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Smart Physics Approaches for Climate Change Impact Assessment on Sweetcorn Evapotranspiration and Yield across Nigeria's Agro-Ecological Zones under Different Climate Scenarios

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ABSTRACT

Climate change has emerged as one of the most critical environmental challenges affecting agricultural sustainability, hydrological systems and food security globally. In Nigeria, increasing temperature, rainfall variability and hydro-climatic extremes pose severe threats to rain-fed agricultural systems, particularly cereals production across diverse agro-ecological zones. This study applies smart physics-based approaches involving climate modelling, agro-hydrological simulations, data analysis and advanced environmental modelling tools to evaluate the impacts of climate change on maize evapotranspiration (ET) and yield under Representative Concentration Pathways (RCP2.6 and RCP8.5). Climate projections derived from HadGEM2-ES, NorESM1-M and MPI-ESM-MR models were integrated with the DSSAT CERESmaize model to assess future crop responses across rainforest, savannah and Sahel ecological zones in Nigeria. Results indicate substantial warming under future scenarios, with temperature increases exceeding 7°C under RCP8.5 in the Sahel. Evapotranspiration demand increased significantly by about 20% to 50% across all regions due to intensified atmospheric evaporative demand, while maize yield declined sharply under high emission scenarios, by above 50% in the Sahel. Yield-to-Evapotranspiration efficiency (YPEM) deteriorated substantially by about 75 to 85%, particularly in savannah and Sahel regions, indicating increasing hydro-agricultural stress and declining water-use efficiency. The findings provide scientific evidence for climate adaptation, technological innovation and sustainable agricultural management in Nigeria.

Keywords:
Smart physics,
Climate change,
Evapotranspiration,
Maize yield.

INTRODUCTION

Climate change represents one of the greatest scientific and developmental challenges of the twenty-first century (Olasina, 2021; Isa et al., 2023; Zapata et al., 2026). Climate change refers to long-term alterations in the Earth's climate system, primarily resulting from anthropogenic increases in greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases. These emissions originate mainly from fossil fuel combustion, industrial activities, deforestation, land-use change and agricultural practices. The enhanced greenhouse effect traps outgoing longwave radiation within the atmosphere, leading to global warming and significant modifications in atmospheric circulation, precipitation patterns, hydrological processes and the frequency and intensity of extreme weather events. Consequently, climate change affects ecosystems, biodiversity, water resources, agriculture, human health and socio-economic development worldwide (Ajayi et at., 2022; FAO, 2023; Ogolo et al., 2024; Wang et al., 2022). These changes are particularly severe in sub-Saharan Africa, where agriculture remains highly dependent on climate sensitive environmental systems (Abiodun, 2022;

Adejuwon, 2022; Haensler et al., 2023; Eshetie et al., 2026; IFPRI, 2023). Nigeria is highly vulnerable to climate variability because a significant proportion of its agricultural activities depend on rainfall patterns and environmental stability (FMA, 2022; Matthew et al., 2015; Oguntunde et al, 2022). Variations in temperature, precipitation, humidity and solar radiation significantly influence crop growth, evapotranspiration and water-use efficiency (Niang et al., 2022; WMO, 2024). Maize is one of the most important staple crops in Nigeria, and is particularly sensitive to heat stress and moisture deficits (Yahaya et al., 2025).

Agriculture is among the sectors most vulnerable to climate change because crop growth and development are closely regulated by climatic variables throughout the growing season (Adejuwon, 2022). Rising temperatures accelerate crop phenological development by shortening the duration of vegetative and reproductive growth stages, often resulting in reduced grain filling and lower yields. Changes in precipitation alter soil moisture availability and increase the frequency of droughts and floods, while variations in solar radiation directly affect photosynthesis and biomass accumulation. These combined effects increase evapotranspiration demand, reduce water-use efficiency, and ultimately threaten food production and food security, particularly in rain-fed agricultural systems such as those predominant in Nigeria.

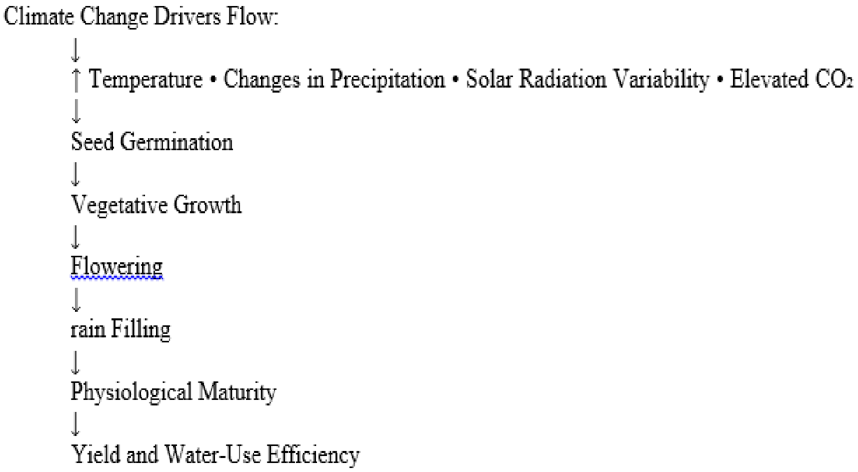

Figure 1: Influence of Climatic Variables on Maize Phonological Development

Side arrows indicating:

i. Heat stress
ii. Water stress
iii. Increased evapotranspiration
iv. Reduced photosynthesis
v. Shortened grain-filling period

The principal climatic variables considered in this study are precipitation, solar radiation, evapotranspiration, and water-use efficiency because they directly regulate crop productivity. Precipitation represents the primary source of water available for crop growth and soil moisture replenishment. Solar radiation provides the energy required for photosynthesis and controls atmospheric energy balance. Evapotranspiration (ET) is the combined loss of water through soil evaporation and plant transpiration and represents the atmospheric demand for water. Water-use efficiency (WUE) describes the amount of crop biomass or grain yield produced per unit of water consumed through evapotranspiration (Ogolo and Matthew, 2022). These variables are strongly interconnected: precipitation determines water availability, solar radiation supplies energy for photosynthesis and evapotranspiration, temperature influences atmospheric evaporative demand, evapotranspiration governs crop water consumption, and water-use efficiency reflects how effectively crops convert available water into economic yield under varying climatic conditions.

The emergence of smart physics approaches involving computational modelling, climate simulations, artificial intelligence-assisted environmental monitoring, remote sensing technologies and advanced numerical analysis has created new opportunities for understanding complex environmental systems (Zougmoré et al., 2021). Smart physics combines traditional physical principles with digital technologies, computational algorithms and environmental intelligence systems to improve prediction, monitoring and adaptation processes (Ogolo and Matthew, 2022). Smart physics approaches in climate science are increasingly applied in:

i. Climate forecasting and simulation
ii. Environmental data analytics
iii. Crop-climate interaction modelling
iv. Agro-hydrological assessment
v. Decision-support systems

vi. Precision agriculture
vii. Climate risk mapping

Although numerous studies have investigated climate variability, crop productivity and hydrological processes independently, relatively few have integrated climate projections, evapotranspiration dynamics, water-use efficiency and crop simulation modelling within a unified smart physics framework across Nigeria's contrasting agro-ecological zones. This study addresses that research gap by integrating multi-model climate projections, DSSAT crop simulations and agro-hydrological analysis to quantify future changes in sweetcorn evapotranspiration, water-use efficiency and yield under RCP2.6 and RCP8.5 scenarios. The findings provide scientific evidence to support climate adaptation planning, sustainable agricultural water management and food security policy in Nigeria.

MATERIALS AND METHODS

Study Area and Baseline Climate Conditions

The study covers representative agro-ecological zones in Nigeria including (figure 2):

i. Rainforest Zone – Akure
ii. Guinea Savannah Zone – Lokoja
iii. Coastal Zone – Port Harcourt
iv. Sudan/Sahel Zone – Katsina

These zones exhibit distinct climatic characteristics, ranging from humid tropical conditions in southern Nigeria to semi-arid conditions in northern Nigeria (Akinyemi et al., 2022; Anabaraonye et al., 2022). The selected locations provide a comprehensive representation of Nigeria’s climatic variability and agricultural vulnerability.

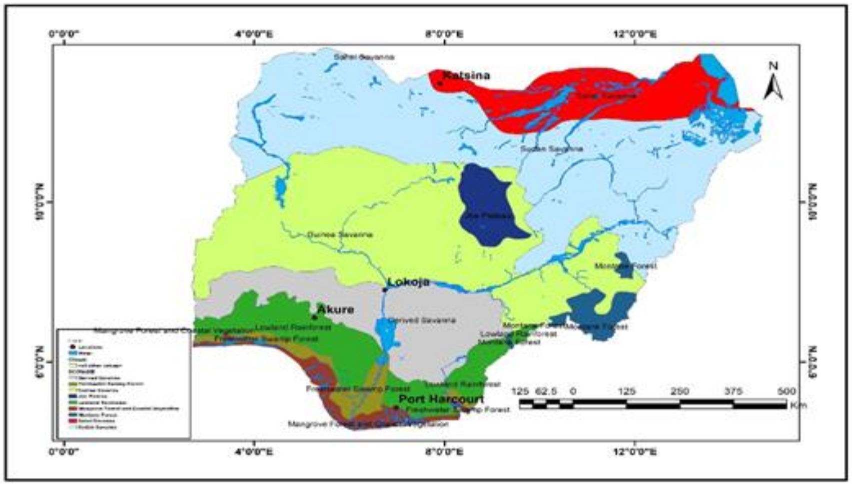

Figure 2: Map of Nigeria Showing the Study Area. Source: map.png

Climate Data and Models

Historical climate data covering 1984-2023 (NiMET, 2023; NiMET, 2024) were obtained and analyzed alongside future climate projections derived from HadGEM2-ES, NorESM1-M and MPI-ESM-MR. The climate models were selected because of their strong performance in representing tropical climate systems and regional climate variability (Matthew et al., 2015). Future climate projections were analyzed under RCP2.6 (low-emission scenario) and RCP8.5 (high-emission scenario). The study considered Near Future (2030 - 2064) and Far Future (2065 - 2099). Climate variables analyzed included maximum temperature, minimum temperature, precipitation and solar radiation. Climate datasets were processed from NetCDF format using MATLAB, extracted using FERRET, and processed using ClimPACT2 software.

Historical climatic conditions (1984–2023) were used as the baseline for comparison with projected climate scenarios. Mean historical climatic characteristics were:

Akure: Precipitation = 5.08 mm day^{-1}; Tmax = 28.97°C; Tmin = 20.98°C; Solar radiation = 20.46 MJ m^{-2} day^{-1}.

Lokoja: Precipitation = 3.41 mm day^{-1}; Tmax = 31.52°C; Tmin = 22.20°C; Solar radiation = 18.06 MJ m^{-2} day^{-1}.

Port Harcourt: Precipitation = 7.70 mm day^{-1}; Tmax = 30.59°C; Tmin = 23.56°C; Solar radiation = 17.80 MJ m^{-2} day^{-1}.

Katsina: Precipitation = 1.84 mm day^{-1}; Tmax = 34.93°C; Tmin = 21.32°C; Solar radiation = 21.47 MJ m^{-2} day^{-1}.

These historical climatic conditions served as the reference against which projected climatic changes under RCP2.6 and RCP8.5 scenarios were evaluated.

Smart Physics and Computational Framework

The smart physics framework integrated climate physics, numerical simulation, environmental data analytics and crop process modelling within a unified computational environment. Historical and projected climate datasets were first extracted from NetCDF files using FERRET software and subsequently processed in MATLAB for quality control, data conversion and preprocessing. ClimPACT2 software was used to compute climate extreme indices and characterize historical climatic variability. Processed climate variables were then supplied as input to DSSAT for crop growth and evapotranspiration simulations.

The computational workflow therefore consisted of five sequential stages:

i. Acquisition of historical and projected climate datasets.
ii. Climate data extraction, quality control and preprocessing.
iii. Climate trend and extreme-event analysis.
iv. Crop growth and evapotranspiration simulation using DSSAT.
v. Statistical analysis and inter-scenario comparison.

This integrated computational framework enabled the assessment of climate–crop–water interactions under different emission scenarios and provided quantitative estimates of future sweetcorn productivity.

Crop Modelling and Evapotranspiration Simulation

Sweetcorn growth and yield were simulated using the CERES-Maize module of DSSAT Version 4.8.2, while crop evapotranspiration (ET) was estimated using the FAO-56 Penman–Monteith method implemented within DSSAT. Daily climate inputs consisted of maximum temperature, minimum temperature, precipitation and solar radiation derived from historical observations and future climate projections. Soil physical characteristics, crop genetic coefficients and management practices were parameterized for each study location using site-specific information.

Model simulations were performed for the historical baseline period (1984–2023), Near Future (2030–2064) and Far Future (2065–2099) under RCP2.6 and RCP8.5 scenarios. The principal outputs analysed were seasonal evapotranspiration (ET), grain yield and Yield-to-Evapotranspiration Ratio (YPEM), calculated as:

YPEM = Grain Yield (kg ha^{-1}) / Seasonal Evapotranspiration (mm)

The DSSAT model simulated crop phenological development, biomass accumulation, grain filling and maturity based on the interactions between climate variables, soil conditions and crop physiological processes.

Environmental Stress Factor Analysis

Environmental stress analysis focused on the combined influence of temperature, precipitation, solar radiation and evapotranspiration on sweetcorn productivity. Temperature stress was evaluated from projected increases in maximum and minimum temperatures relative to the historical baseline. Water stress was assessed using changes in precipitation and seasonal evapotranspiration, while radiation stress was examined through projected changes in incoming solar radiation.

The combined effects of these climatic variables on crop phenology, grain filling, biomass production and water-use efficiency were interpreted using DSSAT simulated outputs. Yield reductions observed under future climate scenarios were attributed to increased atmospheric evaporative demand, shortened crop growth duration, reduced soil moisture availability and increased heat stress during reproductive growth stages.

Statistical Analysis

Descriptive statistics, trend analysis and scenario comparisons were performed for all climatic and crop variables. Multi-model ensemble averaging of HadGEM2-ES, NorESM1-M and MPI-ESM-MR projections was employed to minimize uncertainties associated with individual climate models.

Percentage changes in climatic variables and sweetcorn yield were computed relative to the historical baseline using:

$$Percentage\ Change\ (\%) = \frac{Future - Historical}{Historical} X100$$

Percentage yield reduction reported in the Results section was calculated as:

$$Yield\ Reduction\ (\%) = \frac{Historical\ Yield - Projected\ Yield}{Historical\ Yield} X100$$

Differences among ecological zones, climate scenarios and projection periods were evaluated through comparative statistical analyses and results were presented using line graphs and heatmaps.

RESULTS AND DISCUSSION

Temperature Projections

The projected maximum temperature (Tx) increased across all four agro-ecological zones under both emission scenarios (Figure 3). Relative to the historical baseline, mean maximum temperature increased by approximately 5.7 – 8.3°C in Akure**,** 4.0 – 6.8°C in Lokoja**,** 2.3 – 4.8°C in Port Harcourt and 1.6 – 4.9°C in Katsina, with the largest increases occurring during the Far Future (2065 – 2099) under RCP8.5. Although Katsina exhibited smaller relative percentage increases during the near future, absolute maximum temperatures exceeded 39°C, indicating severe thermal stress for rain-fed sweetcorn production.

The maximum temperature (Tx) heatmap visualization shows a uniform warming signal across all locations, with positive changes under every scenario and period. The intensity of warming is consistently greater under RCP8.5 than RCP2.6 and increases markedly from the near-future to the far-future period, indicating a clear scenario and time dependency. Akure and Lokoja experience relatively stronger increases in Tx, particularly under far-future RCP8.5, while Port Harcourt shows more moderate warming, reflecting the thermal buffering effect of the coastal environment. Katsina, although exhibiting smaller percentage increases under RCP2.6, experiences substantial warming under RCP8.5, reinforcing concerns about extreme heat stress in semi-arid northern regions especially under I-don't-care scenario.

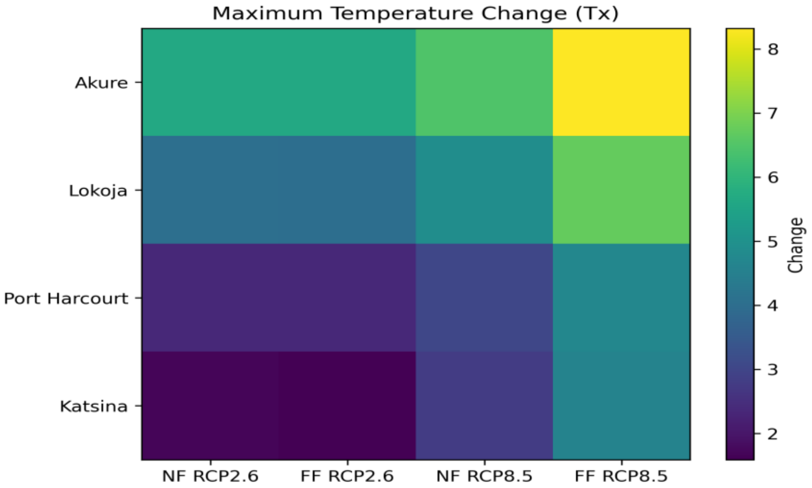

Figure 3: Heatmap Visualization of Future Maximum Temperature Change (Tx)

The figure 4 minimum temperature heatmap indicates widespread nighttime, with increases observed across all locations and scenarios. The magnitude of Tn change is generally comparable to or exceeds that of Tx, especially under RCP8.5, suggesting a reduction in diurnal temperature range. Lokoja and Katsina shows the strongest increase in minimum temperature, particularly in the far-future RCP8.5 scenario, implying enhanced nighttime heat retention and elevated thermal stress, suggesting reduced nocturnal cooling and potential impacts on crop respiration and human comfort. Akure also displays significant increases, while Port Harcourt shows relatively smaller but consistent warming. These patterns underscore the growing importance of minimum temperature changes in shaping crop physiology, evapotranspiration and heat stress impacts.

The minimum temperature (Tn) increased by approximately 3 – 7°C, with Lokoja and Katsina recording the greatest nocturnal warming. Rising nighttime temperatures imply reduced nocturnal cooling, increased crop respiration, and reduced recovery from daytime heat stress, thereby increasing evapotranspiration demand and reducing biomass accumulation.

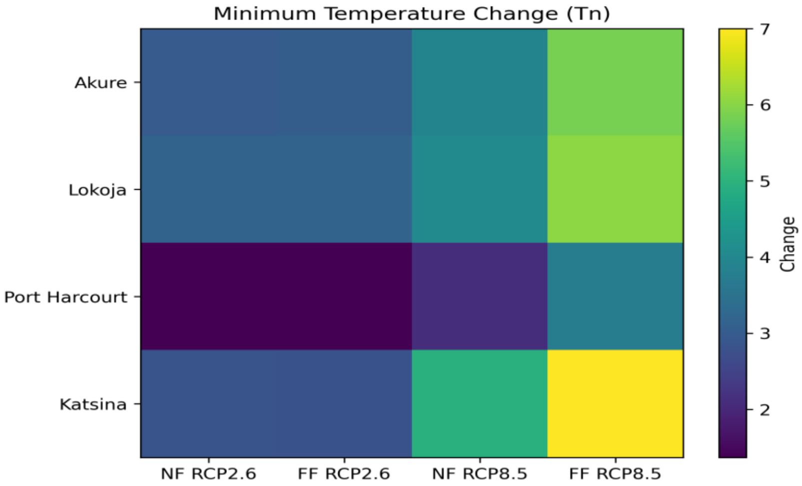

Figure 4: Heatmap Visualization of Future Minimum Temperature Change (Tn)

Precipitation Variability

Projected precipitation responses varied substantially among agro-ecological zones (Figure 5). Relative to the historical baseline, Lokoja exhibited the largest precipitation increase, ranging from approximately +1.8 to +2.8 mm day⁻¹, while Port Harcourt recorded modest increases of approximately +0.5 to +1.6 mm day⁻¹ under RCP8.5. Akure experienced only slight changes (−0.3 to +1.0 mm day⁻¹), whereas Katsina consistently exhibited precipitation deficits ranging from approximately −0.9 to −0.3 mm day⁻¹ across all future scenarios.

For the purpose of interpretation, rainfall anomalies greater than ±1 mm day⁻¹ were classified as substantial climatic shifts, values between ±0.3 and ±1 mm day⁻¹ as moderate changes, and values below ±0.3 mm day⁻¹ as minor departures from the historical baseline. These results demonstrate increasing spatial variability and north–south contrasts in future rainfall distribution.

Lokoja exhibits consistently large positive changes in precipitation under both RCP2.6 and RCP8.5, with the magnitude intensifying from the near-future to the far-future period, indicating a robust wetting signal. In contrast, Katsina shows persistent and substantial declines in precipitation across all scenarios, reflecting heightened aridity under future climate conditions. Akure and Port Harcourt display comparatively modest changes, with slight decreases or near-neutral responses under RCP2.6 and moderate increases emerging under RCP8.5 in the far future. Generally, the heatmap highlights a strong north-south contrast in precipitation response, suggesting divergent hydro-climatic risks across Nigeria’s climate zones. These variations suggest growing instability in regional hydrological systems.

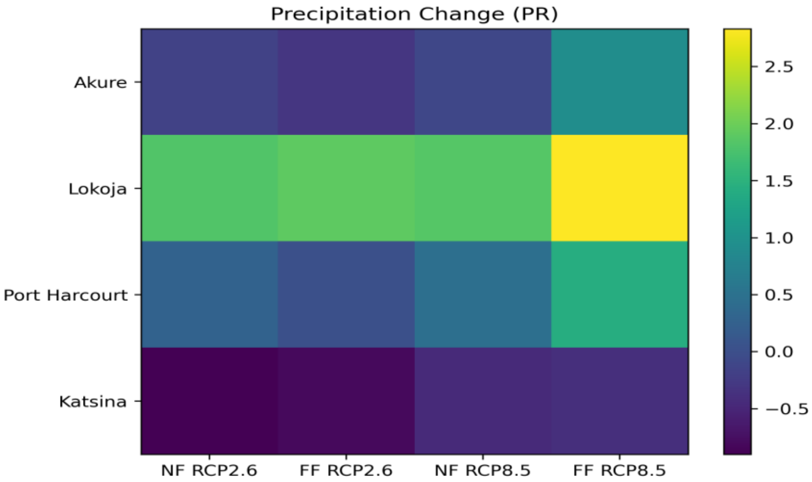

Figure 5: Heatmap Visualization of Future Precipitation Change (Pr)

Solar Radiation Change (SRD)

This heatmap in figure 6 depicts projected changes in solar radiation under near-future (NF) and far-future (FF) conditions for RCP2.6 and RCP8.5 scenarios. Lokoja and Katsina consistently show strong positive changes, indicating increased incoming solar energy that may enhance evapotranspiration rates. Port Harcourt exhibits slight reductions under RCP2.6, shifting to modest increases under RCP8.5, likely influenced by coastal cloud dynamics. The intensification of solar radiation under high-emission and far-future scenarios, when combined with rising temperatures, may significantly amplify evaporative demand and crop water requirements, particularly in inland and northern regions.

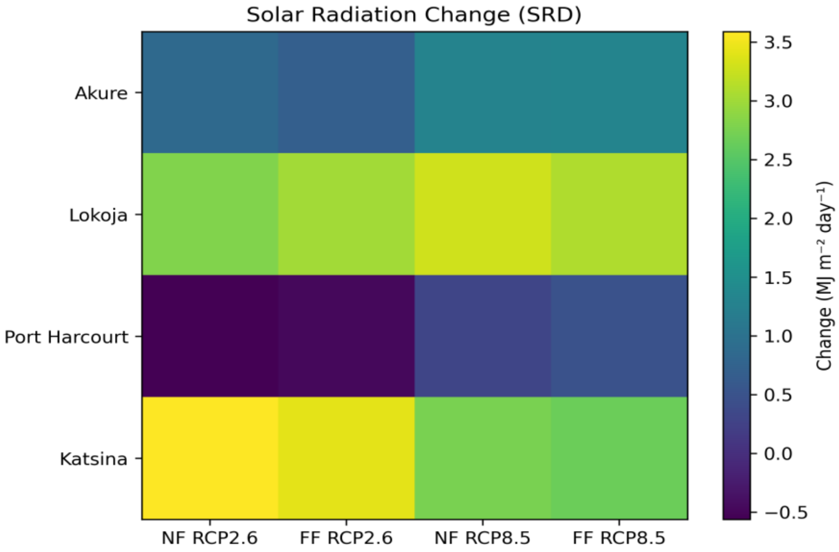

Figure 6: Heatmap Visualization of Future Solar Radiation Change (SRD)

Solar radiation provides the primary energy source that drives evaporation from the soil surface and transpiration from plant leaves. Consequently, increasing solar radiation directly increases reference evapotranspiration (ET_0). When elevated solar radiation occurs simultaneously with rising air temperature, atmospheric vapour pressure deficit increases, resulting in enhanced evaporative demand. Unless compensated by adequate rainfall or irrigation, greater evapotranspiration reduces soil moisture availability, increases crop water stress, lowers stomatal conductance, suppresses photosynthesis and ultimately reduces grain yield.

Evapotranspiration (ET) and Maize Yield Response

Projected warming significantly increased evapotranspiration demand across all agro-ecological zones, primarily driven by rising temperature, increased solar radiation and enhanced atmospheric evaporative demand. Semi-arid regions exhibited the strongest evapotranspiration increase due to high thermal stress. This significantly reduced projected maize yield across Nigeria. Under RCP8.5, yield decline exceeded 50% in several regions, Savannah and Sahel zones exhibited the highest vulnerability. Heat stress and water deficits reduced crop productivity substantially. The outcome reveal increasing risks to food security under future climate change.

The simultaneous increase in maximum temperature, minimum temperature and solar radiation substantially increased atmospheric evaporative demand throughout the growing season. According to the Penman–Monteith equation, evapotranspiration increases with increasing net radiation and air temperature because both variables increase the energy available for water vaporization and atmospheric moisture demand. Consequently, future climate scenarios are expected to accelerate soil water depletion and increase crop water requirements, particularly in the Guinea Savannah and Sahel regions. Thermal stress and evapotranspiration are strongly coupled. Elevated temperatures increase the saturation vapour pressure deficit (VPD) between the leaf surface and the atmosphere, thereby increasing transpiration rates. Initially, evapotranspiration rises under moderate warming; however, prolonged thermal stress causes partial stomatal closure to reduce water loss. This simultaneously limits CO_2 uptake, reduces photosynthetic efficiency, shortens the grain-filling period and ultimately decreases maize yield.

Percentage yield reduction was calculated relative to the corresponding RCP2.6 yield using:

$$Yield\ Reduction\ (\%) = \frac{Yield_{8.5} - Yield_{2.6}}{Yield_{2.6}} X100$$

In the near-future period, maize yield reductions were relatively moderate across the three climatic zones, with Akure, Lokoja and Katsina showing reductions of 18.75%, 16.67% and 12.50%, respectively (Table 1). Under this period, the climatic conditions projected under RCP 8.5 are still within a partially tolerable threshold for sweet corn cultivation. Although temperature increases and rainfall variability begin to affect crop growth, physiological processes such as germination, flowering and grain filling may still occur with limited disruption. The comparatively smaller reduction observed in Katsina may be associated with the existing adaptation of maize varieties and farming systems in semi-arid environments to water stress and high temperature conditions. In the far-future period, however, the reductions became substantially more severe, particularly under the high-emission RCP 8.5 scenario. Lokoja experienced the highest decline (-92.31%), followed by Katsina (-75%) and Akure (-40%). These pronounced reductions indicate that prolonged exposure to elevated greenhouse gas concentrations may significantly exceed the thermal and moisture tolerance thresholds of maize.

Table 1: Mean Rain-Fed Maize Yield Distribution across Nigerian Climatic Regions under RCP 2.6 and RCP 8.5 Scenarios for Near- And Far-Future Periods

Time Horizon	Climatic Region (Station)	RCP 2.6 Yield (Mt ha^{-1})	RCP 8.5 Yield (Mt ha^{-1})	Yield Reduction (%)	p-value	Significance
Near Future	Akure (Rainforest)	1.6	1.3	-18.75	<0.05	*
Near Future	Lokoja (Guinea Savannah)	1.2	1.0	-16.67	<0.05	*
Near Future	Katsina (Sahel Savannah)	0.8	0.7	-12.50	>0.05	NS
Far Future	Akure (Rainforest)	1.5	0.9	-40.00	<0.05	*
Far Future	Lokoja (Guinea Savannah)	1.3	0.1	-92.31	<0.01	**
Far Future	Katsina (Sahel Savannah)	0.8	0.2	-75.00	<0.01	**

Notes: Significance levels: * $p < 0.05$; ** $p < 0.01$; NS = not significant.

Heatmap shading indicates severity of yield reduction under RCP 8.5 relative to RCP 2.6.

The figure 7 below illustrates the projected distribution of rain-fed maize yield across three major Nigerian climatic regions - Rainforest, Savannah and Sahel - under two greenhouse gas emission scenarios: RCP 2.6 and RCP 8.5. The results reveal substantial regional disparities in maize productivity and demonstrate the strong influence of climate change intensity on future crop performance. Under the RCP2.6 low-emission scenario, maize yield decreases progressively from the Rainforest region (approximately 1.5 mt/ha) to the Savannah (1.3 mt/ha) and further to the Sahel region (0.8 mt/ha). This pattern reflects the natural climatic gradient across Nigeria. The Rainforest zone benefits from relatively high annual rainfall, moderate atmospheric humidity, longer growing seasons and more favorable soil moisture conditions, which collectively enhance maize growth and grain development. The Savannah region, although moderately suitable for maize production, experiences greater rainfall variability and seasonal dry periods that limit yield potential compared to the humid south. In the Sahel region, low rainfall, high evaporative demand and recurrent drought conditions substantially constrain maize productivity, resulting in the lowest projected yields. In contrast, the RCP8.5 high-emission scenario shows a much sharper decline in maize yield across all climatic zones. Yield in the Rainforest decreases to approximately 0.9 mt/ha, while the Savannah region experiences an extreme decline to nearly 0.1 mt/ha. The Sahel shows a slight recovery relative to Savannah but remains critically low at approximately 0.2 mt/ha. These results suggest that intensified greenhouse gas emissions and associated warming may significantly reduce the suitability of rain-fed maize cultivation across Nigeria. The graph shows that future maize productivity in Nigeria is highly dependent on greenhouse gas emission pathways. Under lower emissions (RCP2.6), maize production may remain moderately sustainable, especially in the humid southern regions. However, under the high-emission RCP 8.5 scenario, substantial yield collapse is projected, particularly in the Savannah and Sahel zones.

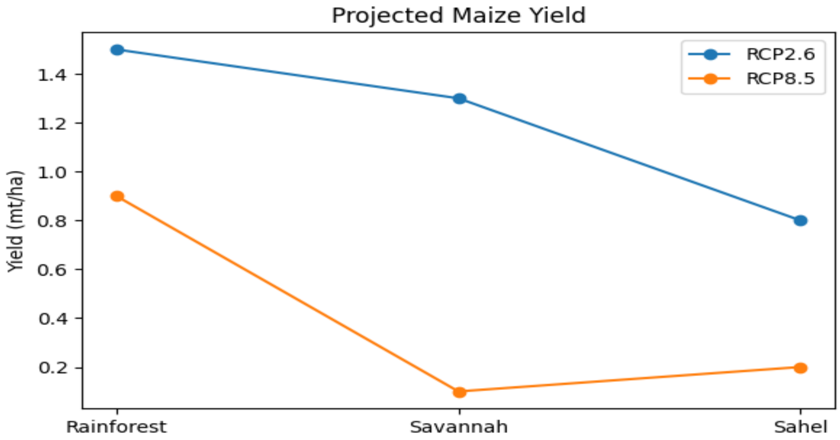

Figure 7: Projected Maize Yield under RCP Scenarios

Water-Use Efficiency

The distribution of the Average Maize Yield to Evapotranspiration Ratio (YPEM) across the selected Nigerian climatic regions reveals how efficiently maize converts water lost through evapotranspiration (ET) into grain yield under different climate change scenarios. The YPEM indicator, expressed in kg/ha/mm, is an important measure of crop water productivity because it reflects the quantity of maize yield produced per unit of water consumed.

The results in Table 2 show clear regional and scenario-based variations in maize water productivity under both low-emission (RCP 2.6) and high-emission (RCP 8.5) climate pathways. Under the RCP2.6, relatively stable or moderately improved YPEM values were observed in Akure and Lokoja during the future periods. Akure increased slightly from 4.6 to 4.7 kg/ha/mm, representing a 2.17% increase, while Lokoja increased from 4.0 to 4.5 kg/ha/mm, corresponding to a 12.5% increase. These improvements suggest that under lower greenhouse gas concentrations, future climatic conditions may still support efficient utilization of available water for maize production. Moderate warming combined with relatively stable rainfall conditions may enhance physiological activity and water-use efficiency without causing severe moisture stress. In contrast, Katsina recorded a decline from 6.2 to 4.9 kg/ha/mm under RCP 2.6, representing a 20.97% reduction. Although Katsina initially exhibited the highest YPEM values among the regions, indicating strong water-use efficiency under current semi-arid conditions, future increases in temperature and evapotranspiration demand may significantly reduce soil moisture availability and crop performance over time. Under the RCP8.5 high-emission scenario, the reductions in YPEM became substantially more severe across all regions. Akure declined from 3.8 to 2.8 kg/ha/mm (-26.32%), Lokoja declined dramatically from 3.4 to 0.5 kg/ha/mm (-85.29%), and Katsina reduced from 4.8 to 1.2 kg/ha/mm (-75%). These sharp declines indicate that future extreme warming conditions may greatly impair maize water productivity in Nigeria.

Table 2: Distribution of Average Maize Yield to Evapotranspiration Ratio (YPEM) under Different Climate Scenarios

	Mean Maize Yield - ET Ratio (YPEM, kg/ha/mm)					
	RCP 2.6			**RCP 8.5**		
	Near Future	**Far Future**	**% Change**	**Near Future**	**Far Future**	**% Change**
Akure	4.6	4.7	2.17	3.8	2.8	-26.32
Lokoja	4	4.5	12.5	3.4	0.5	-85.29
Katsina	6.2	4.9	-20.97	4.8	1.2	-75

The figure 8 graph illustrates the distribution of maize Yield–Evapotranspiration Efficiency (YPEM) across the Rainforest, Savannah and Sahel climatic regions of Nigeria under two climate change scenarios: RCP 2.6 and RCP 8.5. YPEM, expressed in kg/ha/mm, represents the amount of maize grain yield produced per unit of water lost through evapotranspiration (ET). It is therefore an important indicator of crop water-use efficiency and agricultural sustainability under changing climatic conditions. The graph reveals a strong contrast between the low-emission (RCP 2.6) and high-emission (RCP 8.5) scenarios.

Under the RCP2.6 scenario, YPEM values remain relatively high and stable across all climatic regions. The Rainforest region records approximately 4.7 kg/ha/mm, the Savannah about 4.5 kg/ha/mm and the Sahel nearly 4.9 kg/ha/mm. These values indicate that maize is able to utilize available water relatively efficiently under moderate climate change conditions. The slight reduction observed in the Savannah region may reflect moderate moisture stress or increased evapotranspiration demand, but overall, the system remains agriculturally sustainable. The relatively high YPEM in the Sahel under RCP 2.6 is particularly important. Despite receiving lower rainfall, crops in semi-arid environments often develop adaptive mechanisms such as efficient stomatal regulation, deeper rooting systems and conservative water-use strategies. Consequently, maize may produce relatively more yield per unit water consumed under moderate climatic stress conditions. In contrast, the RCP8.5 scenario shows a dramatic reduction in YPEM across all regions. The Rainforest declines to approximately 2.8 kg/ha/mm, the Savannah drops sharply to nearly 0.5 kg/ha/mm, while the Sahel records about 1.2 kg/ha/mm. These substantial reductions indicate severe deterioration in maize water productivity under intensified climate warming.

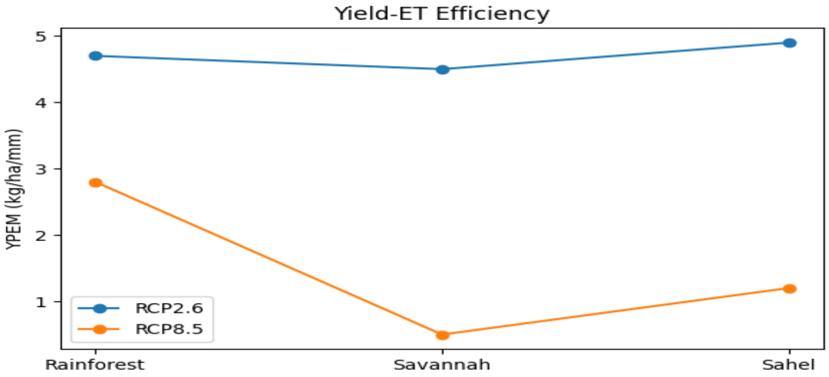

Figure 8: Yield-Evapotranspiration Efficiency under Future Climate Scenarios.

The graph demonstrates that future climate change may significantly reduce the efficiency with which maize converts water into grain yield, particularly under high greenhouse gas emissions. Under RCP 2.6, maize production remains relatively resilient across Nigerian climatic zones, suggesting that climate mitigation efforts could help sustain agricultural productivity. However, under RCP 8.5, the sharp decline in YPEM indicates increasing vulnerability of rain-fed maize systems to future water stress and climatic extremes.

Discussion

Generally, results revealed significant warming across all agro-ecological zones under future climate scenarios. Under RCP8.5, Katsina exhibited the highest warming intensity in the far future. Savannah and Sahel zones experienced more severe warming than southern regions. The increase in temperature indicates intensified atmospheric evaporative demand and increased hydro-climatic stress. The findings demonstrate that future climate change will significantly alter agro-hydrological systems across Nigeria. Increasing temperature intensifies atmospheric evaporative demand, leading to higher evapotranspiration rates and greater crop water requirements. However, projected rainfall changes do not compensate for increasing water demand, resulting in severe moisture stress during critical crop growth stages. The stronger warming observed in northern Nigeria aligns with previous studies showing greater vulnerability of semi-arid regions to future climate extremes. For instance, IPCC (2023) projected accelerated warming over tropical regions, while similar increases in evapotranspiration have been reported by Zapata et al. (2026).

Rising temperatures accelerate crop phenological development, shortening the grain-filling period and reducing biomass accumulation. Excessive heat during flowering could impair pollen viability and fertilization, leading to poor kernel development and substantial yield loss. Higher temperatures increase atmospheric evaporative demand, causing greater evapotranspiration rates. Under rain-fed conditions, this intensifies soil moisture depletion and exposes crops to drought stress, particularly in the Guinea Savannah and Sahel regions.

Changes in rainfall distribution, delayed onset of rains and increased dry spell frequency reduce effective water availability during critical growth stages. Even where annual rainfall increases slightly, poor temporal distribution still negatively affects maize productivity. Lokoja's extreme decline may be linked to its transitional climatic position between the humid south and drier north, making it highly sensitive to combined heat and moisture stress. Katsina, already characterized by arid conditions, becomes increasingly vulnerable under intensified warming due to limited soil moisture reserves and recurrent drought conditions.

The results suggest that climate change, particularly under high-emission pathways, may severely threaten rain-fed maize production across Nigeria. The findings emphasize the urgent need for climate adaptation strategies such as drought-tolerant maize varieties, improved irrigation systems, soil moisture conservation practices and climate-smart agricultural management to sustain future food security. The yield-to-evapotranspiration ratio (YPEM) declined significantly under future climate scenarios. This indicates reduced water-use efficiency, increased hydro-agricultural stress and reduced productivity per unit water consumed. The strongest decline occurred under RCP8.5 in the savannah region. The results shows that maize water-use efficiency in Nigeria may remain relatively sustainable under low greenhouse gas emissions (RCP 2.6), particularly in southern and middle-belt regions. However, under the high-emission RCP 8.5 pathway, severe declines in YPEM suggest that future climate change could drastically reduce the efficiency with which maize converts water into yield. This has major implications for:

i. food security,
ii. agricultural sustainability,
iii. irrigation planning,
iv. And climate adaptation strategies in Nigeria.

The findings therefore emphasize the urgent need for drought- and heat-tolerant maize varieties, supplemental irrigation systems, improved soil moisture conservation techniques, and climate-smart agricultural practices to enhance future crop water productivity under changing climatic conditions. The study further demonstrates the growing importance of smart physics approaches in environmental management and agricultural planning. Smart physics systems provide:

i. Improved climate prediction
ii. Enhanced environmental monitoring
iii. Data-driven agricultural forecasting
iv. Real-time environmental analytics
v. Climate risk assessment capabilities

The integration of climate physics, numerical modelling, remote climate datasets and DSSAT crop simulations demonstrates how smart physics methodologies improve climate-risk assessment and agricultural decision support. In this study, smart physics contributed directly through climate projection, evapotranspiration modelling, crop simulation and quantitative evaluation of future food security risks.

CONCLUSION

This study demonstrates that climate change will significantly increase hydro-climatic stress across Nigeria's agro-ecological zones under future climate scenarios. Rising temperature and increasing evapotranspiration demand are expected to reduce maize productivity and water-use efficiency, particularly under RCP8.5 high-emission scenario. The study further highlights the importance of smart physics approaches involving climate modelling, computational analysis, digital environmental systems and agro-hydrological simulations for understanding and managing future climate risks. The integration of smart physics technologies into climate science and agricultural systems provides a powerful pathway toward technological advancement, climate resilience and sustainable food security in Nigeria.

Based on the findings, the following adaptation strategies are recommended:

i. Development of drought-resistant maize varieties
ii. Expansion of irrigation infrastructure
iii. Climate-smart agricultural practices
iv. Improved soil moisture conservation
v. Smart environmental monitoring systems
vi. Digital climate advisory services

Integrated climate-risk management systems

REFERENCES

Abiodun, B. J. (2022). Climate change and food security in Africa: Implications for sustainable development. *Environmental Research Letters*, *17*(4), 041002. https://doi.org/10.1088/1748-9326/ac5f3b

Adejuwon, J. O. (2022). Rainfall variability and crop yields in Nigeria. *Climatic Change, 171, 42*.

Ajayi, V. O., Fuwape, J. A., and Oluleye, A. (2022). Trends and variability in climate extremes over Nigeria. *Environmental Research Communications*, 4(12), 125006. https://doi.org/10.1088/2515-7620/ac9f4f

Akinyemi, O., Ajayi, V. O., Adefisan, E. A., and Ogunjobi, K. O. (2022). Spatio-temporal characterization of climatic zones and aridity patterns in northern Nigeria. *Climate*, *10*(8), 108. https://doi.org/10.3390/cli10080108

Anabaraonye, B., Amaechi, M., Okolo, N. V., Adeniyi, T. F. and Nwobu, E. A. (2022). The impacts of climate change on biodiversity in Nigeria. *International Journal of Research in Civil Engineering and Technology*, *3(2), 01-05*.

Ayanlade, A., and Radeny, M. (2022). Climate extremes and impacts on crops in semi-arid West Africa. *Science of the Total Environment*, 812, 152454. https://doi.org/10.1016/j.scitotenv.2021.152454
ClimPACT2. User guide. https://github.com/ARCCSS-extremes/climpact2/

Dogliotti, S., van Ittersum, M. K., and Rossing, W. A. H. (2020). A system analysis of agricultural development: The role of yield gaps and resource use efficiency. *Agricultural Systems*, *177*, 102714. https://doi.org/10.1016/j.agsy.2019.102714

Eshetie, H. A., Alamirew, T., Abera, A., Sahlu, D. and Ayalew, A. D. (2026). Climate change impacts on potential evapotranspiration and crop water demand in the Tana Subbasin, upper Nile Basin, Ethiopia. *Journal of water and climate change jwc202603*. https://doi.org/10.2166/wcc.2026.023

Food and Agricultural Organization, FAO (2023). The State of Food and Agriculture in Nigeria. FAO Report.
Federal Ministry of Agriculture, FMA (2022). *National Agriculture Resilience Framework.* Abuja, Nigeria.

Haensler, A., Hagemann, S., and Jacob, D. (2023). Regional climate projections for West Africa: Insights from Coordinated Regional Climate Downscaling Experiment (CORDEX). *Climate Dynamics*, 60(7-8), 2245-2264. https://doi.org/10.1007/s00382022-06317-y

Hoogenboom, G. C. H., Porter, V., Shelia, K. J. Boote, U., Singh, W., Pavan, F. A. A., Oliveira, L. P., Moreno-Cadena, T. B., Ferreira, J. W., White, J. I., Lizaso, D. N. L., Pequeno, B. A., Kimball, P. D., Alderman, K. R., Thorp, S. V., Cuadra, M. S., Vianna, F. J., Villalobos, W. D., Batchelor, S., Asseng, M. R., Jones, A., Hopf, H. B., Dias, L. A., Hunt, and Jones J. W. (2023). Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.8.2 (www.DSSAT.net). DSSAT Foundation, Gainesville, Florida, USA.

IFPRI (2023). Climate change, agriculture, and food security in West Africa. IFPRI Discussion Paper.

Intergovernmental Panel on Climate Change, IPCC (2023). *Climate change 2023: Synthesis report*. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC.https://www.ipcc.ch/report/ar6/syr/

Isa, Z., Sawa, B. A., Abdussalam, A. F. (2023). Impact of climate change on climate extreme indices in Kaduna River basin, Nigeria. *Environ. Sci. Pollut. Res.* 30, 77689–77712(2023). https://doi.org/10.1007/s11356-023-27821-5

Matthew, O. J., Abiodun, B. J. and Salami, A. T. (2015). Modelling the impacts of climate variability on crop yields in Nigeria: performance evaluation of RegCM3-GLAM system. *Meteorol. Appl.* **22**, 198–212 (2015), published online 3 March 2014 in Wiley Online Library (wileyonlinelibrary.com)
https://doi.org/10.1002/met1443

Niang, I., Ruppel, O. C., and Abdrabo, M. A., (2022). Climate change impacts, adaptation, and vulnerability in Africa. In: IPCC AR6 WGII. Cambridge University Press.

Nigerian Meteorological Agency (NiMet). (2023). *Historical Weather Data for Selected Locations in Nigeria (1984-2023)*. NiMet, Abuja, Nigeria.

NiMet (2024). Nigeria Climate Outlook 2024. Nigerian Meteorological Agency Report.

Ogolo, E. O. and Mathew, O. J. (2022). Spatial and temporal analysis of observed trends in extreme precipitation events in different climatic zones of Nigeria. *Theoretical and Applied Climatology, (2022), 1-17*.

Ogolo, E. O. Ojo, O. S. and Olabisi I. O. (2024). Spatio-temporal distribution of intensity and frequency of extreme temperature events over Nigeria. *Theoretical and Applied Climatology, (2022), 1-17.* https://doi.org/10.1007/s00704-024-05215-y

Oguntunde, P. G., Lischeid, G., and Dietrich, O. (2022). Observed and projected climate change in West Africa: Evidence from temperature and precipitation datasets. Environmental Challenges, 7, 100481. https://doi.org/10.1016/j.envc.2022.100481

Olasina, G. (2021). Climate change in Nigeria: Causes, effects, and solutions. *EnvironmentalNews Nigeria*. https://www.environewsnigeria.com/climate-change-nigeria-causes-effects-solutions/

Wang, H., Zhou, T., Yu, Y., and Chen, X. (2022). Intensification of climate extremes under global warming. *Nature Climate Change*, *12*(1), 28–34.https://doi.org/10.1038/s41558-021-01245-3

World Meteorological Organization, WMO (2024, November 11). *State of the climate 2024update*. https://public.wmo.int/

Yahaya, O. M., Ogolo, E. O., Agele, S. O., Ajayi, V. O. and Anselm, O. O. (2025). Sensitivity analysis of climate change impacts on maize yield in some climate regions of Nigeria using DSSAT version 4.8.2. *Financial Engineering, vol. 3, pp78-100.* https://doi.org/10.37394/232032.2025.3.9

Zapata, N., Medina, E. T. and Playan, E. (2026). Meteorological drivers modulate evapotranspiration trends under climate warming in Northeastern Spain. *Irrig Sci44, 81 (2026).* https://doi.org/10.1007/s00271-026-01117-1

Zougmoré, R. B., Partey, S. T., Ouédraogo, M., et al. (2021). Toward climate-smart agriculturein West Africa: a review of climate change impacts, adaptation strategies, and policyoptions. *Regional Environmental Change*, 21(2), 56.https://doi.org/10.1007/s1011302101750-0