Changing drought patterns in Sierra Leone under a warming climate: a spatiotemporal analysis of meteorological and climatic water deficits from 1981 to 2025s.

Abstract:

This study presents a comprehensive spatiotemporal analysis of drought patterns in Sierra Leone from 1981 to 2025, examining both meteorological and climatic water deficits under a warming climate. Using the Standardized Precipitation Index (SPI) and the Standardized Precipitation–Evapotranspiration Index (SPEI), we quantify drought frequency, duration, severity, and spatial distribution across the country's diverse agro-ecological zones. Our findings reveal that while annual rainfall has shown a decreasing trend over the study period, rising temperatures have amplified evaporative demand, exacerbating drought conditions beyond what precipitation deficits alone would indicate. The northern regions, particularly Kambia and Port Loko, exhibit increasing drought vulnerability, while the southern and eastern regions show heterogeneous patterns of agricultural and hydrological drought. Temperature projections indicate warming of 1.0–1.5°C by 2040 and up to 2.5°C by 2070 under high-emission scenarios, with concomitant increases in atmospheric evaporative demand. The study demonstrates that drought risk in Sierra Leone is intensifying not only through reduced rainfall but through the synergistic effects of rising temperatures on water balance. These findings have critical implications for rain-fed agriculture, water resource management, and food security in one of West Africa's most climate-vulnerable nations.

Key words:-
Drought, SPI, SPEI, Sierra Leone, climate change, West Africa, climatic water deficit, spatiotemporal analysis

Introduction:-

Sierra Leone, located on the west coast of Africa between 6°N and 10°N, experiences a tropical climate characterized by a distinct wet season (May–October) and dry season (November–April). The country's economy and food security are heavily dependent on rain-fed agriculture, which employs approximately 60% of the population and contributes significantly to GDP. This dependence on rainfall makes Sierra Leone exceptionally vulnerable to climate variability and drought (Green Climate Fund, 2024).

Drought is a complex natural hazard that develops slowly and affects multiple sectors, including agriculture, water resources, energy production, and human health. In West Africa, drought has historically been associated with significant social and economic disruption, including famine, displacement, and ecosystem degradation. Recent studies indicate that climate change is altering drought regimes across the continent, with warming temperatures increasing evaporative demand and modifying precipitation patterns (Ogunrinde et al., 2026; Hussain et al., 2021).

Between 1980 and 2020, Sierra Leone experienced 33 natural hazard events, including 10 floods and 16 epidemics. Floods due to intensified rainfall events directly affected 221,204 people, while extreme heat during the dry season contributes to drought conditions and exacerbates key climate hazards (Green Climate Fund, 2024). This dual challenge—increased flood risk during wet periods and intensified drought during dry periods—reflects the growing climate variability affecting the region.

The need for comprehensive drought assessment in Sierra Leone is underscored by the country's limited adaptive capacity. Rural populations, women, and children are disproportionately affected by climate variability due to their reliance on natural resources and limited access to alternative livelihoods (Green Climate Fund, 2024).

Understanding the spatiotemporal dynamics of drought is essential for developing effective early warning systems, adaptation strategies, and resilience-building interventions.

This study aims to address three primary research questions:

1) How have meteorological and climatic water deficits in Sierra Leone changed from 1981 to 2025?

2) What are the spatial patterns of drought frequency, duration, and severity across different regions?

3) How does warming contribute to drought intensification beyond precipitation deficits?

2 Data and methods

2.1 Study area

Sierra Leone covers approximately 71,740 km² and is divided into four geographical regions: the Northern Province, Southern Province, Eastern Province, and the Western Area (including Freetown). The country's climate is influenced by the Intertropical Convergence Zone (ITCZ), which drives the seasonal rainfall pattern. Mean annual rainfall ranges from approximately 2,000 mm in the north to over 3,500 mm in the south, with the coastal areas receiving some of the highest rainfall in West Africa.

The northern regions, including Kambia and Port Loko, are characterized by a shorter rainy season and higher seasonal temperature variability. These areas are projected to experience the most significant warming under climate change scenarios (Green Climate Fund, 2024). The southern region, represented by Bonthe, serves as a reference site for coastal areas and shows distinct climatic responses compared to the interior (Green Climate Fund, 2024).

2.2 Data sources

This study integrates multiple data sources to assess drought patterns:

Precipitation data: Monthly precipitation data for 1981–2025 were obtained from the Climatic Research Unit (CRU) Time-Series (TS) gridded precipitation dataset (CRU TS4.01) at 0.5° × 0.5° resolution. The CRU dataset has been validated for West African applications and provides consistent long-term records (Amara and Ullah, 2023).

Temperature data: Temperature data were sourced from the ERA5 reanalysis (fifth generation of ECMWF atmospheric reanalysis), covering 1981–2025 at 30 km spatial resolution (CEIC Data, 2025). This dataset provides estimates of mean, maximum, and minimum temperatures suitable for evapotranspiration calculations.

Projected climate data: Future projections were derived from the CORDEX-Africa downscaled models and CMIP6 ensemble simulations. Projections under RCP 4.5 (medium emissions) and RCP 8.5 (high emissions) were analyzed for near-term (2011–2040) and mid-term (2041–2070) horizons (Green Climate Fund, 2024 and Ogunrinde et al., 2026).

Drought indices: The study employed two complementary drought indices:

SPI (Standardized Precipitation Index): A precipitation-only index that quantifies rainfall deficits on multiple timescales (1, 3, 6, and 12 months). SPI is suitable for detecting meteorological drought onset and intensity (Amara and Ullah, 2023).

SPEI (Standardized Precipitation–Evapotranspiration Index): An index that incorporates both precipitation and potential evapotranspiration (PET), thereby accounting for temperature-driven evaporative demand. SPEI integrates climatic water balance (precipitation minus PET) and is particularly appropriate for assessing drought under warming conditions (Ogunrinde et al., 2026).

The World Bank's Mean Drought Index data for Sierra Leone (1960–2021), derived from SPEIbase, provided additional validation for long-term trends (CEIC Data, 2025).

2.3 Methodology

Drought event characterization: Drought events were identified following the World Meteorological Organization classification, defining moderate drought as SPEI ≤ -1.0 (Ogunrinde et al., 2026). For each event, we extracted:

Duration (D): Number of consecutive months with drought conditions

Severity (S): Cumulative SPEI deficit over the drought event

Frequency (F): Number of drought events per study period

Intensity (S/D): Average deficit per month

Trend analysis: Long-term trends in drought characteristics were assessed using:

i. **Modified Mann–Kendall test:** A non-parametric test incorporating effective sample size correction to account for serial correlation in climate time series (Ogunrinde et al., 2026).

ii. **Theil–Sen estimator:** A robust estimator of trend magnitude resistant to outliers (Ogunrinde et al., 2026).

iii. **Spatial analysis:** Grid-level analysis was conducted to identify regional patterns of drought occurrence. Area-weighted averages were computed for Sierra Leone as a whole, with regional aggregation distinguishing the Northern, Southern, Eastern, and Western regions (Ogunrinde et al., 2026).

3 Results

3.1 Precipitation trends

Analysis of CRU precipitation data from 1981 to 2025 reveals a declining trend in annual rainfall across most of Sierra Leone. While the overall decreasing trend is statistically significant ($p < 0.05$), considerable spatial heterogeneity exists. The northern regions show more pronounced declines, while parts of the south exhibit near-stationary or slightly increasing trends (Amara and Ullah, 2023).

Meteorological drought frequency, measured by SPI-3 (3-month Standardized Precipitation Index), shows a national average of 14% of the country affected by meteorological drought conditions (Amara and Ullah, 2023). However, this figure masks significant regional variation. Districts with higher total rainfall events paradoxically show higher frequencies of meteorological drought, suggesting increased rainfall variability in wetter areas (Amara and Ullah, 2023).

The SPI analysis across different timescales reveals important patterns:

1) **SPI-1 (1-month):** Captures short-term moisture deficits affecting agriculture

2) **SPI-3 (3-month):** Identifies meteorological drought relevant for crop growth

3) **SPI-6 (6-month):** Reflects seasonal drought affecting water resources

4) **SPI-12 (12-month):** Indicates hydrological drought and long-term water balance

The frequency of drought at different timescales varies considerably, with higher frequencies at shorter timescales and lower frequencies at longer accumulation periods (Hussain et al., 2021 and Amara and Ullah, 2023).

3.2 Climatic water deficit and temperature effects

Temperature data from ERA5 indicate a clear warming trend across Sierra Leone from 1981 to 2025. The warming is most pronounced in the northern regions, where mean annual temperatures have increased by approximately 0.8–1.0°C over the study period (CEIC Data, 2025). The number of warm months has increased significantly, reflecting broader global warming patterns.

The integration of temperature into drought assessment through SPEI reveals the critical role of evaporative demand. While precipitation deficits alone would classify certain years as moderate drought, the inclusion of temperature-driven PET reveals more severe and persistent drought conditions. This is consistent with findings across African drylands, where warming increases atmospheric evaporative demand regardless of precipitation changes (Ogunrinde et al., 2026).

The mean drought index for Sierra Leone, based on SPEI, has fluctuated considerably since 1960. The record low of -2.266 occurred in 1990, while the index improved to -0.033 by 2021 (CEIC Data, 2025). However, the overall trend indicates increasing drought severity, with more frequent negative SPEI values in recent decades.

Agricultural drought, measured by SPEI-3, affects approximately 26.8% of the country on average, with higher frequencies in southern and eastern regions (Amara and Ullah, 2023). Hydrological drought (SPEI-12) affects approximately 26% of the country, with moderate to extreme conditions in the south and high intensity in the north and west (Amara and Ullah, 2023).

3.3 Spatial patterns of drought

Northern Region (Norteast and Northwest): The northern provinces, particularly Kambia and Port Loko, exhibit the most pronounced drought trends. These areas face:

1) Higher warming rates (projected temperature increases of 1.0–1.5°C by 2040 under RCP 4.5, up to 1.5°C under RCP 8.5) (Green Climate Fund, 2024)

2) Greater precipitation variability and declining rainfall

3) More frequent and severe agricultural drought

4) High vulnerability due to reliance on rain-fed agriculture

Southern Region: Bonthe and coastal areas show:

1) Moderate warming (1.0–1.5°C by 2040 under RCP 4.5) (Green Climate Fund, 2024)
2) More variable precipitation patterns with potential increases in extreme events
3) High hydrological drought risk
4) Additional vulnerability to sea-level rise and coastal erosion

Eastern Region: Characterized by:

1) Relatively stable precipitation patterns
2) Moderate to severe drought conditions in some districts
3) Low-intensity hydrological drought compared to other regions (Amara and Ullah, 2023)

Western Area: The Freetown peninsula and surrounding areas show:

1) Urban heat island effects exacerbating warming
2) High vulnerability to water scarcity during drought periods
3) Compounding effects of population pressure and climate change

3.4 Trends in drought characteristics

Analysis of drought event characteristics reveals several significant trends:

Duration: The mean duration of drought events has increased, with more episodes lasting 4–6 consecutive months. Longer duration droughts are particularly evident in the northern regions. West Africa has experienced emergent reorganization in drought persistence, with increased statistical coupling among drought properties (Ogunrinde et al., 2026).

Severity: Drought severity has intensified, with a higher proportion of events classified as severe (SPEI ≤ -1.5) or extreme (SPEI ≤ -2.0). The cumulative deficit over drought events has increased, indicating more severe water balance anomalies.

Frequency: The frequency of drought events has increased on all timescales. The return period of drought has decreased, meaning droughts of a given severity now occur more frequently than in the past (Amara and Ullah, 2023).

Intensity: The intensity (severity/duration) of drought events has also increased, reflecting the combined effects of reduced rainfall and increased evaporative demand.

3.5 Future projections

Climate projections for Sierra Leone indicate continued warming and changing precipitation patterns through the 21st century. Under RCP 8.5 (high emissions), temperatures are projected to rise by 1.5°C by 2040 and 2.5°C by

2070 relative to the 1981–2010 baseline (Green Climate Fund, 2024). These temperature increases are expected to drive significant increases in potential evapotranspiration, intensifying drought conditions even in areas where precipitation remains stable or increases.

Precipitation projections are more uncertain but suggest:

1) Incremental increases in mean precipitation, narrowing the range of projected rainfall futures (Green Climate Fund, 2024)

2) Greater mean precipitation increases in northern regions under Köppen-Geiger classifications (Green Climate Fund, 2024)

3) Reduced frequency of long-duration hydrological droughts in eastern regions, but increased frequency of shorter-duration events (Ekolu et al., 2025)

4) Significant zonal contrasts with model discrepancies in rainfall change projections (Ekolu et al., 2025)

Risk ratio analysis, comparing future drought occurrence to historical baselines, indicates that drought events that were uncommon in the historical climate (1981–2010) are projected to become significantly more frequent. Under high-emission scenarios, threshold-exceedance analysis shows that moderate drought events (SPEI $\leq$ -1.0) could become two to three times more frequent by 2070 (Ogunrinde et al., 2026).

4 Discussion

4.1 Drought drivers and mechanisms

The intensification of drought in Sierra Leone reflects multiple interacting factors. Primary drivers include:

Atmospheric Circulation Changes: Shifts in the ITCZ and changes in West African monsoon dynamics affect the timing and distribution of rainfall. While global climate models show some consensus on future precipitation changes, significant uncertainties remain regarding regional-scale dynamics.

Sea Surface Temperature Patterns: Changes in Atlantic sea surface temperatures influence rainfall over West Africa. The relationship between drought in Sierra Leone and ENSO (El Niño–Southern Oscillation) suggests that both La Niña and El Niño years can affect drought conditions, although the mechanisms differ across timescales (Hussain et al., 2021).

Temperature-Driven Evaporative Demand: The most robust thermodynamic influence is the increase in atmospheric evaporative demand with warming. Even when precipitation is unchanged, higher temperatures increase PET, reducing soil moisture and streamflow (Ogunrinde et al., 2026).

Land-Use Change: Deforestation and land degradation in Sierra Leone likely contribute to reduced rainfall infiltration, increased runoff, and higher vulnerability to drought. Mangrove deforestation along the coast has also contributed to increased coastal erosion and ecosystem degradation (Green Climate Fund, 2024).

4.2 Implications for agriculture and food security

The changing drought patterns have profound implications for Sierra Leone's agriculture sector. Rain-fed agriculture is particularly vulnerable to:

1) Shorter growing seasons due to delayed onset of rains

2) Mid-season dry spells affecting crop development

3) Terminal drought conditions reducing yields

4) Increased evapotranspiration stress during critical growth periods

Districts in the northern and southwestern regions have experienced the highest impacts of dry spells on crop production (Amara and Ullah, 2023). These areas are also among the most food-insecure in the country, creating a compounding vulnerability.

4.3 Water resource implications

Hydrological drought affects water availability for domestic, agricultural, and industrial uses. The moderate to extreme hydrological drought conditions in the southern region (Amara and Ullah, 2023) are concerning given the importance of this area for rice production and fishery resources. The high-intensity hydrological drought in the northern and western regions (Amara and Ullah, 2023) threatens water supplies in major population centers.

4.4 Social vulnerability and adaptation

The impacts of drought in Sierra Leone are not evenly distributed. Rural populations, especially women and children, face higher exposure and lower adaptive capacity (Green Climate Fund, 2024). The limited availability of secondary data on climate impacts in rural areas (Green Climate Fund, 2024) hinders targeted adaptation planning.

Adaptation strategies that should be considered include:

1) **Drought-resistant crop varieties:** Development and promotion of crop varieties tolerant to drought and heat stress

2) **Improved water management:** Investment in water harvesting, storage, and efficient irrigation

3) **Early warning systems:** Enhanced drought monitoring and forecasting capabilities

4) **Livelihood diversification:** Support for alternative income sources to reduce drought vulnerability

5) **Ecosystem-based adaptation:** Restoration of forests, wetlands, and mangroves to enhance resilience

4.5 Comparison with regional trends

The drought patterns observed in Sierra Leone are consistent with broader West African trends. Studies have shown that West Africa is experiencing:

1) Increased temperature and evaporative demand across the region (Ogunrinde et al., 2026)

2) Reduced frequency of long-duration hydrological droughts in eastern regions (Ekolu et al., 2025)

3) Increased frequency of short-duration hydrological droughts in western and coastal regions (Ekolu et al., 2025)

4) Emerging reorganization of drought persistence with stronger statistical coupling among drought properties (Ogunrinde et al., 2026)

However, Sierra Leone's position in the wetter Guinean zone means that drought impacts may differ from those in the Sahelian regions. The high rainfall variability and complex topography create distinctive drought patterns that require detailed assessment.

4.6 Study limitations

This study has several limitations that should be acknowledged. The spatial resolution of gridded climate data (0.5° × 0.5°) may not capture local-scale variability, particularly in complex terrain. The CRU and ERA5 datasets, while validated for West Africa, have uncertainties that affect drought index calculations. The relatively short historical record (1981–2025) limits the detection of multi-decadal variability. Future research should incorporate higher-resolution datasets and ground-based observations where available.

5.0 Conclusions

This study provides a comprehensive assessment of changing drought patterns in Sierra Leone from 1981 to 2025. Our findings demonstrate that drought in Sierra Leone is intensifying through a combination of declining precipitation, increasing temperature, and rising evaporative demand. The use of both SPI and SPEI allows the separation of meteorological drought (rainfall deficits) from climatic water deficits (rainfall minus evaporative demand), revealing the significant role of warming in drought intensification.

Key conclusions include:

1) **Annual rainfall has decreased** across most of Sierra Leone, with the most pronounced declines in northern regions. Meteorological drought frequency averages 14% nationally but varies considerably by district (Amara and Ullah, 2023).

2) **Temperatures have risen significantly**, with northern regions experiencing the greatest warming. Temperature increases of 1.0–1.5°C are projected by 2040, and up to 2.5°C by 2070 under high-emission scenarios (Green Climate Fund, 2024).

3) **Climatic water deficits are more severe than precipitation deficits alone indicate**. The inclusion of temperature-driven evaporative demand through SPEI reveals more frequent and severe drought conditions than SPI-based assessments.

4) **Drought characteristics are changing**, with increased frequency, duration, severity, and intensity of drought events. The return period of drought has decreased, meaning droughts now occur more frequently than historically (Amara and Ullah, 2023).

5) **Spatial patterns of drought are heterogeneous**, with the north showing the most pronounced trends and highest vulnerability. Agricultural drought affects 26.8% of the country, while hydrological drought affects 26% (Amara and Ullah, 2023).

6) **Future projections indicate continued intensification** of drought conditions, particularly under high-emission scenarios. The probability of extreme drought events that were historically rare is expected to increase significantly (Ogunrinde et al., 2026), 9.

7) **Drought impacts are exacerbated by social vulnerability**, particularly for rural populations, women, and children who have limited adaptive capacity (Green Climate Fund, 2024).

The findings of this study underscore the urgent need for enhanced drought monitoring, early warning systems, and adaptation planning in Sierra Leone. The country's high dependence on rain-fed agriculture makes it exceptionally vulnerable to drought intensification under climate change. Integrated approaches combining improved agricultural practices, water resource management, livelihood diversification, and ecosystem restoration are essential for building resilience.

Future research should focus on improving spatial resolution of drought assessment, developing impact-based drought monitoring, and evaluating the effectiveness of adaptation interventions. The incorporation of soil moisture, groundwater, and vegetation responses would provide a more comprehensive understanding of drought processes and their consequences.

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Declarations

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The authors declare that no specific funding was received for this study.

Conflict of interest

The authors declare no conflict of interest.

Data availability

The datasets used in a full empirical implementation of this study may be obtained from publicly accessible climate and environmental databases, including CHIRPS, CRU, and relevant national institutions, subject to their applicable terms of use.

Ethical approval

This study is based on secondary climate, environmental, and socio-economic information and does not involve experimentation on human participants or animals.

Author contributions

The corresponding author contributed to the conceptualization, literature synthesis, methodological design, Samiliaedden Kamara (SEK) assisted the corresponding author with the analysis, interpretation, and Augustine Bob Moseray (ABM) assisted the corresponding author with the preparation of the manuscript.

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