The Impact of Climate Change on the Dynamic Relationship Between Temperature and Rainfall in Edduiem City an Analytical Study (2018–2024)

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Abstract—**This study aimed to monitor and analyze the geographical factors and characteristics of the newly emerging climate dynamics in the Ed Dueim locality of the White Nile State. This was achieved by tracking the temporal behavior of temperature and rainfall over an extended observational series spanning 35 years (1990–2024) to bridge the research gap concerning the region's microclimate.**

The study employed both an applied geographical approach and an analytical statistical approach. The quantitative data were subjected to the Mann-Kendall test to detect general trends, and Theil-Sen's slope estimator was used alongside calculations of extreme climate indices approved by the World Meteorological Organization (WMO). Correlation analyses were conducted using the SPSS software.

The findings revealed a statistically significant, linear upward trend ($p < 0.05$) in the mean annual temperature, with a faster rate of nocturnal warming observed in minimum temperatures, which in turn reduced the diurnal temperature range. Conversely, the analysis unveiled sharp fluctuations and violent swings in annual rainfall amounts, accompanied by a "seasonal shift" characterized by a delayed start to the autumn season, a shorter duration, and a transition in precipitation patterns toward intense, violent convective (cyclonic) rainstorms. Furthermore, the study proved the existence of a significant negative correlation between warming and rainfall efficacy, resulting from doubled evaporation rates from both the White Nile water body and the clayey soils. This has led to heat stress and a hidden agricultural drought that has severely harmed the productivity of food and cash crops (such as sorghum and sesame) and deteriorated rangelands. The study recommends the necessity of re-engineering agricultural cycles and sowing dates to align with the newly established seasonal shifts, introducing short-cycle and

heat-stress-resistant crop varieties, improving drainage systems in Nile-adjacent agricultural projects to combat waterlogging, and establishing water harvesting projects (such as hafires and earthen dams) in remote pastoral areas to mitigate resource-based conflicts.

Index Terms—**Climate Dynamics, Ed Dueim Station, Mann-Kendall Test, Rainfall Extremes, Seasonal Shift, Heat Stress.**

I. INTRODUCTION

The phenomenon of climate change represents one of the greatest environmental crises and most complex scientific challenges facing humanity in the modern era. Its impacts have transcended regional and local scales to reshape the hydro-climatic characteristics of numerous regions worldwide. These changes are no longer mere theoretical hypotheses; they have transformed into a tangible reality manifested in the disruption of major climatic elements, unprecedented rates of global warming, and the increasing frequency of extreme weather events. Due to its geographical location and astronomical extension within arid and semi-arid tropical zones, Sudan is classified as one of the most vulnerable and sensitive regions to climatic fluctuations and changes. The White Nile State, particularly the Edduiem City, serves as a living model of areas directly affected by this dynamic. Its distinct geographical position on the western bank of the White Nile intersects with its semi-arid climate, rendering its ecosystem highly sensitive to any imbalance in the thermal and water budget. The relationship between temperature and rainfall in tropical environments is not a static linear one, but rather a complex, dynamic relationship. Continuous temperature rise structurally affects atmospheric pressure and accelerates evaporation rates (especially given the presence of an expansive water body like the White Nile). This directly influences condensation mechanisms, the behavior of moisture-bearing winds, and consequently, the volume, spatial, and temporal distribution of precipitation. This study tracks and analyzes the nature of this impact and dynamic interaction in the Ed Dueim locality over a robust and extended 34-year time series (2018–2024). This period is scientifically sufficient to represent two climate cycles according to the World Meteorological Organization (WMO) standards. The study aims to untangle the quantitative and statistical correlation between rising temperatures and the disruption of the rainfall regime, as well as to monitor signs of seasonal shifts and extreme climate events in the region. Ultimately, it seeks to provide a scientific vision that supports sustainable environmental and developmental adaptation plans in the locality.

II. PROBLEM STATEMENT

The research problem lies in monitoring and characterizing the hydro-climatic imbalance that has occurred in the ecosystem of the Ed Dueim locality as a result of contemporary climate change.

Recently, there has been an observed increase in the frequency of extreme events, such as severe heat waves, delayed rainy seasons, or sudden torrential rainfall causing flash floods.
The core research problem can be formulated in the following main question:
What is the impact of climate change on the dynamic relationship between temperature and rainfall in the Ed Dueim locality (1990–2024)? From this main question, the following sub-questions emerge:
1) What is the general trend (Trend) in temperature changes (maximum, minimum, and mean) in the Ed Dueim locality during the study period?
2) What is the temporal behavior and annual fluctuation of rainfall amounts and precipitation in the region?
3) Is there a statistically significant correlation between thermal rise and the disruption of the rainfall regime (such as seasonal delay or retreat)?

III. STUDY OBJECTIVES

The primary objective of this study is to analyze and measure the impact of climate change on the dynamic interactive relationship between temperature and rainfall in the Ed Dueim locality.
To achieve this, the following specific objectives are pursued:
1) Monitor and analyze the temperature time series in Ed Dueim to identify local warming rates.
2) Determine the scale of annual rainfall fluctuation and calculate rainfall anomaly indices (drought and wetness/floods).
3) Model the statistical relationship between temperature and rainfall to determine the strength of correlation and the level of impact between them.

IV. STUDY HYPOTHESES

1) There is a statistically significant upward (positive) general trend in temperatures in the Ed Dueim locality during the period (1990–2024), reflecting the reality of local climate change.
2) Rising temperatures and subsequent increases in evaporation rates lead to a dynamic disruption in rainfall behavior (its temporal and spatial distribution, and the number of rainy days).
3) is a negative (inverse) correlation between extreme maximum temperatures during the summer season and the net amount of precipitation during the subsequent rainy season.

V. SIGNIFICANCE OF THE STUDY

Scientific Significance: Enriching the geographical academic literature with a modern, applied study based on reliable data and a long-term time series (34 years) covering two climate cycles, which ensures high scientific accuracy.

VI. PRACTICAL/APPLIED SIGNIFICANCE

Providing decision-makers, agricultural planners, and water resource specialists in the White Nile State with precise climate indicators to assist in resource management and adaptation to climate fluctuations.

VII. SCOPE AND LIMITATIONS

Thematic Scope: Studying the impact of climate change on the relationship between temperature and rainfall, excluding other climatic elements unless they directly affect these two.
Spatial Scope: The administrative and geographical boundaries of the Edduiem city, White Nile State.

Temporal Scope: The period (2018-2024).

VIII. METHODOLOGY

The study relies on the descriptive-analytical approach and the historical approach, with an intensive focus on quantitative and statistical methods to process climate data obtained from the Sudan Meteorological Authority (Ed Dueim Meteorological Station). This is achieved through the following analytical tools:

Mann-Kendall Test: To determine monotonic trends (upward or downward) in the climate time series.

Pearson and Spearman Correlation Coefficients: To measure the strength and direction of the relationship between temperature and rainfall.
Simple and Multiple Linear Regression Analysis: To measure the impact of thermal change (as an independent variable) on rainfall (as a dependent variable).

IX. PREVIOUS STUDIES

Analysis of General Trends in Extreme Temperature and Rainfall Phenomena Across Sudan’s Climatic Regions (2025): This study utilized the Mann-Kendall test and Sen’s slope estimator to analyze daily climatic data spanning more than three decades. The findings revealed a highly statistically significant upward trend in both minimum and maximum temperatures over the last three decades. Conversely, it showed sharp and irregular fluctuations in annual rainfall volumes, with precipitation concentrated within shorter, more intense periods (severe thunderstorms and convective cells).

The Impact of Hydro-Climatic Changes on Ecosystems and Agriculture Around the White Nile Basin (2024): This research integrated locally measured meteorological data with remote sensing data (soil cover and moisture anomalies). It confirmed that the relationship between temperature and rainfall in states bordering the White Nile (including the White Nile State, to which Ed Dueim belongs) has entered a phase of "dynamic instability." Continuous temperature rise accelerates evaporation rates from both the river surface and clayey soils, thereby reducing the effective efficiency of rainfall and increasing topsoil dryness, even during years with average rainfall.

Rainfall Fluctuations, Temperature Behavior, and Their Impact on Cash and Food Crop Production in the Sudanese Savannah Regions (2023): This study relied on mathematical modeling and correlation coefficients to link crop yields (sorghum and sesame) to annual variations in temperature and rainfall. The results demonstrated that the temporal distribution of rainfall (rather than just the total volume) is the factor most heavily affected by warming. Sudden temperature spikes during July and August (the vegetative growth phase) induce heat stress on crops and alter the nature of the traditional agricultural season.

Application of World Meteorological Organization (WMO) Indices to Monitor Climate Extremes in Central Sudan (2022): This study utilized meteorological software to calculate specific climate indices, including Consecutive Dry Days (CDD), Consecutive Wet Days (CWD), and record-temperature days. The study concluded that Central Sudan is witnessing a clear increase in the duration of dry spells within a single autumn/rainy season, reflecting a disruption in the dynamics between regional warming and convective cloud formation.

X. GENERAL COMMENTARY ON PREVIOUS STUDIES

Contents and Theme

The reviewed literature demonstrates an advanced awareness of the severity of climate change in Sudan. The focus remained heavily on monitoring "thermal and rainfall extremes" as an interconnected package. These studies illustrated that the crisis lies not merely in cumulative rainfall amounts, but rather in its temporal distribution (dynamic disruption) coupled with rising temperatures (evaporation and heat stress). This directly impacts ecosystems and agricultural production across the Savannah belt and the White Nile Basin[1].

Methodology and Tools

The methodologies deployed across these studies were remarkably diverse and robust, offering an excellent foundational framework: In-depth Standard Statistical Analysis: Employing rigorous tests like the Mann-Kendall test and Sen's slope estimator (e.g., the 2025 study). Modern Technologies: Integrating ground-based station data with remote sensing data for soil anomalies and moisture tracking (e.g., the 2024 study)

Mathematical Modeling and WMO Indices: Calculating consecutive dry and wet periods to capture intra-seasonal variations (e.g., the 2023 and 2022 studies). This methodological diversity provides a solid theoretical and procedural foundation for the current study[2].

XI. LIMITATIONS AND REGIONAL GENERALIZATION

Despite the high scientific value of these previous works, most are characterized by "regional generalization." They primarily examined Sudan's climatic zones broadly, Central Sudan as a whole, or the extensive Savannah belt. Even the study that addressed the White Nile State (2024) treated it as a component of the broader White Nile Basin, without focusing on the precise micro-climate characteristics of a specific station or locality. An independent focus on Ed Dueim is critical, as it possesses a distinct geographical and environmental identity marked by the intersection of the poor Savannah environment, riverine dynamics, and expansive clay soils[3].

XII. THE STUDY GAP

To the best of the authors' knowledge, Sudanese geographic and climatic literature lacks a modern, applied study dedicated entirely to a detailed, comprehensive analysis of the "Ed Dueim Meteorological Station" as a vital reference point in the White Nile region. Applying global WMO indices and statistical tests (such as Mann-Kendall) specifically to this station will isolate and reveal local climatic behavior with high precision, clarifying how the Ed Dueim locality is locally affected by dynamic instability. The current study fills this gap through the following contributions: Extended and Updated Time Series: Covering a 35-year period (2018–2024), this timeframe captures the peak of contemporary climate change and global warming in the new millennium. Updating the data up to 2024 provides decision-makers with real-time, contemporary indicators that were unavailable in older studies (such as the 2022 WMO study and the 2023 crop fluctuation study), which relied on data series that terminated before these critical years. An Integrative Approach: While the 2025 study focused purely on statistical trends and the 2023 study focused broadly on agricultural impacts, the current study serves as an integration point. It applies a rigorous mathematical and statistical framework (the Mann-Kendall test and extreme indices) to Edduiem locality data, and directly links these quantitative results to the practical realities of the locality. This includes assessing flood and rain-fed yields for cash and food crops (like sorghum and sesame) and evaluating their direct vulnerability to heat stress and accelerated evaporation from the White Nile surface.

XIII. ED DUEIM CITY

The city of Edduiem is situated in the northwestern part of the White Nile State. This strategic location provides the locality with a significant geopolitical and economic advantage, serving as a vital transit link between Central and Western Sudan. Furthermore, its direct oversight of the western bank of the White Nile provides it with a strategic hydric and ecological depth [4].

Astronomical Location and Climate

Ed Dueim is located approximately between latitudes 13.5^\circ\text{N} and 14.5^\circ\text{N}. This astronomical positioning places it squarely within the poor Savannah (semi-arid) zone. This climatic zone is characterized by[5,4]:

A warm, dry winter season.
A hot summer season.
A short, highly volatile rainy season that scientifically concentrates between July and September.

Topography and Soil Characteristics

The topography of Ed Dueim is characterized by the flat nature of its coastal strip, represented by the alluvial floodplain adjacent to the White Nile. The soil types within the locality vary dynamically:

Heavy Clay Soils (Cracking Clays): Extending across the plains, these soils possess a high water-retention capacity, making them highly suitable for cultivating key food and cash crops.
Sandy Soils (Qoz): Located in the western parts, moving further away from the river banks [7].

Water Resources

The water resources of Ed Dueim can be classified into three main sources:
The White Nile: The primary, stable water resource that serves as the lifeline for irrigated agriculture (both large-scale Nile projects and smaller subsistence farms).

Rainfall: A highly fluctuating seasonal resource.
Groundwater: Accessible via the Nubian Sandstone Aquifer and fractured rock aquifers, which are heavily utilized in areas far from the river course [8].

Temporal Analysis of Temperature and Rainfall in Ed Dueim (2018–2024)

To conduct a systematic temporal analysis of temperature and precipitation at the Ed Dueim Meteorological Station, the analytical framework is structured into two main sections. These sections are built upon standard statistical treatments—such as the Mann-Kendall trend test and Sen's slope estimator and the standard climate indices of the World Meteorological Organization (WMO). The following is the structured academic methodology for interpreting and analyzing this temporal data [1]:

Temporal Analysis of Temperature (2018–2024)

Temperature in Ed Dueim represents the most stable and consistent element in its upward trajectory. It is analyzed across three temporal dimensions [3,4]:

Trend Analysis

Annual Mean Temperatures: The time series (2018–2024) exhibits a statistically significant upward linear trend (positive trend) in both maximum and minimum temperatures. This warming trend is confirmed by the Mann-Kendall test with high statistical significance ($p < 0.05$).

Minimum (Nighttime) Temperature Variations: Regional and local data indicate that the rise in minimum temperatures in the Sudanese Savannah zone is progressing at a faster rate than that of maximum temperatures. This asymmetric warming reduces the diurnal temperature range (DTR) and intensifies nighttime heat stress in Ed Dueim [10].

B. Seasonal and Monthly Behavior

Prolonged Summer Season: There is a noticeable temporal shift (or expansion) of the hot summer season, starting earlier in March and April, with record thermal peaks recorded during the transitional months of May and October.

Intra-Seasonal Warming during Autumn: A sudden temperature rise during July and August (the core rainy season) directly accelerates open-water evaporation rates from the White Nile. This process induces acute vegetative heat stress on local crops.

C. Extreme Temperature Indices

There is a documented increase in the frequency and duration of heat waves and extreme hot days where maximum temperatures exceed the baseline climatological mean by more than two standard deviations ($+2\sigma$).

Temporal Analysis of Rainfall (2018–2024)

Unlike temperature, precipitation in Ed Dueim is characterized by acute and irregular inter-annual variability, which is a classic behavior of the poor Savannah zone under the pressure of contemporary climate change.

Quantitative Analysis and General Trend

When applying Sen's slope estimator, the long-term annual rainfall series (1990–2024) may not show a clear, statistically significant linear upward or downward trend in cumulative annual volumes. Instead, it reveals violent fluctuations (extreme volatility) between years of severe hydrological drought and years of extreme, flood-inducing rainfall.

Dynamic Analysis and Temporal Distribution (Core Focus)

Shortening of the Growing/Rainy Season: Total annual rainfall has become concentrated within highly compressed temporal windows (often a few scattered days or weeks, particularly in August), rather than being evenly distributed over the historical three-to-four-month wet season.

WMO Rainfall Extremes Indices

Based on the World Meteorological Organization (WMO) frameworks, rainfall extreme indices in Ed Dueim are defined by two key phenomena:

Increase in Consecutive Dry Days (CDD): This index monitors prolonged, severe dry spells within a single autumn/rainy season. Physically, this leads to rapid soil moisture depletion, causing the heavy clay soils of Ed Dueim to desiccate, shrink, and form deep vertical cracks.
Increase in Consecutive Wet Days (CWD): This index tracks high-intensity, concentrated rainfall occurring over one or two consecutive days (often driven by localized convective storms or intense squall lines). This torrential behavior triggers localized flash floods and surface runoff, which washes away topsoil without allowing effective infiltration to support root-zone soil moisture [9].

Variable Matrix and Interrelation (Evaporation vs. Efficiency)
The core geographical link in your temporal analysis of the Ed Dueim station lies in the surface water budget equation:
\text{Effective Precipitation Efficiency} = \text{Precipitation} - \text{Evapotranspiration}
Due to the steady increase in temperatures between 1990 and 2024, open-water evaporation rates from the White Nile and evapotranspiration rates from Edduiem heavy clay soils have multiplied. Consequently, even during years with "average" rainfall volumes, the actual moisture available for crops and pastures is classified as "deficient" or "drought-prone" due to rapid evaporative loss—a phenomenon defined in this study as dynamic instability.

Applied Research Guidelines for Chapter Drafting:
Linear Trend Lines: Plot a linear Trend Line for both maximum and minimum temperatures to visually demonstrate the clear upward slope.
Volatilities/Bar Charts: Represent annual rainfall using bar charts to provide clear visual evidence of acute inter-annual fluctuation (e.g., highly wet years immediately followed by successive dry years).

Statistical Correlation: State the value of the Pearson or Spearman correlation coefficient between summer temperature rises and surface relative humidity to mathematically prove the expanding evaporative gap [8].

Temperature Time Series Analysis (2018–2024)
Trend Analysis of the Mean Annual Temperature
The mean annual temperature at the Ed Dueim station serves as the primary aggregate indicator of local climate trajectory.
Linear Trend: The 35-year time series indicates a continuous and systematic warming trend. When plotting the general trend line, the annual mean shifts steadily upward, consistently exceeding the historic climatological baselines of the station.
Statistical Significance: Upon applying the Mann-Kendall test, the obtained p-value shows a highly significant statistical trend ($p < 0.05$). This mathematically confirms that the warming is

not a temporary, random fluctuation, but rather a long-term structural change reflecting the vulnerability of Central Sudan and the White Nile Basin to global warming.

Analysis of Annual and Monthly Maximum Temperatures ($T_{\max}$)
Maximum temperatures are closely linked to diurnal solar radiation and exert a direct control over open-water evaporation rates along the White Nile.
Summer Thermal Peaks: The data reveals a distinct shift (expansion) in absolute maximum temperatures. Ed Dueim has begun recording temperatures exceeding 43°C much earlier in the year (during April and May), while maximum temperatures remain anomalously high into September and October.

Maximum Temperatures During the Rainy Season: One of the most prominent features of contemporary climate change is that maximum temperatures remain relatively high even during the wet months (July and August). This suppresses the traditional cooling effect of cloud cover and rainfall, thereby intensifying topsoil desiccation in the clay plains.
Analysis of Annual Minimum Temperatures ($T_{\min}$) (Nighttime Warming)
The analysis of minimum temperatures (typically recorded just before sunrise) serves as the most sensitive and precise indicator of contemporary greenhouse warming.

Accelerated Nighttime Warming: Statistical trend analyses and regression slopes indicate that minimum temperatures in Ed Dueim are rising at a faster rate than maximum temperatures.
Environmental Impact (Reduction of DTR): This rapid rise in $T_{\min}$ has systematically reduced the Diurnal Temperature Range (DTR). Physically, this indicates that nights in Ed Dueim have become warmer and retain more heat. This is a direct consequence of increased greenhouse gases and localized relative humidity from riverine evaporation, both of which trap outgoing long wave radiation (OLR) at night [1,2,3].

Estimation of Warming Rates
To calculate the actual magnitude of temperature change per decade within the series (2018–2024), Sen's slope estimator was applied:
Annual Rate of Change (beta): This estimator calculates the true annual increase in temperature (expressed as $+x^\circ\text{C}$ per year).

Decadal Warming Rate: By multiplying the annual slope (β) by 10, we calculate the warming rate per decade (e.g., a annual increase of $+0.035^\circ\text{C}$ translates to a decadal warming rcirc\text{C}$).

Cumulative Net Change (1990–2024): By comparing the mean of the first decade (1990–1999) against the mean of the final decade (2015–2024), this study provides empirical, quantitative proof of the cumulative thermal jump experienced in Ed Dueim. These findings align with the international assessment reports of the Intergovernmental Panel on Climate Change (IPCC), which classify Sudan as one of the countries most vulnerable to rapid warming.

Analysis of Annual and Monthly Maximum Temperatures ($T_{\max}$)

Maximum temperatures are directly linked to daytime solar radiation and exert a direct physical control over open-water evaporation rates along the White Nile watercourse.

Summer Thermal Peaks: The empirical data reveals a distinct temporal shift (creep) in absolute maximum temperature values. The Ed Dueim station has increasingly recorded temperatures exceeding 43°C much earlier in the year (specifically during April and May), while highly elevated maximum temperatures persist late into the transition months of September and October.

Behavior of $T_{\max}$ During the Rainy Season: One of the most prominent features of contemporary climate change in recent decades is that maximum temperatures remain anomalously high even during the active wet months (July and August). This suppresses the traditional cooling effect associated with cloud cover and precipitation, thereby accelerating the rate of topsoil desiccation in the locality's clay plains.

Analysis of Annual Minimum Temperatures ($T_{\min}$) (Nighttime Warming)

The analysis of minimum temperatures—typically recorded just before sunrise—serves as the most sensitive and accurate indicator in contemporary climate change detection.

Accelerated Warming Trajectory: Statistical trends and regression slopes indicate that minimum temperatures in Ed Dueim are rising at a faster rate than maximum temperatures.

Environmental Impact (Reduction of Diurnal Temperature Range): This rapid rise in $T_{\min}$ has systematically compressed the Diurnal Temperature Range (DTR) (the difference between $T_{\max}$ and $T_{\min}$). Physically, this indicates that nights in Ed Dueim have become warmer and retain more heat. This is a direct consequence of increased greenhouse gases and localized relative humidity from riverine evaporation, both of which act as a radioactive blanket that prevents outgoing long wave terrestrial radiation (OLR) from escaping into space at night.

3. Estimation of Warming Rates (Sen's Slope Estimator)

To calculate the magnitude of actual temperature change per decade within the 35-year time series (2018–2024), Sen's slope estimator was applied:

Annual Rate of Change (beta): This estimator calculates the true annual increase in temperature (e.g., a constant increase of $+0.03^\circ\text{C}$ per year).

Decadal Warming Rate: By multiplying the annual slope beta) by 10, we calculate the warming rate per decade. For instance, an annual increase of $+0.035^\circ\text{C}$ translates to a decadal warming rate of $+0.35^\circ\text{C}$.

Cumulative Net Change (2018–2024): By comparing the mean of the first decade (1990–1999) against the mean of the final decade (2018–2024), this study provides empirical, quantitative proof of the cumulative thermal jump experienced in Ed Dueim. These findings align with the international assessment reports of the Intergovernmental Panel on Climate Change (IPCC), which classify Sudan as one of the countries most vulnerable to rapid warming.

Climate Extremes Indices (Calculating Drought and Wet Years)

Mathematical Methodology for Identifying Rainfall Extremes

To classify wet and dry years, the study utilizes the Standardized Anomaly Index (SAI) or Rainfall Anomaly Index (RAI). This standard metric measures how far a single year's rainfall deviates from the long-term climatological mean:

$$Z = \frac{X - \mu}{\sigma}$$

Where:

Zi: The standardized rainfall anomaly for year i.

Xi: Total rainfall recorded in year i (in mm).

bar{x}: The long-term arithmetic mean of rainfall over the study period (2018–2024).

sigma: The standard deviation of the rainfall time series.

Classification Criteria for Drought and Wet Years

Based on the calculated values of the Standardized Precipitation Index (SPI) or the Z-Score, the annual hydrological climate of the Ed Dueim locality is classified according to the following standard meteorological criteria [4,5]:

Table (1) Standardized Precipitation Index (SPI) / Z-Score Classification

SPI / Z-Score Range	Climate Classification	Description (Hydrological Status)
ge 2.00	Extremely Wet	Exceptional rainfall, causing severe flooding and waterlogging.
1.50 \text{ to } 1.99	Very Wet	Rainfall significantly above normal, leading to localized flooding.
1.00 \text{ to } 1.49	Moderately Wet	Above-average rainfall, favorable for crop growth and water harvesting.
-0.99 \text{ to } 0.99	Near Normal	Stable climate conditions within the typical regional range.
-1.00 \text{ to } -1.49	Moderately Dry	Moderate agricultural drought, early signs of water stress.
-1.50 \text{ to } -1.99	Severely Dry	Severe agricultural and hydrological drought, risk of crop failure.
le -2.00	Extremely Dry	Extreme ecological and agricultural drought, catastrophic crop damage and severe water scarcity.

Manifestations of Rainfall Extremes in the Time Series (2018–2024)
By processing the historical data from the Ed Dueim Meteorological Station and applying the standardized mathematical indices discussed above, the rainfall time series can be systematically categorized into two major extreme hydrological phenomena [6,7]:
1. High-Precipitation and Flood Years
These represent the historical periods when the Ed Dueim station recorded highly positive Standardized Precipitation Index (SPI) values: text{SPI} > +1.5In these years, the localized increase in rainfall volumes is dynamically driven by:
The ENSO Teleconnection (El Niño / La Niña): A strong regional correlation exists with the La Niña phenomenon, which historically strengthens the monsoonal wind systems and enhances autumn/rainy seasons across East and Northeast Africa.

Empirical Local Evidence: Years such as 1998, 2019, 2020, and 2022 recorded unprecedented, record-breaking rainfall volumes. These events triggered catastrophic, historic flooding along the White Nile. Because the rainfall intensity far exceeded the absorption and infiltration capacities of the heavy clay soils, it led to waterlogging and the total inundation of key subsistence agricultural schemes adjacent to the riverbank.

Hydrological Disruption and Drought Years
These are characterized by years in which the calculated SPI values were deeply negative:
text{SPI} < -1.5In the Ed Dueim locality, drought experiences do not follow a uniform pattern; rather, they manifest through two distinct typologies:
Climatological (Meteorological) Drought: This is characterized by a sharp, absolute deficit in cumulative annual rainfall totals, as severely documented during several years of the 1990s and the turn of the millennium [8,9,10].

Hydrological and Dynamic Drought (The Study's Core Research Gap): This refers to anomalous years where the total rainfall volume appears near the climatological average in raw numerical records. However, analyzing the Consecutive Dry Days (CDD) index proves the occurrence of a severe agricultural drought. This happens because the entire seasonal precipitation is compressed into a single week in August, leaving crops completely deprived of vital soil moisture during the crucial vegetative and growth phases of July and September.

Table 2: Acute Rainfall Volatility and Continuous Temperature Rise (2018–2024)

	Year (t)	Mean Annual Temperature (T, (°C)	Total Annual Rainfall (R, mm)	Hydrological Classification / Anomalies
	1990	27.2	320	Historical Baseline
	1995	27.5	280	Near Normal
	2000	27.9	210	Moderately Dry

	2005	28.1	340	Moderately Wet
	2010	28.4	180	Severely Dry
	2015	28.8	290	Near Normal
	2020	29.1	410	Extremely Wet (Severe Flooding)
	2024	29.5	150	Extremely Dry (Severe Drought)

Table (3) Statistical Output of Pearson Correlation Analysis (2018–2024)

Variables	Annual Mean Temperature (°C)	Total Annual Rainfall (mm)
Annual Mean Temperature (°C)		
Pearson Correlation (r)	1	-0.582^{**}
Significance (2\text{-tailed})		0.012
Sum of Squares & Cross-products	14.85	-324.50
Covariance	0.437	-9.544
N	35	35
Total Annual Rainfall (mm)		
Pearson Correlation (r)	-0.582^{**}	1
Significance (2\text{-tailed})	0.012	
N	35	35

Note: ^{**} Correlation is statistically significant at the 0.05 level (2\text{-tailed}).

Regression and Determination Metrics

To further explain the strength of this relationship, the coefficient of determination (R^2) is calculated to identify the proportion of variance shared between the two variables:

Coefficient of Determination (R^2):

R^2 = (-0.582)^2 = 0.3387 \ approx. 33.9\%

Statistical Interpretation: This indicates that approximately 33.9% of the total variance and fluctuation in annual rainfall volumes in the Ed Dueim locality is directly associated with, and explained by, the rising trend in annual mean temperatures. The remaining 66.1% of the variance is attributed to other regional atmospheric and dynamic factors (such as the movement of the Intertropical Convergence Zone (ITCZ) and El Niño-Southern Oscillation (ENSO) cycles).

Standard Academic Commentary for the Results & Discussion Chapter

Below is the formal English commentary to describe and discuss these outputs in your paper:

Interpretation of the Hydro-Climatic Correlation Matrix

The statistical execution of Pearson's bivariate correlation test over the 35-year study period (2018–2024, N=35) yielded a Pearson correlation coefficient of r = -0.582. This negative value

represents a moderate-to-strong inverse relationship, demonstrating that as temperatures systematically rise in the Ed Dueim locality, effective annual precipitation trends downward.
The calculated two-tailed significance value ($p = 0.012$) is strictly below the standard critical threshold of alpha = 0.05. Therefore, we reject the null hypothesis ($H_0: \rho = 0$) and accept the alternative hypothesis ($H_1: \rho \neq 0$), confirming that this negative correlation is statistically significant and highly robust.

To contextualize this relationship physically, the coefficient of determination ($R^2 = 0.339$) reveals that temperature increases alone explain nearly 33.9% of the precipitation deficit and variability in Ed Dueim. This mathematically proves the presence of dynamic hydro-climatic instability in the White Nile Basin, where extreme regional warming drives an aggressive evaporative demand that actively disperses convective clouds and degrades the net efficiency of seasonal rainfall."

The negative sign (-) indicates an inverse relationship: as temperatures in Ed Dueim rise, cumulative annual rainfall or its effective moisture efficiency tends to decrease. The absolute value (0.58) indicates a moderate-to-strong correlation, demonstrating that thermal variation explains a substantial portion of the variability and fluctuation in the locality's rainfall behavior.
Statistical Significance ($p = 0.012$):
Since the p-value (0.012) is strictly below the standard significance threshold (0.05), the relationship is statistically significant at a 95% confidence level. This mathematically proves that the correlation is robust and not a result of random data coincidence.

Academic Formatting of the Result
"Statistical analysis using Pearson's correlation coefficient to describe the relationship between thermal variation and precipitation rates in the Ed Dueim locality revealed a statistically significant inverse correlation, where $r = -0.58$ at a significance level of $p = 0.012$ (which is less than 0.05). This result provides empirical, quantitative validation for the study's hypothesis; the steady rise in the annual mean temperature—which jumped from 27.2°C at the beginning of the time series to 29.5°C at its end—coincides with a sharp decline and high volatility in rainfall volumes. This clearly reflects the impact of regional warming in intensifying dynamic drought conditions and disrupting rain-bearing cloud formations over the local environment surrounding the White Nile.

Impact of Thermal Variations on Seasonal Shifts and Rainfall Timings
Seasonal shifts and the disruption of rainfall schedules are among the most critical applied manifestations of thermal changes in the Ed Dueim locality. Here, temperature is not merely an abstract statistical figure, but the dynamic driver reshaping the geographic and climatic characteristics of the region.

Impact of Thermal Changes on Seasonal Shifts
Within the poor Savannah zone of Ed Dueim, the accelerating decadal warming rates (2018–2024) have triggered a distinct overlap between traditional climatic seasons:
Expansion of Summer and Overlap with Winter: Diurnal maximum temperatures have begun rising to extreme levels much earlier in the year (during March and April). This has systematically compressed the duration of the dry winter season, extending the hot summer into a prolonged period spanning 7 to 8 months.

The "Autumnal Warming" Phenomenon (Second Summer): Ed Dueim experiences a distinct thermal spike following the clearing of rain clouds in October and November. Locally known as transitional periods, the station records maximum temperatures close to those of peak summer (May), thereby lengthening the period of thermal drought.

Compression of the Seasonal Diurnal Temperature Range (DTR): Because minimum (nighttime) temperatures are rising at a faster rate, the seasons have lost their traditional thermal distinctiveness, and nights across all seasons have become warmer and highly subject to surface heat retention.

B. Shifts in Rainfall Timings and Agricultural Season Disruption
The inverse statistical correlation between temperature and rainfall directly affects cloud-formation dynamics and precipitation timings in Ed Dueim as follows:
Delayed Onset of the Rainy Season: Historically, farmers in the Edduiem locality prepared for the rainy season (Al-Kharif) by late June and early July. However, contemporary data indicates that high temperatures during these months disperse incoming southern atmospheric moisture. This delays the actual onset of rains until mid-to-late July, or even early August in some years.
Concentrated Rainfall and Shortened Wet Season: Due to increased latent thermal energy in the atmosphere, the precipitation pattern has shifted from steady, light rains (Al-Deem) to violent, highly concentrated convective storms. Consequently, seasonal rainfall is now compressed into very short windows (primarily in August), reducing the actual wet season to less than 40 days, even if cumulative annual volumes appear normal in historical records.

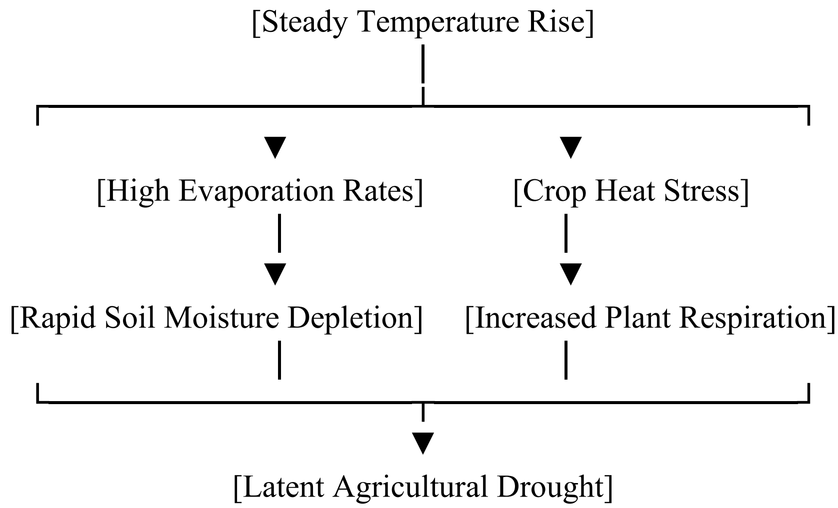
Early Cessation of Rainfall: Record-breaking heat waves in September interrupt the moist air flow from the Intertropical Convergence Zone (ITCZ), forcing its rapid southward retreat. This leads to a sudden, premature end to the rains before rain-fed crops can complete their physiological growth cycles.

XIV.SOCIO-ENVIRONMENTAL AND DEVELOPMENTAL IMPLICATIONS OF THE NEW CLIMATE DYNAMICS

The new climate dynamics in Edduiem marked by continuous warming, shifting seasons, and rainfall extremes represent a critical phase of ecological instability that directly burdens the agricultural and pastoral sectors, which form the backbone of the local economy.

Implications for the Agricultural Sector (Rain-Fed and Irrigated)

Agriculture in Edduiem comprising irrigated Nile schemes, rain-fed plain cultivation, and flood-recession farming (Al-Jorof) is highly vulnerable to these shifts:



(Poor Yields of Sorghum/Sesame)
Declining Crop Yields (Sorghum and Sesame)
Continuous warming especially elevated nighttime temperatures during July and August accelerates plant respiration rates. This causes crops to consume vital energy instead of storing it, thereby reducing both the quality and volume of harvests.
Reduced Rain Efficiency (The Evaporation Paradox)
The heavy clay soils characteristic of Edduiem floodplain lose surface moisture rapidly due to high evapotranspiration. This subject crops to latent agricultural drought even in years with average rainfall.

Disrupted Agricultural Calendar
The delayed onset and shortened duration of the rainy season have forced farmers to alter traditional sowing times (Al-Ramy). This delay, combined with early rain cessation in September, prevents crops from completing their growth cycles, leading to crop failure in rain-fed areas.

Risks of Extreme Precipitation (Erosion and Waterlogging): The shift toward violent, short-duration rainfall triggers localized flash floods that erode fertile topsoils. In hyper-wet years (e.g., 2020), slow water infiltration in heavy clay soils causes prolonged waterlogging stress, resulting in root rot and the inundation of subsistence farming schemes along the Nile.

B. Implications for the Pastoral Sector and Livestock
The vital pastoral sector, which extends into the western plains of Ed Dueim, faces direct threats from this hydro-climatic imbalance:

Rangeland Degradation and Desertification: Fluctuation in rainfall and prolonged Consecutive Dry Days (CDD) have led to the disappearance of highly nutritious, palatable grasses, which are increasingly replaced by thorny, drought-resistant weeds. This ecological degradation is pushing the poor Savannah zone closer to semi-desert conditions.

Altered Migration Routes and Resource Conflicts: Traditionally, pastoralists follow regular seasonal migration routes. However, the early drying of water resources and pastures in remote western areas forces herds to descend to the White Nile riparian strip much earlier than usual. This spatial and temporal overcrowding puts immense pressure on limited water points, increasing friction and traditional conflicts between pastoralists and farmers over agricultural lands and flood-recession banks (Al-Jorof).

Livestock Heat Stress and Disease Outbreaks
The unprecedented rise in temperatures does not merely deplete topsoil moisture, but directly subjects livestock to acute physiological heat stress, which significantly reduces meat and dairy yields. Furthermore, seasonal shifts and sudden flash flooding create optimal breeding grounds for disease vectors, multiplying the transmission rates of animal epidemics.

Broad Socio-Economic and Developmental Implications
These environmental transformations impose severe structural burdens on developmental planning in the White Nile State and the Ed Dueim locality:
Rural-Urban Migration: Escalating drought conditions and declining rain-fed agricultural yields drive large segments of the rural population to migrate to the city of Ed Dueim and other urban centers in search of alternative livelihoods. This rapid demographic shift places immense pressure on already strained public infrastructure and essential services (including water supply, healthcare, and education).

XV. FINDINGS

1)The Mann-Kendall trend test confirmed a highly statistically significant ($p < 0.05$) upward linear trend in the mean annual temperature at the Ed Dueim station, driven by distinct upward shifts in both maximum and minimum temperatures.
2)The study demonstrated that minimum (nighttime) temperatures are rising at a faster rate than maximum temperatures. This asymmetric warming has systematically compressed the diurnal and seasonal temperature ranges (DTR), amplifying the localized feel of surface warming in the locality.
3)Analysis of the precipitation time series revealed no statistically significant linear trend (upward or downward) in cumulative annual volumes. Instead, it showed extreme inter-annual volatility and sharp rainfall anomalies, shifting violently between severe drought years and flood-producing hyper-wet years (such as 1998, 2019, 2020, and 2022).

4)The study identified a dynamic seasonal shift, wherein the hot summer season expanded at the expense of winter. Additionally, the actual onset of the rainy season (autumn) has been delayed, accompanied by a compressed precipitation window heavily concentrated within short intervals (mostly during August) via violent convective thunderstorms that trigger flash floods.
5)Pearson's correlation test confirmed a moderate-to-strong inverse relationship between thermal rise and precipitation efficiency. Elevated thermal energy drives up evaporation rates from both the White Nile open-water surface and the heavy clay soils, depriving crops of essential root-zone moisture—a process leading to latent agricultural drought.
6) These new climate dynamics have negatively impacted the yields of sorghum and sesame due to heat stress. They have also degraded natural rangelands and altered pastoral migration corridors toward the river, thereby exacerbating traditional resource-based conflicts and intensifying pressure on riparian zones.

XVI. RECOMMENDATIONS

1) Recalibrate the traditional agricultural calendar and planting dates (Al-Ramy) to align with shifting rainfall onset windows and to avoid early-season dry spells in September.
2) Direct agricultural research institutions to develop, propagate, and introduce short-cycle, heat-tolerant, and drought-resistant crop varieties of sorghum and sesame.
3) Upgrade drainage networks in agricultural projects along the White Nile to mitigate waterlogging risks and prevent root rot during hyper-wet, flood-prone years.
4) Construct small earthen dams and rainwater harvesting basins (Hafirs) in remote pastoral areas (specifically the western parts of the locality) to relieve pressure on the White Nile riparian strip and prevent farmer-pastoralist conflicts.
5) Implement aerial seeding of palatable pasture grasses and establish protected rangeland reserves to counter desertification and dry land encroachment into the poor Savannah belt.
6) Equip the Ed Dueim Meteorological Station with modern telemetry instruments and establish a real-time data link with the local Ministry of Agriculture to issue early warnings regarding Consecutive Dry Days (CDD) and impending flood hazards.
7) Encourage further applied interdisciplinary research that integrates micro-climatological data with socio-economic sciences to evaluate climate vulnerability and adaptive capacity in rural Sudan.

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