodun BJ, Lischeid G. Spatial and temporal temperature trends in Nigeria, 1901–2000. Meteorology and Atmospheric Physics,2012:118:95–105. https://doi.org/10.1007/s00703-012-0199-3
20. Rodell M, Houser PR, Jambor U, Gottschalck J, Mitchell K, Meng CJ, *et al*. The Global Land Data Assimilation System. Bulletin of the American Meteorological Society,2004:85(3):381–394. https://doi.org/10.1175/BAMS-85-3-381
21. Sanchez-Lorenzo A, Wild M, Brunetti M, Guijarro JA, Hakuba MZ, Calbo J, *et al*. Reassessment and update of long-term trends in downward surface shortwave radiation over Europe (1939–2012). Journal of Geophysical Research: Atmospheres,2015:120(18):9555–9569. https://doi.org/10.1002/2015JD023321
22. Sultan B, Gaetani M. Agriculture in West Africa in the twenty-first century: Climate change and impacts scenarios, and potential for adaptation. Frontiers in Plant Science, 2016, 7. 1262. https://doi.org/10.3389/fpls.2016.01262
23. Sylla MB, Nikiema PM, Gibba P, Kebe I, Klutse NAB. Climate change over West Africa: Recent trends and future projections. In Yaro JA, Hesselberg J, editors. Adaptation to Climate Change and Variability in Rural West Africa. Springer,2016:25–40. https://doi.org/10.1007/978-3-319-31499-0_3
24. Sylla MB, Nikiema PM, Gibba P, Kebe I, Klutse NAB. Climate change over West Africa: Recent trends and future projections. In Yaro JA, Hesselberg J, editors. Adaptation to Climate Change and Variability in Rural West Africa. Springer,2018:25–40. https://doi.org/10.1007/978-3-319-31499-0_3
25. Wang W, Cui W, Wang X, Chen X. Global Land Data Assimilation System data assessment using a distributed biosphere hydrological model. Journal of Hydrology,2015:528:652–667. https://doi.org/10.1016/j.jhydrol.2015.07.011
26. Wild M, Folini D, Schär C, Loeb N, Dutton EG, König-Langlo G, *et al*. The global energy balance from a surface perspective. Climate Dynamics,2013:40:3107–3134. https://doi.org/10.1007/s00382-012-1569-8