

The Africa Sovereign Climate Facility ("ASCF")

Annex 23: Climate Risk Assessment

Table of Contents

0. Executive Summary	5
1. Introduction.....	7
2. Study area, data and methods.....	9
2.1 Study area.....	9
2.2 Data	9
2.2.1 Gridded observations	9
2.2.2 Reanalysis dataset.....	9
2.2.3 Model data.....	9
2.3 Methodology	12
2.3.1 Identification of homogeneous climatic zones.....	12
2.3.2 Analysis of the climatological mean.....	12
2.3.3 Extreme climate indices	12
2.3.4 Agricultural relevant indicators.....	14
2.3.5 Renewable Energy Potential	15
3. Result of Climate Analysis for Angola.....	17
3.1 Historical analysis.....	18
3.1.1 Climatological analysis of seasonal mean temperature and precipitation	18
3.1.2. Analysis of Annual cycle for each Homogeneous Zone.....	18
3.1.3. Analysis of Annual cycle at the Infrastructure Sites: Corimba and Chicomba.....	19
3.2 Projected changes in base parameters and climate extremes	25
3.2.1. Spatial pattern of the projected change in mean temperature and precipitation	25
3.2.2. Projected changes in sector-relevant extreme environmental/climate factors	26
3.3. Assessment of Renewable Energy Resources	28
3.3.1 Wind Energy Potential	28
3.3.2 Solar Energy Potential.....	28
3.3.3 Hydropower Energy Potential	28
3.4 Conclusions and Recommendation for adaptation Strategies	29
3.4.1 Summary and Conclusions.....	29
3.4.2 Proposed Recommendations for Adaptation.....	30
4. Result of Climate Analysis for Republic of Benin.....	31
4.1 Historical analysis.....	31

4.1.1 Climatological analysis of seasonal mean temperature and rainfall	31
4.1.2. Analysis of Annual cycle for each Homogeneous Zone.....	31
4.1.3 Trend Analysis at Homogeneous Zones	33
4.1.3. Trend Analysis at the infrastructure site: The GDIZ	36
4.1.4 Spatial distribution of sector relevant extreme environmental/climate factors	38
4.2. Projected change in base parameters and climate extremes	40
4.2.1. Spatial pattern of the projected change in mean temperature and precipitation	40
4.2.2. Projected changes in sector relevant extreme environmental/climate factors.....	41
4.3. Assessment of renewable energy resources	44
4.3.1 Wind energy potential.....	44
4.3.2 Solar energy potential.....	45
4.3.3 Hydropower Potential.....	45
4.4. Conclusion and Recommendation for Adaptation Strategies.....	45
4.4.1. Summary and Conclusion	45
4.4.2 Recommendations for Adaptation Strategies	46
5. Result of Climate analysis for Côte d'Ivoire	49
5.1 Historical analysis.....	49
5.1.1 Climatological analysis of seasonal mean temperature and rainfall	49
5.1.2. Analysis of Annual Cycle for each Homogeneous Zone	49
5.1.3 Analysis of Annual Cycle at the Infrastructure Site: The Humbole region	50
5.1.4 Trend analysis at homogenous zone and infrastructure sites	51
5.1.5 Spatial distribution of sector-relevant extreme environmental/climate factors.....	54
5.2 Projected changes in base parameters and climate extremes	56
5.2.1 Spatial pattern of the projected change in mean temperature and precipitation	56
5.2.2. Projected changes in sector-relevant extreme environmental/climate factors	56
5.3 Assessment of Renewable Energy Resources	58
5.3.1 Wind Energy Potential.....	58
5.3.2 Solar Energy Potential	59
5.3.3 Hydropower Potential.....	59
5.4 Conclusion and Recommendation on Adaptation Strategies	60
5.4.1 Summary and conclusion.....	60
5.4.2 Recommendation for Adaptation Strategies	60
6.0 Nigeria	62
6.1 Historical analysis.....	62

6.1.1. Climatological analysis.....	62
6.1.2 Analysis of Annual Cycle for each Homogeneous Zone	63
6.1.3 Present-day and projected climate change hotspots.....	63
6.1.4 Spatial distribution of sector-relevant extreme environmental/climate factors	66
6.2 Project change in base parameters and climate extremes	67
6.2.1 Spatial pattern of the projected change in mean temperature and precipitation	67
6.2.2. Projected changes in sector-relevant extreme environmental/climate factors	68
6.3 Assessment of Renewable Energy Resources	70
6.3.2 Solar Energy Potential	70
6.3.3 Hydropower Potential.....	70
6.4 Conclusion and Recommendation and Adaptation Strategies	70
6.4.1 Summary and Conclusion	70
7.0 Conclusion.....	72
Reference	75

0. Executive Summary

As climate-related hazards become an increasing threat across Africa, it is imperative to conduct thorough climate assessments to understand their impacts on key sectors. This report presents a comprehensive climate impact assessment for the Republic of Benin, Côte d'Ivoire, Angola and Nigeria. Conducted within the framework of the Africa Sovereign Climate Facility, the assessment aims to provide a scientific basis for targeted climate investments, thereby justifying the need to mobilize climate finance to address pressing climate change challenges in these countries. The analysis employs observational datasets and ensemble outputs from high-resolution climate models, focusing on the present-day period (1985–2014) and two future periods: the near future (2025–2054) and the far future (2055–2084). Climate projections are assessed under two Shared Socioeconomic Pathways (SSPs)—SSP2-4.5 and SSP5-8.5—to examine potential climate impacts under moderate and high-emission scenarios.

The methodology incorporates homogeneous climate zone classifications refined by spatial and literature-based criteria. Historical climate conditions are evaluated through temperature and precipitation, while future projections consider both base climate parameters and extreme climate indices such as heat stress, drought, and flood risk indicators. Agricultural and water resource indicators, including irrigation demand and water availability, are analyzed using FAO-endorsed hydrological balance equations. Renewable energy potential is assessed to explore viable options for solar, wind, and hydro energy development, ensuring energy security and climate resilience.

Findings indicate significant warming trends, increased precipitation variability, and intensified extreme weather events across all four countries. In Côte d'Ivoire, average temperatures have already increased by 1.0–1.5°C in recent decades, with northern areas reaching 34°C, exacerbating evapotranspiration and lowering agricultural productivity. Future climate projections suggest a significant temperature increase of 1.5–4.5°C by the late 21st century, with inland and southern areas facing the highest warming. This warming is expected to intensify heat stress, with the number of hot days exceeding 35°C rising by 30 to 60 days annually, particularly in southern Angola and northern Benin. Benin's projections show rising temperatures, with northern regions experiencing 27–30°C in DJF and 30–33°C in MAM. Drought indicators also project an increase in the frequency and severity of droughts, particularly in southern Angola, southern Benin, and parts of Côte d'Ivoire. In contrast, extreme rainfall events are projected to become more intense, with northern Angola and coastal regions in Côte d'Ivoire seeing an increase in heavy rainfall events. These changes will lead to higher flood risks, particularly in flood-prone areas such as the northern parts of Angola and the coastal zones of Côte d'Ivoire. In Nigeria, warming is projected to continue across all three zones, with temperature increases exceeding 3°C above present-day levels under the SSP5-8.5 scenario by the late 21st century, while remaining below 2°C under SSP2-4.5.

The projected changes in heat stress, drought, and heavy rainfall will have severe consequences for key sectors in each country. In Angola, the combination of rising temperatures and increased drought frequency threatens crop yields and water availability for hydropower generation. Reduced rainfall will decrease river flows, impacting hydropower production. Benin's industrial zones, including the GDIZ, will be increasingly exposed to heat stress, disrupting operations, while more frequent and intense flooding will damage infrastructure. In Côte d'Ivoire, the agricultural sector, such as the production of rice, will suffer from shifting rainfall patterns and heat stress. The rise in heavy rainfall and flooding could damage crops, and challenge infrastructure resilience. Extreme climate indices in Nigeria show rising trends in heatwaves, droughts, and floods, with heat stress most severe in the northern and central regions and intense rainfall events more common in the south. Future projections indicate increasing temperature extremes and rainfall variability, leading to more frequent and

prolonged heatwaves and droughts, which threaten infrastructures related to energy, agriculture, and water resources. A clear upward trend in sea level rise is evident in both present-day observations and future climate projections along the coasts of Benin and Angola. This increasing trend heightens the exposure of critical infrastructure sites, particularly around Porto-Novo Lagoon and Lake Nokoué in Benin, as well as in Corimba, Angola, to coastal flooding, erosion, and saltwater intrusion.

Despite these risks posed by climate change, renewable energy potential offers opportunities to harness as a strategic component for adaptation and pathways to sustainable development. In Angola, there is a significant potential for solar (5.0–6.5 kWh/m²/day) and wind energy, particularly along its coast. It also has extensive hydropower potential that can be optimized by innovating dam designs and implementing smart grid technologies to maintain energy production despite the adverse impact of climatic changes. Benin holds strong potential for solar (~100MW) and wind energy, making it well-positioned to meet the energy demands of the GDIZ industrial zone and promote energy security and sustainable industrialization. In Côte d'Ivoire, the abundant solar power potential, particularly in the northern regions, could provide an opportunity for integrating solar energy into agricultural practices, thereby enhancing resilience and ensuring stable energy supply for irrigation systems and supporting agricultural mechanization in critical crop-producing areas. Nigeria's substantial renewable energy resources provide a crucial pathway for climate adaptation and energy sustainability. The Sahel and Savannah regions exhibit the highest wind energy potential, with wind power densities reaching approximately 150 W/m² in northern states such as Borno, Sokoto, Zamfara, and Gombe, compared to a lower maximum of about 70 W/m² in the Guinea Coast. Solar energy potential is also highest in the Sahel and Savannah zones, peaking at 4.8 MW, while the Guinea Coast records the lowest values at 3.3 MW, and the tropical rainforest areas range between 4.2 and 4.5 MW.

To mitigate climate risks, strengthening climate adaptation strategies is essential. Priorities include climate-smart agriculture, improved water resource management, disaster preparedness, and resilient infrastructure investments. Countries must invest in early warning systems, policy reforms, and community-based adaptation initiatives to build long-term sustainability. Additionally, expanding hydropower, solar, and wind energy while addressing infrastructure gaps will be crucial for energy security and economic resilience. Angola, Benin, Côte d'Ivoire and Nigeria can strengthen their resilience to climate change and support long-term economic growth by incorporating climate adaptation into national policies, advancing sustainable energy solutions, and enhancing regional collaboration.

1. Introduction

Africa, despite its wealth of natural resources, faces persistent challenges in food and water security, energy access, and sustainable infrastructure, with many countries underperforming in these areas (Simpson et al., 2023). As rapid urbanization, climate change, and socio-economic disparities intensify, addressing these challenges holistically is essential for fostering resilience and sustainable development. The agricultural sector, which employs the majority of the population, is constrained by low productivity, climate variability, and inadequate infrastructure (Awulachew et al., 2008 n.d.). Climate change exacerbates droughts, floods, and erratic rainfall, while poor infrastructure hinders food distribution and water management. This report examines climate impact on food and water security, and access to energy in Côte d'Ivoire, Benin, Nigeria and Angola, highlighting the unique challenges and opportunities in each country.

Food security remains a critical issue, worsened by climate change and economic instability. In Nigeria, for instance, food insecurity has been on the rise (Fawole & Özkan, 2017; Ifeanchi & Okudu, 2020) and is closely linked to climate variability and change, which affects agricultural productivity and exacerbates poverty (Ogunpaimo et al., 2021). The reliance on rain-fed agriculture makes the country particularly vulnerable to droughts and floods, leading to significant fluctuations in food production (Ogunpaimo et al., 2021; Utsev et al., 2023). In Angola, during the peak lean season (February–May 2023), 1.3 million people—4% of the population—faced high levels of acute food insecurity, with the southwestern regions being the most affected. Similarly, in Benin, the disruption of the agricultural calendar due to changing climatic conditions has been recognized as a principal concern, with farmers attesting to the adverse effects of climate variability on their agricultural productivity (Gbemavo et al. 2022). Weather extremes and economic shocks were identified as key drivers of the crisis (GRFC, 2024). Water security is equally critical, as many countries face challenges related to water scarcity and management. Water scarcity poses a significant challenge to food security in Africa, particularly in sub-Saharan regions heavily reliant on agriculture (Besada & Werner, 2015). The relationship between water availability and food production is crucial for creating sustainable food systems (Vilakazi et al., 2019). The population of Angola grew by 127% between 2012 and 2020, which posed a serious challenge on water supply. Eleven million Angolans (34%) experienced unimproved water sources and surface water (UNICEF, 2023). Côte d'Ivoire also faces challenges in water management, where agricultural practices often lead to the depletion of water resources, impacting both food production and access to safe drinking water (Soro et al., 2017). Climate change poses a significant threat to water security in Côte d'Ivoire, with changing rainfall patterns and increased temperatures affecting the availability of freshwater resources. Studies indicate that climate variability has led to more frequent and severe droughts, impacting agricultural productivity and water supply (Wudil et al., 2023). The degradation of water quality due to climate change and human activities further complicates the situation, making it essential to adopt integrated water resource management strategies (Wudil et al., 2023). Integrated water resource management is essential to ensure sustainable agricultural practices and enhance food security across these nations (Kumar, 2015).

The adoption of renewable energy technology for increased energy access, sustainable infrastructure, and energy-efficient built environments can significantly improve the region's ability to manage these challenges. Crucially, a comprehensive understanding of both current and future climate impacts is vital to developing effective solutions. Climate change will continue to alter precipitation patterns, increase the frequency of extreme weather events, and strain already-scarce resources, making it imperative to adapt infrastructure and urban planning to meet these challenges.

Owing to the critical role that climate change plays in modulating the water, food and energy security, there is a growing body of literature (e.g., Utsev, et al., 2023; Umugwaneza et al., 2021) that assesses the impact of

climate change on water and food security in various African countries, including Benin, Angola, Côte d'Ivoire and Nigeria. These studies highlight the multifaceted challenges posed by climate change, particularly in terms of water resource availability and agricultural productivity, which are critical for ensuring food security. For instance, they noted that with increased greenhouse gas concentrations, global temperatures are projected to increase, and climate extreme events are likely to be more frequent thereby affecting water availability and agricultural productivity (Aggarwal & Singh, 2010). This is likely to pose challenges for food security, particularly in vulnerable regions like Africa (Aggarwal & Singh, 2010; Turrall et al., 2011). While integrated assessment approaches between climate change and sustainable development goals, including energy, and food security have been highlighted at continental and global scale, there is a lack of a comprehensive assessment of current and future climate change impact on the water and food security, and access to energy nexus with a proposal of suitable adaptation options for Angola, Benin, Côte D'Ivoire, and Nigeria.

The assessment is conducted within the framework of the Africa Sovereign Climate Facility, which aims to mobilize climate finance to address pressing climate change challenges in the assessed countries. The objective of this report is to provide a comprehensive assessment of how current and projected climate change impacts water and food security and access to energy through a methodical approach that combines observational climate data and high-resolution downscaled climate model outputs under two emission scenarios. This integrated methodology not only enhances the accuracy of climate impact assessments but also provides critical insights for developing effective adaptation and mitigation strategies in the face of climate change.

The climate assessment employs observational data, specifically the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) rainfall data, alongside the ERA5 reanalysis dataset and NASA Earth Exchange Global Daily Downscaled Climate Projections (NEX-GDDP-CMIP6) models. The analysis spans a present-day period from 1985 to 2014 and projects into two future periods: 2025-2054 and 2055-2084, under two Shared Socioeconomic Pathways (SSPs), namely SSP245 and SSP585.

A comprehensive assessment and understanding of how current and future climate change affects water and food security as well as renewable energy potential, a major source to increased energy access, is crucial for developing adaptive strategies that enhance resilience and sustainability. This understanding not only informs effective resource management practices but also supports the development of policies that can mitigate the adverse effects of climate change on vulnerable populations and critical infrastructure. As climate change continues to pose significant challenges, prioritizing this understanding will be essential for achieving food security, energy security, and sustainable development.

2. Study area, data and methods

2.1 Study area

The assessment is carried out over 5 countries located within West and Central Africa. Côte d'Ivoire, Nigeria and Benin (Western and Guinea coast), and Angola (central and southwest). These countries lie in different climatic and ecological zones thus, facing a multitude of issues in terms of climate change adaptation and mitigation (Redelsperger et al., 2006). Due to substantial differences in their location relative to the Atlantic Ocean, land surface coverage ranging from dense forest cover to semi-desert, those regions are characterized by very diverse hydro-meteorological regimes.

2.2 Data

2.2.1 Gridded observations

The Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS, Funk et al., 2015), developed by the Climate Hazards Group at the University of California, combines satellite imagery and ground-based rainfall observations to produce high-resolution precipitation estimates. This dataset is valuable for monitoring rainfall patterns and extremes in regions where ground-based observations are sparse or non-existent. CHIRPS produce daily, pentadal, and monthly rainfall estimates, covering the period from 1981 to the present (Funk et al., 2015; Dinku et al., 2018). However, in this report, the analysis is limited to the 1985-2014 period to match the historical model simulation period.

2.2.2 Reanalysis dataset

The ERA5 (Hersbach et al., 2020) dataset is the fifth generation of global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). Among the notable improvements of ERA5 over its predecessor, ERA-Interim, is its improved numerical model version and enhanced data assimilation techniques, which incorporate a wider array of observational data, including satellite measurements and ground-based observations. ERA5 features hourly atmospheric estimates covering a period from 1950 to present at a spatial resolution of approximately 31 km (0.25°), making it a valuable resource for climate research and applications, particularly in regions where traditional weather stations are sparse. Studies (e.g., Gleixner et al., 2020; Gbode et al., 2023) have shown that ERA5 generally correlates well with observed temperature data across various locations in Africa, indicating its reliability for capturing both mean and extreme temperature events.

2.2.3 Model data

The NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP, Thrasher et al., 2022) dataset utilizes bias correction and statistical downscaling techniques to refine the coarse outputs from the Coupled Model Intercomparison Project Phase 6 (CMIP6) to provide high-resolution present and future climate data. This is particularly crucial as global climate models typically operate at resolutions that are too coarse for effective local or regional climate impact assessments.

The primary method used in generating the NEX-GDDP data involves two main steps: bias correction and spatial disaggregation. In the first step, bias correction is applied to the raw outputs from the Coupled Model Intercomparison Project Phase 6 (CMIP6) models. This is achieved by comparing the model outputs with historical observational data to identify systematic biases in the GCMs. The bias correction process adjusts the model outputs to better align with observed climate conditions, thereby enhancing the reliability of the projections, assuming the same bias structure will prevail in future GCM projections. The second step involves spatial disaggregation, which refines the corrected GCM outputs to a higher spatial resolution of $0.25^\circ \times 0.25^\circ$ (approximately 25 km). This is crucial for local and regional climate studies, as many GCMs operate at much coarser resolutions that are inadequate for detailed analyses (Chen et al., 2017). The bias corrected spatially disaggregated (BCSD) method effectively translates the large-scale climate signals captured by GCMs into finer-

scale projections that can be used for various applications, including hydrological modeling and climate impact assessments.

Furthermore, the NEX-GDDP dataset encompasses a multimodel ensemble approach, which integrates outputs from multiple CMIP6 models. This ensemble technique enhances the robustness of the projections by capturing a range of possible future climate scenarios, thereby providing a more comprehensive view of potential climate impacts (Thrasher et al., 2022). The dataset covers historical periods from 1950 to 2015 and future scenarios extending to 2100, under different Shared Socioeconomic Pathways (SSPs). In this assessment, 10 ensembles (Table 2.1) are selected for further analysis based on preliminary assessment of the raw CMIP6 models. It should be noted that, when the data from NEX-GDDP exhibits a strong disagreement with observations and/or reanalysis in terms of magnitude and temporal trend, a statistical post processing method is applied to both historical and projected field to correct the simulated trend. For instance, a statistical postprocessing method using multiple regression analysis is developed and applied to NEX-GDDP temperature and incoming shortwave radiation and ERA5 incoming shortwave radiation field to produce a bias corrected incoming shortwave radiation field. Similar procedure is applied to downscale, and bias correct the CMIP6 based sea surface height field.

Table 2.1: Details of the 10 NEX-GDDP-CMIP6 models used in this report

S/N	Model	Institute	Resolution (°lon × °lat)	References
1	ACCESS-CM2	Commonwealth Scientific and Industrial Research Organization	1.88×1.25	Dix et al (2019a), Dix et al (2019b)
2	EC-Earth3	EC-EARTH consortium	0.70×0.70	EC-Earth (2019a), EC-Earth (2019b)
3	EC-EARTH3-Veg	EC-EARTH consortium	0.70×0.70	EC-Earth (2019c), EC-Earth (2019d)
4	FGOALS-g3	Chinese Academy of Sciences Flexible Global Ocean-Atmosphere-Land System Model	2.0×2.0	Li (2019a,b)
5	GFDL-ESM4	Geophysical Fluid Dynamics Laboratory (GFDL)	1.25×1.00	Krasting et al (2018), John et al (2018)
6	INM-CM4-8	Institute of Numerical Mathematics	2.00×1.50	Volodin et al (2019a), Volodin et al (2019b)
7	INM-CM5-0	Institute of Numerical Mathematics	2.00×1.50	Volodin et al (2019c), Volodin et al (2019d)
8	IPSL-CM6A-LR	Institute Pierre-Simon Laplace (IPSL)	2.50×1.26	Boucher et al (2018), Boucher et al (2019)
9	MPI-ESM1-2-LR	Max Planck Institute	1.88×1.88	Wieners et al (2019a), Wieners et al (2019b)

10	NorESM2-MM	NorESM Climate Modelling Consortium	0.9×1.3	Bentsen et al (2019a,b)
----	------------	-------------------------------------	---------	-------------------------

2.3 Methodology

This study investigates the impacts of climate change on multiple sectors, focusing on distinct time slices: baseline/historical (1985–2014) and future projections (2025–2054 and 2055–2084). Climate projections are analyzed under two shared socioeconomic pathways (SSP245 and SSP585) scenarios providing a range of potential climate outcomes.

2.3.1 Identification of homogeneous climatic zones

For performing detailed climate analysis at local and sub-regional scale, homogenous climatic zones were identified and analysis were carried out over such homogeneous zones or at the infrastructure sites. The homogenous climate zones were guided by the Köppen climate classification system and were further refined based on specific criteria, including the relative size of the climate zones, insights from reviewed literature, and spatial proximity. Additionally, smaller climatic zones with relatively insignificant proportions were amalgamated with neighbouring, larger zones to maintain consistency in the classification framework. The final climate zone classifications were limited to three primary climate zones per country, with the exception of Benin which retained its classification based on literature review, the classification of climatic zones for other countries followed specific methodologies:

1. Angola: The Cwb and Cwa regions, along with a small, isolated area of tropical savannah in the east, were merged to form a temperate zone. The warm desert and semi-arid regions were combined into an arid zone, resulting in a total of three climate zones for the country.
2. Côte d'Ivoire: Climatic zones were delineated based on the findings of Diarrassouba et al. (2024), which projected changes in the country's climate zoning (*Atmospheric and Climate Sciences*, 14, 62-84. doi: 10.4236/acs.2024.141004).

2.3.2 Analysis of the climatological mean

This analysis examines the climatological mean of key baseline parameters, including mean temperature (Tmean), minimum temperature (Tmin), maximum temperature (Tmax), precipitation (Pr), solar radiation, and wind speed. Historical observational data are systematically compared with modeled simulations to assess the accuracy and reliability of climate models. This evaluation not only highlights model performance but also helps identify significant long-term trends, providing valuable insights into climate variability and potential future changes.

2.3.3 Extreme climate indices

Sixteen extreme climate indices (Table 2.2) were generated using the World Meteorological Organization's Expert Team on Sector Specific Climate Indices (ET-SCI) recommended ClimPACT2 tool. These indices are categorized into heat-based, drought-based, and flood-based indicators to provide a comprehensive understanding of potential climate extremes.

Table 2.2: Extreme climate indices used in this assessment.

Index	Indicator name	Definition	Unit
R20mm	Number of very Heavy rainy days	No. of days for which PR > 20mm/day	days
Prcptot	Total wet day precipitation	Sum of daily PR >= 1mm	mm
R99ptot	Fraction of annual PR from very heavy rainy days	100* (Annual sum of daily PR > 99th percentile)/Prcptot	%
Rx1day	Max. 1-day PR	Max. 1-day PR total	mm
Rx5day	Max. 5-day PR	Max. 5-day PR total	mm
CDD	Consecutive dry days	Max. annual number consecutive dry days (PR <1mm)	days
SPI	Standardized Precipitation Index	Measure of 'drought' on scale of 3,6, 12months(McKee, 1995)	Unit less
SPEI	Standardized Precipitation Evaporation Index	Measure of 'drought' on scale of 3,6,12months(Beguería et al., 2010)	Unit less
WSDI	Warm spell duration indicator	Annual no. of days contributing to events in which 6 or more consecutive days experience Tmax> 90th percentile	days
HWF	Heat wave frequency	Number of days that contribute to the heat wave	Days
HWD	Heat wave duration	The length of the longest duration of the heat wave	Days

HWA	Heat wave amplitude	The peak daily value in the hottest heatwave as defined by the 90th percentile of TX	°C
TXx	Max TN	Warmest daily TN	°C
TNn	Min TX	Coldest daily TX	°C
R10mm	Number of days when PR >= 10 mm	Number of days when PR >= 10 mm	days
CWD	Consecutive Wet Days	Maximum annual number of consecutive wet days (when PR >= 1.0 mm)	days

2.3.4 Agricultural relevant indicators

Key agricultural relevant indicators, including water availability, irrigation requirements, and crop water demand, were computed using approaches recommended by the Food and Agriculture Organization (FAO). Simple hydrological balance equations at the grid-point level were employed to analyze water resource availability and agricultural needs under changing climate conditions.

To estimate water availability, the interplay between precipitation (P) and evapotranspiration (ET) is critical. Water availability can be defined as the amount of water that is accessible for use, which is influenced by both the input from precipitation and the output through evapotranspiration. The fundamental equation used to assess water availability in this report is expressed as:

$$\text{Water Availability [WA]} = P - ET$$

This equation highlights that water availability is determined by the balance between the water received through precipitation and the water lost through evapotranspiration. When precipitation exceeds evapotranspiration, there is a surplus of water, indicating higher water availability; conversely, when evapotranspiration exceeds precipitation, it results in a deficit, leading to reduced water availability (Gbode et al., 2022; Ballarin et al., 2023; Zhao et al., 2021).

To compute crop water demand and irrigation requirements, the reference evapotranspiration (ET_0) serves as a fundamental parameter. The most widely accepted method for estimating ET_0 is the FAO-56 and is given as.

$$ET_0 = 0.0023(T_{\text{mean}} + 17.8)(T_{\text{max}} - T_{\text{min}})^{0.5} R_a$$

where T_{mean} , T_{max} , T_{min} , and R_a are the mean, maximum, minimum temperatures, and extraterrestrial radiation, respectively.

The methodology for computing irrigation requirements involves several key steps that integrate climatic data, crop water demand and effective rainfall. This process is essential for optimizing water use in agricultural practices and ensuring that crops receive adequate moisture throughout their growth cycles.

Once ET_0 is calculated, crop water requirements can be approximated by the actual evapotranspiration (ET_a) from ET_0 by applying a crop coefficient (K_a), which accounts for the specific water needs of different crops at various growth stages. The relationship can be expressed as:

$$ET_a = K_a \times ET_0$$

Where K_a values are derived from empirical studies and vary based on crop type, growth stage, and environmental conditions (Ewaid et al., 2019; Gbode et al., 2022). For instance, K_a values are typically higher during the peak growth stages and lower during the initial and late stages of crop development. Accurate K_a values can be derived from empirical studies or established databases (Pejić et al., 2021; Sobenko et al., 2018).

Effective rainfall or precipitation (P_{exh}) must be considered in the irrigation requirement calculation. Effective rainfall is the portion of total precipitation that contributes to soil moisture and is available for crop use. It can be parameterized using various methods such as the FAO's effective rainfall estimation guidelines (Carvalho et al., 2018) or empirically as the one below.

$$P_{exh} = P * C$$

Where: P is the total Precipitation (mm) and C is the Coefficient of effective precipitation (dimensionless). Please note that C varies based on factors such as soil type, crop type, and local climatic conditions. While C ranges from 0.5 to 0.8, depending on the specific context, in this assessment a value of 0.7 is adopted.

The irrigation requirement (IR) can then be computed as:

$$IR = ET_a - P_{exh}$$

This equation indicates that the irrigation requirement is the difference between the actual evapotranspiration (crop water demand) and the effective rainfall. If the effective rainfall exceeds the crop's water needs, the irrigation requirement may be zero or negative, indicating that no irrigation is necessary.

This approach allows for the tailoring of irrigation practices to meet the specific demands of crops, thereby optimizing water use efficiency.

2.3.5 Renewable Energy Potential

Renewable energy sources, such as solar, hydro and wind can play a pivotal role in enhancing food security while simultaneously ensuring energy security. For regions like Sub-Saharan Africa where access to energy is limited, the integration of renewable energy into agricultural practices can facilitate sustainable irrigation systems and mechanization can increase crop yields and hence can improve food security by increasing food availability and reducing malnutrition (Kinda, 2021). The potential of renewable energy as a sustainable solution to mitigate the impacts of climate change is increasingly recognized across various regions and sectors. Transitioning to renewable energy sources is crucial not only for reducing these emissions but also for enhancing energy security and promoting sustainable development (Owusu & Asumadu-Sarkodie, 2016). However, the effectiveness of renewable energy in combating climate change is influenced by various climatic factors, such as temperature, precipitation, radiation and wind speed, which can affect the performance and viability of renewable energy systems (Yalew et al., 2020). This interplay necessitates a comprehensive understanding of how climate change impacts renewable energy generation and the subsequent economic implications.

The potential for renewable energy development is assessed by analyzing wind, hydropower, and solar energy resources. The evaluation involves quantifying energy generation potential under current climate conditions, providing insights into the viability of renewable energy as a sustainable solution.

2.3.5.1 Wind energy potential

The wind energy potential (wind power per unit area) can be calculated using the formula, which relates wind speed to wind power density:

$$P = \frac{1}{2} \rho V^3$$

where (P) is the power (in watts/m²), (ρ) is the air density (approximately 1.225 kg/m³ at sea level), and (V) is the wind speed (in m/s). Please note that the wind is at the turbine installed height, say at 80m and is not the surface wind. In order to account for the height difference between the climate model output height and the turbine installed height, we have employed wind profile power law relating the wind speed at whatever altitude (h=80m) to the known wind speed at a reference level (h₀=10m) as follows:

$$V(h) = V(h_0)[h/h_0]^{0.7}$$

Given that the wind turbine is working in a certain wind regime where the production is halting when the wind speed is below a minimum cut-in speed (4m/s). The turbine also stops when the wind speed is higher than the maximum cut-off speed (25m/s) for security reasons.

2.3.5.2 Solar energy potential

The photovoltaic power potential (PVP) can be estimated using the power rating or the energy rating method. The power rating method uses the integration of instantaneous photovoltaic power generation over time, while the energy rating method estimates the photovoltaic potential by multiplying the total solar irradiance during a specific period of time by a performance ratio (Dubey et al. 2013). Photovoltaic (PV) electricity generation depends on surface-downwelling shortwave radiation, and other atmospheric variables affecting panel efficiency, namely surface air temperature (TAS) and surface wind velocity (VWS).

According to Jerez et al., (2015), the photovoltaic potential can be calculated as.

$$PV_{pot}(t) = P_R(t) \frac{RSDS(t)}{RSDS_{STC}}$$

where STC refers to standard test conditions ($RSDS_{STC}=1,000 \text{ W m}^{-2}$), those for which the nominal capacity of a PV device is determined as its measured power output, and PR is the so-called performance ratio, formulated to account for changes of the PV cells efficiency due to changes in temperature as:

$$P_R(t) = 1 + \gamma [T_{cell}(t) - T_{STC}]$$

where T_{cell} is the PV cell temperature, $T_{STC}=25^\circ\text{C}$ and γ is taken here as $-0.005^\circ\text{C}^{-1}$, considering the typical response of monocrystalline silicon solar panels. Finally, T_{cell} is modelled considering the effects of temperature, radiation and wind (TAS, RSDS and VWS) on it as:

$$T_{cell}(t) = c_1 + c_2 TAS(t) + c_3 RSDS(t) + c_4 VWS(t)$$

with $c_1=4.3^\circ\text{C}$, $c_2=0.943$, $c_3=0.028^\circ\text{C m}^2 \text{ W}^{-1}$ and $c_4=-1.528^\circ\text{C sm}^{-1}$ (Chenni et al. 2007).

Hence, if ambient conditions (RSDS, TAS and VWS) correspond to the STCs, PVpot equals 1 and PV power production reaches the rated value. If they are so that Tcell is higher (lower) than 25 °C and/or RSDS lower (higher) than 1,000 W m⁻², PVpot will be lower (higher) than the unit and the PV power output will be lower (higher) than the nominal power of the module.

2.3.5.3 Hydropower potential

This methodological framework enables a comprehensive assessment of climate impacts across various sectors. To estimate the hydropower potential based on river discharge, spatial discharge data were processed. Annual total discharge data (in km³/year) covering the period 2000–2021 were obtained from a previously routed runoff dataset (Akpoti et al., 2024). The mean annual discharge for each river segment was computed over the 22-year period and subsequently converted to flow rate (m³/s). Hydropower potential was then calculated using the standard hydropower equation:

$$P(W) = \eta \times \rho \times g \times Q \times H$$

where P is the theoretical power output (Watts), $\eta=0.85$ is the assumed turbine-generator efficiency, $\rho=1000\text{kg/m}^3$, is the density of water, $g=9.81\text{m/s}^2$ is gravitational acceleration, Q is the computed mean annual flow rate, and H=50 m is the assumed hydraulic head. The resulting power potential was converted to megawatts (MW). To validate the estimated spatial hydropower potential, we used data from the Renewable Power Plant Database for Africa (RePP Africa) developed by Peters et al. (2023). This database provides a harmonized and curated inventory of existing and proposed renewable energy facilities, including detailed information on 1074 hydropower plants across the African continent, with georeferenced locations and installed capacity in megawatts. The comparison enabled us to assess the plausibility of our modeled hydropower estimates against actual hydropower infrastructure records for countries, thereby supporting the technical validation of the computed potential.

3. Result of Climate Analysis for Angola

The Republic of Angola is located on the west coast of the southern African region, between latitudes 4°22'S and 18°03'S and longitudes 11.7°E and 24°E. It has a land area of about 1,246,700 km², making it the seventh largest country on the continent, with a population of over 36.7 million in 2023. Angola shares borders with the Atlantic Ocean to the west, Namibia to the south, Zambia to the east, and the Democratic Republic of Congo to the north. Angola's Gross Domestic Product (GDP) expanded by 2.90% in the third quarter of 2024 compared to the previous quarter. Since 2000, GDP growth has averaged 2.78%, reaching a peak of 23.20% in the fourth quarter of 2007 and a record low of -9.50% in the first quarter of 2015.

Angola has a tropical to subtropical climate with distinct dry and rainy seasons. The country's climate is influenced by altitude, longitude, and the Benguela Current. The rainy season lasts from October to May and is characterised by hot and humid conditions, while the dry season, known as the Cacimbo season, occurs from June to September and is the coolest period of the year. Rainfall decreases from north to south and from east to west, with the Maiombe forest in the north receiving the highest amounts and Luanda, on the coast, receiving the least. Average temperatures range from 22–23°C during the rainy season and 18–20°C during the dry season. Droughts are frequent, particularly in the south

Angola's agriculture, forestry, and fisheries sectors remain underdeveloped but have strong growth potential due to the country's favorable geography, diverse ecology, and abundant natural resources. Two-thirds of the population rely on agriculture for food, employment, and income. With its fertile land and varied climate, Angola has the capacity to become one of Africa's leading agricultural producers. Additionally, the country has

significant hydroelectric potential, with most electricity generated from dams on the Cuanza, Cunene, Catumbela, and Dande rivers. However, a large portion of the country's power infrastructure remained inoperative into the 2000s due to disruptions caused by the National Union for the Total Independence of Angola. Since 2002, efforts have been made to repair, renovate, and expand these facilities, gradually improving hydropower generation capacity.

3.1 Historical analysis

3.1.1 Climatological analysis of seasonal mean temperature and precipitation

Precipitation patterns in Angola are highly seasonal (RCRC, 2021). The length of the rainy season, which generally lasts from September to April, varies by region. Rainfall is consistently more abundant in the interior than in coastal areas (Sawe, 2019), as observed during the DJF, MAM, and SON months. The peak rainfall, reaching up to 250 mm/month, occurs during the DJF months, particularly in central Angola. Consistent with Correia et al. (2025), the northern regions receive more rainfall than the southern regions during the MAM and SON months. The observed precipitation patterns align closely with the model output (NEX-GDDP CMIP6 ensemble mean) across all quarters or seasons.

The central plateaus remain cooler throughout the year (DJF, MAM, JJA, and SON) due to their high elevation. During the dry season (JJA), also known as Cacimbo (NAPA, 2011; RCRC, 2021), Angola exhibits two distinct temperature zones. Northern Angola, with its tropical savanna climate, is warmer than southern Angola, which has a temperate climate. The SON season records the highest mean temperatures across the country, with values exceeding 23°C in most regions except the plateaus. This is consistent with Hunter et al. (2020), which reported a historical (1980–2010) mean temperature of 23.9°C. Similarly, Correia et al. (2025) observed mean temperatures in the southern and central plateau regions ranging from 21°C to 22°C, while the northern and coastal regions recorded higher values between 24°C and 25°C, aligning with our results.

3.1.2. Analysis of Annual cycle for each Homogeneous Zone

The climate across Angola includes arid, temperate, and tropical conditions (Pinto et al., 2023). The annual variability of precipitation in these climate zones, indicates peak rainfall in March and a distinct dry season from May to September. There is slight dispersion or disagreement in the NEX-GDDP CMIP6 ensemble mean distribution during the peak rainfall months (October–April) compared to the austral winter months (May–September), where the distribution shows stronger agreement. The mean values are close to the median values during the peak rainfall months across all climate zones. Peak rainfall is slightly above 120 mm/month in the arid climate, about 200 mm/month in the temperate climate, and just below 200 mm/month in the tropical savanna climate. All three climate zones receive little to no rainfall during the dry season from June to August.

Temperature patterns across the three climate zones show that July, the driest month, has the lowest temperatures. Monthly temperature variability in the tropical savanna is minimal, generally ranging between 23.5°C and 24.5°C annually. In contrast, the arid and temperate climates exhibit greater temperature variability. The lowest temperatures occur in July, with values around 20°C in the arid climate and 19.5°C in the temperate climate, while peak temperatures reach approximately 25.5°C in October for the arid climate and nearly 24°C in September for the temperate climate. Pereira et al. (2024) reported a weak seasonal cycle over Angola, with mean monthly temperatures below 20°C in the wet season and around 16°C in the dry season.

The NEX-GDDP CMIP6 ensemble mean distribution shows strong agreement in the arid and temperate climate zones throughout the year. However, in the tropical savanna, some months exhibit slight dispersion or

disagreement. The mean values remain close to the median values in the distributions, indicating a symmetrical dataset.

3.1.3. Analysis of Annual cycle at the Infrastructure Sites: Corimba and Chicomba

Corimba, located in the coastal Luanda region of Angola, experiences a tropical to sub-tropical climate characterized by high humidity, warm temperatures, and low rainfall due to the cold Benguela current. The area generally has mean temperatures around 25.5°C, accompanied by high humidity (approx. 79%) and persistent coastal winds (RCRC, 2021). Chicomba, with coordinates (14.13°S, 14.91°E), is a town and municipality in the province of Huila, Angola. The municipality had a population of 168,114 in 2022 "Angola: Administrative Division (Provinces and Municipalities) - Population Statistics, Charts and Map". www.citypopulation.de. Retrieved 2024-11-29).

1. *Precipitation*

The observed and NEX-GDDP CMIP6 annual cycles or variability of the precipitation indicated peak precipitation, with values around 150 mm (225 mm), in the month of March (April) and little or no rain in the months of June to September (May to early August) for the Corimba (Chicomba) project sites respectively. The dry months are referred to as the austral winter months. This is consistent with the weather pattern in most parts of Angola. In the Chicomba project site, the NEX-GDDP CMIP6 slightly underestimated the observation during the peak rainfall months between October and April except in January and February. The mean and median values are generally close to each other, suggesting a symmetrical distribution during the rainfall months. There is little or no dispersion or disagreements in the NEX-GDDP CMIP6 ensemble mean distribution, particularly in the Corimba project site during the peak rainfall months (October – April). The austral winter months (May to September) have strong agreements in the NEX-GDDP CMIP6 distribution because there was no rain.

B. Maximum Temperature

Maximum temperatures are lowest, with values around 29°C, in the driest months of July and August, as shown in the Corimba project site. In Corimba, the warmest month is February with a peak temperature of about 33°C. Whereas in Chicomba, the warmest month is September which is consistent with the Chicomba project site. In Corimba peak maximum temperatures, of over 32°C are common in the months of January, February and March based on observations. On the contrary, Chicomba experiences lowest maximum temperatures during the months of January to July. The NEX-GDDP CMIP6 ensemble generally underestimated the observation all year round in Corimba with the highest bias in July to September, whereas in the Chicomba it overestimated the observation only during the cooler months of November to May. The distribution of the NEX-GDDP CMIP6 ensemble seemed to be roughly symmetrical due to the closeness between the mean and median values all year round for both Corimba and Chicomba sites.

C. Minimum Temperature

Similar to the maximum temperatures, the minimum temperatures are lowest in the month of July with values as low as 17.5°C in Corimba and 10°C in Chicomba. Peak nighttime or early hours temperatures (minimum temperatures) are consistent between October and April as shown by the plots of Corimba and Chicomba. The NEX-GDDP CMIP6 reproduced the annual cycle of minimum temperature well for both project sites although it slightly overestimated the observation at Corimba site. The distribution of the NEX-GDDP CMIP6 ensemble is roughly symmetrical due to the closeness between the mean and median values all year round and both in Corimba and Chicomba.

Observed annual precipitation varied significantly, ranging from 450 mm to 800 mm in the arid zone, slightly between 1000 mm and 1100 mm in the temperate zone, and between 1100 mm and just under 1300 mm in the tropical savanna zone. Based on the slope, the historical ensemble trend indicates precipitation has increased faster in the tropical savanna than in the other two zones. Specifically, the annual increase is 3.11 mm in the tropical savanna, compared to 1.35 mm in the arid zone and 1.09 mm in the temperate zone.

Under the SSP2.45 scenario, projected annual precipitation increases for the arid, temperate, and tropical savanna zones between 2025 and 2100 are 0.55 mm, 0.46 mm, and 1.67 mm, respectively. The SSP5.85 scenario projects higher increases of 0.62 mm, 0.73 mm, and 3.05 mm per year for the arid, temperate and tropical savanna climates. These projections indicate that precipitation will increase significantly in the tropical savanna compared to the other two zones. Toward the end of the century, precipitation variability is expected to widen compared to the near and mid-century periods.

2. *Temperature*

Observed temperatures range between 23.3°C and 23.8°C in the arid zone, between 21°C and 22°C in the temperate zone, and between 23.5°C and 24°C in the tropical savanna zone. The historical ensemble trend indicates an almost equal annual temperature increase across all three zones: 0.02°C in the arid zone and 0.03°C in the temperate and tropical savanna zones. Pinto et al. (2023) reported that warming is evident across Angola, with multiple datasets showing a mean annual temperature increase of 1.4°C [1.01–1.78°C] at a rate of 0.2°C [0.14–0.25°C] per decade since 1951.

Projections under the SSP2.45 scenario indicate an annual temperature increase of approximately 0.02°C across all three zones, while the SSP5.85 scenario projects a higher increase of approximately 0.05°C per year. By the end of the near (2015–2054), mid (2055–2084), and far (2085–2100) future periods, maximum warming under SSP2.45 is projected to reach 0.8°C, 1.4°C, and 1.7°C, respectively. Under SSP5.85, these values increase to 2°C, 3.5°C, and 4.25°C (closer to 4.9°C by Carvalho et al., 2016) for the near, mid and far futures, respectively. Additionally, Soares et al. (2024) recently projected an end-of-century warming of approximately 7°C for maximum and 6°C for minimum temperatures in southeastern Angola under the RCP8.5 scenario.

The temperature difference between the two scenarios widens progressively toward the end of the century because of the 0.03°C difference in the annual temperature increment. The SSP5.85 scenario shows greater variability, particularly toward the century's end. Overall, temperatures have been increasing at nearly the same rate across all three climate zones, and this trend is expected to continue in the future.

3.1.4.1 *Trend Analysis at the Infrastructure sites: Corimba and Chicomba*

1. *Precipitation*

The observed precipitation trends for the two project sites in Corimba and Chicomba indicated dry years between 1984 to 1990. Thereafter, the two project sites consistently get wetter. The increasing trend for the observed precipitation is most significant in the Chicomba project site with values of 64.133 mm/decade, whereas in the Corimba project site the precipitation trend is 37.293 mm/decade. Frequent annual spikes were observed over the years. The simulated historical ensemble trend showed that the two project sites have been experiencing drier years since 1984. The trend line showed that the Corimba project site would begin to experience wetter years from 2015 based on the decadal anomaly of 10.999 mm/decade. The Chicomba project site is likely to experience drier years up to about 2025 based on the historical ensemble. In the Corimba project site the SSP2-4.5 projected an increasing trend of 4.509 mm/decade in precipitation between 2025 and 2100, whereas the SSP5-8.5 scenario projected a trend of 5.429 mm/decade in precipitation between 2025 and 2100. This generally depicts that wetter conditions will increase both in the near and far future. In the Chicomba

project site the SSP2-4.5 projected an increase of 5.709 mm/decade in precipitation between 2025 and 2100, whereas the SSP5-8.5 scenario projected a decrease of -0.498 mm/decade in precipitation between 2025 and 2100.

2. *Maximum Temperature*

The observed maximum temperature trends for the Corimba project site suggested warmer years from 1984 up to 2000. Thereafter, the project site begins to have cooler variabilities. This is shown by the -0.468 °C/decade. The Chicomba project site showed no significant decadal anomaly based on the observed data. This is also shown by the -0.006 °C/decade. The historical ensemble trend showed that the two project sites experienced cooler years up to 2000 and warmer years thereafter both on a marginal basis. The historical ensemble is 0.169 °C/decade for the Corimba project site and 0.267 °C/decade for the Chicomba project site. In the Corimba project site the SSP2-4.5 projected an increase of 0.193 °C/decade in maximum temperatures between 2025 and 2100, whereas the SSP5-8.5 scenario projected an increase of 0.417 °C/decade in maximum temperatures between 2025 and 2100. This generally depicts that warmer conditions will increase both in the near and far future. In the Chicomba project site the SSP2-4.5 projected an increase of 0.243 °C/decade in maximum temperatures between 2025 and 2100, whereas the SSP5-8.5 scenario projected a decadal anomaly increase of 0.556 °C/decade in maximum temperatures between 2025 and 2100. Warmer conditions will also persist both in the near and far future in the Chicomba project site.

3. *Minimum Temperature*

The observed minimum temperature trends for the Corimba and Chicomba project sites indicates no significant trend. This is reflected in the magnitude of trend i.e. 0.08 °C/decade for the Corimba project site and 0.046 °C/decade for the Chicomba project site. The historical ensemble trend value is 0.233 °C/decade for the Corimba project site and 0.325 °C/decade for the Chicomba project site. In the Corimba project site minimum temperature is projected to increase by 0.209 °C/decade between 2025 and 2100 under SSP2-45 scenario, whereas under the SSP5-8.5 scenario, it is projected to increase by up to 0.466 °C/decade. This generally depicts that warmer conditions will be exacerbated both in the near and far future. In the Chicomba project site under the SSP2-4.5 scenario, minimum temperature is projected to increase by 0.235 °C/decade between 2025 and 2100, whereas for the SSP5-8.5 scenario, the minimum temperature is projected to increase by 0.545 °C/decade. This implies that the current warmer conditions will also persist both in the near and far future at the Chicomba project site.

4. *Sea Level Height*

The observed sea level height trend for Corimba project site shows a negative anomaly from 1984 to 2000 and a positive anomaly thereafter up to recent year, based on both the observed and historical ensemble data. This indicates that sea level heights were below average values prior to 2000 but have risen above average levels since then. This trend is shown by the anomaly of 0.027 meters/decade and 0.02 meters/decade for the observation and historical ensemble datasets, respectively. The SSP2-4.5 scenario projected an increase of 0.02 meters/decade in sea level height between 2025 and 2100, whereas for the SSP5-8.5 scenario, sea surface height is projected to increase by 0.04 meters/decade between 2025 and 2100. This generally depicts that sea level heights will increase both in the near and far future.

3.1.5. Spatial distribution of sector-relevant extreme environmental/climate factors

1. Historical Heat stress indicators

The warmest daytime temperatures (TXX) from 1985 to 2014, as indicated by both observations and the NEX-GDDP-CMIP6 ensemble show that the plateau region in west-central Angola remains consistently cooler than other regions due to its high elevation. The NEX-GDDP-CMIP6 ensemble mean overestimated observations in the eastern and southeastern parts of the country while underestimating them in the southwest. Peak warmest daytime temperatures (TXx) in southern Angola reach nearly 40°C for both the GDDP-CMIP6 ensemble (eastern and southeastern regions) and observations (extreme southwest). Observational data indicate that northern Angola is generally cooler than the south during the day. Significant differences are evident in the southwest and eastern zones, where the NEX-GDDP-CMIP6 ensemble underestimated observed temperatures in the southwest but overestimated them in the east.

Heatwave duration (HWD) is longer in the northwest and west-central regions of Angola, exceeding 10 days based on observations, whereas most other areas experience HWD below six days. Major differences appear in the northwest and west-central regions, where observed HWD is longer than what the NEX-GDDP-CMIP6 ensemble indicates. Conversely, the ensemble suggests that southern Angola experiences longer HWD compared to the north, which is attributed to the savanna climate in the north and the temperate dry climate in the south.

The Warm Spell Duration Indicator (WSDI), representing the annual number of warm-period days, ranges mostly between 3 and 10 days across Angola, based on both observations and the GDDP-CMIP6 ensemble mean. Observations show peak values of about 12 days in the plateau region while minimum values of about one day occur in the extreme northeast. The NEX-GDDP-CMIP6 ensemble estimates WSDI predominantly between 3 and 5 days in coastal and northern areas, with slightly higher values in other regions. This is consistent with Correia et al. (2025), which reported that WSDI is more significant in the southern and central inland provinces, with maximum values exceeding five days in some regions.

The pattern of heat wave frequency (HWF) closely follows that of HWD, with more frequent heat waves occurring in the northwest and plateau areas, extending into the coastal regions. The NEX-GDDP-CMIP6 ensemble shows a slight difference in HWF between the north (slightly below six events) and the south (slightly above six events). Major differences between the two datasets appear in the northwest and eastern regions (particularly the southeast), where the NEX-GDDP-CMIP6 ensemble underestimates HWF in the northwest but overestimates it in the east.

The Heat Wave Number (HWN) represents the total number of individual heat waves. The NEX-GDDP-CMIP6 ensemble overestimates HWN by up to one event across eastern Angola. The distribution patterns of HWN differ between the two datasets; observations indicate a clear distinction between eastern and western Angola, whereas the NEX-GDDP-CMIP6 ensemble suggests a gradual increase in HWN from north to south. The number of heat waves occurring during the estimated summer period (1985–2014) remains below 2.5 on average.

The Heat Wave Amplitude (HWA), which represents the hottest day within the most intense heat wave, with higher values in southern Angola based on both datasets. HWA is less dominant in the plateau regions, as indicated by both observations and the NEX-GDDP-CMIP6 ensemble. The ensemble overestimates observations by up to 5°C across eastern Angola (north, central, and south), while underestimating them in most coastal and southwestern regions. In the plateaus, HWA temperatures remain below 31°C. The NEX-GDDP-CMIP6 ensemble shows the highest HWA, nearing 45°C, in the south-central region.

Coldest night temperatures (TNn), are warmer in northern and coastal Angola compared to central and southern regions, as indicated by both observations and the GDDP-CMIP6 ensemble. The NEX-GDDP-CMIP6 ensemble slightly overestimates observations in most coastal areas, while underestimating them elsewhere. TNn values drop as low as 5°C in central and southern Angola, whereas northern and coastal areas record values close to 20°C.

2. *Historical flood indicators*

The NEX-GDDP-CMIP6 ensemble slightly overestimated the observed maximum one-day precipitation (Rx1Day) by up to 15 mm/day, particularly in inland coastal areas. Both the observed data and the NEX-GDDP-CMIP6 ensemble indicate that Rx1Day generally hovers around 30 mm/day across most parts of Angola.

The R20mm climatology follows a similar pattern to Rx5Day. The NEX-GDDP-CMIP6 ensemble overestimated the observed R20mm by up to 10 days in inland coastal areas. However, it remained consistent with observations in most other regions, except in the east, where it slightly underestimated precipitation. Observations indicate that R20mm is higher in the plateau than in surrounding areas. This aligns with Correia et al. (2025), which highlights significantly higher R20mm values in the mountainous regions of Huíla, Huambo, and southern Benguela, reaching around 12 days. Both datasets confirm that most other regions, particularly coastal areas in Namibe, Benguela, and Luanda, experience very few R20mm days, in some cases not exceeding a single day.

Annual total wet-day precipitation (PRCPTOT) patterns are consistent between observations and the NEX-GDDP-CMIP6 ensemble. Both datasets indicate that northern and central Angola remain wetter than the south and coastal areas throughout the year. PRCPTOT exceeds 1400 mm annually in the north, while in the south, it drops to around 500 mm. The plateau also experiences high PRCPTOT values. The GDDP-CMIP6s ensemble underestimated PRCPTOT in the extreme northeast, southeast, and plateau areas by up to 150 mm/year while overestimating it in parts of the northwest.

The contribution from extremely wet days (R99pTOT) is overestimated by the NEX-GDDP-CMIP6 ensemble in inland coastal areas. The ensemble estimates that over 5% of total precipitation in coastal and nearby inland areas comes from very heavy rainy days, with contributions decreasing eastward, particularly in the northeast. Both datasets identify the northeast as having the lowest R99pTOT values. Observations also suggest that extreme southern Angola receives more heavy precipitation than other parts of the country.

The Rx5Day precipitation pattern is similar to Rx1Day but with higher values. Like Rx1Day, the NEX-GDDP-CMIP6 ensemble overestimated Rx5Day in inland coastal areas by up to 60 mm/day. Observations indicate that most of Angola, particularly the south, consistently records Rx5Day values slightly above 76 mm, whereas the north registers slightly lower values. Both datasets show closely aligned Rx5Day values in the east and south.

The number of days with at least 10 mm of precipitation (R10mm) is higher in central and northern Angola, ranging between 36 and 60 days. Both datasets show an increase in R10mm with latitude from south to north. In the southern and coastal areas, R10mm is below 20 days. Historical records from Correia et al. (2025) confirm that southern and coastal provinces have the lowest R10mm values, with some regions experiencing fewer than five such days annually. The NEX-GDDP-CMIP6 ensemble overestimated R10mm in the north-central and central regions extending to the south-central areas while underestimating it in the plateau and extreme southeast.

The longest wet spells, measured as Consecutive Wet Days (CWD), dominate central Angola based on both observed and GDDP-CMIP6s datasets. The extreme southwest also has the lowest CWD values, aligning with Correia et al. (2025). The NEX-GDDP-CMIP6 ensemble slightly overestimated CWD in central and eastern Angola by up to 10 days, while underestimating it in some western regions.

3. *Historical water deficit indicators*

The SPI climatology indicates that drought occurrences do not exceed three days in most parts of Angola, based on both observed data and the NEX-GDDP-CMIP6 ensemble. This suggests that drought conditions are minimal across the country. The GDDP-CMIP6 ensemble, however, depicts the southern zones as drier than the north. Similar to SPI, the SPEI climatology shows that drought occurrences remain below three days in most parts of Angola. While both datasets suggest minimal drought conditions, the NEX-GDDP-CMIP6s ensemble overestimates drought frequency in most regions except for a small area in the extreme southwest. Both datasets highlight peak drought occurrences in the western coastal areas.

The longest dry spells, represented by Consecutive Dry Days (CDD), are more severe in southern Angola than in the northern regions, as indicated by both observed data and the NEX-GDDP-CMIP6s ensemble. Both datasets show a decrease in CDD from south to north, following a similar pattern, though the GDDP-CMIP6s ensemble overestimates CDD in most parts of the country, particularly in the north. The highest CDD values, close to 235 days, are recorded in the southern zones, whereas less drought-prone areas, particularly in northern Angola, experience around 78 days of CDD. This aligns with Correia et al. (2025), which found that southern and central provinces have high CDD values (>92 days), while northern regions record lower values (56–79 days). Overall, northern Angola is less susceptible to water deficits than the extreme south.

3.2 Projected changes in base parameters and climate extremes

3.2.1. Spatial pattern of the projected change in mean temperature and precipitation

1. *Near and Far Future Temperature*

The projected change indicates a general increase in temperature from north to south in the near future. During the DJF season, the increase is more pronounced in the south than in the north, as shown by both scenarios. Significant values at the 95% confidence level are well distributed across the country for this season. Both scenarios project a positive temperature change across Angola, with the worst-case scenario (SSP5.85) showing higher values in southern Angola.

During the Cacimbo dry season (JJA), temperatures are expected to rise moderately by about 1°C in most parts of Angola, aligning with previous findings (CCDR, 2022) that project a 1–1.5°C increase between 2020 and 2040 relative to 1981–2010. The most significant warming is expected in southern Angola during the SON period. Across all four plots, the north appears less affected by temperature increases than the south, with significant values at the 95% confidence level well represented.

In the mid-future, both scenarios indicate a continued increase in mean temperature across all seasons. The SSP5.85 scenario projects a higher temperature increase than SSP2.45. During the DJF period, the northwest (Zaire region) is expected to experience the least temperature increase, while Cabinda shows a slightly higher projected warming than most other regions. Significant values at the 95% confidence level are well distributed across the country. In the SON period, the projected temperature increase remains more pronounced in the south than in the north, consistent with both scenarios.

2. *Near and Far Future Precipitation*

The projected near-future change indicates increased precipitation across most of Angola during the DJF period, except in the southeastern zone, where a slight decrease is expected. The projected increase reaches up to 42 mm, as shown by both scenarios, during DJF, the peak of Angola's rainy season. This is consistent with Soares et al. (2024), who reported an expected increase in rainfall during wet seasons. Significant values at the

95% confidence level are well distributed across areas of projected precipitation increase, except in the southeastern zone.

During the MAM period, the projected increase in precipitation is slightly lower than in DJF but follows a similar pattern, with the southeastern zone remaining an area of projected decline, particularly under the SSP2.45 scenario. In contrast, precipitation is expected to decrease during the dry periods of JJA and SON, except in the extreme northwest. This is consistent with Soares et al. (2024), who noted a decline in rainfall during dry seasons. With rainfall typically beginning in September and October, some areas in the extreme northwest show a projected increase in precipitation, linking to the DJF period. Central Angola is expected to experience the most significant decline, with reductions of up to 15 mm. Overall, Angola's rainy season is projected to become wetter, while the dry season will become drier in the near future. No significant values at the 95% confidence level are found for the MAM, JJA, and SON periods.

The mid-future precipitation projections follow a similar pattern but indicate a slightly greater increase compared to the near future. Precipitation in DJF is projected to increase by up to 48 mm, which is 6 mm higher than in the near future. As before, the extreme southeast is expected to experience a decrease during DJF. Most of Angola is projected to have a slight precipitation increase (below 15 mm) during the MAM period. Similar to the near future, precipitation is expected to decrease in JJA and SON, with central Angola being most affected, except for the extreme northwest. Overall, the rainy season in Angola is projected to become wetter, while the dry season is expected to be drier, consistent with Soares et al. (2024). Carvalho et al. (2016) noted that precipitation will generally decrease over time by about 2% by the end of the century. As in the near future, no significant values at the 95% confidence level are found for the MAM, JJA, and SON periods.

3.2.2. Projected changes in sector-relevant extreme environmental/climate factors

1. *Projected heat stress indicators*

The projected increase in the hottest daytime temperatures (TXx) in the near future under the SSP2.45 and SSP5.85 scenarios. Projections indicate an increase of up to 4.8°C. By the mid-century, the increase could reach nearly 10°C relative to the baseline. Pinto et al. (2023) also project rising extreme temperatures, with warmer days becoming even hotter. While both scenarios indicate this trend, SSP5.85 shows higher estimates than SSP2.45. Coastal areas of Angola are projected to experience the least increase, likely due to air-sea interactions.

The projected increase in the number of days contributing to warm spells (WSDI) is evident across Angola, consistent with Correia et al. (2025). The increase generally declines from west to east, with the highest values in coastal regions. In the near future, the increase is lower than in the mid-century. SSP5.85 overestimates WSDI compared to SSP2.45. By the mid-century, WSDI is expected to exceed 225 days in western Angola, compared to 150 days in the near future.

Heat wave duration (HWD) is projected to increase more in western Angola than in the east. The easternmost regions are projected to experience the least increase. By the mid-century, the duration of heat waves is expected to be higher than in the near future. SSP2.45 projects longer heat wave durations in the west, whereas SSP5.85 indicates more prolonged events in northern Angola. Under SSP5.85, the total annual heat wave duration could reach 90 days in some northern areas.

The hottest day of the most extreme heat wave is projected to increase relative to the baseline. In the near future, HWA is expected to increase gradually from the northwest to the southeast, reaching close to 3°C under both scenarios. By mid-century, SSP5.85 projects higher increases than SSP2.45, with the highest values in Lunda Norte and Lunda Sul.

The projected increase in coldest night temperatures (TNn) suggests slightly warmer nights across Angola, particularly in coastal areas. Near-future projections indicate an increase of about 2.7°C. Pinto et al. (2023) also highlight this warming trend, with cooler nights becoming significantly warmer. By mid-century, nighttime temperatures could be 8°C above the baseline in northern Angola under SSP5.85, while SSP2.45 projects an increase of around 6°C.

Heat Wave Frequency (HWF) is expected to be highest in the northwest and gradually decrease toward the southeast. This pattern remains consistent in both near- and mid-century projections, although SSP5.85 estimates higher values than SSP2.45 in some areas. By mid-century, HWF is projected to reach up to 90 events per year.

2. Projected change in flood indicators

Projected changes indicate an overall increase in maximum 1-day precipitation (RX1DAY) across most of Angola, except in Uíge and Lunda Norte in the north. This trend is evident in both the near future and mid-century under SSP2-4.5 and SSP5-8.5 scenarios. The highest increases are expected in Cuanza Sul and Malanje, particularly under SSP2-4.5. In contrast, southern Angola shows only a slight decrease. Significant values at the 95% confidence level appear across most of the country by mid-century but are less pronounced in northern Angola in the near future.

The number of days with precipitation above 20 mm (R20MM) is projected to rise across much of Angola, particularly in the northern provinces of Zaire and Uíge, where increases of up to five days are expected. This trend is consistent with previous study by Correia et al. (2025,) indicating an increase of 2–4 days in R20mm in the northern and northeastern regions, including Bengo, Uíge, and Lunda Norte/Sul. By mid-century, this increase extended into Cuanza Norte and Cuanza Sul. Southern Angola, especially under SSP2-4.5, shows a slight decline in R20mm, while most other regions experience an increase.

Projected changes indicate a decrease in total annual wet-day precipitation (PRCPTOT) in southeastern Angola, with SSP2-4.5 showing the most significant reductions, exceeding 45 mm/year. In contrast, Zaire, Uíge, Bengo, and Cuanza Norte are expected to see the highest increases, reaching up to 135 mm annually under both scenarios in the near future and mid-century. The contribution of extremely wet days to total annual precipitation (R99PTOT) is projected to increase, particularly along the western axis of Cuanza Sul. This trend is stronger by mid-century, with the highest increases seen in high-altitude regions of Cuanza Sul, where SSP5-8.5 projects a rise of up to 7%.

Changes in Rx5Day closely mirror those of Rx1Day but extend to additional areas. While the highest increases under SSP2-4.5 occur in Cuanza Sul and Malanje for Rx1Day, Rx5Day also includes Cuanza Norte, Zaire, and Huambo. Uíge and Lunda Norte show projected declines in both indicators. Changes of up to 13 mm are observed, while the extreme southeast remains largely unaffected. Previous studies indicate a 5–10% increase in Rx5Day in the near term and 10–15% by 2040–2060 under RCP8.5.

Southern Angola is expected to see a decrease in R10mm, while central regions show a gradual increase, with peak values in the north. By mid-century, northern Angola, particularly Lunda Norte and parts of Uíge, will experience the most significant increase, with Zaire province seeing up to 10 additional R10mm days. Consecutive wet days (CWD) are projected to decline slightly in southeastern Angola and southern Bie and Moxico provinces. However, most other regions will see an increase, with Zaire province experiencing the highest rise, about four additional days both in the near future and mid-century.

3. *Projected water deficit indicators*

Projected changes in standardized precipitation index (SPI) indicate an increase in drought occurrences across most of Angola, except in the extreme northwest. This projected increase is less than one day and is observed under both the SSP2.45 and SSP5.85 scenarios for the near and mid future. These projections are based on the SPI index, which relies solely on precipitation. The increase in drought occurrence is more pronounced in the mid future than in the near future, suggesting a rising trend towards mid-century, particularly in the eastern and southern regions, consistent with Soares et al. (2024). The SPI further indicates that drought occurrences will decrease in the extreme northwest in both the near and mid future.

The SPEI, an extension of the widely used SPI, accounts for both precipitation and potential evapotranspiration, making it more responsive to the impact of rising temperatures on water demand. The SPEI follows a similar pattern to the SPI. In both the near and mid future, drought occurrences are projected to decrease in the extreme northwest under both scenarios. Meanwhile, central and southern Angola show a projected increase in drought occurrences, close to 6 days over a three-month SPEI time scale, consistent with findings from Soares et al. (2024).

The projected change in Consecutive Dry Days (CDD), indicates an increase in dry days in the extreme northwest (Zaire region) in both the near and mid future, as captured by the SSP2.45 and SSP5.85 scenarios. This is consistent with Correia et al. (2025). The projected increase exceeds nine days, particularly in the mid future. In contrast, the Lunda Norte region in extreme northern Angola shows a projected decrease in consecutive dry days for both time periods.

In the mid future, central and southern Angola are projected to experience an increase in consecutive dry days under both scenarios. The increase is more pronounced and statistically significant in the southern regions from 2040–2060 under RCP8.5, according to Pinto et al. (2023). Carvalho et al. (2016) also reported an intensification of drought conditions across most of Angola toward the end of the century. In the near future, the extreme southwest is projected to experience a decrease in consecutive dry days, particularly under SSP5.85. However, in the mid future, this same region shows a projected increase of over nine days relative to the baseline.

3.3. Assessment of Renewable Energy Resources

3.3.1 Wind Energy Potential

The annual averaged daily wind power energy potential highlights that wind energy potential is highest in the southern Namibe province and the coastal areas of Bengo province, where values reach up to 200 W/m². The Cunene province in southern Angola follows, with wind power density close to 120 W/m². Other regions of Angola exhibit lower wind energy potential, with values below 100 W/m².

3.3.2 Solar Energy Potential

The Cunene and southern Namibe provinces in southwest Angola receive the highest annual solar energy levels in the country, with values reaching up to 5 MW. These provinces present ideal locations for large-scale solar farm projects, which could significantly contribute to electricity generation and help meet regional energy demands. In contrast, the extreme northwest and the northern Cabinda regions have the lowest solar energy potential in Angola.

3.3.3 Hydropower Energy Potential

Angola's hydropower potential is vast, estimated at 18.2 GW, primarily concentrated in the Cuanza, Longa, Queve, Catumbela, and Cunene river basins. However, only 20% of this potential is currently utilized. The

government has identified 100 locations suitable for mini-hydro projects, with a cumulative capacity of 600 MW, as part of its goal to expand electricity access to 60% of the population by 2025. By then, renewable energy is expected to constitute 70% of the country's installed capacity. Currently, only about 33% of the population has access to electricity. Angola also aims to strengthen its energy supply and position itself as an electricity exporter within the Southern African Development Community (SADC).

Hydropower generation exceeds 2,000 MW, mainly from the Cuanza River basin. Two plants are operational, while three proposed projects, and one plant under construction, reflecting ongoing development efforts. In the Cunene basin, located in southern Angola, four hydropower plants exist—two operational and two proposed. The Chicomba dam, an isolated small-scale hydropower plant in Lubango, Huila province, generates between 23–41 MW. Across Angola, the number of proposed hydropower sites surpasses those currently in operation. If all proposed projects become operational, the total hydropower capacity could exceed 13,000 MW.

Unlocking this potential requires significant private investment and technical assistance to support institutions responsible for project development. Expanding electricity access, diversifying the energy mix, and reducing fuel dependence will depend on increasing private sector-led renewable energy investments.

3.4 Conclusions and Recommendation for adaptation Strategies

3.4.1 Summary and Conclusions

The climate analysis for Angola highlights significant trends in temperature, precipitation, and extreme weather events. Historical data (1985–2014) and future projections (2025–2054 and 2055–2084) reveal a consistent increase in temperature, with mean annual temperatures projected to rise by 1.5–2.8°C under SSP2-4.5 and by 2.5–4.5°C under SSP5-8.5 by the late 21st century. The highest temperature increases are expected in the southern and inland regions.

Precipitation patterns indicate increasing variability, with a projected increase in the north and a decline of 5–15% in annual rainfall projected in certain regions, particularly in the south. Drought frequency is expected to rise, exacerbating water scarcity issues. Conversely, extreme rainfall events are projected to intensify, increasing the risk of flooding, particularly in northern Angola. These changes pose significant risks to agriculture, water resources, and infrastructure.

Extreme climate indices, including heatwaves, consecutive dry days, and heavy precipitation events, demonstrate an increasing trend. The number of hot days ($T_{max} > 35^{\circ}\text{C}$) is expected to rise by 30–60 days annually by 2055–2084, intensifying heat stress and affecting both human health and crop yields. The number of consecutive dry days is projected to increase, further stressing water availability.

The agricultural sector is highly vulnerable, with reduced soil moisture and increased irrigation demand. Water availability analysis shows a deficit in evapotranspiration balance, particularly in arid and semi-arid zones, requiring strategic interventions in water management.

Given the projected increase in sea-level rise trend, there will be a risk of more frequent coastal flooding and wave reach, which accelerates erosion and undermines building foundations, roads, bridges, and rail lines near Corimba. Sea level rise also leads to saltier groundwater and more frequent contact with seawater to increase corrosion of buried utilities and reinforced concrete, leading to premature failure.

Renewable energy potential assessments indicate a positive outlook for solar and wind energy development. Solar radiation levels remain high, averaging 5.0–6.5 kWh/m²/day, supporting large-scale photovoltaic

deployment. Wind speeds in coastal and elevated regions exceed 5 m/s, making wind power a viable alternative. Hydropower potential remains promising but is susceptible to fluctuations in rainfall patterns.

In conclusion, Angola faces significant climate risks, necessitating adaptive measures in built infrastructure, water management, resilient agricultural practices, and sustainable energy transitions. Strategic planning and investment in climate adaptation and mitigation will be crucial in safeguarding livelihoods, ensuring food security, and enhancing economic resilience in the face of climate change.

3.4.2 Proposed Recommendations for Adaptation

To address the projected climate risks, a multi-sectoral adaptation strategy is necessary. Key recommendations include:

1. **Water Resource Management:** Implement integrated water resource management (IWRM) strategies to enhance water conservation, improve irrigation efficiency, and expand water storage capacity. The development of drought-resistant crops and rainwater harvesting techniques should be prioritized to mitigate the impact of reduced rainfall and prolonged dry spells.
2. **Climate-Resilient Agriculture:** Promote sustainable agricultural practices, including agroforestry, conservation agriculture, and climate-smart irrigation techniques. Investment in research and development for drought-resistant crop varieties and soil moisture retention methods is crucial.
3. **Disaster Risk Reduction and Preparedness:** Strengthen early warning systems for droughts, floods, and extreme heat events. Improve infrastructure resilience, particularly in flood-prone and drought-affected areas, to minimize damage from climate-related disasters.
4. **Asset-level adaptation for built infrastructure:** Upgrade drainage and pumping systems, including back-up power, to cope with higher sea levels and compound rainfall-surge events; retrofit underground spaces with better pumping and flood gates. Elevating electrical equipment and sensitive services above design flood levels, substituting with corrosion-resistant materials, and updating building codes and design standards to reflect future sea levels and storm statistics.
5. **Renewable Energy Expansion:** Scale up investments in renewable energy sources such as solar, wind, and hydropower to enhance energy security and reduce dependence on fossil fuels. Decentralized renewable energy systems should be promoted to support rural electrification and sustainable agricultural mechanization.
6. **Community-Based Adaptation:** Engage local communities in climate adaptation planning and implementation, ensuring the inclusion of traditional knowledge and local expertise. Capacity-building programs should be developed to enhance community resilience to climate stressors.
7. **Policy and Governance:** Strengthen climate policies and institutional frameworks to support adaptation initiatives. Increase access to international climate finance to fund adaptation projects, infrastructure development, and technological innovations.

By implementing these adaptation strategies, Angola can build resilience to climate change, protect vulnerable communities, and ensure sustainable development in the face of future climate challenges.

4. Result of Climate Analysis for Republic of Benin

The Republic of Benin, a West African nation bordered by Togo, Nigeria, and Burkina Faso, has a diverse geography, including coastal plains, savannahs, and forested regions. These geographical features significantly influence the country's economy, particularly its agriculture, which depends heavily on climatic conditions. The coastal area, with access to the Atlantic Ocean, supports fishing and trade, while the interior is primarily agricultural, producing key crops such as cotton, maize, and cassava. The Ouémé River and its tributaries are essential for irrigation and transportation, further shaping agricultural productivity and economic activities (Hounnou et al., 2019a; Hounnou et al., 2019b).

Agriculture remains the backbone of Benin's economy, contributing significantly to GDP and employing approximately 60% of the population. Cotton is the country's primary export crop, while maize, yams, and cassava are staple foods. However, the sector faces challenges such as fluctuating market prices, inadequate infrastructure, and increasing vulnerability to climate change. The reliance on rain-fed agriculture makes Benin particularly susceptible to climate variability, which can lead to crop failures and food insecurity. Addressing these challenges requires integrated management strategies that enhance food and water security in a changing climate (Ekpodessi & Nakamura, 2022; Akpa et al., 2023).

4.1 Historical analysis

4.1.1 Climatological analysis of seasonal mean temperature and rainfall

To evaluate the performance of the NEX-GDDP-CMIP6 ensemble mean for Benin, historical results were compared with observational datasets from ERA5. During DJF, both CHIRPS and NEX-GDDP-CMIP6 datasets indicate minimal rainfall (0–10 mm/month) across Benin, reflecting the dry season dominated by Harmattan winds. In MAM, precipitation increases as the rainy season begins, particularly in southern Benin, where CHIRPS records 60–100 mm/month and 30–50 mm/month in the north, a pattern closely mirrored by NEX-GDDP-CMIP6. In JJA, the peak of the West African Monsoon, sees maximum rainfall in central Benin (CHIRPS: 240–250 mm/month, NEX-GDDP-CMIP6: 200–240 mm/month), while the south receives comparatively less (100–180 mm/month), possibly due to regional atmospheric circulation or orographic effects. In SON, as the monsoon retreats, rainfall declines, with CHIRPS showing 50–180 mm/month from north to south, while NEX-GDDP-CMIP6 estimates slightly lower values.

During DJF, both ERA5 and NEX-GDDP-CMIP6 datasets indicate mild temperatures across Benin (25–28°C in the south, 27–30°C in the north), with minimal variability due to the dry Harmattan season. In MAM, temperatures increase as the rainy season begins, with ERA5 recording 28–31°C in the south and 30–33°C in the north, while NEX-GDDP-CMIP6 shows slightly lower values. The more rapid warming in the north is linked to reduced vegetation and lower moisture availability. JJA brings cooling due to monsoonal rains, with ERA5 showing 26–29°C nationwide, while NEX-GDDP-CMIP6 records slightly lower values, reducing the north-south temperature gradient. In SON, as the monsoon retreats, temperatures rise again (ERA5: 27–32°C, NEX-GDDP-CMIP6: 26–31°C), driven by declining rainfall and increased solar heating. Both datasets exhibit consistent spatial patterns, confirming their reliability while highlighting model-specific differences.

4.1.2. Analysis of Annual cycle for each Homogeneous Zone

The annual precipitation cycle across Benin's Guinean, Sudano-Guinean, and Sudanian zones indicates peak rainfall in August for the Guinean and Sudano-Guinean zones, while the Sudanian zone exhibits a bimodal

pattern with peaks in July and September. A distinct dry season occurs from November to February. The NEX-GDDP CMIP6 ensemble shows slight dispersion during July but strong agreement from July to September. Mean precipitation values are close to median values during peak rainfall months (October to April) across all zones. Peak rainfall slightly exceeds 240 mm/month in the Guinean zone, reaches approximately 260 mm/month in the Sudano-Guinean zone, and remains just below 200 mm/month in the Sudanian zone. All three climate zones experience little to no rainfall during the dry season months of November to February.

Temperature variations indicate that July is the coolest month across all zones. The annual temperature variability is less than 8°C in the Guinean zone (ranging from 26°C to just under 34°C), less than 6°C in the Sudano-Guinean zone (25°C to under 31°C), and less than 5°C in the Sudanian zone (25°C to under 30°C). The lowest temperatures (26°C in the Guinean zone and 25°C in the other two) occur in August, while the highest temperatures are observed in March and April. The NEX-GDDP CMIP6 ensemble exhibits strong agreement in the Sudano-Guinean zone across most months.

4.1.2.1 Analysis of Annual Cycle at the Infrastructure Site: GDIZ

The annual precipitation cycle over the GDIZ project site in Benin follows a bimodal pattern, with peak rainfall in June (165 mm/month) and October (160 mm/month), separated by a brief dry spell in August. The NEX-GDDP-CMIP6 ensemble accurately captures this bimodal structure but overestimates the June peak and underestimates the October peak.

The temperature cycle at the site exhibits distinct seasonal variations, with the lowest observed temperature in August (25.2°C) and the highest in March (29.2°C). While the model ensemble systematically overestimates temperatures across all months, it effectively captures the overall trend, including the seasonal decline towards August and subsequent warming.

1. Analysis of Annual Cycle of precipitation and temperature in Lake Nokoué

2. Precipitation

The precipitation annual cycle at Lake Nokoué shows a bimodal rainfall regime characteristic of southern Benin and the wider Guinea Coast region. . Rainfall rises sharply from near-zero in January through to a pronounced first peak in June, where it reaches approximately 235 mm/month, the highest monthly total in the entire annual cycle. This is followed by a sharp decline into a mid-summer dry season in July and August, with rainfall dropping to around 90-120 mm/month. This drop in rainfall during summer is consistent with a well-known "Little Dry Season" characteristic of southern Benin. A second, weaker wet season then emerges from September through October, reaching approximately 150–155 mm/month before rainfall tapers off steeply through November and December back to dry season conditions.

The performance of the NEX-GDDP CMIP6 ensemble mean against observations is generally good in terms of the representation of annual cycle. During the dry season months of January through February and the transition months of March and April, the model ensemble agrees reasonably well with observations, with both tracking closely in the range of 25–130 mm/month. Similarly, during the second wet season in September and October, the model and observational values are in very close agreement at around 150–158 mm/month, and the box plots in these months are tight, reflecting strong inter-model consistency. While the observations record approximately 235 mm/month at the height of the first wet season, the CMIP6 ensemble mean sits at around 228 mm/month, a much closer match than seen in the temperature variables. The model ensemble slightly overestimates rainfall during July, where the observed value of approximately 140 mm/month is considerably lower than the model ensemble value of ~151 mm/month.

3. *Minimum Temperature*

The annual cycle of minimum temperature at Lake Nokoué reveals a well-defined bimodal seasonal pattern. The box plots representing the spread of individual model members are generally narrow, reflecting strong inter-model agreement across most months.

The warmest minimum temperatures occur in March, where both the observations and model ensemble peak at approximately 25.2–25.3°C. Following this, minimum temperatures decline sharply through June and reach their absolute lowest values in July and August, bottoming out at approximately 22.7–22.9°C. This mid-year cooling reflects the influence of the West African monsoon and the atmospheric cooling brought by increased cloud cover, rainfall, and the southwesterly monsoon flow. From September onward, temperatures recover gradually, reaching around 23.6°C in October and climbing to a local secondary peak near 24.0°C in November before slightly declining again in December. The total annual range of minimum temperatures is relatively modest, spanning roughly 2.5°C between the March peak and the August trough, which is characteristic of the thermally stable equatorial coastal zone. The strong agreement between observations and the CMIP6 ensemble mean across all twelve months provides confidence in using these models for future climate projections over Lake Nokoué

4. *Maximum Temperature*

The annual cycle of maximum temperature (4.4.3) at Lake Nokoué exhibits a pronounced seasonal pattern driven by the West African monsoon system, with a much larger amplitude than what was observed in the minimum temperature cycle. However, the most immediately striking feature of this plot is the substantial and consistent warm bias in the NEX-GDDP CMIP6 ensemble mean relative to the observational record across virtually every month of the year. The observational record shows peak maximum temperatures occurring in February and March, reaching approximately 31.0–31.2°C, corresponding to the hot dry season preceding the onset of the first rains. Temperatures then decline steadily through the rainy season months, reaching their lowest values in July and August at around 27.0–27.2°C, a trough that reflects the strong cooling effect of the West African monsoon, persistent cloud cover, and reduced solar radiation reaching the surface. This represents a seasonal range of nearly 4°C in the observed record, considerably larger than the ~2.5°C range seen in the minimum temperature cycle, which is physically consistent since daytime temperatures are more sensitive to cloud cover, rainfall, and seasonal changes in solar angle. A secondary recovery is evident from September through December, with temperatures climbing back toward ~30.5°C by December.

The ensemble mean follows the correct seasonal shape, peaking in February–March and troughing in July–August, but at a systematically elevated level throughout. The model ensemble places February maximum temperatures near 34°C compared to the observed ~31°C, and even the July–August trough in the models sits near 28.5–29°C against the observed 27°C. The box plots for most months are notably narrow, indicating strong inter-model agreement on these elevated values, which suggests the warm bias is not a consequence of a few outlying models but rather a shared systematic overestimation across the ensemble for this location.

4.1.3 Trend Analysis at Homogeneous Zones

1. *Precipitation Trends and Variability*

Climate projections for precipitation and temperature across Benin's three climatic zones: Guinean, Sudano-Guinean, and Sudanian reveal notable hydroclimatic changes in the region.

Guinean Climate Zone: Historical observations indicate a slight increase in precipitation, with notable fluctuations. The highest recorded rainfall occurred around 2000 (1300–1400 mm/year), while the lowest was

in 2002 (~800 mm/year). The historical ensemble shows a modestly increasing trend (slope: 0.4054), suggesting a slightly wetter past climate. However, future projections indicate a contrasting shift. Under SSP2-4.5, precipitation is projected to decline slightly (slope: -0.0891), while SSP5-8.5 suggests a more pronounced decrease (slope: -1.1537). This implies that under a high-emissions scenario, the Guinean zone could experience significant drying, with precipitation ranging between ~820 mm/year and 1200 mm/year, a level notably lower than historical variations.

Sudano-Guinean Climate Zone: The Sudano-Guinean zone exhibits a more pronounced historical increase in precipitation (slope: 3.0255), with relatively stable precipitation levels between 950 mm/year and 1400 mm/year. Future projections diverge from the Guinean climate pattern, indicating a wetter future. Under SSP2-4.5, precipitation is projected to increase modestly (slope: 0.0921), whereas SSP5-8.5 suggests a stronger intensification (slope: 1.2515). This implies that under a high-emissions scenario, precipitation could exceed 1400 mm/year by the late 21st century.

Sudanian Climate Zone: As the driest of the three zones, the Sudanian climate historically exhibits an increasing precipitation trend (slope: 3.5876), with annual precipitation ranging between 800 mm and 1200 mm/year. Future projections reinforce this wetting trend, particularly under SSP5-8.5, where precipitation is projected to increase significantly (slope: 2.4585). Unlike the Guinean zone, which may experience drying, the Sudanian region is likely to become wetter under high-emissions conditions, with precipitation fluctuating between 970 mm/year and 1400 mm/year. SSP2-4.5 also suggests an increase (slope: 0.4482), though at a slower rate, highlighting the influence of different emission pathways on regional hydroclimatic trends.

2. *Temperature Trends*

Temperature trends across Benin's three climatic zones show a consistent warming pattern, though with varying rates of increase.

Guinean Climate Zone: Historical observations indicate a gradual warming trend (slope: 0.0359), with temperature fluctuations between 26.8°C and 27.8°C. Future projections suggest accelerated warming, with SSP5-8.5 projecting the highest rate of increase (slope: 0.0426) and temperatures expected to range between 28°C and 32.5°C by the end of the century. SSP2-4.5 projects a lower warming rate (slope: 0.0203), with temperatures ranging between 28°C and 30.5°C. This suggests that warming is inevitable even under a moderate-emissions scenario, though the extent of temperature increase is significantly higher under high-emissions pathways.

Sudano-Guinean Climate Zone: Similar to the Guinean zone, historical observations in the Sudano-Guinean zone show an upward temperature trend (slope: 0.0287), with fluctuations between 26.8°C and 28°C. Future projections indicate a slightly higher rate of warming compared to the Guinean zone. Under SSP5-8.5, the projected warming rate is steeper (slope: 0.0498), with temperatures ranging between 27.8°C and 32°C. Meanwhile, SSP2-4.5 suggests a more gradual increase (slope: 0.0239), with temperatures fluctuating between 27.9°C and 30°C. These findings indicate that warming in the Sudano-Guinean zone is slightly more pronounced, which could have significant implications for water availability and heat stress in this transitional climatic region.

Sudanian Climate Zone: As the warmest of the three zones, the Sudanian climate historically exhibits an increasing temperature trend (slope: 0.0246), with observed temperatures ranging between 27.8°C and 28.8°C. Future projections suggest substantial acceleration in warming, particularly under SSP5-8.5, which projects the highest slope (0.0509), with temperatures fluctuating between 28.5°C and 33°C. Meanwhile, SSP2-4.5 suggests a more modest warming trend (slope: 0.0249), with temperatures ranging between 28°C and 30.5°C. These findings indicate that, under high-emission scenarios, the Sudanian zone will likely experience the most extreme warming, further intensifying aridity and heat stress in an already dry environment.

4.1.3. Trend Analysis at the infrastructure site: The GDIZ

Historical observations indicate a slight increase in precipitation over time, with notable fluctuations. The highest recorded annual precipitation exceeded 1,400 mm, while the lowest was approximately 800 mm. The historical ensemble shows a modest upward trend (slope = 0.5387), suggesting a slightly wetter past climate. However, future projections indicate a shift towards drier conditions. Under SSP2-4.5, precipitation is projected to decline slightly (slope = -0.1811), while SSP5-8.5 suggests a more pronounced decrease with a steeper slope of -1.2382. This indicates that under a high-emissions future, the GDIZ zone may experience significant drying, with projected precipitation ranging between 900 mm and 1,250 mm per year, a notable decline from historical variations.

For temperature, historical observations reveal a gradual increase in temperature, with slight fluctuations. The highest recorded temperature exceeded 28.5°C, while the lowest was approximately 26.8°C. The historical ensemble indicates a modest warming trend (slope = 0.0363), reflecting a gradually warming past climate. Future projections suggest further temperature increases, with varying intensities. Under SSP2-4.5, warming is expected to be less intense (slope = 0.0201), while SSP5-8.5 projects a steeper warming trend (slope = 0.0426). This suggests that under a high-emissions scenario, the GDIZ zone could experience significant warming, with projected temperatures fluctuating between 27.8°C and 32.5°C, marking a substantial increase compared to historical records.

1. Trend Analysis at Lake Nokoué

a. Precipitation

The precipitation plot for Lake Nokoué presents the observed precipitation trend (+4.397 mm/decade) and the historical model simulation (+11.248 mm/decade) both lack significance. This means that the historical wetting trends in both the observational record and the model simulation are not statistically significant. This is immediately reflected in the enormous year-to-year variability during the historical period, swinging between approximately -300 mm/year and +280 mm/year. Such interannual fluctuations are characteristic of West African rainfall, which is strongly influenced by the highly variable West African monsoon and sea surface temperature anomalies in the Atlantic, Pacific and Indian Oceans. The historical model run follows a similar near-zero trajectory but with far less interannual spread, suggesting the models considerably underestimate the observed year-to-year rainfall variability at Lake Nokoué.

The future projections, however, tell a markedly different and concerning story. Both the SSP2-4.5 and SSP5-8.5 scenarios project declining rainfall over Lake Nokoué through the 21st century, and crucially, both of these declining trends are statistically significant. Under SSP2-4.5, rainfall is projected to decrease at -5.858 mm/decade, a relatively modest but consistent drying signal. Under SSP5-8.5, the drying intensifies dramatically to -16.985 mm/decade, nearly three times the rate of the moderate scenario. By 2100, the SSP5-8.5 ensemble mean sits at approximately -100 to -150 mm/year below the baseline, with some individual model members projecting drying well beyond -200 mm/year. The SSP2-4.5 trajectory is more moderate, hovering around -50 to -75 mm/year anomaly by end of century.

b. Minimum Temperature

The annual minimum temperature trend for Lake Nokoué reveals a consistent and statistically significant warming signal. The observational data shows a modest warming trend of 0.145°C/decade, with year-to-year fluctuations oscillating around the zero-anomaly baseline but tracking a gradual upward trajectory. The historical model simulation, by contrast, registers a substantially higher warming rate of 0.474°C/decade, more

than three times the observed rate. The observed trend, while more modest, is nonetheless statistically significant and confirms that real-world warming of overnight minimum temperatures at the lake is already underway. From 2015 onward, the two future scenarios, SSP2-4.5 and SSP5-8.5, branch from roughly the same starting anomaly of approximately +0.5°C and diverge progressively over the course of the century. Under the intermediate emission scenario (SSP2-4.5, blue), minimum temperatures are projected to warm at a rate of 0.213°C/decade, reaching an anomaly of approximately +2.0 to +2.5°C by 2100. Under the high-emission, business-as-usual scenario (SSP5-8.5, red), the warming rate accelerates to 0.464°C/decade, nearly identical to the historical model rate, and the projected anomaly climbs steeply to approximately +4.0 to +4.5°C by 2100, with the upper bound of the uncertainty envelope approaching +5.5°C. After 2050, the two scenarios diverge sharply, and by 2100 the gap between them reaches approximately 2°C, a difference that carries ecological and socioeconomic consequences for a shallow, ecologically sensitive water body like Lake Nokoué.

Warming of nocturnal temperatures reduces the overnight thermal recovery period that aquatic ecosystems depend on buffering daytime heat stress. Lake Nokoué, a shallow coastal lagoon that supports significant fisheries and human livelihoods in southern Benin, sustained increases in minimum temperatures of the magnitude projected under SSP5-8.5 could meaningfully alter water column stratification, accelerate evaporation, intensify algal blooms, and disrupt fish reproductive cycles.

3. *Maximum Temperature*

The maximum temperature record at Lake Nokoué shows a clear and statistically significant warming trend across all data series, with every reported rate marked with an asterisk confirming statistical significance. The observed shows a warming rate of 0.161°C/decade during the historical period, while the historical model simulation runs considerably higher at 0.358°C/decade. As was the case with the minimum temperature analysis, this model-observation gap persists in the Tasmax record, suggesting a systematic warm bias in the model's representation of daytime temperatures over this region, though both trends are firmly positive.

Under SSP2-4.5, maximum temperatures are projected to warm at 0.191°C/decade, reaching an anomaly of approximately +2.0°C by 2100. Under the high-emission SSP5-8.5 scenario, the rate nearly doubles to 0.391°C/decade, driving the anomaly to approximately +3.5 to +4.0°C by end of century.

d. Sea Level Height (ZOS) Annual Trend at Lake Nokoué

The sea level height trend plot for Lake Nokoué carries shows statistical significance. During the historical period, the observational record and the historical model simulation are in excellent agreement, both tracking a slow but steady rise from a negative anomaly of approximately -0.03 to -0.04 metres in the early 1980s toward approximately +0.02 metres by 2014. The observed trend of 0.019 metres/decade and the historical model trend of 0.015 metres/decade are consistent. This close model-observation agreement in sea level gives considerably more confidence in the reliability of the future sea level. From 2015 onwards, both SSP scenarios rise steeply and monotonically with very little interannual noise. Under SSP2-4.5, sea level rises at 0.017 metres/decade, reaching approximately +0.16 metres above the baseline by 2100. Under SSP5-8.5, the rate nearly doubles to 0.033 metres/decade, driving sea level to approximately +0.28 to +0.30 metres above baseline by end of century, nearly twice the SSP2-4.5 projection. When this sea level rise signal is considered alongside the projected rainfall decline discussed previously, this has implications for Lake Nokoué. The lake sits in a low-

lying coastal zone connected to the Gulf of Guinea, and a sea level rise of 0.28–0.30 metres under the high emission scenario, combined with drying rainfall trends reducing freshwater input, would significantly alter the lake's hydrological balance, potentially increasing saltwater intrusion from the ocean, reducing the freshwater buffer that sustains the lake's aquatic ecosystem, and threatening the livelihoods of the fishing communities settled along its shores.

4.1.4 Spatial distribution of sector relevant extreme environmental/climate factors

1. *Historical Heat stress indicators*

An analysis of heat stress indicators across Benin during the historical period (1985–2014), comparing observational data (OBS) with the NEX-GDDP-CMIP6 ensemble mean, reveals significant biases with critical implications for climate risk management and adaptation strategies.

The warmest daily maximum temperature (TXX) follows a north-south gradient, with observed values ranging from 36.5–38°C in the south to 39.5–42.5°C in the north. However, the NEX-GDDP-CMIP6 ensemble overestimates TXX in the south by up to 3°C while underestimating it in the north by approximately 1.7°C. These biases could distort heat risk assessments, leading to exaggerated projections of urban heat stress in the south and underestimated extreme heat risks in the Sahelian north, where agricultural productivity and water resources are particularly vulnerable.

Observed data of Warm Spell Duration (WSDI) show shorter warm spells (≤ 4.5 days) in coastal regions and longer heat events (6.75–9+ days) in the north. However, the The NEX-GDDP-CMIP6 ensemble underestimates WSDI in the north (-3.3 days) while overestimating it in the central and southern regions (+5.6 days). This could lead to misallocated adaptation efforts, with policymakers focusing on heatwave preparedness in overestimated regions while neglecting persistently extreme heat in the north.

The frequency of extreme heat events (HWF) is underestimated by ~ 2 events per year in the north but overestimated by up to 3 events in the central and southern regions. These discrepancies could undermine early warning systems and disaster preparedness, leaving northern communities underprepared for prolonged exposure to extreme temperatures.

Observed heatwave duration (HWD) typically ranges from 3–6 days in the south to 6–9 days in the north. While the NEX-GDDP-CMIP6 ensemble models capture this trend, they underestimate heatwave duration in the north by up to 3 days, which could impact preparedness planning in more vulnerable northern areas.

The intensity of heatwaves (HWA) relative to the 90th percentile threshold is overestimated in the south but underestimated in the north. Observed amplitudes range from 31.5–33°C in the south to 34.5–39°C in the north, yet the GCM starts with an overestimated baseline of 34.5°C in the south, leading to exaggerated heat risk assessments in coastal cities while downplaying extreme heat in the north. The NEX-GDDP-CMIP6 ensemble underestimates TNN by up to -5°C in the northeast and along the coast, predicting colder nights than observed. This could lead to misguided expectations about nighttime cooling trends, affecting building energy efficiency planning and urban heat island mitigation strategies.

These biases underscore the urgent need for localized climate model calibration and integration of high-resolution observational data before informing heat stress mitigation and climate adaptation policies in Benin. Overestimation of extreme heat in the south could misdirect resources toward urban cooling strategies, while underestimation in the north might leave heat-stressed communities without adequate preparedness measures.

2. *Historical flood indicators*

The analysis of precipitation indices reveals a strong latitudinal gradient, with higher rainfall in the central-western region and a decline towards the north, consistent with monsoonal influences. While the model captures this overall pattern, it systematically underestimates rainfall, particularly in the central-west and southern regions. PRCPTOT follows a clear latitudinal gradient, with the highest values in the central-west and a gradual decrease northward, consistent with monsoonal influences. The model captures this distribution but systematically underestimates rainfall, particularly in the central-west and southern regions. Bias analysis confirms a significant underrepresentation of rainfall in high-precipitation zones.

The highest frequency of heavy rainfall days, R10MM, is observed in the central region, decreasing towards the north. While the model captures this pattern, it underestimates values in the south while overestimating rainfall in the central and northwest regions. Bias analysis highlights regional discrepancies, with underrepresentation in the south and overestimation in localized areas. Extreme rainfall events, R20MM, are most frequent in the central-west, while the north and south experience fewer heavy rainfall days. The model significantly underestimates R20MM nationwide, particularly in the central and southern regions, failing to capture the observed spatial gradient. Bias analysis reveals severe underestimation, particularly between 7°N and 9°N, where extreme rainfall events are most frequent.

R99PTOT is highest between 7°N and 9°N, decreasing towards the north. However, the model depicts a more uniform distribution, failing to represent localized variations. Bias analysis shows substantial underestimation in the central region, with smaller discrepancies in the north. RX1DAY findings highlight maximum daily precipitation occurring in the central zone, with lower values towards the north and south. The model captures a general latitudinal gradient but systematically underestimates extreme precipitation, particularly in the south and central regions. Bias analysis shows the most significant underestimations between 7°N and 9°N, where observed extreme precipitation is highest.

CWD (Consecutive Wet Days) results show that the longest wet spells occur in the southern and central regions, gradually decreasing towards the north. The model fails to accurately capture this gradient, underestimating CWD values, particularly in the central and southern zones. Bias analysis indicates a systematic underrepresentation of prolonged wet periods, especially in the areas where observed CWD is highest.

3. *Historical water deficit indicators*

The Standardized Precipitation Index (SPI) climatology over Benin (1985–2014) reveals a distinct latitudinal gradient, with lower SPI values in the south (1.3–1.6 days) that increase northward (1.6–1.9 days), reflecting regional variability. However, the NEX-GDDP-CMIP6 model fails to capture this spatial heterogeneity, instead producing an overestimated and uniform distribution, particularly in the southern and central regions, where biases reach 0.6–0.8 days. In the north, biases are lower but still indicate an overestimation of SPI.

Similarly, the Standardized Precipitation Evapotranspiration Index (SPEI) climatology exhibits regional variation, with extreme drought conditions more frequent in localized hotspots around 7°N–8°N and 8°N–10°N. The NEX-GDDP-CMIP6 model significantly overestimates SPEI across Benin, particularly in the southern-central region, where simulated drought durations exceed observations by more than 1.0 days. In the north, biases range from 0.6 to 0.8 days, with the model failing to capture finer-scale variations.

Consecutive Dry Days (CDD) follows a clear south-to-north gradient, increasing from 24–48 days in the south to 72–144 days in the north. While the model reproduces this general pattern, it systematically overestimates

CDD, particularly in the central region, where biases range from 22.2 to 40 days. Overestimation is less pronounced in the northernmost and southernmost areas, where biases remain minimal.

4.2. Projected change in base parameters and climate extremes

4.2.1. Spatial pattern of the projected change in mean temperature and precipitation

1. *Near and Mid-Future Temperature*

The projected temperature changes in Benin for 2015–2054 under the SSP2-4.5 and SSP5-8.5 scenarios exhibit distinct seasonal and spatial variations. The highest warming occurs during DJF (December–February) and MAM (March–May), particularly in central and northern regions, with temperatures rising by 1.25°C to 1.5°C under SSP2-4.5 and up to 1.75°C under SSP5-8.5. In contrast, JJA (June–August) and SON (September–November) show slightly lower warming (0.75°C to 1.25°C under SSP2-4.5 and 1.0°C to 1.25°C under SSP5-8.5), likely due to increased cloud cover and precipitation. The central region consistently experiences the highest warming across seasons, whereas the southern coastal region sees smaller temperature increases due to oceanic moderation. Under SSP5-8.5, warming intensifies across all seasons, driven by stronger radiative forcing and greenhouse gas effects. The pre-monsoon (MAM) and dry (DJF) seasons are particularly affected, exacerbating heat stress risks, especially in northern and central Benin.

For 2055–2084, projected temperature increases under SSP2-4.5 and SSP5-8.5 remain seasonally and spatially distinct but intensify. Under SSP2-4.5, DJF and MAM show the highest warming, reaching 1.5°C to 2.0°C, particularly in central and northern Benin. JJA and SON experience slightly lower increases, likely moderated by increased cloud cover and precipitation during the monsoon season. The warming pattern remains relatively uniform, with statistically significant trends. Under SSP5-8.5, temperature increases are nearly double those under SSP2-4.5, exceeding 3.0°C, particularly in northern Benin during DJF and MAM. Dry season warming is more pronounced, heightening heat stress risks for agriculture and water resources. While JJA and SON exhibit comparatively lower warming, the increases remain substantial. The northern regions face the strongest temperature rises, whereas southern coastal areas experience relatively lower warming due to oceanic influence.

2. *Near and Mid-Future Precipitation*

Projected seasonal precipitation changes in Benin for 2015–2054 under SSP2-4.5 and SSP5-8.5 exhibit distinct patterns across seasons and regions, with both increases and decreases in rainfall. Under SSP2-4.5, DJF (December–February) sees minimal precipitation changes (0 to 3 mm/month) across most areas, with slight increases (3 to 6 mm/month) in the central region and decreases (0 to -3 mm/month) in the north. MAM (March–May) shows reduced rainfall in the south (-3 to -6 mm/month), while the north, particularly the northeast, experiences increases (3 to 15 mm/month). JJA (June–August) presents a clear south-to-north gradient, with precipitation increasing by up to 18 mm/month in the north. SON (September–November) exhibits the most significant increases, ranging from 3 to 21 mm/month and affecting large areas.

Under SSP5-8.5, DJF shows mixed patterns, with both increases (3 to 9 mm/month) and decreases (-3 to -6 mm/month) across different regions. MAM follows a south-to-north gradient, with reductions of up to -6 mm/month in the south and increases of up to 9 mm/month in the north, though with lower statistical significance. JJA records consistent precipitation increases, peaking at 21 mm/month in the north and southwest. SON experiences the most substantial changes, with increases ranging from 6 to 21 mm/month, making it the season with the highest rainfall increases under SSP5-8.5. These projections suggest intensified West African monsoon effects in JJA and SON, particularly in the north, while MAM and DJF reductions in the

south indicate potential shifts in rainfall distribution. Compared to SSP2-4.5, SSP5-8.5 shows more extreme precipitation changes, underscoring the need for climate adaptation strategies.

For 2055–2084, projected precipitation changes reveal notable seasonal and spatial variations under SSP2-4.5 and SSP5-8.5, with critical implications for water resources, agriculture, and climate adaptation. Under SSP2-4.5, DJF sees slight precipitation increases in the north, while central and southern regions show mixed responses, including minor decreases, potentially affecting dry-season water availability. MAM highlights a south-to-north shift in rainfall, with reductions of up to -6 mm/month in the south and increases of up to 9 mm/month in the north, posing challenges for southern agriculture while benefiting northern regions. JJA experiences widespread rainfall increases (6–18 mm/month), particularly in the north, aligning with intensified monsoon activity that supports water availability and agriculture but raises flood risks. SON exhibits substantial increases across Benin, with the highest changes (6–18 mm/month) in the north, potentially extending the growing season but increasing flood-related vulnerabilities.

Under SSP5-8.5, precipitation changes are more extreme, reflecting stronger climate forcing. DJF sees slight rainfall increases (0–9 mm/month) in the south and center, while the north experiences reductions (0 to -3 mm/month), potentially worsening dry-season challenges. MAM presents the most significant rainfall reductions in southern Benin (-3 to -18 mm/month), exacerbating water scarcity during a critical agricultural period, while the north sees slight increases (3–9 mm/month), reinforcing spatial shifts in rainfall. JJA shows intensified precipitation increases (3–21 mm/month) in the north, indicating stronger monsoon rains that could enhance agricultural output but also escalate flood risks. SON emerges as the season with the highest precipitation increases, particularly in the north and central regions, where values exceed 30 mm/month, suggesting longer growing seasons but necessitating robust flood management strategies.

4.2.2. Projected changes in sector relevant extreme environmental/climate factors

1. *Projected Change in Heat Stress Indicators*

Projected changes in annual maximum temperature (TXX) under SSP2-4.5 and SSP5-8.5 indicate increasing warming trends. In the near future (2025–2054), warming is spatially variable, with the southernmost region experiencing the highest increases (1.5°C–3.0°C). By the mid-future (2055–2084), warming intensifies, with temperature increases reaching up to 4.5°C in the south, while the north surpasses 3.0°C, signaling rising extreme heat risks. Under SSP5-8.5, warming is even more pronounced, with near-future temperature increases of 2.0°C–3.0°C in the south and a sharp rise in the mid-future, exceeding 4.5°C in some northern areas, underscoring the urgency of mitigation efforts.

Projected changes in annual minimum temperature (TNN) also indicate significant warming. Under SSP2-4.5, near-future increases range from 2.7°C to 5.4°C, with peak warming around 10°N. By the mid-future, warming intensifies, with central and southern areas experiencing increases of 5.4°C–8.1°C. Under SSP5-8.5, near-future warming reaches 5.4°C in the north, while mid-future projections indicate widespread increases of 5.4°C–8.1°C, particularly affecting central and southern regions, reinforcing the risk of extreme heat events.

Projections for the Warm Spell Duration Index (WSDI) show a significant increase in heat extremes. Under SSP2-4.5, warm spells extend up to 105 days in the near future, increasing to 210–315 days by the mid-future, particularly in central and northern regions. Under SSP5-8.5, WSDI rises more drastically, reaching 105–210 days in the near future and exceeding 315 days across the entire country by late century, highlighting the potential for near-continuous extreme heat if emissions remain high.

Projected heatwave changes in Benin indicate a north-south gradient in heatwave amplitude (HWA_TX90) under SSP2-4.5, with increases ranging from 0.5°C–1.5°C in the south to up to 4°C in the north by mid-century. Under SSP5-8.5, temperature increases are more pronounced, exceeding 6°C in the north. Heatwave duration (HWD_TX90) is expected to lengthen significantly, with the most substantial changes occurring under SSP5-8.5, where some areas may experience heatwaves for more than 100 additional days annually. Heatwave frequency (HWF_TX90) also rises sharply, particularly in the north, where heatwaves could become nearly continuous under extreme scenarios. These trends underscore the growing heat-related risks, particularly in northern Benin, emphasizing the need for targeted climate adaptation strategies.

2. Projected change in flood indicators

Projected changes in precipitation and extreme rainfall indicators under SSP2-4.5 and SSP5-8.5 reveal significant spatial and temporal disparities, underscoring the influence of different emission pathways on regional hydrological patterns. PRCPTOT projections indicate a general northward increase in total annual precipitation under both scenarios, but with varying intensity and spatial gradients. While SSP2-4.5 suggests a steady intensification of precipitation across northern latitudes, SSP5-8.5 presents a more complex pattern, with drying trends in the southernmost regions and stronger wetting signals concentrated in the north. These trends suggest potential shifts in the West African Monsoon, with implications for water resources, agriculture, and ecosystem stability.

The analysis of R10MM, which represents the frequency of heavy precipitation days, further highlights these spatial disparities. Under SSP2-4.5, heavy rainfall events increase markedly, particularly in the north, where extreme precipitation days exceed 10.8 days in some areas by the mid-future. This persistent rise suggests a heightened risk of hydrological stress and flooding. In contrast, SSP5-8.5 exhibits a contrasting spatial pattern, with decreasing heavy rainfall days in the western and southern regions and increasing frequency in the north and localized eastern areas. These trends indicate an evolving precipitation regime in which intensified northern rainfall may exacerbate flood hazards and land degradation.

Projections for R20MM, which quantifies extreme rainfall days exceeding 20 mm, align with R10MM trends, reinforcing the northward intensification of heavy precipitation. Under SSP2-4.5, the northeastern region emerges as a hotspot, with extreme rainfall events steadily increasing over time. This trend strengthens under SSP5-8.5, where R20MM days extend further northward, reaching localized peaks of more than 4.5 additional extreme rainfall days. These findings highlight amplified risks of flash floods, soil erosion, and infrastructure damage in the most affected regions.

R99PTOT projections, representing total precipitation from the most extreme wet days, further emphasize the intensification of extreme rainfall in northern areas. Under SSP2-4.5, widespread increases in extreme precipitation are evident, though the northwestern region exhibits relatively smaller gains. In contrast, SSP5-8.5 amplifies extreme precipitation, particularly in northern and central regions, where projected increases in R99PTOT exceed those under SSP2-4.5. These trends indicate a growing likelihood of extreme rainfall events, which could challenge existing flood management strategies and necessitate enhanced climate resilience measures.

Projected changes in RX1DAY and RX5DAY, which indicate shifts in extreme rainfall intensity, reveal significant regional variations. Under SSP2-4.5, RX1DAY intensifies northward, with the highest increases concentrated in northern and central regions, suggesting a rising risk of flash flooding. RX5DAY follows a similar trend, with prolonged extreme rainfall events becoming more frequent, particularly in the mid-future (2055–2084). Under

SSP5-8.5, RX1DAY projections display a more variable pattern, with some southern regions experiencing reductions while northern areas face intensified extreme rainfall. RX5DAY shows stronger divergence, with central and northern areas experiencing a pronounced increase in multi-day extreme precipitation, reinforcing concerns over flood risks and hydrological stress. These trends underscore growing challenges for water management and disaster preparedness, particularly under high-emission scenarios

3. *Projected water deficit indicators*

Projected changes in SPEI, SPI, and CDD over Benin under SSP2-4.5 and SSP5-8.5 reveal significant latitudinal variations in drought intensity, precipitation patterns, and dry spell durations.

SPEI projections indicate an overall increase in drought conditions in the near future, particularly under SSP5-8.5, where negative trends dominate. However, by the mid-future, southern Benin exhibits signs of wetting, with SSP5-8.5 suggesting a reversal in trends, pointing to potential long-term shifts in hydroclimatic responses. SPI projections follow a similar spatial gradient, with wetter conditions emerging in the south, while the north experiences prolonged drought episodes. This trend is particularly evident under SSP5-8.5, where drying intensifies over time, reinforcing the increasing risk of hydroclimatic extremes.

Projected changes in CDD further emphasize this divergence, with southern Benin showing significant reductions in dry spell duration, especially in the mid-future, indicating improved water availability. In contrast, northern Benin experiences an increase in CDD, signaling prolonged droughts, with SSP5-8.5 exhibiting stronger and more persistent drying trends. These results highlight the increasing divergence between wetting in the south and drying in the north, emphasizing the need for spatially targeted adaptation strategies.

4.3. Assessment of renewable energy resources

4.3.1 Wind energy potential

The wind speed climatology map for Benin reveals distinct spatial variations in the annual mean daily wind power density, reflecting the influence of geography on wind patterns. Wind speeds, measured in W/m^2 , vary significantly from north to south, shaping the country's wind energy potential.

In the northern region (above 10°N latitude), wind power density is relatively high, ranging from 2.25 W/m^2 to 3.0 W/m^2 . This area, characterized by open landscapes and fewer physical obstructions, experiences stronger and more consistent winds, making it a viable candidate for wind energy development. However, infrastructure and logistical considerations must be evaluated for large-scale implementation. The central region (approximately 8°N to 10°N) exhibits a decrease in wind power density, mostly ranging between 1.5 W/m^2 and 2.25 W/m^2 . This reduction may be attributed to transitional climate conditions and varied topography, which could dissipate wind energy and result in more inconsistent wind speeds.

At an 80-meter height, the wind speed climatology highlights two prominent wind energy hotspots: the northernmost and southernmost regions. In the north, wind power density exceeds 3 W/m^2 , reinforcing its potential for wind energy exploitation. In the southern coastal region (below 8°N latitude), wind power densities are even higher, exceeding 3.75 W/m^2 . This is largely due to coastal wind dynamics, influenced by land-sea interactions and the proximity to the Gulf of Guinea, which generate strong and consistent winds. The southern coast's proximity to population centers and existing energy infrastructure makes it a prime location for wind energy development. In contrast, the central region (8°N to 10°N) shows significantly lower wind power density, ranging from 2.25 W/m^2 to 3.0 W/m^2 . This may be due to transitional climate conditions and varied terrain, which disrupt wind flow and lead to weaker, less reliable winds.

The wind power density climatology across Benin reveals a latitudinal gradient, reflecting variations in atmospheric dynamics and surface roughness. The southern coastal region exhibits the highest wind power densities ($110\text{--}150 \text{ W/m}^2$), largely due to lower surface roughness over the ocean and the sea-land thermal gradient, which enhances onshore and offshore wind circulations. Moving inland, wind power density declines

sharply, with the central region experiencing values between 50 and 70 W/m². This reduction aligns with increasing surface drag from topography and vegetation.

Further northward (beyond 10°N), wind power density increases again, reaching 70–110 W/m². This is likely driven by stronger wind regimes in the Sahelian zone, influenced by regional atmospheric circulation patterns, such as harmattan winds, and the reduced surface roughness of semi-arid landscapes. These factors enhance wind speeds, improving the wind energy potential in northern Benin.

4.3.2 Solar energy potential

The spatial distribution of annual solar energy potential in Benin exhibits a distinct latitudinal gradient, with values increasing progressively from the southern coastal regions to the northern interior. In the southernmost region (7°N to 8°N), solar energy potential is lowest, ranging between 3.6 MW and 4.2 MW. This coastal and near-coastal zone experiences higher cloud cover, humidity, and precipitation, which attenuate incoming solar radiation, limiting energy generation potential.

Moving northward, solar energy potential increases noticeably, with a more pronounced gradient beyond 9°N. The highest values are recorded in the northernmost region (10°N to 12°N), where solar power potential exceeds 4.5 MW, reaching above 4.8 MW in some locations. This semi-arid zone, characterized by lower cloud cover and reduced precipitation, receives more consistent and intense solar radiation, making it the most favorable area for large-scale solar power generation.

This northward increase in solar energy potential aligns with general climatological patterns, where coastal areas tend to experience more atmospheric moisture and cloud formation, reducing solar radiation availability. In contrast, the drier northern interior benefits from clearer skies, allowing for higher and more stable solar radiation levels, reinforcing its suitability for solar energy development.

4.3.3 Hydropower Potential

Hydropower distribution in Benin exhibits a distinct spatial concentration, with proposed facilities primarily located in the southern and central regions, where river systems such as the Ouémé and Mono provide sufficient hydrological potential. The majority of identified projects are still in the proposal stage (P), with only one site currently under construction (U). This highlights a critical gap between planning and implementation, underscoring the need for accelerated investment and technical execution. Notably, the presence of a single high-potential site (1,191 MW) represents a transformative opportunity for the energy sector, contingent on the mobilization of financial and technical resources.

In southern Benin, the Glo-Djigbé Industrial Zone (GDIZ) stands to benefit from proximity to proposed hydropower plants, ensuring a stable electricity supply for energy-intensive industries, including textiles, agro-processing, and manufacturing.

4.4. Conclusion and Recommendation for Adaptation Strategies

4.4.1. Summary and Conclusion

Given the critical role that climate variability and change plays in modulating Benin's critical sectors, a thorough climate impact assessment on water and food security and on sustainable development infrastructure is of paramount importance. This assessment analysed the present-day climate and projected change in mean and extremes together with the impact on water and food security as well as on selected infrastructure. This is

achieved by analysing observational datasets and ensembles of high resolution downscaled model simulations for current and future climates.

The climate analysis for the Republic of Benin reveals significant trends impacting the country's agricultural sector and overall economic stability. The historical analysis, based on the NEX-GDDP-CMIP6 and ERA5 datasets, indicates an increase in average temperatures, with southern Benin experiencing 25–28°C during the dry DJF season and northern Benin seeing 27–30°C. In the MAM season, temperatures rise further, reaching 28–31°C in the south and 30–33°C in the north, largely due to reduced vegetation and lower moisture retention.

Precipitation patterns show substantial seasonal variation. During the peak of the West African Monsoon (JJA), central Benin receives the highest rainfall (200–250 mm/month), while the southern and northern regions experience comparatively lower amounts. However, recent trends indicate a decline in total annual rainfall and more erratic precipitation patterns, affecting soil moisture availability and leading to increased drought frequency.

Agriculture, which employs around 60% of Benin's population and contributes significantly to GDP, is highly vulnerable to these climatic shifts. The decline in rainfall and more intense dry seasons negatively impact staple crops such as maize, yams, and cassava. Cotton, a major export commodity, has also experienced yield reductions due to prolonged dry spells. These climatic variations threaten food security and economic sustainability, necessitating urgent adaptation measures.

While the increase of temperature in future climate is expected, our analysis indicates that the largest increase in both precipitation and temperature is noted over northern Benin compared to the coastal region. This is consistent with the projected increase in both heat stress and flood occurrence indicators

4.4.2 Recommendations for Adaptation Strategies

A. Climate impact on GDIZ

The GDIZ solar farm and energy storage project represents a crucial step toward energy autonomy and sustainability. However, climate change poses significant challenges that must be addressed through adaptive design and operational strategies. By integrating climate-resilient infrastructure, heat mitigation techniques, and sustainable energy management systems, the project can achieve long-term efficiency and reliability while contributing to Benin's energy security and climate resilience.

1. Climate Assessment for the 100 MW Solar Farm and 40MW Energy Storage Station in the Glo Djibe Industrial Zone (GDIZ), Benin

The proposed energy intervention in Benin aims to construct a 100MW solar farm and a 40MW energy storage station to ensure energy autonomy for the Glo Djibe Industrial Zone (GDIZ) Special Economic Zone. Given the evolving climate signals in Benin, this assessment integrates historical climatology, projected changes, and key adaptation measures to enhance the resilience and efficiency of the infrastructure.

Given the climate projections, the following adaptation measures are recommended to ensure the resilience and efficiency of the solar farm and energy storage system:

2. Heat Management and Cooling Strategies

- 1. High-Temperature Resistant Solar Panels:** Deploy photovoltaic (PV) modules with high-temperature tolerance and improved thermal efficiency to mitigate performance losses due to excessive heat.

2. **Passive and Active Cooling Systems:** Implement passive cooling strategies (e.g., panel elevation for airflow) and active cooling systems (e.g., water or air-based cooling) to prevent overheating.

3. *Flood and Water Management*

1. **Elevated Infrastructure Design:** Construct the solar farm and storage station with an elevated foundation to mitigate the risk of flash flooding due to extreme precipitation events.
2. **Improved Drainage Systems:** Develop robust stormwater drainage systems to manage runoff from increased RX5DAY precipitation events, reducing erosion and structural damage.

3. *Energy Storage and Grid Stability*

1. **Climate-Resilient Battery Storage:** Utilize lithium-ion or flow battery technologies with optimized thermal management to maintain energy efficiency under high temperatures.
2. **Hybrid Energy Integration:** Consider supplementing solar power with wind energy, particularly leveraging the relatively higher wind power density along the coastal region where GDIZ is located.

3. *Structural Reinforcements for Extreme Events*

1. **Wind-Resistant Infrastructure:** Reinforce solar panel mounting systems to withstand potential wind gusts, ensuring stability during extreme wind events.
2. **Adaptive Energy Load Management:** Implement smart grid technology to balance energy output fluctuations due to climate variability, ensuring consistent power supply to GDIZ.

3. *Long-Term Sustainability Strategies*

1. **Climate Monitoring and Early Warning Systems:** Establish a climate monitoring system to track temperature, precipitation, and extreme weather events, allowing for adaptive energy production planning.
2. **Policy Integration for Climate Adaptation:** Collaborate with national and regional stakeholders to align energy infrastructure development with climate adaptation policies and sustainability goals.

(B) Impact of sea level rise on Lake Nokoue, Porto Novo Lagoon

Sea-level rise increases the risk of erosion, which directly threatens near-coast lakes and ports through more frequent inundation and structural damage.

Near-coast lakes: increasing sea level and storm surges can push saltwater into coastal lakes, lagoons, and connected rivers, changing water levels, salinity, and ecosystem function.

Ports and maritime facilities: sea-level rise increases the frequency of overtopping and terminal flooding, damaging quays, cranes, warehouses, and access roads, and disrupting trade. Higher water levels and stronger surges also accelerate wear and raise maintenance and retrofit costs to the port infrastructure and facilities.

Adaptation Strategies:

Adaptation for coastal lakes and ports usually combines “protect, accommodate, and retreat” strategies, together with a stronger planning and governance to phase investments over time. These includes:

Protection: Thies include raising and reinforcing seawalls, dikes, revetments, and breakwaters to reduce overtopping and wave attack around ports, lakeshores, and coastal roads.

Apply nature-based and hybrid measures: Restoring or createing wetlands and beach nourishment to absorb wave energy and limit erosion around coastal lakes and shorelines. Using hybrid solutions (e.g., vegetated foreshores in front of levees, living shorelines) to protect infrastructure while providing co-benefits for biodiversity and recreation.

Asset-level adaptation for ports and built infrastructure: Upgrade drainage and pumping systems, including back-up power, to cope with higher sea levels and compound rainfall–surge events; retrofit underground spaces with better pumping and flood gates. Elevating electrical equipment and sensitive services above design flood levels, substituting with corrosion-resistant materials, and updating building codes and design standards to reflect future sea levels and storm statistics.

5. Result of Climate analysis for Côte d'Ivoire

Côte d'Ivoire, located in West Africa, is characterised by a diverse geography, including coastal plains, savannahs, and mountainous regions. Spanning approximately 322,463 square kilometers, the country hosts a variety of ecosystems, ranging from tropical rainforests in the south to savannahs in the north. This geographical diversity significantly shapes agricultural practices and economic activities. The coastal region, home to major cities like Abidjan, is a hub for trade and commerce. In contrast, the interior areas are predominantly agricultural, producing key crops such as cocoa, coffee, and cashew nuts, which are vital to the national economy (Yoroba et al., 2023; Métangbo et al., 2023).

Agriculture remains the backbone of Côte d'Ivoire's economy, contributing substantially to Gross Domestic Product (GDP) and employing a large portion of the population. Beyond economic stability, the agricultural sector is crucial in ensuring food security, as it provides the primary source of sustenance for the country's inhabitants.

However, climate variability poses significant challenges to both food and water security. Côte d'Ivoire experiences a tropical climate with distinct wet and dry seasons, both critical for agricultural productivity. Year-to-year rainfall fluctuations threaten crop yields and exacerbate food insecurity, particularly among vulnerable populations reliant on rain-fed agriculture (Timité et al., 2022; Comoé & Siegrist, 2013). The intricate link between climate change and food and water security is evident in the adaptive strategies employed by farmers. Addressing these interconnected challenges requires a multifaceted approach that enhances understanding of climate variability and promotes the implementation of effective adaptation measures.

5.1 Historical analysis

5.1.1 Climatological analysis of seasonal mean temperature and rainfall

To evaluate the performance of the CMIP6 ensemble mean for Côte d'Ivoire, historical simulations were compared with observational datasets from ERA5. The spatial distribution of mean temperature across different seasons shows a similar range of 23°C to 30°C in both datasets. The seasonal climatological cycle is consistent, with the highest temperatures occurring during MAM (March-April-May) and the lowest during JJA (June-July-August). The CMIP6 ensemble accurately captures the peak mean temperature in northern Côte d'Ivoire during MAM. However, it exhibits a cold bias of up to -2°C during DJF (December-January-February), particularly in the western regions. Overall, the models effectively represent the seasonal mean temperature pattern, with the highest values in the north gradually decreasing toward the south and west, aligning well with observed climatological trends. The seasonal rainfall distribution in Côte d'Ivoire, highlights distinct regional and seasonal variations. The peak rainfall season occurs during JJA (June-July-August), with monthly values reaching up to 370 mm, particularly in the eastern and northeastern regions, where precipitation is more abundant than in other areas. The rainy season extends into SON (September-October-November), maintaining moderate rainfall levels. At the same time, DJF (December-January-February) is characterised by dry conditions, with total rainfall consistently below 40 mm per month across all datasets. During MAM (March-April-May), rainfall is more concentrated in the southern regions, while the northern areas remain drier. A clear latitudinal gradient is observed, with rainfall decreasing progressively from south to north. The NEX-GDDP-CMIP6 dataset slightly underestimates rainfall compared to CHIRPS observations, particularly during peak rainfall, though the general spatial and seasonal patterns remain consistent across datasets.

5.1.2. Analysis of Annual Cycle for each Homogeneous Zone

Côte d'Ivoire has a diverse climate, influenced not only by the seasonal northward and southward movement of the Intertropical Convergence Zone (ITCZ) but also by its proximity to the Atlantic Ocean. Regardless of the

dataset (CHIRPS), a bimodal rainfall regime is observed in the central and coastal zones, as shown in the annual precipitation cycle. The two rainfall peaks occur in June, with CHIRPS recording 360 mm and the NEX-GDDP-CMIP6 ensemble mean 300 mm, and in October, with 180 mm and 140 mm, respectively, in the coastal climate zone. This pattern is also evident in the central climate zone, where rainfall reaches 180 mm in June and exceeds 200 mm for the NEX-GDDP-CMIP6 ensemble mean in June and October.

In contrast, a unimodal rainfall regime is observed in the northern climate zone, with a single peak in August, reaching 220 mm for CHIRPS and 240 mm for the models. The maximum mean temperature across Côte d'Ivoire follows a similar pattern across all climate zones, ranging from about 25°C in August to approximately 32°C in March in both observational data and the NEX-GDDP-CMIP6 ensemble mean. However, a slight shift is observed in the coastal zone, which appears slightly cooler, while the models overestimate the mean temperature throughout the year.

5.1.3 Analysis of Annual Cycle at the Infrastructure Site: The Humbol region

The rainfall regime over the Humbol region follows a unimodal pattern, as indicated by both observed datasets (CHIRPS) and the NEX-GDDP-CMIP6 ensemble mean. The peak rainy season occurs in September, with total rainfall reaching 168 mm in CHIRPS and 190 mm in the model ensemble, indicating a reasonable agreement between observed and simulated rainfall patterns. The rainy season extends from February to November, providing a prolonged wet period that supports agricultural activities.

Regarding temperature trends, March is the hottest month, with an average temperature of 29.2°C in both observations and model simulations. Conversely, July and August are the coldest months, with temperatures dropping to 25.2°C in CHIRPS and 25.0°C in the models. This consistency reinforces the reliability of climate models in capturing seasonal temperature variations. The combination of a unimodal rainfall pattern and seasonal temperature trends creates a favorable climatic setting for rain-fed agriculture, particularly during the extended rainy season. However, potential biases in rainfall magnitude between observations and models should be further assessed to enhance climate projections and refine their implications for water resource management and agricultural planning in the Humbol region.

5.1.3.1 Analysis of Annual Cycle at the Infrastructure Site: La Vallée du Ton

a. Minimum Temperature

The minimum temperature annual cycle at La Vallée du Ton reveals a well-defined seasonal pattern, but one that is characterized by a persistent and systematic warm bias in the CMIP6 ensemble mean relative to observations across virtually every month of the year. Minimum temperatures rise from a cool dry season low of approximately 21.1°C in January, peak during the pre-monsoon period in March and April at around 23.5–23.6°C, then decline through the rainy season to a mid-year trough around July–August at approximately 21.2–21.3°C before partially recovering through October–November to around 21.9–22.0°C, and finally dropping again in December to approximately 21.1°C. The total observed annual range spans roughly 2.5°C, which is modest but agriculturally meaningful for heat-sensitive crops. The CMIP6 ensemble mean consistently sits above the observed values, with the warm bias most pronounced in the cooler months. January observations record approximately 21.1°C while the model ensemble places this at ~20.2°C. However, in March and April the model places minimum temperatures near 24.5°C against the observed 23.5°C, a warm bias of approximately 1°C. More strikingly, in December the model ensemble mean sits at approximately 20.0°C while observations record 21.1°C, and one model member produces an extreme outlier near 17.5°C, a clear indication of at least one poorly performing model in the ensemble for this month. The box plots are generally narrow, suggesting the warm bias is a shared characteristic across most ensemble members rather than driven by outliers, which

makes it a systematic rather than random error. Hydro-agricultural planning in the Bandama River Basin, the observed seasonal cycle is the more reliable reference. The coolest nights occurring in January, July–August, and December define the thermal windows most suitable for cultivating temperature-sensitive crops, while the warm March–April period coincides with peak pre-season land preparation and early planting, a period where crop heat stress risk is already elevated and will intensify further under projected future warming.

b. Maximum Temperature

The annual cycle of daytime maximum temperatures at La Vallée du Ton displays a strong and clearly defined seasonal changes, with a total observed range of approximately 7–8°C between the hottest and coolest months, considerably larger than what was seen in the minimum temperature cycle. The observational record peaks in February at approximately 34.9°C, reflecting the intense heat of the late dry season before the onset of rains. Temperatures then drop sharply and continuously through the rainy season, reaching their lowest values in July and August at around 27.3°C, before recovering steadily through the second half of the year back toward ~33.3°C in December. The CMIP6 ensemble mean again exhibits a consistent and systematic warm bias relative to observations across all months, mirroring the pattern seen in the Tasmin cycle. The bias is most pronounced during the hot dry season months of February and March, where the model places temperatures near 35.8°C against the observed ~34.9°C, and remains present even through the cooler monsoon months. The box plots are impressively narrow throughout the year, confirming this is a shared systematic overestimation across the ensemble rather than a consequence of outlying models. Hydro-agricultural planning in the Bandama River Basin, the observed peak temperatures of nearly 35°C in February–March coincide with the critical pre-planting and land preparation window and represent conditions already close to the thermal stress thresholds of many staple crops. Under projected future warming, these dry season peaks will intensify further, making early-season crop management and water availability for pre-irrigation increasingly critical considerations for the basin.

c. Precipitation

The precipitation annual cycle at La Vallée du Ton reflects a predominantly unimodal rainfall regime, characteristic of the Sudano-Guinean transition zone within the Bandama River Basin. The observational record shows near-zero rainfall from December through February, marking a pronounced dry season, before a sharp and continuous rise begins in March (~40 mm/month) accelerating through April, May, and June. Rainfall peaks in September at approximately 260 mm/month, making it the wettest month of the year, before collapsing abruptly through October and November back to dry season conditions by December. The CMIP6 ensemble mean captures the overall unimodal shape reasonably well. However, the models consistently overestimate rainfall during the peak wet season months, particularly from May through October, where the ensemble mean runs noticeably above observations, most visibly in May (~205 mm modelled vs ~185 mm observed) and sustaining higher values through the September peak. The box plots during these wet season months are relatively wide, indicating meaningful spread among individual models and reduced confidence in the exact seasonal rainfall totals. In hydro-agricultural context, the highly concentrated wet season from April to October defines the available period for rainfed agriculture and reservoir recharge along the Bandama River. The sharp onset and equally sharp cessation of rainfall in November creates a narrow effective growing season, and any irrigation infrastructure must be sized to bridge the long November-to-March dry period.

5.1.4 Trend analysis at homogenous zone and infrastructure sites

5.1.4.1 Trend Analysis at Homogenous Zones

In the coastal climate zone, an increasing trend is observed from 1985 to 2014, with a rate of 0.3°C per decade, while a less stable trend is noted from 1981 to 1990. The trajectory and rate of temperature increase vary depending on the SSP scenario. Under the medium GHG emission scenario (SSP2-4.5), the annual mean

temperature in the coastal climate zone could rise at a rate of 0.18°C per decade, stabilising around 29°C. In contrast, under the very high GHG emission scenario (SSP5-8.5), the rate could reach 0.41°C per decade, exceeding 30°C.

In the centre climate zone, the mean temperature increased at the same rate as the coastal zone from 1985 to 2014. Projections indicate continued warming under both scenarios, with a rate of 0.3°C per decade for SSP2-4.5 and 0.45°C per decade for SSP5-8.5, leading to temperatures exceeding 28.5°C and 30.5°C, respectively, by the end of the century.

In the northern climate zone, the warming rate from 1985 to 2014 was lower (0.2°C per decade) compared to the other zones. However, future projections show the highest rates of increase, reaching 0.25°C per decade under SSP2-4.5 and 0.45°C per decade under SSP5-8.5. With these trends, the mean temperature could exceed 29°C under SSP2-4.5 and 31°C under SSP5-8.5 by the end of the century.

Precipitation trends across Côte d'Ivoire's climate zones over the past decades reveal varying regional impacts on agriculture. In the coastal zone, historical data show a significant decline of -14.1 mm per decade, with future projections indicating stabilization under SSP2-4.5 (-0.95 mm per decade) and continued, though less intense, drying under SSP5-8.5 (-9.8 mm per decade). This reduction threatens water availability for cocoa and oil palm, increasing the need for irrigation. In the centre zone, precipitation has slightly decreased (-2.7 mm per decade historically, -2.3 mm per decade under SSP2-4.5, and -5.7 mm per decade under SSP5-8.5), potentially shortening the growing season for staple crops like maize and cassava, requiring drought-resistant varieties.

In contrast, the northern zone shows an increasing precipitation trend (+11.9 mm per decade historically, +3.0 mm per decade under SSP2-4.5, and +3.6 mm per decade under SSP5-8.5), which could benefit sorghum and millet but also raise flood risks, necessitating better drainage systems. While increased rainfall in the north may improve water availability, its variability could still threaten food security. To adapt, farmers must implement climate-smart practices such as rainwater harvesting, agroforestry, and improved irrigation techniques to optimize water use and ensure sustainability.

5.1.4.2 Trend Analysis at the infrastructure site: The Humbol Region

The Humbol region has undergone significant climatic changes between 1985 and 2014, with both temperature and rainfall exhibiting increasing trends. The mean temperature rose at a rate of 0.23°C per decade during the historical period, indicating a gradual warming trend. Future projections under SSP2-4.5 and SSP5-8.5 suggest continued warming, with temperatures increasing by 0.21°C per decade under SSP2-4.5 and 0.51°C per decade under SSP5-8.5. By the end of the century, temperatures are expected to exceed 29°C under SSP2-4.5 and 31°C under SSP5-8.5, reinforcing a stronger warming trend under high-emission scenarios.

For rainfall, the historical period recorded a significant increase, with an upward trend of 11.7 mm per decade, suggesting progressively wetter conditions. Future projections indicate continued but slower increases, with mean rainfall rising by 3.4 mm per decade under SSP2-4.5 and 4.4 mm per decade under SSP5-8.5. While this suggests a potentially wetter climate, the lower rate of increase compared to historical trends implies that future rainfall variability may differ, possibly influenced by shifts in seasonal distribution, intensity, or extreme weather events. The combination of rising temperatures and increasing rainfall presents both opportunities and challenges for agriculture and water resources in the Humbol region. While enhanced rainfall may improve crop growth and water availability, higher temperatures, particularly under SSP5-8.5, could lead to heat stress, increased evapotranspiration, and shifts in growing seasons. These findings highlight the urgent need for climate adaptation strategies, including heat-tolerant crops, improved irrigation systems, and climate-resilient agricultural planning, to mitigate risks.

5.1.4.3 Trend Analysis at the infrastructure site: La Vallée du Ton

a. Minimum Temperature

The minimum temperature record for La Vallée du Ton shows statistically significant warming across all data series, with the observed nocturnal warming rate of $0.13^{\circ}\text{C}/\text{decade}$ during the historical period sitting below the model simulation of $0.279^{\circ}\text{C}/\text{decade}$, a model warm bias that is consistent with what CMIP6 ensembles. Under SSP2-4.5, nighttime minimum temperatures are projected to rise at $0.249^{\circ}\text{C}/\text{decade}$, reaching approximately $+2.5^{\circ}\text{C}$ above baseline by 2100. Under SSP5-8.5, the rate escalates sharply to $0.537^{\circ}\text{C}/\text{decade}$, the highest warming rate recorded across all variables analyzed at this site, pushing the anomaly toward $+4.7$ to $+5.0^{\circ}\text{C}$ by end of century, with the upper uncertainty bound approaching $+6^{\circ}\text{C}$. Both future trends are statistically significant. Warmer nights reduce the thermal recovery period for crops, increasing overall physiological stress and shortening effective growing windows for temperature-sensitive cultivars. Elevated nighttime temperatures also accelerate soil moisture loss and raise crop water demand beyond what daytime temperature increases alone would suggest, compounding the irrigation pressure already indicated by the maximum temperature projections. Furthermore, persistently warmer nights favour the proliferation of pests and fungal pathogens that thrive in warm, humid nocturnal conditions, a biological risk factor that any agricultural planning framework for this basin must incorporate.

b. Maximum Temperature

The maximum temperature record for La Vallée du Ton situated within the Bandama River Basin of Côte d'Ivoire, shows a statistically significant and warming trend across all data series. The observed daytime warming of $0.202^{\circ}\text{C}/\text{decade}$ during the historical period is well captured by the CMIP6 model simulation at $0.173^{\circ}\text{C}/\text{decade}$, a notably close agreement that lends credibility to the future projections for this location. Daytime maximum temperatures in the basin are projected to rise by approximately $+2.0^{\circ}\text{C}$ by 2100 under the moderate SSP2-4.5 scenario ($0.217^{\circ}\text{C}/\text{decade}$), and by approximately $+3.5$ to $+4.0^{\circ}\text{C}$ under the high-emission SSP5-8.5 scenario ($0.413^{\circ}\text{C}/\text{decade}$). Both future trends are statistically significant. The two scenarios track closely until around 2040, after which they diverge increasingly, meaning the window for meaningful mitigation action is relatively short before the trajectories become irreconcilable. For a hydro-agricultural project in the Bandama River Basin, these findings carry direct practical implications. A sustained increase in daytime maximum temperatures of this magnitude will intensify evapotranspiration demand from crops and surrounding vegetation, placing greater stress on water resources drawn from the Bandama River system. Irrigation water requirements will rise progressively across the century, particularly under SSP5-8.5, while higher temperatures will also accelerate reservoir evaporation losses and potentially alter the seasonal flow regime of the river. Planning and infrastructure design for any long-term hydro-agricultural investment in this basin should therefore account for a daytime temperature environment that will be measurably and irreversibly warmer than present-day conditions, with the severity depending critically on the global emissions pathway followed.

c. Precipitation

The precipitation trend for La Vallée du Ton presents a significant model-observation discrepancy in the historical period. The observed trend of $-0.992 \text{ mm}/\text{decade}$ is not statistically significant, meaning that historically, rainfall in the basin has shown no meaningful directional change, only pronounced interannual variability, with annual anomalies swinging between roughly $-400 \text{ mm}/\text{year}$ and $+300 \text{ mm}/\text{year}$. This high natural variability in itself is an important consideration. The historical model simulation, by contrast, shows a

statistically significant wetting trend of +46.891 mm/decade, a substantial and concerning overestimation relative to observations that undermines confidence in the models' representation of rainfall processes over this basin. The two scenarios diverge sharply in both direction and statistical robustness. Under SSP2-4.5, the projected drying of -1.559 mm/decade is not statistically significant, suggesting that under moderate emissions, rainfall at La Vallée du Ton is unlikely to change systematically from current conditions, though large year-to-year variability will persist. Under SSP5-8.5 however, a statistically significant drying trend of -20.608 mm/decade emerges, with the ensemble mean declining toward -100 to -150 mm/year below baseline by 2100 and individual models occasionally projecting far steeper deficits. For hydro-agricultural planning along the Bandama River, these findings shows that under moderate emissions where the mean rainfall trend is non-significant, the persistent and extreme interannual variability demands that any reservoir, irrigation scheme, or water management infrastructure be designed with substantial buffering capacity to accommodate drought years. Under the high-emission pathway, a progressively drying rainfall regime combined with the rising temperature-driven evapotranspiration demand discussed previously would create a compounding water deficit that could compromise the long-term viability of irrigated agriculture in the basin.

5.1.5 Spatial distribution of sector-relevant extreme environmental/climate factors

1. *Historical Heat Stress Indicators*

The spatial distribution of heat stress indicators for Côte d'Ivoire during the historical period (1985–2014) compares observational data (OBS) with the NEX-GDDP-CMIP6 GCM ensemble mean, as well as their bias (CMIP6 - OBS), revealing significant discrepancies with critical implications for climate risk management and adaptation strategies.

The GCM overestimates the warmest daily maximum temperature (TXX) in southern Côte d'Ivoire, where observed values range from 30°C to 40°C, with the highest temperatures in the north and the lowest in the central regions. The GCM simulates values between 31°C and 40°C, leading to an exaggerated perception of heat stress risks, potentially impacting health, agriculture, and energy planning. Similarly, the GCM significantly overestimates the warm spell duration indicator (WSDI) by more than six days, particularly in the northern regions, which could inflate heat stress response efforts while neglecting other vulnerable areas.

The heatwave duration (HWD) is underestimated in the southern to central parts of the country by 0.5 to 1 day, with observed climatology ranging from 2 to 7 days, whereas the GCM estimates 2 to 5 days, potentially hindering effective planning for prolonged heat events. The heatwave frequency (HWF) is also underestimated by up to three days in most parts of the country, which could underrepresented heat-related risks in climate policies.

For the heatwave amount (HWA), the GCM underestimates values by -1°C to -1.5°C in the north and southeast while overestimating them by 1°C to 1.5°C in the west and east, which may distort the accuracy of heat health action plans. Additionally, the coldest daily minimum temperature (TNN) is generally overestimated by 2°C in most areas, while underestimated by -2°C in the west, with the GCM simulating a range of 13°C to 26°C compared to the observed 12°C to 24°C.

These biases highlight the need for localised model adjustments and validation before informing policy decisions, as misrepresentations could undermine disaster risk reduction strategies, heatwave management plans, and agricultural resilience programs. Addressing these inconsistencies by integrating observational data and refining model outputs will be crucial for developing effective climate adaptation strategies to safeguard vulnerable communities in Côte d'Ivoire.

2. *Historical flood indicators*

Relative to observations, the GCM significantly underestimates the maximum 1-day precipitation (RX1DAY). Observations indicate a climatological average of approximately 39 mm across most parts of Côte d'Ivoire, with peak values reaching 50 mm in the southern and western regions (between latitudes 7°–5°N). In contrast, the GCM estimates RX1DAY at a lower nationwide average of around 35 mm. A similar underestimation is observed for the maximum consecutive 5-day precipitation (RX5DAY), where the GCM captures the spatial variability but reports lower precipitation values, particularly in central areas.

Conversely, the GCM grossly overestimates the maximum length of wet spells (CWD) especially in the southern and western regions. The model estimates CWD between 23 and 55 consecutive days, while observations indicate a much lower range of 5 to 25 days. Furthermore, the GCM fails to capture high rainfall intensity compared to OBS. Specifically, it underestimates the number of days with rainfall exceeding 20 mm (R20MM), with model simulations showing fewer than six days across all regions, whereas observations report more than 12 days.

However, the GCM reasonably captures the number of days with rainfall exceeding 10 mm (R10MM). Observations indicate more than 40 days with rainfall above 10 mm across major regions of Côte d'Ivoire, while model estimates are noticeably lower

3. *Historical water deficit indicators*

The Standardized Precipitation Index (SPI) indicates that severe drought conditions occur more frequently in northern Côte d'Ivoire than in the southern regions, based on observational data. In contrast, NEX-GDDP-CMIP6-GCMs estimate fewer occurrences of severe drought conditions across most parts of the country. Similarly, the Standardized Precipitation and Evapotranspiration Index (SPEI) reveals consistently high observed occurrences of severe drought in northern Côte d'Ivoire, while NEX-GDDP-CMIP6-GCMs report lower frequencies compared to observations. In regions with high drought incidence, severe drought events exceed 11 occurrences for SPI and 9 for SPEI. Overall, the CMIP6 ensemble slightly underestimates both indices across the country.

The longest dry spell, represented by Consecutive Dry Days (CDD), is more severe in northern Côte d'Ivoire than in the southern zones, as shown by both observational data and NEX-GDDP-CMIP6-GCMs. Both datasets exhibit a north-to-south decline in CDD, following a similar spatial pattern. The highest CDD values range between 40 and 60 days in the most affected northern areas, while in the less drought-prone southern regions, values are around 40 days. This pattern highlights a lower susceptibility to water deficits in southern Côte d'Ivoire compared to the extreme north. The CDD index is generally overestimated in the extreme north, while it is underestimated from central to southern Côte d'Ivoire.

4. *Historical rice suitability*

Rice suitability across Côte d'Ivoire shows significant variations between observed data and NEX-GDDP-CMIP6 model projections for the period 1985–2014 with notable regional differences. Observations indicate moderate suitability (~0.45) in the northwestern and extreme northern regions, suggesting favorable agro-climatic conditions, while the central region exhibits very low suitability (0.0–0.1), likely due to rainfall limitations, soil constraints, or temperature stress.

In contrast, NEX-GDDP-CMIP6 models estimate lower suitability (0.2–0.35) in the northwest, suggesting an underestimation of favorable conditions, while in the extreme west, they project slightly higher suitability (~0.4) than observed, possibly due to climate biases in rainfall or temperature representation. Both datasets align in identifying very low suitability (0.0–0.1) in the central region, confirming its climatic constraints for rice cultivation.

These discrepancies may stem from model biases in precipitation and temperature patterns, affecting the simulation of suitable conditions. While the northwest remains a key rice-growing zone, further analysis is needed to understand why NEX-GDDP-CMIP6 models underestimate its suitability. The extreme west, however, could represent a potential expansion area if model projections prove accurate. Given the central region's unsuitability, alternative crops or improved irrigation strategies may be necessary. Addressing these differences is essential for refining climate models and informing agricultural decisions under future climate scenarios.

5.2 Projected changes in base parameters and climate extremes

5.2.1 Spatial pattern of the projected change in mean temperature and precipitation

1. *Near and Mid-Future Temperature*

During the period 2015–2044, temperatures in Côte d'Ivoire are projected to increase by 0.5–1.0°C compared to the baseline (1985–2014), with this warming trend consistent across most seasons and regions. Under the high GHG emission scenario (SSP5-8.5), the temperature rise could reach 1.5°C in many parts of the country. Moreover, these changes are statistically significant at the 95% confidence level, indicating a high likelihood of occurrence.

For the period 2055–2084, projected temperature increases are even more pronounced. Under the SSP2-4.5 scenario, temperatures are expected to rise by 1.5–2.0°C, particularly in the northern region during the DJF and MAM seasons. In the SSP5-8.5 scenario, warming is projected to be more intense and widespread, exceeding 2.5°C across most of the country, with statistically significant changes at the 95% confidence level.

2. *Near and Mid-Future Precipitation*

During the SON season, precipitation is projected to increase by more than 12 mm from 2025 to 2054 compared to the baseline (1985–2014) across Côte d'Ivoire, with both scenarios showing consistent trends. This increase is expected to be more pronounced in the 2055–2084 period, exceeding 36 mm in most parts of the country.

In contrast, rainfall during the JJA season—the wettest period in Côte d'Ivoire—is projected to increase slightly (0 to 24 mm) in both future periods (2025–2054 and 2055–2084) relative to the baseline. However, a slight decrease may occur in the northwestern region during 2055–2084 under both scenarios. For the MAM season, precipitation is expected to decrease by more than 12 mm across the country during 2055–2084 compared to the baseline.

5.2.2. Projected changes in sector-relevant extreme environmental/climate factors

1. *Projected Change in Heat Stress Indicators*

The near- and mid-future projections of heat stress indicators over Côte d'Ivoire under two SSP scenarios. For the near future, the model generally simulates increased warming across most indicators and regions. The NEX-GDDP-CMIP6 ensemble mean projects an increase in the warmest daily maximum temperature (TXX), ranging from 1–2°C under SSP5-8.5 in northern regions and 1.1–2.2°C in other regions relative to the historical period. Under SSP2-4.5, TXX is projected to increase by 0.8–1.8°C in central and northern regions and by 0–0.9°C in other regions. These trends are consistent with mid-future projections, where further warming is expected, particularly in northern Côte d'Ivoire. Similarly, the coldest daily minimum temperature (TNN) is expected to follow the same pattern as TXX, with mid-future increases ranging from 2–3.5°C under SSP5-8.5 and 0–1.6°C to 1.6–3.1°C under SSP2-4.5.

For the warm spell duration indicator (WSDI), the NEX-GDDP-CMIP6 ensemble mean projects significantly more warm days across all regions, with increases of 230–320 days under SSP5-8.5 and 105–210 days under SSP2-4.5 compared to the historical average. This suggests a rise in heatwaves across Côte d'Ivoire due to global warming. Heatwave duration (HWD) is projected to increase by 30–60 days under SSP2-4.5 and 65–95 days under SSP5-8.5 in the mid-future.

Mid-future projections (2055–2084) indicate a more pronounced warming scenario. These rising temperatures will likely increase the total water and nutrient requirements of key crops, posing risks to food and livelihood security. Elevated temperatures could also disrupt crop physiological processes. For instance, higher temperatures are known to reduce plant height, impair flowering, and lower yields for several crops, including tomatoes (Ezin et al., 2018). Additionally, crops such as sorghum may experience accelerated growth stages, shortening their life cycle and reducing total yield, particularly in northern Côte d'Ivoire.

2. Projected change in flood indicators

The NEX-GDDP-CMIP6 GCM projections indicate increases in most indices. For instance, during the mid-future period (2025–2054), the maximum 1-day precipitation (RX1DAY) is projected to rise by 3–9 mm across most of the country. The annual count of days with precipitation exceeding 20 mm (R20MM) is expected to decrease slightly (0 to -0.5 days) in eastern, central, and western Côte d'Ivoire, while other regions may experience slight increases of 0 to 1 day. Total annual precipitation (PRCPTOT) is projected to increase by 40–90 mm under SSP2-4.5, whereas under SSP5-8.5, an increase of around 40 mm is projected in central and northern regions, while a decrease is expected in the south.

For RX5DAY (maximum 5-day precipitation), projections suggest a greater increase under SSP2-4.5 than SSP5-8.5. In the near future, northern regions are expected to see a larger increase (9–18 mm) than southern regions (0–4 mm) under SSP2-4.5, while western and eastern regions may experience a decrease (-5 mm). Under SSP5-8.5, RX5DAY is projected to increase by 6–12 mm in the north and 0–2 mm in the south, with a decrease (-6 mm) in the eastern region.

The projected increase in R10MM (days with precipitation exceeding 10 mm) is significant under both SSP2-4.5 and SSP5-8.5, ranging from 3–6 days, while a slight decrease (-2 days) is expected in southern Côte d'Ivoire. For the maximum length of wet spells (CWD), an increase of 2 days is projected in the northeastern region, whereas portions of the extreme southeast and southwest are expected to experience a decrease under both SSP2-4.5 and SSP5-8.5.

In the mid-future (2055–2084), these trends are expected to intensify, particularly under SSP5-8.5, where extreme precipitation indices show stronger increases. Northern Côte d'Ivoire is projected to experience a significant rise in heavy precipitation events, while parts of the south may see a reduction in wet spell duration. These changes have critical implications for flood risk management, agriculture, and water resource planning. More intense rainfall events could increase the likelihood of flash floods, soil erosion, and infrastructure damage, necessitating adaptive measures such as improved drainage systems and climate-resilient agricultural practices. Conversely, reductions in consecutive wet days in some regions may lead to more erratic rainfall patterns, potentially affecting crop yields and food security.

3. Projected water deficit indicators

Projections of water stress indicators for Côte d'Ivoire suggest that the frequency of droughts (SPI, SPEI, CDD) is expected to decrease in the northern regions during the near future (2025–2054), while southern areas are

projected to experience an increase in drought frequency compared to the historical baseline (1985–2014). This decline in drought events in the north aligns with the projected reduction in some flood indicators over the same areas

Mid-future projections (2055–2084) indicate a similar spatial pattern, but with greater intensity under both SSP2-4.5 and SSP5-8.5. Drought conditions are expected to intensify in the southern and central regions due to rising temperatures and increasing evapotranspiration rates. Meanwhile, the northern regions, projected to experience more intense wet extremes, could see a further reduction in drought frequency.

The intensification of drought conditions in the south could have significant implications for agriculture, water resources, and food security. Increased water stress may reduce crop yields, disrupt hydropower generation, and heighten competition for water resources. Conversely, the projected increase in wet conditions in the north could elevate flood risks, necessitating improved flood management strategies. These shifts in drought and flood patterns across Côte d'Ivoire underscore the need for adaptive water resource management, resilient agricultural practices, and enhanced climate risk mitigation strategies.

4. *Projected rice suitability*

Future projections of rice suitability in Côte d'Ivoire under SSP2-4.5 and SSP5-8.5 for the near future (2025–2054) and mid-future (2055–2084) indicate a general increase compared to the historical period (1985–2014), suggesting improving agro-climatic conditions for rice cultivation.

In the near future, SSP2-4.5 projects moderate suitability (~ 0.2) across most northern and central regions, reflecting a gradual enhancement of favorable conditions. However, SSP5-8.5 indicates a stronger increase, with suitability ranging between 0.15 and 0.45 in the north and center, and 0.1 to 0.2 in the south, suggesting a more pronounced positive impact under this high-emission scenario. The mid-future projections (2055–2084) follow a similar pattern, reinforcing expectations of sustained improvements. The stronger suitability increase under SSP5-8.5 suggests that higher temperatures and potential shifts in precipitation patterns may create more favorable conditions for rice growth, possibly through extended growing seasons or enhanced water availability.

However, while rising temperatures may initially boost suitability, extreme heat stress and increased rainfall variability could pose long-term risks, particularly under SSP5-8.5. The projected improvements in the north and center suggest emerging opportunities for expanding rice cultivation, but effective water management and adaptation strategies will be essential to sustain productivity. The relatively lower increase in suitability in southern Côte d'Ivoire indicates that gains may be more constrained in traditionally wetter regions, where excess rainfall or increased humidity could limit productivity.

Overall, these projections highlight a potential shift in rice-growing zones, with northern and central Côte d'Ivoire becoming more viable cultivation areas. This underscores the need for climate-resilient agricultural planning and adaptive strategies to balance the benefits of increasing suitability with the challenges posed by future climate extremes.

5.3 Assessment of Renewable Energy Resources

5.3.1 Wind Energy Potential

Annual mean daily wind power density in Côte d'Ivoire varies significantly across different climate zones, reflecting the influence of geographical and atmospheric conditions. The highest wind power potential is

observed in coastal areas, where wind power density exceeds 130 W/m². This is primarily due to the influence of sea breezes and coastal winds, which enhance wind speeds, making these regions suitable for wind energy development, particularly for offshore and nearshore wind farms.

In the eastern part of the northern climate zone, wind power density reaches approximately 100 W/m², indicating moderate wind resources that could support small- to medium-scale wind energy projects. However, in other parts of the country, wind power density remains relatively low, ranging between 50 and 60 W/m², suggesting limited feasibility for large-scale wind power generation. In these areas, wind energy may be more viable as part of small-scale hybrid systems, complementing solar power.

Overall, the coastal regions and parts of northern Côte d'Ivoire present the most promising opportunities for wind energy development, supporting the country's renewable energy expansion and efforts toward sustainable electricity access.

5.3.2 Solar Energy Potential

Côte d'Ivoire's annual solar energy potential varies across its climate zones, influenced by differences in solar radiation, cloud cover, and atmospheric conditions. The northern region has the highest solar energy potential, ranging from 4.5 to 5.5 MW, due to its relatively dry climate, lower cloud cover, and high solar irradiance. These conditions make it highly suitable for large-scale solar farms and off-grid electrification projects.

In the central zone, solar energy potential is lower, ranging from 3 to 4 MW, likely due to increased cloud cover and seasonal variations in solar radiation. However, solar energy development remains feasible, particularly for hybrid energy systems. The extreme southern zone has a slightly higher solar potential, around 4 MW, but remains constrained by coastal climatic influences such as high humidity and frequent cloudiness. Despite these regional variations, Côte d'Ivoire has significant solar energy potential, particularly in the north, where large-scale solar power projects could play a key role in the country's renewable energy strategy.

5.3.3 Hydropower Potential

When looking at the distribution of existing and potential hydropower capacities across the country, major installations are concentrated in the southwest and central regions, where power generation reaches up to 280 MW. While most plants are operational, some are under construction or proposed, reflecting ongoing development. Hydropower potential varies significantly, with the highest capacity (104–146 MW) found along major river systems, whereas the northern and eastern regions exhibit lower potential. This distribution highlights the need for strategic investment in expanding renewable energy, addressing regional disparities, and ensuring climate resilience in hydropower planning.

Hydropower distribution has significant implications for agricultural planning, particularly in irrigation, food security, and rural electrification. Regions with high hydropower potential can support large-scale irrigation projects, reducing dependence on erratic rainfall and enhancing crop yields. Reliable electricity from hydropower can also improve agro-processing, cold storage, and water pumping systems, strengthening agricultural value chains. Conversely, areas with low hydropower capacity may face challenges in mechanized farming and irrigation expansion, requiring alternative energy solutions such as solar or wind power. Additionally, climate variability and shifting rainfall patterns could impact river flows, necessitating integrated water resource management to balance energy production and agricultural needs. Strategic planning is essential to ensure sustainable development, minimize conflicts over water use, and enhance agricultural resilience across different regions.

5.4 Conclusion and Recommendation on Adaptation Strategies

5.4.1 Summary and conclusion

The climate analysis for Côte d'Ivoire highlights significant variations in temperature and precipitation that impact the country's economic and agricultural sectors. The country's geographical diversity, ranging from coastal plains to savannahs and mountainous regions, shapes its climate patterns and vulnerability to climate change.

Recent climate data indicate a rising trend in average temperatures, with an increase of approximately 1.0°C to 1.5°C over the past few decades. The northern regions, which experience higher temperatures, have recorded values reaching up to 34°C in the hottest months, while the coastal areas have experienced milder but steadily increasing temperatures. This warming trend has contributed to increased evapotranspiration rates, reducing soil moisture availability and affecting agricultural productivity.

Rainfall patterns in Côte d'Ivoire exhibit strong seasonal variations. The southern tropical rainforest regions receive the highest annual rainfall, with totals exceeding 1,500 mm, while the northern savannah areas receive around 1,000 mm. However, recent trends suggest a shift in rainfall distribution, with increased frequency of short, intense rainfall events leading to flooding in some areas, while prolonged dry spells contribute to drought conditions in others. These climatic shifts pose a serious challenge to key agricultural crops such as cocoa, coffee, and cashew nuts, which form the backbone of Côte d'Ivoire's economy.

Additionally, coastal regions face increasing risks due to rising sea levels, leading to erosion and saltwater intrusion, which threaten freshwater resources and agricultural lands. The vulnerability of these regions is further exacerbated by rapid urbanization and deforestation, which reduce natural barriers against climate-related impacts.

5.4.2 Recommendation for Adaptation Strategies

To mitigate the adverse effects of climate change in Côte d'Ivoire, a comprehensive set of adaptation strategies is necessary. The following recommendations are proposed:

1. **Sustainable Agricultural Practices:** Encourage the use of climate-resilient crop varieties, improved irrigation techniques, and agroforestry to enhance agricultural productivity despite changing climatic conditions.
2. **Water Resource Management:** Develop water storage and conservation systems, such as reservoirs and rainwater harvesting, to ensure a stable water supply during dry periods and reduce the risk of crop failure.
3. **Coastal Protection Measures:** Implement shoreline protection initiatives, including mangrove restoration and seawall construction, to mitigate the impact of rising sea levels and coastal erosion.

4. **Disaster Risk Management:** Strengthen early warning systems and climate monitoring networks to provide timely alerts on extreme weather events, reducing the risk to communities and agricultural activities.
5. **Reforestation and Land Management:** Promote afforestation and reforestation programs to restore degraded lands, enhance carbon sequestration, and improve water retention in soils.
6. **Policy and Governance Improvements:** Integrate climate adaptation strategies into national policies and development plans, ensuring long-term commitment and financial investment in resilience-building measures.
7. **Community Engagement and Education:** Raise awareness among local populations about climate change adaptation techniques, supporting farmers and coastal communities in developing sustainable livelihoods.

By implementing these strategies, Côte d'Ivoire can enhance its resilience to climate change, safeguarding its economic stability and food security while ensuring sustainable development for future generations.

6.0 Nigeria

Nigeria is geographically located between latitudes 4° and 14° North and longitudes 3° and 15° East, covering an area of approximately 923,768 km². It shares borders with the Niger Republic to the north, the Atlantic Ocean to the south, Cameroon to the east, and the Benin Republic to the west. The country is divided into three distinct climatic zones—Guinea Coast (4–8°N), Savannah (8–11°N), and Sahel (11–14°N)—which are defined by similarities in land use, climate, and ecosystems (Omotosho and Abiodun 2007). The West African monsoon heavily influences these zones, a critical rainfall source supporting agriculture and other key economic sectors.

As a tropical country, Nigeria experiences high temperatures year-round, with the coastlands being relatively wet and the northern regions significantly arid. It has two main seasons: dry and wet. The dry season, lasting from November to March, is marked by low humidity and high temperatures, reaching up to 42°C in the country's northern parts. The wet season, in contrast, is characterised by high humidity and lower daytime temperatures, typically below 30°C (Ogunrinde et al. 2019).

It is Africa's most populous country and one of its top four economies (World Bank, 2024). Rich in natural resources (Arogundade, Hassan, and Mduduzi 2024), its economy and population are deeply intertwined with climate-sensitive activities like rain-fed agriculture. This reliance makes the country particularly vulnerable to climate change, with agriculture being among the sectors most affected. Extreme weather events—such as droughts, floods, and soil erosion—pose significant challenges, leading to substantial economic losses and hindering national development (Arogundade et al., 2024). Rising sea levels threaten coastal communities in the south, including Lagos, with flooding and waterborne diseases. Meanwhile, increasing temperatures, droughts, and reduced precipitation disrupt hydropower systems, fisheries, and agricultural productivity, exacerbating food insecurity and adversely impacting nutrition and public health (Dauda 2023).

Deforestation, land-use changes, and the energy sector are the primary contributors to Nigeria's greenhouse gas (GHG) emissions (USAID, 2024). The nation's vulnerability to climate change is underscored by its ranking of 152 out of 181 countries on the 2022 ND-GAIN Index. This ranking highlights its high sensitivity to climate disruptions, particularly due to its dependence on agriculture. The World Bank reports that approximately 78% of Nigeria's land is dedicated to agriculture, which is predominantly rain-fed, with less than 1% under irrigation. Most farming is conducted by small-scale farmers relying on traditional techniques, leaving them particularly exposed to climate variability.

Furthermore, Nigeria's diverse geography renders it prone to a wide range of catastrophic weather events. Its large population, extensive coastline, limited access to climate financing from public and private sources, and inadequate adaptation knowledge compound its susceptibility to climate impacts. Addressing these challenges will require substantial investments in climate resilience and adaptive capacity.

Hence, understanding current and historical climate change and variations is crucial for Nigeria's future development, particularly in its agriculture, energy and hydrological sectors. Comprehending the impacts of climate change on the country's diverse climatic zones and economic activities is essential to developing effective adaptation and mitigation

6.1 Historical analysis

6.1.1. Climatological analysis

OBS indicates that the MAM season is the warmest, with temperatures exceeding 30°C in many areas, whereas the DJF season is the coolest, with temperatures below 23°C in the northern regions. The spatial distribution of OBS air temperatures remains relatively consistent in the JJA and SON seasons. The coldest temperatures across all seasons are observed in the country's central region, particularly over the Jos Plateau.

The model reproduces the observed spatial distribution pattern for all seasons and effectively represents the cold temperature areas over the Jos Plateau. However, it exhibits a warm bias in the JJA and SON seasons, indicating an overestimation of temperatures, and a cold bias in the southwestern parts of the country during the DJF season, suggesting an underestimation in this region.

OBS shows that rainfall is highest in the southern part of the country compared to the central and northern regions, with variations influenced by proximity to oceanic and desert areas. The JJA season is the wettest, with precipitation reaching 370 mm/month, followed by SON and MAM. The DJF season corresponds to the dry period, with mean seasonal precipitation below 80 mm/month.

The model captures key precipitation characteristics across all four seasons, particularly in the high-precipitation regions in the south. However, it generally underestimates precipitation compared to observations, especially in the southernmost areas.

6.1.2 Analysis of Annual Cycle for each Homogeneous Zone

There is general agreement between the datasets, with the model accurately capturing the timing of peak monthly rainfall. For instance, the model well reproduces the bimodal precipitation cycle over the Guinea Coast, characterized by a peak in July, a brief decline in August, and a second peak in September. Similarly, the Savannah and Sahel zones, which exhibit a single peak in August, are accurately simulated.

The NEX-GDDP-CMIP6 model effectively represents the mean annual cycle but slightly overestimates temperatures in certain months. For example, in the Guinea Coast zone, temperatures from March to November are overestimated by approximately 0.5°C. Likewise, in the Savannah and Sahel zones, the model slightly overestimates temperatures from August to November and September to May, respectively.

6.1.3 Present-day and projected climate change hotspots

6.1.3.1 Trend analysis

The annual precipitation time series for observations and the ensemble mean exhibit a fluctuating upward trend across all three zones during the historical period (1985–2014). In each zone for the historical period, the observations generally lie within the model spread. This increasing trend is projected to continue under both climate scenarios (SSP2-4.5 and SSP5-8.5), with some indication of scaling based on emissions scenarios, though with substantial year-to-year variability.

For temperature, observations generally lie within the model spread for the Savannah zone but are positioned at the lower end in the Guinea Coast and Sahel zones, indicating that models tend to overestimate historical mean temperatures. The NEX-GDDP CMIP6 ensemble mean projects continued warming across all three zones, with temperature increases exceeding 3°C above present-day levels under SSP5-8.5 by the late 21st century, while remaining below 2°C under SSP2-4.5. A clear distinction between the two scenarios emerged by the mid-21st century, demonstrating the scaling effect of emissions scenarios.

6.1.3.2 Annual cycle of Temperature and precipitation over the project sites: Northern Nigeria Distribution Line Upgrade

The analysis of the annual cycle of maximum temperature (Tmax) over Nigeria reveals a clear north–south gradient and strong seasonality. In the North West, Tmax reaches its peak in April, exceeding 37°C, before declining sharply during the rainy season (July–August) to around 30°C, then rising again slightly in October. A similar trend is observed in the North East, where Tmax peaks at around 36.5°C and dips during the same monsoon months. The Federal Capital Territory (F.C.T) also follows this seasonal pattern, with Tmax rising to approximately 35.5°C in March–April and dropping to ~30°C during the wet season. In contrast, the South East

and South West regions experience lower Tmax values throughout the year, generally ranging from 28°C to 34°C, with a more moderated annual cycle due to their proximity to the Atlantic and higher humidity.

In terms of minimum temperature (Tmin) the northern regions—particularly the North East and North West—show a broader thermal amplitude compared to the south. Tmin in these regions peaks at around 25°C in May–June and decreases substantially during the Harmattan months (December–January), reaching as low as 15°C. The F.C.T also displays noticeable variability, with Tmin rising to ~24°C in March–April and dropping to about 18°C during the dry season. This strong seasonal contrast in the northern regions reflects the influence of both the monsoon and the Harmattan winds, leading to hotter days and cooler nights, especially during the dry season.

In the southern zones, namely the South East and South West, the Tmin annual cycle is more stable and less variable throughout the year. Temperatures in these regions range narrowly between 21°C and 24°C, owing to consistent cloud cover, higher moisture content, and less influence from continental air masses. These patterns collectively demonstrate the significant climatic differences between Nigeria's north and south, with implications for agriculture, water demand, and heat stress risk management.

The analysis of precipitation over Nigeria reveals distinct regional and seasonal patterns based on the historical baseline period (1985–2014). The annual cycle shows that the Federal Capital Territory (F.C.T) experiences a unimodal rainfall pattern, peaking at approximately 250 mm in August. In the North East and North West, the peak occurs in August as well, reaching around 180 mm and 170 mm respectively, with a sharp onset and retreat of the rainy season. The South West exhibits a bimodal pattern with two rainfall peaks—about 140 mm in June and September—separated by a noticeable dip in August. Similarly, the South East shows two pronounced peaks of around 170 mm in June and September, characteristic of the region's bimodal regime, also reflecting the common “August break.” These regional differences in seasonal rainfall distribution are critical for planning agricultural activities and managing water resources in Nigeria.

6.1.3.3. Analysis of Annual cycle at the Infrastructure Site: Lafia Solar PV Power Plant

Over the Lafia solar power infrastructure site in north-central Nigeria, precipitation exhibits a pronounced unimodal annual cycle characteristic of the West African monsoon regime, with a peak in August (~270 mm month⁻¹). Rainfall increases progressively from March through August before declining sharply towards November, while the period from December to February remains largely dry. This seasonal precipitation regime strongly modulates atmospheric conditions relevant to photovoltaic (PV) performance, including cloud cover, humidity, and aerosol removal through wet deposition. Surface air temperature shows a clear seasonal response to this rainfall cycle. Maximum temperature peaks in March at approximately 38 °C, preceding the onset of the rainy season, after which it declines steadily to a minimum of about 26 °C in August. This cooling corresponds to enhanced cloud cover and reduces solar irradiance during the peak monsoon period. Minimum temperature follows a similar seasonal evolution, peaking in April (~26 °C) before declining through the wet season. The coolest nighttime conditions occur in December and January, with minimum temperatures near 22 °C. The NEX-GDDP-CMIP6 model effectively represents the annual variation of these parameters at the infrastructural site capturing the peak and periods of decline and its magnitude for all variables effectively, increasing our confidence to assess the projected changes in this variables using these model simulations.

6.1.3.3 Trend analysis over over the project sites: Northern Nigeria Distribution Line Upgrade

Across all five zones—FCT, North East, North West, South West, and South East—Tmax exhibits a steady increasing trend throughout the 21st century. The historical warming rate ranges from 0.019°C/year (FCT) to

0.024°C/year (South West), with a notable acceleration under future scenarios. Under SSP2-4.5, the rate stabilizes around 0.020–0.022°C/year, indicating moderate warming. However, under SSP5-8.5, the warming rate nearly doubles, reaching 0.041–0.044°C/year in most zones, showing stronger increases particularly after 2050. The South West and South East zones, starting from lower Tmax values, show substantial rises under SSP5-8.5, nearing or exceeding 36°C by 2100.

This trajectory implies intensifying heat extremes, with the northern zones (North East and North West) becoming especially vulnerable due to their already high baseline Tmax values. The FCT and South West show slightly lower warming rates historically but are projected to converge with the northern regions under the high-emissions pathway. These trends pose increasing risks for human health, agriculture, and water stress, particularly in the dry seasons.

The Tmin trends are more pronounced than Tmax, especially under future projections. Historical trends show Tmin increasing at a faster rate (0.034–0.039°C/year) than Tmax. Under SSP2-4.5, warming continues moderately (0.023–0.027°C/year), but under SSP5-8.5, the rates climb sharply to 0.051–0.060°C/year, particularly in the North East and North West. This indicates strong nighttime warming, a key indicator of climate change impacts on health (e.g., heat stress) and energy use (e.g., cooling demand).

By 2100, under SSP5-8.5, Tmin values exceeded 25°C in most regions, with the North West and North East surpassing that threshold more rapidly. The South East and South West follow similar trajectories but from slightly lower starting points. Elevated Tmin suggests warmer nights, which may reduce crop productivity (e.g., by impairing respiration) and negatively affect vulnerable populations, especially urban dwellers without access to cooling.

During the historical baseline period (1985–2014), the annual cycle shows a strong north-south gradient in rainfall distribution. The North West and North East experience a short rainy season peaking in August, with minimal rainfall outside the June–September window, characteristic of semi-arid to Sahelian climates. In contrast, the South West and South East exhibit a longer rainy season from March to October, with the South East showing a bimodal pattern due to the typical August break. The F.C.T follows a unimodal pattern with a peak in August. Future projections (2015–2100), analyzed under SSP2-4.5 and SSP5-8.5 scenarios, indicate modest but regionally varied increases in annual precipitation. The F.C.T and North West are projected to see more substantial increases, particularly under SSP5-8.5 (up to 2.5 mm/year), while changes in the South West and South East remain below 1 mm/year. These projections suggest a potential intensification of rainfall in northern Nigeria under high-emission scenarios, which may have implications for water availability, agriculture, and flood risk, while the southern regions may experience relatively stable precipitation patterns.

6.1.3.3 Trend analysis over the project sites: Lafia Solar PV Power Plant

Observed long-term precipitation trends over the historical period suggest a modest decline, whereas the ensemble mean from the NEX-GDDP indicates a weak increasing tendency. Future projections reveal scenario-dependent divergence: precipitation is projected to increase slightly under the SSP2-4.5 climate scenario but decline under the SSP5-8.5 climate scenario by the late twenty-first century. These contrasting signals highlight substantial uncertainty in the future hydrological regime over the region.

Temperature trends are more robust. Historical observations indicate an increase in maximum temperature of approximately 0.2 °C per decade. By the end of the twenty-first century, maximum temperature is projected to increase by about 2°C under SSP2-4.5 and up to 3°C under SSP5-8.5. Minimum temperature is projected to rise

more rapidly, reaching increases of approximately 2.5°C and 4.5°C under SSP2-4.5 and SSP5-8.5, respectively. Given that solar energy potential is primarily governed by incoming shortwave radiation, we assess its evolution from the historical period to the end of the twenty-first century. The results indicate a consistent upward trend in surface shortwave radiation under both the SSP2-4.5 climate scenario and SSP5-8.5 climate scenario. This projected increase suggests an enhancement in solar resource availability over the study region toward the end of the century. Consequently, solar energy is likely to remain a viable and sustainable option for long-term electricity generation, with increasing shortwave radiation potentially supporting improved photovoltaic energy yields.

These projected climatic changes have important implications for solar power infrastructure in Lafia. Rising ambient temperatures may negatively affect photovoltaic (PV) performance, as module efficiency typically declines by approximately 0.4–0.5% per °C increase above standard operating temperatures. Under the high-emissions SSP5-8.5 climate scenario, the projected warming could therefore lead to measurable reductions in electricity yield unless mitigation strategies—such as improved module ventilation, passive cooling designs, or temperature-tolerant PV technologies—are implemented. At the same time, projections indicate a gradual increase in surface shortwave radiation toward the end of the century, suggesting a potential enhancement in solar resource availability. This increase in incoming radiation may partly offset temperature-related efficiency losses and support sustained solar power generation over the region.

6.1.4 Spatial distribution of sector-relevant extreme environmental/climate factors

6.1.4.1 *Historical Heat Stress Indicators*

For most indices (except the TNN), the high-value centre of extremely high temperatures in the OBS is concentrated in the North of Nigeria, particularly in the Sahel Savannah and Guinea Savannah. At the same time, the lowest values are found in the southern regions. The CMIP6 ensemble generally captures the spatial distribution of most indices, though differences exist in magnitude, and biases are present.

The northern and central regions (excluding the Jos Plateau) represent the high-value center for TXX, ranging from 41°C to 45°C. The CMIP6 model overestimates HWM and HWA, particularly in the southern rainforest and the northern Sahel Savannah, though their spatial distribution remains consistent with OBS. The northernmost regions, including Borno State and Lake Chad, are the primary high-value centers for HWA (40–42°C) and HWM (39–41°C) in OBS. However, CMIP6 underestimates HWD in the western Guinea Savannah, where high values exceed nine days, resulting in a cold bias.

The CMIP6 spatial patterns for HWF and HWN deviate from OBS. The high-value center of HWF in OBS (9–15 days) is located in the eastern Guinea Savannah but is not captured in CMIP6. Similarly, observed high-value centers for HWN appear in the Sahel Savannah and western Guinea Savannah, whereas the model shifts these high values to the eastern part of the country.

WSDI high-value regions (>12 days) are mainly concentrated in the eastern Guinea Savannah, while lower values (<4 days) are observed in the rainforest and southern Guinea Savannah. CMIP6 underestimates WSDI in high-value regions, producing a cold bias of around 10 days, but it agrees well with OBS in south Nigeria.

The lowest minimum temperature (TNN) in OBS and CMIP6 gradually decreases from south to north. The Sahel and central Guinea Savannah have the lowest temperature centers, while the southern rainforest exhibits the highest TNN values. CMIP6 has a cold bias in most regions of the country.

6.1.4.2 Historical flood indicators

According to OBS, extreme rainfall events (RX1DAY, RX5DAY, R20MM, PRCPTOT, R10MM, and CWD) are more frequent, intense, and prolonged in southern Nigeria. The CMIP6 ensemble demonstrates reasonable skill in capturing the spatial distribution of these indices, though biases exist.

OBS shows that RX1DAY decreases from southern to northern Nigeria, with the highest values exceeding 58 mm/day in the south and the lowest around 10 mm/day in the extreme northwest. CMIP6 underestimates RX1DAY in the south while overestimating it in the northeast. Additionally, CMIP6 fails to accurately represent the high-intensity rainfall region captured by RX5DAY in southern Nigeria, leading to a dry bias.

For R20MM, PRCPTOT, and R10MM, there is better consistency between OBS and CMIP6. The highest values occur in the south and gradually decrease through the central region to a minimum in the north. While CMIP6 reasonably reproduces this distribution, it tends to underestimate precipitation in the southern part of the country. The spatial distribution of very wet days (R99PTOT) in OBS reveals maximum values in the south, southwest, northwest, and northeast, with lower values in the central and northern regions, ranging from 2.6 to 5.6 mm/day. However, CMIP6 struggles to capture this distribution accurately.

CWD, which measures wetness and indicates flood risk, ranges from approximately 5 to 41 days per year in OBS, with a national mean of around 11 days. Higher values are observed in the south and central regions. CMIP6 overestimates CWD across most of the country, with mean biases reaching up to 11 days.

6.1.4.3 Historical water deficit indicators

The drought frequency distribution based on the Standardized Precipitation Index (SPI) and the Standardized Precipitation-Evapotranspiration Index (SPEI) exhibits a similar spatial pattern in observations (OBS) for the historical period 1985–2014. Both indices indicate a uniform distribution of severe drought events, highlighting a persistently dry climate across the country. The CMIP6 ensemble generally overestimates SPI and SPEI, with biases reaching up to one day.

Regarding the consecutive dry days (CDD), the NEX-GDDP-CMIP6 reasonably captures the spatial distribution of the maximum dry spell length. Both OBS and CMIP6 indicate severe drought conditions north of approximately 9°N, where the effects are more pronounced, with dry spells extending up to 234 days. The lowest CDD values are observed in the southern regions of the country.

6.2 Project change in base parameters and climate extremes

6.2.1 Spatial pattern of the projected change in mean temperature and precipitation

6.2.1.1 Near and Far Future Temperature

Under the CMIP6-GCMs scenarios (SSP2-4.5 and SSP5-8.5), temperature increases range from 0.8°C to 1.6°C. Statistically significant trends, determined at a 95% confidence interval, are marked with dots. The analysis indicates significant warming across most regions of Nigeria in all four seasons. Similarly, projections for the mid-future (2055–2084) indicate a substantial increase in mean seasonal temperature across the country compared to the historical period. The warming is more pronounced under the SSP5-8.5 scenario, with temperatures projected to rise by up to 4°C in northern Nigeria. Statistically significant trends, marked with dots, are evident across all regions and seasons in the model projections.

6.2.1.2 Near and Far Future Precipitation

The projected change in seasonal rainfall, relative to the historical period (1985–2014), for the near future (2025–2054). Slight decreases are projected in the extreme north during the DJF season and in the southwest based on the NEX-GDDP CMIP6. Most other regions in Nigeria are expected to experience increases ranging from 0 to 40 mm/year. The JJA and SON seasons show higher projected increases than DJF and MAM. In JJA, the southwest exhibits slightly lower projected changes than other regions, while in SON, the northeast shows smaller increases relative to the rest of the country.

For the mid-future (2055–2084), projected changes in seasonal rainfall are more pronounced during JJA and SON, with significant increases observed across most of the country. However, decreases are expected to persist in the north during DJF and in the southwest during MAM. Projected decreases range between 0 and 20 mm/year, while increases vary between 30 and 100 mm/year in regions with high values during JJA and SON and between 0 and 30 mm/year in other parts of Nigeria.

6.2.2. Projected changes in sector-relevant extreme environmental/climate factors

6.2.2.1 Projected changes heat stress indicators

When it comes to the spatial changes in heatwave characteristics relative to the historical period (1985–2014) for the near future (2025–2054) and mid-future (2055–2084) under the SSP2-4.5 and SSP5-8.5 scenarios, a general increase is observed across all indices—TXX, HWD, WSDI, HWA, HWN, and TNN—though variations exist in magnitude across different regions.

Under SSP2-4.5, the TXX index is projected to increase by up to 1.5°C across most of the country in the near-future, with localised increases reaching 3°C in parts of the Sahel and Guinea Coast. By the mid-future, TXX intensifies further, reaching approximately 4.5°C. Under SSP5-8.5, the projected warming is more pronounced, with TXX increasing by an average of 3°C in the near-future and exceeding 4.5°C in some areas by the mid-future. Heatwave duration (HWD) is expected to increase significantly. Under SSP2-4.5, the near-future average is 10 days across the country. By the mid-future, heatwaves could last up to 50 days in the southernmost part of the Guinea Coast and 20 days in other regions.

The number of heatwaves (HWN) will also increase. Under SSP2-4.5, near- and mid-future projections indicate an increase of 4.5 counts per year in the Sahel and up to 9 counts per year in the Guinea Coast, with a high-value centre in the extreme south reaching 12 counts. Under SSP5-8.5, in the near-future, HWN will increase by up to 12 counts per year in the south and 9 counts per year in the rest of the country. However, in the mid-future, HWN values are projected to decrease slightly in the southern region compared to the rest of the country.

The Warm Spell Duration Index (WSDI) shows an upward trend under both scenarios. Under SSP2-4.5, high-value centres appear in the Sahel and Guinea Coast in both near and mid-future periods. Under SSP5-8.5, WSDI increases further, with high-value centres expanding nationwide. Heatwave amplitude (HWA) is expected to increase from the Guinea Coast to the Sahel. Under SSP2-4.5, near-future projections indicate an increase of up to 1.8°C in the Guinea Coast, reaching 4.2°C in the mid-future. Under SSP5-8.5, HWA in the Sahel is projected to exceed 5.4°C in both near and mid-future periods.

Under SSP2-4.5, the heatwave magnitude (HWM) will decrease in the Guinea Coast in both near- and mid-future periods. Under SSP5-8.5, this decline is expected only in the near-future, while the entire country will experience an increase in HWM in the mid-future. The minimum nighttime temperature (TNN) is projected to increase unevenly across the country.

6.2.2.2 Projected changes in flood indicators

The projected changes in precipitation extreme indices over Nigeria under two SSP scenarios are analysed for the near future (2025–2054) and the far future (2055–2084). The mid-future projections follow a similar pattern to the near-future but with greater intensification. In the near-future (2025–2054), the maximum single-day precipitation (Rx1day) is projected to increase across Nigeria. Under SSP2-4.5, positive changes range from 0 to 5 mm in southern Nigeria and 6 to 10 mm in the north, while SSP5-8.5 projects even higher increases, reaching up to 12 mm in some areas.

The total annual precipitation (PRCPTOT) is expected to increase across most of Nigeria, except for a slight decrease in the southwest. Under both SSP scenarios, the projected increase in PRCPTOT is approximately 130 mm. Both scenarios indicate a positive trend nationwide for the maximum consecutive 5-day precipitation (Rx5day). The spatial distribution under SSP2-4.5 follows a pattern similar to Rx1day, whereas SSP5-8.5 follows more closely with PRCPTOT. Peak Rx5day values are estimated to reach 27 mm under both scenarios.

Changes in Consecutive Wet Days (CWD) show mixed trends. The longest projected decrease in CWD occurs in central Nigeria under SSP5-8.5, while in western Nigeria, SSP2-4.5 indicates a shift toward decreasing trends, including parts of the south. The projected decrease in CWD in western Nigeria is close to 10 days under SSP5-8.5, whereas both scenarios project increases in CWD in southern Nigeria, ranging from 0 to 12 days. For R20mm (days with rainfall ≥ 20 mm), projections under both scenarios indicate a consistent increase across Nigeria, ranging from 0 to 3 days nationwide and reaching up to 9 days in the extreme south under SSP5-8.5.

The contribution of extremely wet days (R99pTOT) is projected to increase across Nigeria. Under SSP2-4.5, values increase progressively from 0 to 2% in the south to 2 to 5% in the north, while SSP5-8.5 projects 2 to 6% increases across most regions.

For the mid-future (2055–2084), projected changes follow the same pattern as the near future but with greater intensification. This indicates a continued increase in extreme precipitation events, particularly under the SSP5-8.5 scenario, where stronger impacts are expected.

6.2.2.3 Projected Drought Indices

The NEX-GDDP Ensmean projects mixed signals (increases and decreases) in SPI and SPEI drought frequency for the near and mid-future, with values ranging between -1.8 and 1.8 events. The SPI index indicates a widespread decrease in drought frequency under both SSP scenarios, particularly in the Sahel and Savannah regions. However, the Guinea coast is projected to experience an increase in drought frequency in the near and mid-future. For the SPEI index, a general decrease in drought frequency is projected for the near future under both SSPs. However, in the mid-future, drought events are expected to increase in the northern Sahel region and the Guinea coast under SSP5-8.5.

Regarding the CDD (Consecutive Dry Days) index, a widespread decrease in drought frequency is projected across most of the country, except for the eastern regions and scattered areas in the north, where drought events are expected to persist under both SSP scenarios.

6.3 Assessment of Renewable Energy Resources

6.3.1 *Wind Energy Potential*

The Sahel and Savannah regions exhibit the highest annual mean daily wind power density, reaching approximately 150 W/m^2 in states such as Borno, Sokoto, Zamfara, and Gombe. In contrast, the Guinea coast records a lower mean wind power density, with maximum values around 70 W/m^2 .

6.3.2 Solar Energy Potential

The annual solar energy potential is highest in the Sahel and Savannah regions, reaching 4.8 MW, making these areas highly suitable for solar power plants. The minimum solar energy potential of 3.3 MW is concentrated in the Guinea coast, while the tropical rainforest region experiences moderate solar potential, ranging between 4.2 and 4.5 MW.

6.3.3 Hydropower Potential

Nigeria, a nation with abundant water resources, has significant hydropower potential that could help address its electricity challenges. However, only a small fraction of this potential has been utilised (Ugwu et al., 2022). The estimated exploitable hydropower potential exceeds 14,120 MW, generating more than 50,800 GWh of electricity annually (Nchege & Okpalaoka, 2023). While hydropower already contributes to the national grid, substantial untapped capacity remains along Nigeria's rivers and waterways.

The majority of proposed and operational hydropower stations are concentrated along Nigeria's two largest rivers, the Niger and Benue, and their tributaries, with a few scattered across smaller rivers in the north and south. Hydropower potential across various rivers ranges from 0.0–3.0 MW to 1,962–3,335 MW, with the highest values recorded along the Niger and Benue Rivers.

6.4 Conclusion and Recommendation and Adaptation Strategies

6.4.1 Summary and Conclusion

The historical climatological analysis of Nigeria from 1985 to 2014 reveals seasonal variations in both temperature and precipitation. The warmest period is during the MAM season, while DJF is the coolest. The Jos Plateau stands out as the coldest region year-round. Although climate models replicate these spatial patterns, they display biases—warm during JJA and SON and cold in southwestern Nigeria during DJF. Rainfall is highest in the southern regions, especially during JJA, and lowest in DJF. Models generally reflect these precipitation patterns but underestimate amounts, especially in the south.

Analyzing the annual climate cycle across Nigeria's homogeneous zones—Guinea Coast, Savannah, and Sahel—models successfully capture the timing of rainfall peaks. The Guinea Coast exhibits a bimodal precipitation pattern, while the other zones show a single peak in August. Temperature simulations show slight overestimations, particularly from March to November in the Guinea Coast. Trend analyses indicate an upward trajectory in both temperature and rainfall from 1985–2014, with future projections under SSP2-4.5 and SSP5-8.5 showing continued increases, especially in temperature, with warming exceeding 3°C under high-emission scenarios.

Regionally, annual cycles of T_{max} and T_{min} show significant north-south gradients and seasonality. Northern Nigeria experiences extreme heat and broad thermal amplitude, with peak T_{max} in April and sharp dips during the rainy season. The south remains more stable due to Atlantic influence. Rainfall patterns also vary: unimodal in the north and FCT, and bimodal in the south due to the August break. Future projections suggest rising

temperatures across all regions, with the most dramatic increases under SSP5-8.5, especially in the North. Tmin trends are more pronounced than Tmax, indicating warmer nights and heightened heat stress risks.

Extreme climate indices reveal increasing trends in heatwaves, droughts, and floods. Historical heat stress indicators show high values in the north and central zones. While models capture spatial patterns, they often over- or underestimate intensities. Flood indicators highlight the south as prone to intense rainfall events, though models sometimes misrepresent high-intensity zones. Drought indices show prolonged dry spells in the north, accurately captured by models. Future projections suggest significant increases in temperature extremes and rainfall variability, with the potential for more frequent and prolonged heatwaves and shifts in rainfall patterns—posing challenges for health, agriculture, and water management.

Given Nigeria's evolving climate dynamics, the country's substantial renewable energy resources offer a vital pathway for climate adaptation and energy sustainability. The Sahel and Savannah regions exhibit the highest wind energy potential, with wind power densities reaching approximately 150 W/m² in states like Borno, Sokoto, Zamfara, and Gombe, compared to a lower 70 W/m² in the Guinea Coast. Solar energy potential is also greatest in the Sahel and Savannah zones, peaking at 4.8 MW, while the Guinea Coast sees minimum values of 3.3 MW, and tropical rainforest areas range between 4.2 and 4.5 MW. Hydropower remains the most underutilized resource, with an estimated exploitable potential exceeding 14,120 MW and an annual generation capacity of over 50,800 GWh. Major opportunities lie along the Niger and Benue Rivers, where site-specific potentials range from 1,962 MW to 3,335 MW. Harnessing these resources strategically can help reduce greenhouse gas emissions, enhance energy access, and mitigate the impacts of intensifying climate extremes across Nigeria.

6.4.2 Recommendation and Adaptation Strategies

Based on projections from the NEX-GDDP CMIP6 Ensmean, medium- and high-emission scenarios indicate increasing risks in the near and mid-future. These risks include rising temperatures, more frequent heatwaves, and extreme rainfall events, which can lead to severe flooding in many regions of Nigeria. While solar energy technologies rely on weather conditions for power generation, extreme weather events—such as heatwaves, floods, and droughts—can disrupt operations, reduce energy output, strain the grid, and damage renewable energy infrastructure.

1. **Impact of Extreme Rainfall and Flooding on Solar PV Infrastructure**

1. Submersion and Equipment Damage – Ground-mounted solar PV systems can be inundated, leading to short circuits, equipment failure, and safety hazards for maintenance personnel.
2. Foundation Erosion and Structural Instability – Heavy rainfall and flooding can wash away soil, weaken mounting pole support, and compromise system stability, leading to potential collapse and costly repairs.
3. Water Ingress and Electrical Failures – Moisture penetration into electrical components can result in short circuits, insulation failure, and decreased system efficiency.
4. Dirt and Debris Accumulation – Excess debris on solar panels can block sunlight, reducing energy output and overall system performance (Nwokolo and Ogbulezie, 2018).
5. Corrosion of Metal Components – Prolonged exposure to harsh environmental conditions can cause rust and material degradation, threatening system longevity.

Adaptation Strategies

1. Robust Framing and Mounting Systems – Use high-quality, corrosion-resistant materials for solar panel frames and supports to prevent degradation under extreme conditions.
2. Strengthening Infrastructure – Elevate substations above flood-prone areas, reinforce transmission towers and power lines against high winds, and use flood-resistant materials in construction.
3. Smart Grids and Advanced Monitoring – Implement real-time monitoring systems with predictive maintenance capabilities to detect anomalies early and prevent failures.
4. Investment in Energy Storage – Deploy battery storage systems to store excess energy during optimal conditions and supply power during peak demand or disruptions, ensuring grid stability and reliability.

5. Impact of Extreme Heat and Drought on Solar PV Systems

High temperatures can significantly affect the performance and longevity of solar power plants, leading to:

1. Increased risk of accidents due to overheating and system failures.
2. Stress on cooling systems and energy storage- reducing efficiency.
3. Accelerated degradation of PV modules, shortening system lifespan.
4. Overheating of inverters- resulting in reduced efficiency, frequent faults, and compromised performance.
5. Expansion and warping of mounting structures- posing public safety risks and increasing maintenance demands.

Adaptation Strategies

1. Climate-Resilient Design – Use heat-resistant materials for power lines and design infrastructure to accommodate higher cooling demands during extreme heat.
2. Selection of Heat-Resistant PV Modules – Deploy photovoltaic modules engineered for high-temperature tolerance and incorporate temperature considerations in new grid infrastructure.
3. Enhanced Cooling and Ventilation – Improve passive airflow designs beneath mounting structures or integrate active cooling systems (forced air or liquid coolant) to prevent overheating.
4. Emergency Preparedness and Response – Develop comprehensive climate adaptation plans, conduct regular drills and simulations, and ensure rapid response mechanisms for extreme heat events.

7.0 Conclusion

As the climate continues to change at an unprecedented rate, the need for proactive planning and adaptation has never been more critical. This climate impact assessment offers a detailed analysis of the current and future climate conditions for four African countries—Benin, Côte d'Ivoire, Angola and Nigeria —providing valuable insights into the challenges they will face in the coming decades. The assessment is carried out under the Africa

Sovereign Climate Facility, which seeks to secure climate financing to tackle urgent climate change challenges in the assessed countries.

The assessment methodology evaluates climate change impacts across multiple sectors by analyzing historical (1985–2014) and future (2025–2054 and 2055–2084) climate projections under SSP2-4.5 and SSP5-8.5 scenarios. Homogeneous climate zones were identified using the Köppen climate classification system and refined based on spatial and literature-based criteria. The climatological mean of key parameters, such as temperature and precipitation was assessed by comparing historical observations with climate model simulations to evaluate performance and detect long-term trends. Extreme climate indices, including heat, drought, and flood-related indicators, were generated using the WMO-recommended ClimPACT2 tool. Agricultural indicators, such as water availability and irrigation demand, were analyzed using FAO-endorsed hydrological balance equations to assess climate impacts on water resources and agricultural productivity. Lastly, the study assessed renewable energy potential by evaluating wind, hydro, and solar energy resources under varying climate conditions to determine their viability as sustainable solutions for enhancing energy security and food production.

The climate analyses for Angola, Benin, Nigeria and Côte d'Ivoire reveal significant warming trends, increased variability in precipitation, and intensified extreme weather events. In Angola, historical and future projections indicate a rise in mean annual temperatures by 1.5–2.8°C under SSP2-4.5 and 2.5–4.5°C under SSP5-8.5 by the late 21st century, with drought frequency increasing in the south and extreme rainfall events intensifying in the north. In Nigeria, warming is projected to continue across all three zones, with temperature increases exceeding 3°C above present-day levels under the SSP5-8.5 scenario by the late 21st century, while remaining below 2°C under SSP2-4.5.

Benin's climate projections highlight increasing temperatures, with northern regions experiencing 27–30°C in DJF and 30–33°C in MAM, while erratic precipitation patterns lead to reduced soil moisture and increased drought frequency, affecting staple crops like maize, yams, and cassava. In Côte d'Ivoire, average temperatures have already risen by 1.0–1.5°C in recent decades, with northern regions recording peak temperatures of 34°C, leading to increased evapotranspiration and reduced agricultural productivity. Rainfall trends in Côte d'Ivoire show short, intense rainfall events causing floods, while prolonged dry spells threaten food and water security. Extreme climate indices in Nigeria show rising trends in heatwaves, droughts, and floods, with heat stress most severe in the northern and central regions and intense rainfall events more common in the south. Future projections indicate increasing temperature extremes and rainfall variability, leading to more frequent and prolonged heatwaves and droughts, which threaten health, agriculture, and water resources.

Our analysis also shows a clear upward trend in sea level rise is evident in both present-day observations and future climate projections along the coasts of Benin and Angola. This increasing trend heightens the exposure of critical infrastructure sites, particularly around Porto-Novo Lagoon and Lake Nokoué in Benin, as well as planned developments in Corimba, Angola, to coastal flooding, erosion, and saltwater intrusion.

Despite these risks posed by climate change, renewable energy potential offers opportunities to harness as a strategic component for adaptation and pathways to sustainable development. In Angola, there is a significant potential for solar (5.0–6.5 kWh/m²/day) and wind energy, particularly along its coast. It also has extensive hydropower potential that can be optimized by innovating dam designs and implementing smart grid technologies to maintain energy production despite the adverse impact of climatic changes. Benin holds strong potential for solar (~100MW) and wind energy, making it well-positioned to meet the energy demands of the GDIZ industrial zone and promote energy security and sustainable industrialization. In Côte d'Ivoire, the

abundant solar power potential, particularly in the northern regions, could provide an opportunity for integrating solar energy into agricultural practices, thereby enhancing resilience and ensuring stable energy supply for irrigation systems and supporting agricultural mechanization in critical crop-producing areas. Nigeria's substantial renewable energy resources provide a crucial pathway for climate adaptation and energy sustainability. The Sahel and Savannah regions exhibit the highest wind energy potential, with wind power densities reaching approximately 150 W/m^2 in northern states such as Borno, Sokoto, Zamfara, and Gombe, compared to a lower maximum of about 70 W/m^2 in the Guinea Coast. Solar energy potential is also highest in the Sahel and Savannah zones, peaking at 4.8 MW, while the Guinea Coast records the lowest values at 3.3 MW, and the tropical rainforest areas range between 4.2 and 4.5 MW.

Strengthening climate adaptation strategies—such as climate-smart agriculture, improved water resource management, disaster preparedness, and infrastructure resilience—will be critical to mitigating these climate impacts. Countries must invest in early warning systems, policy reforms, and community-based adaptation initiatives to enhance long-term sustainability. Expanding hydropower, solar, and wind energy while addressing infrastructure limitations will be crucial for energy security and economic resilience.

Therefore, Angola, Benin, Nigeria and Côte d'Ivoire can strengthen their resilience against climate change while ensuring sustainable economic development for future generations by integrating climate adaptation into national policies, promoting sustainable energy transitions, and fostering regional cooperation.

Reference

- Akpoti, K., Velpuri, N. M., Mizukami, N., Kagone, S., Leh, M., Mekonnen, K., ... & Seid, A. (2024). Advancing water security in Africa with new high-resolution discharge data. *Scientific Data*, 11(1), 1195.
<https://doi.org/10.1038/s41597-024-04034-0>
- Arogundade, S., Hassan, A. S., & Mduduzi, B. (2024). Is climate change hindering the economic progress of Nigerian economy? Insights from dynamic models. *Heliyon*, 10(20), e39288.
- Ayanlade, A., Jeje, O. D., Nwaezeigwe, J. O., Orimoogunje, O. O. I., & Olokeogun, O. S. (2021). Rainfall seasonality effects on vegetation greenness in different ecological zones. *Environmental Challenges*, 4(100144), 100144.
- [Dauda, R. \(2023\). Climate change and food security in Nigeria. Economic and Policy Review.](https://www.ajol.info/index.php/epr/article/view/261292)
<https://www.ajol.info/index.php/epr/article/view/261292>
- Fawole, W. O., & Özkan, B. (2017). Comprehensive review of growing food insecurity in Africa in terms of causes, effects and solutions: The Nigerian example. *Turkish Journal of Agriculture - Food Science and Technology*, 5(6), 629–636.
<https://doi.org/10.24925/turjaf.v5i6.629-636.1113>
- Ifeanacho, M. O., & Okudu, H. O. (2020). Climate change and nutrition security in Nigeria. *Journal of Applied Sciences & Environmental Management*, 24(11), 1853–1860.
<https://doi.org/10.4314/jasem.v24i11.2>
- Nchege, J., & Okpalaoka, C. (2023). Hydroelectric production and energy consumption in Nigeria: Problems and solutions. *Renewable Energy*, 219(119548), 119548.
- Ogunrinde, A. T., Oguntunde, P. G., Akinwumiju, A. S., & Fasinmirin, J. T. (2019). Analysis of recent changes in rainfall and drought indices in Nigeria, 1981–2015. *Journal Des Sciences Hydrologiques [Hydrological Sciences Journal]*, 64(14), 1755–1768.
- Omotosho, J. 'bayo, & Abiodun, B. J. (2007). A numerical study of moisture build-up and rainfall over West Africa. *Meteorological Applications*, 14(3), 209–225.
- Ugwu, C. O., Ozor, P. A., & Mbohwa, C. (2022). *Small hydropower as a source of clean and local energy in Nigeria: prospects and challenges. Fuel communications*, 10, 100046.
- Utsev, J. T., Onyebuchi, M., Onuzulike, C., Akande, E. O., Orseer, A. M., & Tiza, M. T. (2023). Assessing community perspectives on flood preparedness and mitigation strategies in Nigeria. *Journal of Novel Engineering Science and Technology*, 3(01), 6–11.
<https://doi.org/10.56741/jnest.v3i01.434>
- Korkovelos, A., Mentis, D., Siyal, S. H., Arderne, C., Rogner, H., Bazilian, M., Howells, M., Beck, H., & De Roo, A. (2018). A geospatial assessment of small-scale hydropower potential in sub-Saharan Africa. *Energies*, 11(11), 3100.
- RCRC (Red Cross Climate Centre) (2021) Climate Profiles of Countries in Southern Africa: Angola. The Hague:

RCRC.

- Angola. (2012). Angola's Initial National Communication to the United Nations Framework Convention on Climate Change. <https://unfccc.int/sites/default/files/resource/agonc1.pdf>
- Sawe, B. E. (2019). The Climate of Angola. *World Atlas*. <https://www.worldatlas.com/articles/what-type-of-climate-does-angola-have.html>
- Correia, C.D.N.; Amraoui, M.; Santos, J.A. (2025) Assessment of Climate Change in Angola and Potential Impacts on Agriculture. *Climate*, 13, 12. <https://doi.org/10.3390/cli13010012>
- Hunter, R., Crespo, O., Coldrey, K., Cronin, K., New, M. (2020). Research Highlights – Climate Change and Future Crop Suitability in Angola. University of Cape Town, South Africa, undertaken in support of *Adaptation for Smallholder Agriculture Programme' (ASAP) Phase 2. International Fund for Agricultural Development (IFAD), Rome.*
- Pinto, I.; de Perez, E.C.; Jaime, C.; Wolski, P.; van Aardenne, L.; Jjemba, E.; Suidman, J.; Serrat-Capdevila, A.; Tall, A. (2023) Climate change projections from a multi-model ensemble of CORDEX and CMIPs over Angola. *Environmental Research: Climate*, 2, 035007. <https://doi.org/10.1088/2752-5295/ace210>.
- Pereira C. A., J. P. A. Martins, A. H. Fink, J. G. Pinto, A. M. Ramos (2024). Drivers of seasonal rainfall variability over the Angolan and Namibian plateaus. *International Journal of Climatology*. <https://api.semanticscholar.org/CorpusID:271396885>.
- Group, T.W.B. Angola Country Climate and Development Report (CCDR), 2022.
- Soares P.M.M, Jo˜ao A.M. Careto *, Daniela C.A. Lima (2024): Future extreme and compound events in Angola: CORDEX-Africa regional climate modelling projections. *Weather and Climate Extremes*, 45. <https://doi.org/10.1016/j.wace.2024.100691>
- Carvalho, S.C.; Santos, F.D.; Pulquério, M. (2016) Climate change scenarios for Angola: an analysis of precipitation and temperature projections using four RCMs. *International Journal of Climatology*, 37, 3398–3412. <https://doi.org/10.1002/joc.4925>.
- Yoroba, F., Kouadio, N., & Others. (2023). *Climate and Agriculture in Côte d'Ivoire: Perception and Quantification of the Impact of Climate Change on Cocoa Production by 2050*. *International Journal of Environment and Climate Change*, 13(4), 123-135.
- Métangbo, A., B., C., & Others. (2023). *Social Life Cycle Assessment of Cocoa Production*. *Resources*, 13(10), 141.
- Timité, M., Kouadio, Y. L., & Bamba, I. (2022). *Impact of Climate Variability on Food Security in Côte d'Ivoire: A Case Study of Rain-fed Agriculture*. *Climate and Development*, 14(3), 245-260.
- Comoé, H., & Siegrist, M. (2013). *Relevant Drivers of Farmers' Adaptation Strategies to Climate Change in Côte d'Ivoire*. *Global Environmental Change*, 23(1), 81-90.
- Ezin, V., Azokanou, S., & Mahougnon, H. (2018). *Effects of High Temperatures on the Growth and Yield of Tomato (Solanum lycopersicum L.) in West Africa: Physiological and Agronomic Perspectives*. *Agricultural and Environmental Studies*, 32(4), 567-580.
- Peel, M. C., Finlayson, B. L., & McMahon, T. A. (2007). *Updated world map of the Köppen-Geiger climate classification*. *Hydrology and Earth System Sciences*, 11(5), 1633-1644.

- Peters, R., Berlekamp, J., Tockner, K., & Zarfl, C. (2023). RePP Africa—a georeferenced and curated database on existing and proposed wind, solar, and hydropower plants. *Scientific Data*, 10(1), 16. <https://doi.org/10.1038/s41597-022-01922-1>
- USAID (2018). *Climate Risk Profile: Cameroon*. United States Agency for International Development.
- WHO (2024). *World Health Organization Report on Population Estimates*. Geneva, Switzerland.
- World Bank (2024). *Cameroon Economic and Natural Resource Assessment*. Washington, DC.
- Aggarwal, P. K., & Singh, A. K. (2010). Implications of global climatic change on water and food security. In *Water Resources Development and Management* (pp. 49–63). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-04615-5_3
- Awulachew, S.B., Sally, H., Bahri, A., Molden, D. and Giordano, M. (2008). (n.d.). *Water security for food security: Gaps, needs and potential for growth in Sub-Saharan Africa*.
- Beguiría, S., Vicente-Serrano, S. M., & Angulo-Martínez, M. (2010). A multiscalar global drought dataset: the SPEIbase: a new gridded product for the analysis of drought variability and impacts. *Bulletin of the American Meteorological Society*, 91(10), 1351–1354. <https://www.jstor.org/stable/26233020>
- Besada, H., & Werner, K. (2015). An assessment of the effects of Africa's water crisis on food security and management. *International Journal of Water Resources Development*, 31(1), 120–133. <https://doi.org/10.1080/07900627.2014.905124>
- Fawole, W. O., & Özkan, B. (2017). Comprehensive review of growing food insecurity in Africa in terms of causes, effects and solutions: The Nigerian example. *Turkish Journal of Agriculture - Food Science and Technology*, 5(6), 629–636. <https://doi.org/10.24925/turjaf.v5i6.629-636.1113>
- Kotir, J. H. (2011). Climate change and variability in Sub-Saharan Africa: a review of current and future trends and impacts on agriculture and food security. *Environment Development and Sustainability*, 13(3), 587–605. <https://doi.org/10.1007/s10668-010-9278-0>
- Kumar, P. (2015). Hydrocomplexity: Addressing water security and emergent environmental risks. *Water Resources Research*, 51(7), 5827–5838. <https://doi.org/10.1002/2015wr017342>
- McKee, T. B. (1995). Drought monitoring with multiple time scales. *Proceedings of 9th Conference on Applied Climatology, Boston, 1995*. <https://ci.nii.ac.jp/naid/10028178079/>
- Ogunpaimo, O. R., Oyetunde-Usman, Z., & Surajudeen, J. (2021). Impact of climate change adaptation on household food security in Nigeria—A Difference-in-Difference approach. *Sustainability*, 13(3), 1444. <https://doi.org/10.3390/su13031444>
- Owusu, P. A., & Asumadu-Sarkodie, S. (2016). A review of renewable energy sources, sustainability issues and climate change mitigation. *Cogent Engineering*, 3(1), 1167990. <https://doi.org/10.1080/23311916.2016.1167990>
- Simpson, G. B., Jewitt, G. P. W., Mabhaudhi, T., Taguta, C., & Badenhorst, J. (2023). An African perspective on the Water-Energy-Food nexus. *Scientific Reports*, 13(1), 16842. <https://doi.org/10.1038/s41598-023-43606-9>
- Soro, G., Yao, A., Kouame, Y., & Bi, T. (2017). Climate change and its impacts on water resources in the Bandama basin, Côte D'ivoire. *Hydrology*, 4(1), 18. <https://doi.org/10.3390/hydrology4010018>

- Turrall, H., Burke, J., & Faures, J. M. (2011). *Climate change, water and food security*. Food & Agriculture Organization of the United Nations (FAO).
- Utsev, J. T., Onyebuchi, M., Onuzulike, C., Akande, E. O., Orseer, A. M., & Tiza, M. T. (2023). Assessing community perspectives on flood preparedness and mitigation strategies in Nigeria. *Journal of Novel Engineering Science and Technology*, 3(01), 6–11. <https://doi.org/10.56741/jnest.v3i01.434>
- Vilakazi, B. S., Zengeni, R., & Mafongoya, P. (2019). Indigenous strategies used by selected farming communities in KwaZulu Natal, South Africa, to manage soil, water, and climate extremes and to make weather predictions. *Land Degradation and Development*, 30(16), 1999–2008. <https://doi.org/10.1002/ldr.3395>
- Wudil, A. H., Ali, A., Mushtaq, K., Baig, S. A., Radulescu, M., Prus, P., Usman, M., & Vasa, L. (2023). Water use efficiency and productivity of irrigated rice cultivation in Nigeria: An application of the stochastic frontier approach. *Sustainability*, 15(10), 7824. <https://doi.org/10.3390/su15107824>
- Yalew, S. G., van Vliet, M. T. H., Gernaat, D. E. H. J., Ludwig, F., Miara, A., Park, C., Byers, E., De Cian, E., Piontek, F., Iyer, G., Mouratiadou, I., Glynn, J., Hejazi, M., Dessens, O., Rochedo, P., Pietzcker, R., Schaeffer, R., Fujimori, S., Dasgupta, S., ... van Vuuren, D. P. (2020). Impacts of climate change on energy systems in global and regional scenarios. *Nature Energy*, 5(10), 794–802. <https://doi.org/10.1038/s41560-020-0664-z>
- Diarrassouba, M., Diawara, A., Yapo, A.L.M., Kouassi, B.K., Yoroba, F., Kouadio, K., Tiemoko, D.T., Koné, D.I. and Diedhiou, A. (2024) Projected Changes in the Climate Zoning of Côte d'Ivoire. *Atmospheric and Climate Sciences*, 14, 62-84. doi: [10.4236/acs.2024.141004](https://doi.org/10.4236/acs.2024.141004).
- Conceição, P., Fuentes-Nieva, R., Horn-Phathanothai, L., & Ngororano, A. (2011). Food security and human development in africa: strategic considerations and directions for further research*. *African Development Review*, 23(2), 237-246. <https://doi.org/10.1111/j.1467-8268.2011.00283.x>.
- Hales, Simon & Tadross, Mark. (2021). Climate Science Basis: Health in Cambodia. In: Annex II. Country Case Studies Developing the Climate Science Basis for Climate Action.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D. and Simmons, A., 2020. The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), pp.1999-2049.
- Ifeanacho, M. and Okudu, H. (2020). Climate change and nutrition security in nigeria. *Journal of Applied Sciences and Environmental Management*, 24(11), 1853-1860. <https://doi.org/10.4314/jasem.v24i11.2>.
- Thrasher, B., Wang, W., Michaelis, A., Melton, F., Lee, T. and Nemani, R., 2022. NASA global daily downscaled projections, CMIP6. *Scientific data*, 9(1), p.262.