

# Comparative Analysis of Drought Trends in the Sahelian and Soudanian Zones of Mali: Case Study of Cinzana and Kola

Ousmane Mohamed Maiga<sup>1\*#</sup>, Lassina Dit Papa Koné<sup>2,3</sup>, Alikalifa Sanogo<sup>4</sup>, Youssouf Siby<sup>5</sup>, Issouf Coulibaly<sup>6</sup>, Massitan B. Dembélé<sup>7</sup>

<sup>1</sup>West African Science Service Centre on Climate Change and Adapted Land Use, Federal University of Technology, Minna, Nigeria

<sup>2</sup>West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL), Doctoral Research Programme in West African Climate Systems (WACS), Federal University of Technology, Akure, Nigeria

<sup>3</sup>Institute of Water and Energy Sciences (Including Climate Change), Pan African University, Tlemcen, Algeria

<sup>4</sup>West African Science Service Centre on Climate Change and Adapted Land Use, University of Abomey-Calavi, Abomey-Calavi, Benin

<sup>5</sup>West African Science Service Centre on Climate Change and Adapted Land Use, Institut Polytechnique de Formation et de Recherche Appliquée, Katibougou, Mali

<sup>6</sup>Institut d'Économie Rurale (IER), Katibougou, Mali

<sup>7</sup>West African Science Service Centre on Climate Change and Adapted Land Use, Climate Change and Biodiversity Program, Université Félix Houphouët-Boigny, Abidjan, Côte d'Ivoire

Email: \*osomag33@gmail.com, lassinakone406@gmail.com, AlikalifaSanogo@gmail.com, didero532@gmail.com, icouil1984@gmail.com, dembelemassitanbeny@gmail.com

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## Abstract

Understanding hydroclimatic variability in the Sahel and Sudanian zones is critical for improving climate resilience and resource management. This study presents a comparative analysis of drought dynamics in two representative agroecological sites of Mali Cinzana (Sahelian zone) and Kola (Sudanian zone) over the period 1994-2022. Using meteorological data, drought characteristics were assessed through the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI), complemented by trend detection methods (Mann-Kendall, Sen's slope) and the Pettitt test for structural breaks. Results reveal marked local divergences despite the geographical proximity of the sites. At Cinzana, rainfall and temperature trends were not statistically significant, although a positive and significant trend in SPEI-12 suggests a tendency toward wetter annual conditions consistent with the Sahelian "regreening" observed since the 1990s. In contrast, Kola exhibited a sta-

\*First author.

#Corresponding author.

tistically significant warming, particularly in minimum temperature (+0.057°C/year,  $p < 0.001$ ), with a breakpoint in 2008 indicating accelerated nighttime warming. Drought indices at Kola revealed significant negative trends in SPI-12, SPEI-6, and SPEI-9, highlighting an intensification of aridification processes. Correlation analysis between SPI and SPEI confirmed that rainfall remains the dominant driver of drought variability at multi-annual scales, while evapotranspiration, amplified by warming, plays an increasingly critical role at seasonal scales. Overall, these findings demonstrate the coexistence of greening and drying trajectories within short geographic distances, reflecting the high spatial heterogeneity of Sahelian climate dynamics. This heterogeneity underscores the need for fine-scale analyses to refine regional climate projections and to design differentiated adaptation strategies for water resource management and agricultural production.

### Keywords

Climate Change, Climate Trends, Drought, Sahel, Sudanian, SPEI, SPI, Variability

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## 1. Introduction

The biophysical and socioeconomic balances of both natural and man-made ecosystems are significantly impacted by climate change, which is one of the largest environmental problems confronting the globe today (Rockström et al., 2009; Zittis et al., 2022). Global warming, primarily due to human-caused greenhouse gas emissions, is causing mean temperatures to rise, hydrological cycles to change, extreme events to worsen, and biological regimes to be disrupted (Rockström et al., 2009; Siddha & Sahu, 2022). Approximately 41% of the Earth's surface is made up of arid and semi-arid regions, which are particularly vulnerable to severe shocks due to their high reliance on natural resources and low ecological resilience (Li et al., 2022; Zhou et al., 2022). These areas are experiencing rapid soil degradation, reduced plant cover, and increased desertification, all of which threaten ecosystem services and the means of subsistence for the local population (Kumar et al., 2022; Mganga, 2022; Zerbe, 2022).

The breadth and speed of recent climate developments in the Sahel, which is considered to be one of the “hotspots” of climate change, are alarming (Ayugi et al., 2022; Gupta, 2022). Since the 1950s, average temperatures have been increasing along with a shorter, more unpredictable rainy season and increased variability in rainfall (Smart, 2017). The hydrological cycle has been disrupted and food insecurity has increased due to the simultaneous occurrence of extreme rainfall events and severe droughts (Chukwuma Sr, 2025; Daku et al., 2022; Holleman et al., 2020). This climate background emerges in a socio-environmental framework marked by population growth, agricultural intensification, and urbanization, further taxing already fragile natural resources (Orlandi, 2023;

Padgham et al., 2015).

Mali, a country in the Sahel, is a prime illustration of these shifts. Since the 1950s, the country's temperature has been increasing faster than the global average (Sarraf et al., 2022; Traore et al., 2022). Groundwater recharge, rain-fed agriculture, and vegetation formation regeneration are all immediately impacted by disturbances to hydrological cycles. Because rural populations mostly depend on local ecosystems for food, water, energy, and income, their vulnerability increases in such a setting (Faye, 2022; Holleman et al., 2020).

The Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI) are two climate indices that are significant for quantitative understanding of droughts in this cycle. The SPI assesses the variability of meteorological drought across many time periods based solely on precipitation (Cerpa Reyes et al., 2022; Noguera et al., 2022; Panigrahi & Vidyarthi, 2024). However, because the SPEI considers both precipitation and potential evapotranspiration, it is more sensitive to the effects of climate change on water availability (Haile et al., 2022; Morsy et al., 2022)<sup>1</sup>. Both indicators have been widely used to evaluate the frequency and severity of dry periods in West Africa's Sahelian and Soudanian regions (Faye, 2022; Mohammed et al., 2022; Morsy et al., 2022).

In order to inform adaptation plans and sustainable resource management, the joint integration of climatic indices (SPI, SPEI) provides a pertinent analytical framework for comprehending the spatiotemporal evolution of droughts and their effects on Sahelian ecosystems. Accordingly, the current study intends to use the SPI and SPEI indices to do a comparative analysis of drought trends at two sample sites in Mali: Kola, in the Soudanian zone, and Cinzana, in the Sahelian zone. The primary goal is to use the SPI and SPEI indices to compare the drought patterns in Cinzana and Kola between 1994 and 2022. This strategy aims to accomplish three particular objectives: 1) Compare the evolution of climatic trends between these two areas; 2) Identify drought episodes through the SPI and SPEI series; 3) Evaluate the correlation between the SPI and SPEI over various time scales.

## 2. Materials and Methods

### 2.1. Material

#### 2.1.1. Study Areas

Cinzana and Kola, two distinct agroecological zones in Mali, were the sites of the study. With a total size of 1079 km<sup>2</sup> and a location in the Ségou district (13° 15' N; 5° 58' W), Cinzana is part of the Niger River basin but does not have permanent watercourses. Poor ferruginous soils that are prone to erosion make up the majority of the shrubby savannah landscape. Rain-fed agriculture (millet, sorghum, and cowpea) and livestock farming are the main sources of livelihoods; both are susceptible to frequent droughts and land degradation (Halimatou et al., 2016). On the other hand, Kola, which is 261 km<sup>2</sup> in size and located in the Bougouni

<sup>1</sup>Vicente Serrano 2010, Google Scholar.

[https://scholar.google.com/scholar?hl=fr&as\\_sdt=0%2C5&q=vicente+serrano+2010&btnG=](https://scholar.google.com/scholar?hl=fr&as_sdt=0%2C5&q=vicente+serrano+2010&btnG=).



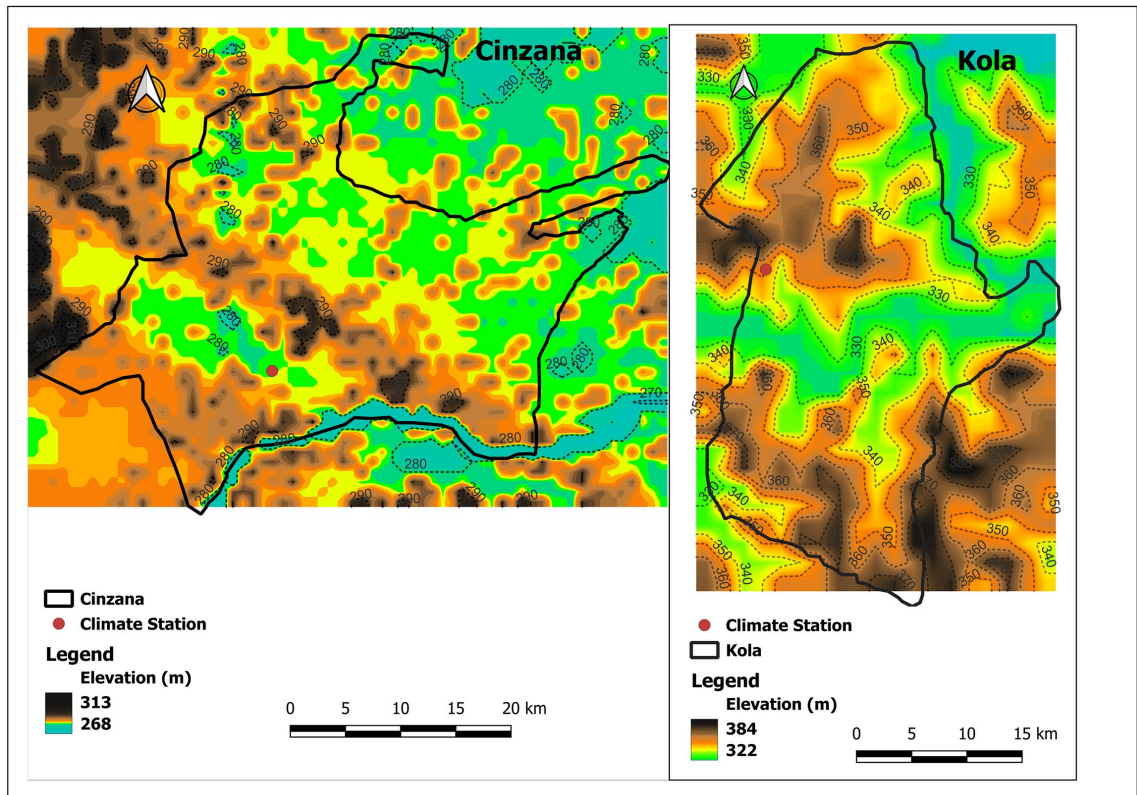


Figure 2. Digital elevation mode.

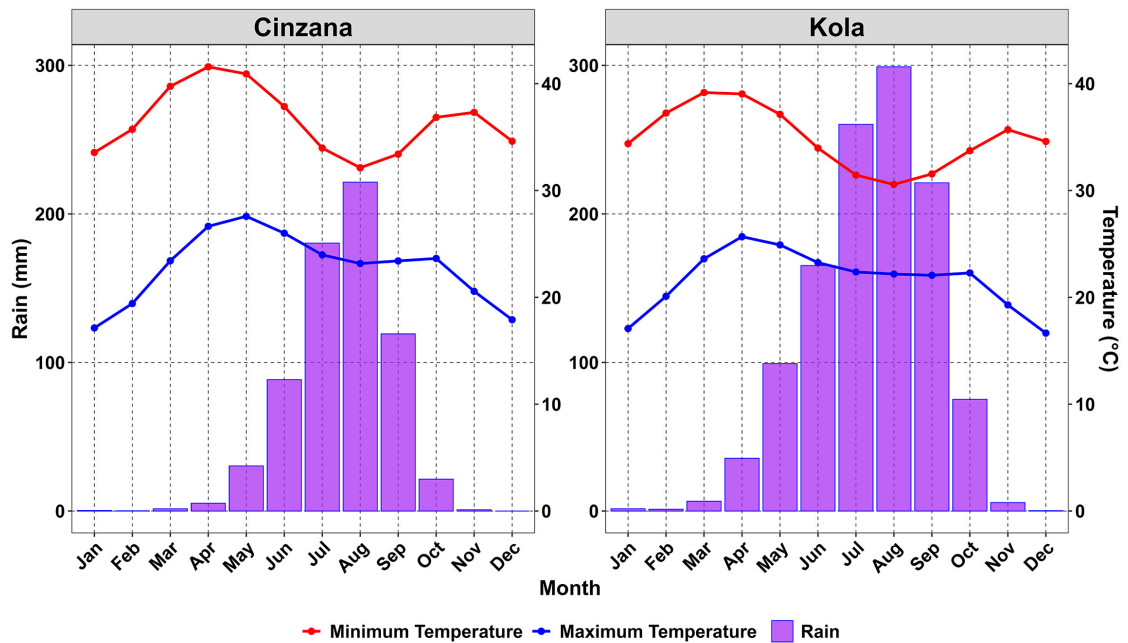


Figure 3. Ombrothermic diagram of the Cinzana and Kola sites.

### 2.1.2. Data Sources

The climatic data used exclusively originate from ground-based meteorological observations collected between 1994 and 2022. The measured variables include

solar radiation, monthly precipitation, maximum temperatures (Tmax), and minimum temperatures (Tmin). All data were sourced directly from the National Meteorology Agency (Direction Nationale de la Météorologie DNM) of Mali. The time series for Cinzana and Kola stations consist of continuous surface observations spanning the entire study period. An initial quality control revealed an extremely low rate of missing monthly values (<0.5%). To ensure the temporal continuity necessary for computing the SPI and SPEI drought indices, the following imputation method was applied: missing Tmax and Tmin values were replaced by the long-term monthly mean, whereas missing precipitation and solar radiation were replaced by the long-term monthly median (this method being favored for robust imputation of asymmetrically distributed variables).

## 2.2. Method

For all statistical studies, R 4.5.1 version was used. Trend package was used to compute the Pettitt test and Mann-Kendall for Sen's slope estimation, statistics for Pearson's correlation and the SPEI package for SPEI and SPI indices. Below is a breakdown of each method's formulas and computing steps.

- Pettitt Test

Breakpoints in the data series (temperatures and precipitation) that indicate a dramatic change in the mean were found using the non-parametric statistical test known as the Pettitt Test (Pettitt, 1979). For all values of  $t$  between 1 and  $N - 1$ , the highest absolute value of an intermediate variable,  $U_{tN}$ , is the Pettitt test statistic, represented by the symbol  $K_N$ .

$$K_N = \max_{1 \leq t < N} |U_{tN}| \quad (1)$$

$U_{tN}$  measures the difference between the two groups of data (before and after  $t$ ).

where the double sum is used to determine  $U_{tN}$ .

$$U_{tN} = \sum_{i=1}^t \sum_{j=t+1}^N \text{sgn}(x_i - x_j) \quad (2)$$

$N$  is the series's total number of data points.

$x_i$  and  $x_j$  are the time series values at times  $i$  and  $j$ .

$\text{sgn}$  is the sign function and is defined as follows:

$$\begin{cases} 1 & \text{if } x_i - x_j > 0 \\ 0 & \text{if } x_i - x_j = 0 \\ -1 & \text{if } x_i - x_j < 0 \end{cases}$$

The  $p$ -value is an approximation calculated from the  $K_N$  statistic to assess the statistical significance of the change point.

$$p \approx 2 \exp\left(-\frac{N^3 + N^2}{6K_N^2}\right) \quad (3)$$

- Estimation of Potential Evapotranspiration (PET)

One crucial metric for determining a water shortage is potential evapotranspiration. The formula put out by Hargreaves and Samani (Hargreaves & Samani, 1985) was used to compute PET. This technique calculates the quantity of water that the soil surface and plants may potentially evaporate based on mean, maximum, and minimum temperatures as well as solar radiation.

$$ETP = 0.0023 \times (T_{\text{mean}} + 17.8) \times (T_{\text{max}} - T_{\text{min}})^{0.5} \times R_a \quad (4)$$

where:

$T_{\text{mean}}$ : average temperature ( $^{\circ}\text{C}$ ).

$T_{\text{max}}$ : maximum minimum temperatures ( $^{\circ}\text{C}$ ).

$T_{\text{min}}$ : minimum temperatures ( $^{\circ}\text{C}$ ).

$R_a$  is the extraterrestrial solar radiation ( $\text{MJ}/\text{m}^2/\text{day}$ ), which is determined by the day of the year and latitude.

- Standardized Precipitation-Evapotranspiration Index (SPEI)

This index combined evapotranspiration and precipitation to evaluate drought. A standardized value is obtained by fitting the water balance (precipitation minus PET) to a statistical distribution. The difference between monthly precipitation ( $P_i$ ) and monthly potential evapotranspiration ( $PET_i$ ) is used to calculate the monthly water deficit ( $D_i$ ).

$$D_i = P_i - PET_i \quad (5)$$

Over the chosen time period, the  $D_i$  values are gathered. This accumulation offers insights into both short-term and long-term drought patterns by enabling the detection of drought conditions at various temporal resolutions.

Over the selected time period, the  $D_i$  values are gathered.

$$D_{mn} = \sum_{i=0}^{m-1} (D_{n-i} - ETP_{n-i}) \quad (6)$$

In any case:

$m$ : time scale.

$D_{mn}$ : total shortfall for month  $n$ .

A three-parameter log-logistic distribution, which is frequently employed in drought research because of its versatility in modeling both positive and negative values, is fitted to the water balance data.

$$F(x) = \left[ 1 + \left( \frac{\lambda}{x - \gamma} \right)^{\beta} \right]^{-1} \quad (7)$$

The scale, shape, and placement characteristics are denoted by  $\lambda$ ,  $\beta$ , and  $\gamma$ , respectively.

Change to a normal distribution, S. M. Vicente-Serrano's estimate serves as the basis for standardizing the SPEI<sup>2</sup>.

If  $P \leq 0.5$ ,

<sup>2</sup>Vicente Serrano 2010, Google Scholar.

[https://scholar.google.com/scholar?hl=fr&as\\_sdt=0%2C5&q=vicente+serrano+2010&btnG=](https://scholar.google.com/scholar?hl=fr&as_sdt=0%2C5&q=vicente+serrano+2010&btnG=)

$$w = \sqrt{-2 \ln(P)} \quad (8a)$$

$$\text{SPEI} = W - \frac{c_0 + c_1 W + c_2 W^2}{1 + d_1 w + d_2 W^2 + d_3 W^3} \quad (8b)$$

If  $P > 0.5$ ,

$$P' = 1 - P \text{ et } \text{SPEI} = -Z \quad (8c)$$

The following constants are used:

$$c_0 = 2.515517, \quad c_1 = 0.802853, \quad c_2 = 0.010328$$

$$d_1 = 1.432788, \quad d_2 = 0.189269, \quad d_3 = 0.001308$$

- Standardized Precipitation Index (SPI)

This drought metric is based only on precipitation. It converts precipitation data into a normalized  $Z$  score for standardized comparison after adjusting it using a gamma distribution (Edwards, 1997).

The distribution of monthly precipitation ( $P$ ) is frequently asymmetrical. Its likelihood is modeled using the gamma distribution.

Gamma probability density function.

$$f(P) = \frac{1}{\beta^\alpha \cdot \Gamma(\alpha)} \cdot P^{\alpha-1} \cdot e^{-P/\beta} \quad (9)$$

where:

$P$  = monthly precipitation ( $P > 0$ );

$\alpha$  = shape parameter ( $\alpha > 0$ );

$\beta$  = scale parameter ( $\beta > 0$ );

$\Gamma(\alpha)$  = gamma function (extension factoriel).

The shape parameter  $\alpha$  and  $\beta$  for SPI is estimated from the precipitation data using:

$$\alpha = \frac{1}{4A} \left( 1 + \sqrt{1 + \frac{4A}{3}} \right); \beta = \frac{\bar{P}}{\alpha} \quad (10a)$$

With:

$$A = \ln(\bar{P}) - \frac{1}{n} \sum_{i=1}^n \ln(P_i) \quad (10b)$$

$\bar{P}$  = mean precipitation,  $n$  = number of observations.

The Cumulative Probability  $G(P)$  is given as:

$$G(P) = \int_0^P f(x) dx \quad (11)$$

It is calculated either numerically or using statistical tables.

Case of zero precipitation ( $P = 0$ )

If  $P = 0$ , the probability is adjusted as:

$$H(P) = q + (1 - q) \cdot G(P) \quad (12)$$

Transformation into a  $Z(\text{SPI})$  was done using the probability  $H(P)$  values:

$$SPI = Z = \begin{cases} -\left(t - \frac{c_0 + c_1t + c_2t^2}{1 + d_1t + d_2t^2 + d_3t^3}\right) & \text{si } 0 < H(P) \leq 0.5, \\ +\left(t - \frac{c_0 + c_1t + c_2t^2}{1 + d_1t + d_2t^2 + d_3t^3}\right) & \text{si } 0.5 < H(P) < 1, \end{cases} \quad (13a)$$

where:

$$t = \sqrt{\ln\left(\frac{1}{(H(P))^2}\right)} \quad (\text{for } H(P) \leq 0.5), \quad (13b)$$

$$t = \sqrt{\ln\left(\frac{1}{(1-H(P))^2}\right)} \quad (\text{for } H(P) > 0.5) \quad (13c)$$

where:

Coefficients approximation of (Abramowitz & Stegun, 1965).

$$c_0 = 2.515517 \quad c_1 = 0.802853$$

$$c_2 = 0.010328 \quad d_1 = 1.432788$$

$$d_2 = 0.189269 \quad d_3 = 0.001308$$

**Table 1.** Classification of SPEI and SPI indices (Cerpa Reyes et al., 2022; Haslinger et al., 2014).

Category	SPEI/SPI value
Extremely wet	≥+2.00
Very wet	+1.50 to +1.99
Moderately wet	+1.00 to +1.49
Near normal	-0.99 to +0.99
Moderately dry	-1.00 to -1.49
Severely dry	-1.50 to -1.99
Extremely dry	≤-2.00

- Mann-Kendall Trends

The Mann-Kendall statistical test (Mann, 1945) is used to ascertain if a time series exhibits a statistically significant monotonic trend (growing or decreasing). It is determined by adding the signs of the differences between each pair that could exist in the dataset.

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad (14)$$

The final outcome of the Mann-Kendall test is the *Z* statistic. The trend's statistical significance is assessed using the normalized *Z* statistic:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{si } S > 0 \\ 0 & \text{si } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{si } S < 0 \end{cases} \quad (15)$$

$\text{Var}(S)$  is variance of  $S$ .

- Sen's Slope estimation

The magnitude of the trends found by the Mann-Kendall test was measured using this technique. It provides a rate of change per unit of time by calculating the median slope of every conceivable pair of points (Sen, 1968).

The definition of the Sen's slope estimator is:

$$Q_{jk} = \frac{x_j - x_k}{j - k} \quad (16)$$

For each pair of points  $(x_j, x_k)$ ,

where  $j > k$ ;

$Q_{jk}$  = individual slope between two data points;

$x_j, x_k$  = data values at times  $j$  and  $k$ .

- Pearson Correlation

This approach allowed us to quantify the direction and magnitude of the linear relationship between SPI and SPEI. Whether the variables are favorably, negatively, or uncorrelated is indicated by their value, which ranges from  $-1$  to  $1^3$ .

The following formula is used to determine the Pearson correlation coefficient ( $r$ ).

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \quad (17)$$

$n$  is the number of data pairs.

$x_i$  et  $y_i$  are the individual values of variables  $x$  and  $y$ .

$\bar{x}$  et  $\bar{y}$  are the means of variables  $x$  and  $y$ , respectively.

## 3. Results

### 3.1. Comparison of Climate Trends

- Evolution of Climate Trends

For the yearly rainfall and temperature time series for the Cinzana and Kola stations, **Table 2** displays the findings of the Pettitt test, Mann-Kendall (MK) test, and Sen's slope estimator. **Table 2** shows the findings from the Mann-Kendall (MK) trend test, Pettitt change-point test, and Sen's slope estimator for the Cinzana and Kola stations' annual rainfall (Rain), maximum temperature (Tmax), and minimum temperature (Tmin).

<sup>3</sup>Pearson, 1895, Google Scholar.

[https://scholar.google.com/scholar?hl=fr&as\\_sdt=0%2C5&q=Pearson%2C+1895&btnG=](https://scholar.google.com/scholar?hl=fr&as_sdt=0%2C5&q=Pearson%2C+1895&btnG=)

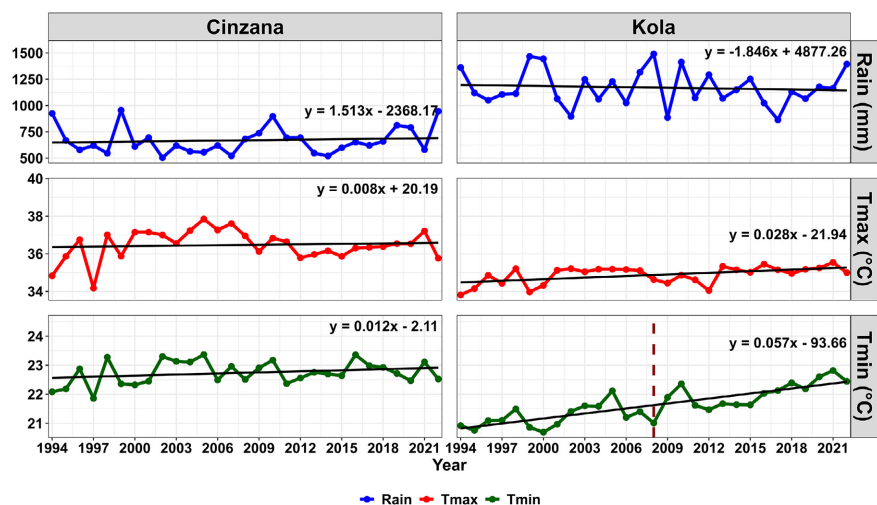
**Table 2.** Pettitt, Mann-Kendall trend analysis and Sen's Slope for climate historic data 1994-2022.

Site	Variable	Pettitt_Year	Pettitt_p	MK_tau	MK_p
Cinzana	Rain	-	0.624	0.108	0.42
Cinzana	Tmax	-	0.304	-0.04	0.778
Cinzana	Tmax	-	0.304	-0.04	0.778
Cinzana	Tmin	-	0.113	0.18	0.177
Kola	Rain	-	1	-0.039	0.778
Kola	Tmax	-	0.091	0304	0.022
Kola	Tmin	2008	0	0.68	0

The analysis of climate trends, based on the linear regression slopes illustrated in **Figure 4** and the statistical significance reported in **Table 2**, reveals distinct evolutions between the two sites.

At Cinzana, the trends observed over the period 1994-2021 are not statistically significant at the 5% threshold. Rainfall shows a slight increase of +1.513 mm/year ( $p = 0.42$ ). Similarly, the maximum temperature (Tmax) exhibits an almost negligible rise of +0.008°C/year ( $p = 0.778$ ). Finally, although the minimum temperature (Tmin) displays a more apparent upward trend of +0.012°C/year, it also remains statistically non-significant ( $p = 0.177$ ). The Pettitt test indicates no statistically significant shift, confirming the absence of a structural break in the Cinzana series.

In contrast, the Kola site exhibits statistically significant warming trends in temperature. While rainfall shows a non-significant declining trend of -1.846 mm/year ( $p = 0.778$ ), the maximum temperature (Tmax) displays a clear and significant increase at a rate of +0.028°C/year ( $p = 0.022$ ). The most striking trend concerns the minimum temperature (Tmin), which rises sharply and significantly at +0.057°C/year ( $p < 0.001$ ). Moreover, this strong increase is accentuated by a break detected in 2008, indicating a marked acceleration of nighttime warming from that year onward.

**Figure 4.** Trends in temperature and precipitation parameters.

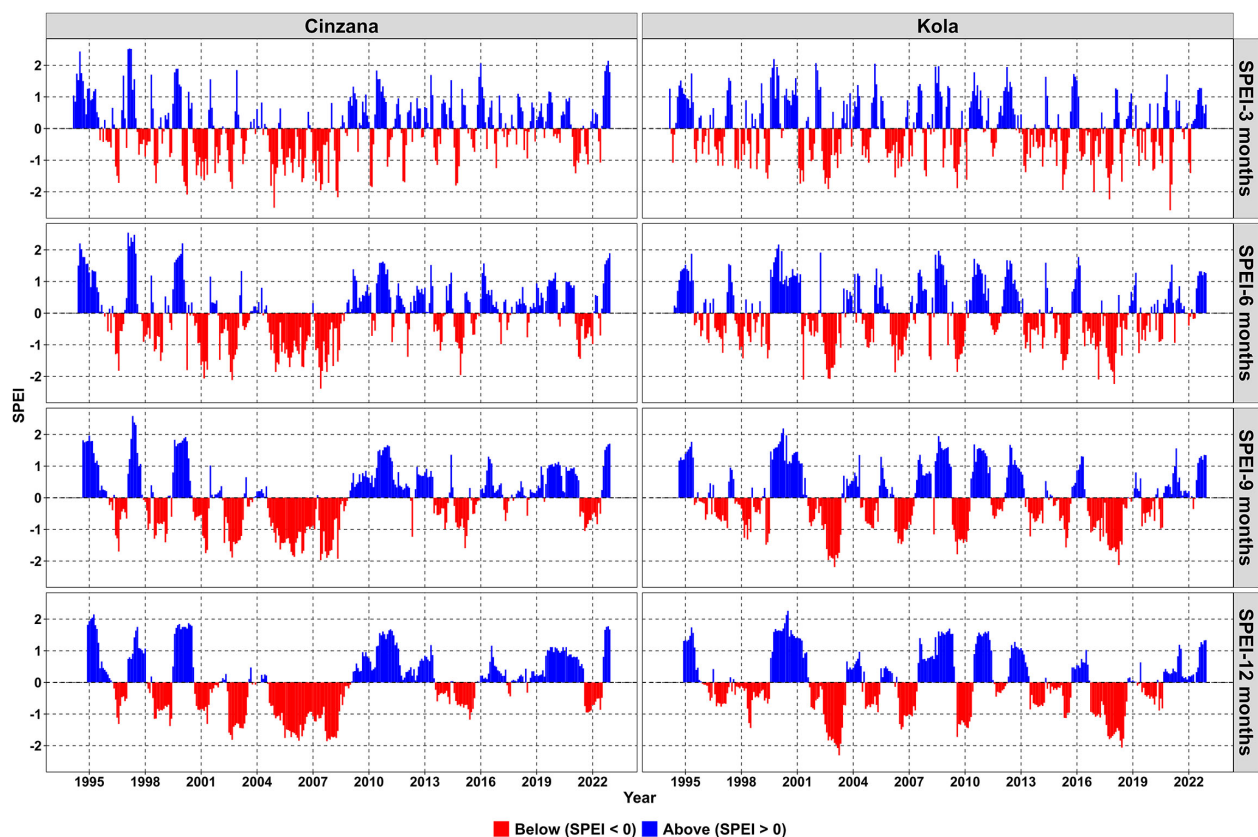
### 3.2. Identification of Drought Episodes Using SPI and SPEI Series

- SPEI series analysis

**Figure 5** illustrates the temporal evolution of the SPEI index from 1995 to 2022 for the Cinzana and Kola sites at different time scales (3, 6, 9, and 12 months). The intensity of drought or wetness is proportional to the distance from the zero axis. For both sites, the SPEI series display an alternation of wet and dry years throughout the study period.

At Cinzana, the period 1994-2008 was dominated by dry years. During this interval, severe to extreme drought events were recorded at different time scales, with notable peaks of  $-2.8$  (SPEI-3 in 2005),  $-2.4$  (SPEI-6 in 2008), and  $-1.80$  (SPEI-12 in 2002). From 2009 to 2022, wetter years prevailed over dry ones.

Similarly, at Kola, the period 1994-2014 was characterized by an alternation of wet and dry years, with a predominance of wet years across all time scales. However, from 2014 to 2021, the site experienced predominantly very dry to extreme dry years, with peaks of  $-2.8$  (SPEI-3 in 2021) and  $-2.2$  (SPEI-6 in 2018). From 2021 to 2022, wet years once again became dominant across all time scales (**Figure 5**).



**Figure 5.** Standardized precipitation evapotranspiration index (SPEI) from 1994 to 2022 in Cinzana and Kola.

- SPI series analysis

The Standardized Precipitation Index (SPI) for Cinzana and Kola highlights wet and dry conditions at different time scales (3, 6, 9, and 12 months).

At Cinzana, the period 1996-1999 was characterized by dry years for SPI-12, and by alternating wet and dry years with a predominance of dry years at the 3, 6, and 9-month scales. The period 2000-2002 was dominated by wet conditions across all time scales, with peaks reaching +2.8 for SPI-3, SPI-6, and SPI-9 in 2000. From 2003 to 2008, Cinzana experienced a prolonged drought, during which SPI-12 dropped to nearly -2, indicating severe to extreme drought. Conditions became wetter between 2009 and 2014, followed by drier years from 2015 to 2019. Finally, the period 2019-2022 was marked predominantly by wet years.

In contrast, Kola experienced a longer drought period relative to normal conditions between 1996 and 2000 for the 9- and 12-month scales, while the 3- and 6-month scales showed alternating wet and dry years with a predominance of dry conditions. The period 2000-2002 was wet across all scales, followed by a dry phase at all scales from 2002 to 2004. Between 2005 and 2017, alternating wet and dry years were observed, with a predominance of wet conditions across all time scales. The period 2018-2021 was marked by another prolonged drought, with a minimum SPI-6 value of -4.1. Finally, from 2021 to 2022, wet years dominated across all time scales (Figure 6).

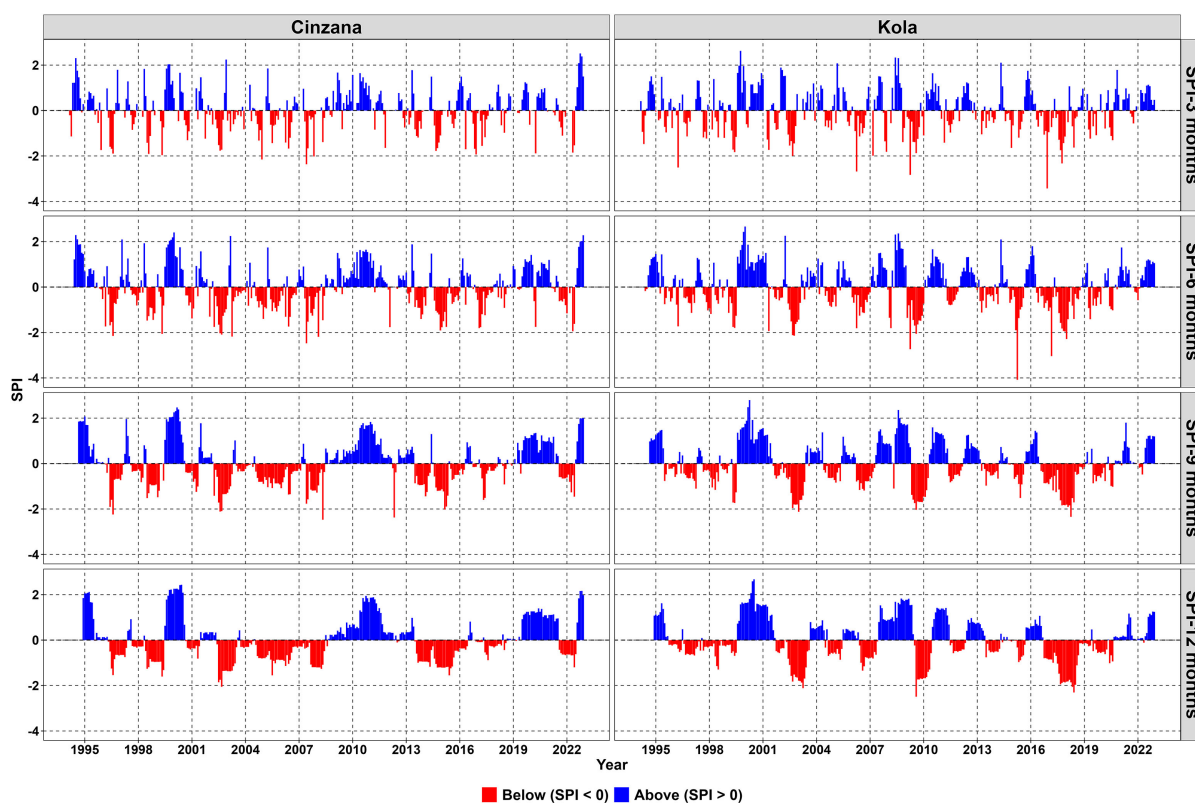


Figure 6. Standardized precipitation index (SPI) from 1994 to 2022 in Cinzana and Kola.

### 3.3. Pearson Correlation between SPI and SPEI

- SPEI and SPI Mann-Kendall Trends and Sen's Slope

Table 3 below shows Mann-Kendall Trend analysis and Sen's Slope results on

SPI and SPEI of both sites.

**Table 3.** Results of the Mann-Kendall trend analysis and Sen's Slope.

Indice	Kendall's Tau		Sen's Slope		p-value (MK)	
	Cinzana	Kola	Cinzana	Kola	Cinzana	Kola
SPI-3	0.0216	-0.0084	0.0003	-0.0001	0.8242	0.5910
SPI-6	0.0152	-0.0373	0.0002	-0.0005	0.3018	0.6755
SPI-9	0.0635	-0.0530	0.0009	-0.0008	0.1446	0.0804
SPI-12	0.0845	-0.0607	0.0012	-0.0009	0.0960	0.0205
SPEI-3	0.0417	-0.0377	0.0006	-0.0006	0.2944	0.2471
SPEI-6	0.0744	-0.0394	0.0011	-0.0006	0.2755	0.0396
SPEI-9	0.0791	-0.0384	0.0013	-0.0006	0.2902	0.0294
SPEI-12	0.0940	-0.0446	0.0015	-0.0007	0.0099	0.2218

The analysis of drought indices (SPI, based on precipitation, and SPEI, based on precipitation and evapotranspiration) presented in **Table 3** reveals contrasting dynamics between the two sites, particularly at longer time scales.

At Cinzana, a general trend toward stability is observed (Kendall's Tau > 0 for all indices), with p-values exceeding the 0.05 significance threshold for most drought indices. However, a notable exception is found for the 12-month SPEI (SPEI-12), which exhibits a statistically significant positive trend ( $p = 0.0099$ ) with a Sen's slope of +0.0015. A positive slope for a drought index reflects a shift toward wetter conditions in the long term, suggesting that the water balance (precipitation minus evapotranspiration) has slightly improved on an annual scale.

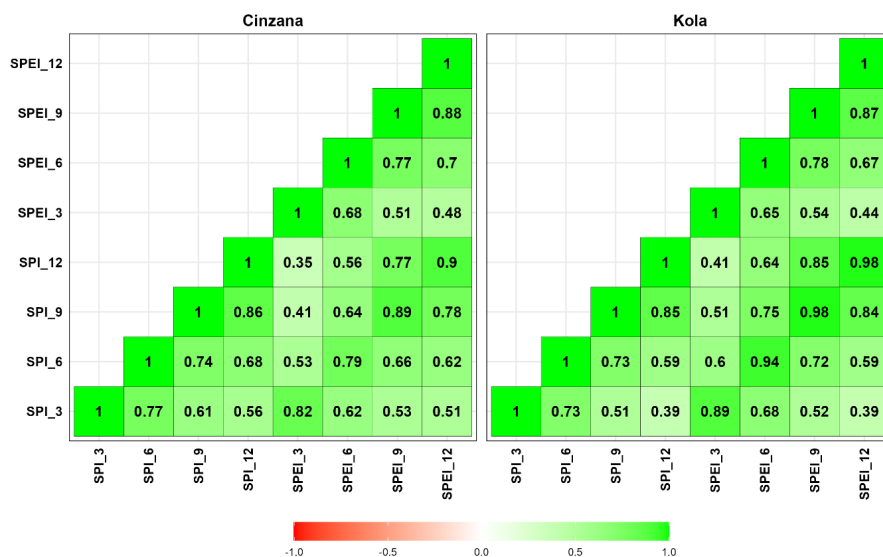
In contrast, the results for Kola confirm a pronounced drying trend. The station's climate is becoming drier, as indicated by negative Kendall's Tau values and negative Sen's slopes. Regarding rainfall-based drought (SPI), a significant long-term drying trend is detected at the 12-month scale (SPI-12), with a negative slope of -0.0009 ( $p = 0.0205$ ). This drying trend becomes even more pronounced when accounting for temperature effects through the SPEI. Significant negative trends are observed at intermediate time scales: SPEI-6 (slope = -0.0006,  $p = 0.0396$ ) and SPEI-9 (slope = -0.0006,  $p = 0.0294$ ). These results indicate that drought conditions, once evapotranspiration is considered, are intensifying over 6- to 9-month periods.

### 3.4. Pearson Correlation between SPI and SPEI

As the time scale grows, the correlation between the SPI and SPEI indices is stronger, according to the Pearson correlation analysis (**Figure 7**). The correlation coefficient ( $r$ ) for Cinzana increases from 0.82 at three months to 0.90 at twelve months. The coefficients for intermediate time scales are 0.89 (9 months) and 0.79 (6 months).

At three months, Kola's correlation coefficient ( $r$ ) is 0.89; by twelve months, it has risen to a very high 0.98.  $R$  is 0.94 (6 months) and 0.98 (9 months) for the interme-

diate stages, indicating a consistent rise in the same direction as the time scale.



**Figure 7.** Pearson correlation between SPI and SPEI.

#### 4. Discussion

Sahelian climatic variability remains highly complex and heterogeneous, as shown by the analysis of drought sequences and climate trends at Cinzana and Kola (1994–2022). Our findings reveal notable local divergences, underscoring the importance of fine-scale analyses for understanding regional climate trajectories in this climate-sensitive region. A striking outcome is the pronounced increase in minimum temperatures ( $+0.057^{\circ}\text{C}/\text{year}$ ,  $p < 0.001$ ) at Kola, reflecting accelerated nighttime warming a key marker of climate change in West Africa (Sarr et al., 2015; Sylla et al., 2016). Its ecological implications are significant, particularly for evapotranspiration rates, soil water budgets, and plant phenology. Comparable intensification of temperature minimal has been reported in Senegal (Faye, 2023; Legg, 2021). By contrast, Cinzana exhibits no significant warming, highlighting strong microclimatic variability, potentially buffered by irrigation, increased vegetation cover, or localized aerosol effects (Biasutti, 2013). This divergence mandates caution when interpreting “regional warming”.

Regarding precipitation, both sites exhibit no statistically significant monotonic trends, reflecting the high interannual variability of Sahelian rainfall already documented by Ali et al. (2005). However, drought indices clarify water balance dynamics: Cinzana’s significant positive trend in SPEI-12 (Sen’s slope =  $+0.0015$ ,  $p = 0.0099$ ) indicates a tendency toward wetter annual conditions, consistent with the “Sahelian greening” (Descroix et al., 2018; Lebel et al., 2018). Conversely, Kola reveals a clear drying trajectory (significant negative trends in SPI-12, SPEI-6, and SPEI-9), aligning with intensifying aridification in parts of the western Sahel (Monerie et al., 2021; Tall et al., 2022). This contradiction (Sanogo, 2022) highlights the spatial heterogeneity where greening and drying

coexist over short distances.

The contrasting trajectories of Cinzana (wetter) and Kola (drier) constitute one of this study's most original findings, reinforcing recent work on the fine spatial variability of Sahelian climate dynamics (Bodian et al., 2020; Nouaceur, 2020). This divergence is largely attributable to differences in land usage, vegetation cover, and socio-economic factors:

- Kola's Warming and Drying: The intense T<sub>min</sub> warming and negative SPEI trends align with Kola's profile, characterized by agriculture including cash crops like cotton, driving significant deforestation and land-use change (Govoeyi et al., 2022). The loss of dense woodland reduces evapotranspiration, amplifying surface warming and accelerating aridification processes. This necessitates robust water management and agroforestry strategies.
- Cinzana's Greening and Stability: Cinzana's stable temperature and positive SPEI-12 trend suggest that increased vegetation cover (regreening) and/or localized irrigation practices (proximity to Niger River influence) buffer regional warming and enhance the water balance (Biasutti, 2013). Socio-economic dependence on rain-fed crops (millet, sorghum) may also promote conservation-focused land management. The implication for agriculture here is maintaining and capitalizing on soil and water conservation (SWC) practices.

These localized divergences stress the importance for climate modeling to adequately represent surface heterogeneities. Finally, the correlation analysis between SPI and SPEI confirms that rainfall variability remains the primary driver of drought at multi-annual scales (correlation > 0.9 at 12 months). However, lower correlations at shorter scales underline the increasing influence of potential evapotranspiration driven by rising temperatures. This reinforces earlier findings that SPEI provides a more comprehensive measure of drought than SPI, crucial for capturing agricultural and ecological droughts at seasonal scales (Gaye & Sow, 2019; Labudová et al., 2017; Nguru & Mwongera, 2022; Tefera et al., 2019).

Overall, these results demonstrate that local responses can diverge markedly, making the understanding of these spatially heterogeneous signals crucial for improving regional climate projections and designing locally adapted strategies for water and agricultural management.

## 5. Conclusion

This study provides new insights into the spatial and temporal heterogeneity of hydroclimatic trends across two neighboring Sahelian stations, Cinzana and Kola, over 1994-2022. The results emphasize that local processes significantly shape regional climate responses in the Sahel.

Four key conclusions can be drawn:

- Temperature asymmetry: Kola exhibits a clear and significant increase in minimum temperature, reflecting accelerated nighttime warming likely linked to land-use changes and vegetation loss, while Cinzana remains thermally stable.
- Contrasting drought dynamics: Although no uniform rainfall trend is ob-

served, drought indices reveal divergent trajectories, with a wetting tendency at Cinzana consistent with the “Sahelian greening”, and a drying signal at Kola indicative of ongoing aridification.

- Evapotranspiration influence: The strong correlation between SPI and SPEI at long time scales confirms rainfall as the main driver of drought, but lower correlations at shorter scales highlight the growing role of temperature-driven evapotranspiration.
- Implications for adaptation: These results demonstrate that regional-scale assessments may obscure critical local contrasts. Accounting for fine-scale variability is therefore essential for improving climate model performance and developing context-specific strategies for agricultural resilience and water management.

Overall, the findings reaffirm that while the Sahel follows broad regional climatic patterns, local trajectories remain highly differentiated, underscoring the necessity of integrating microclimatic and land-use factors into both scientific analyses and policy responses.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

## References

- Abramowitz, M., & Stegun, I. A. (1965). *Handbook of Mathematical Functions: With Formulas, Graphs, and Mathematical Tables* (vol. 55). Courier Corporation.  
[https://books.google.com/books?hl=fr&lr=&id=MtU8uP7XMvoC&oi=fnd&pg=PR9&dq=Abramowitz+%26+Stegun,+1965+&ots=-HTNSmP5Gj&sig=gHvuOgljQaftR3bybIvv\\_Wk\\_Iew](https://books.google.com/books?hl=fr&lr=&id=MtU8uP7XMvoC&oi=fnd&pg=PR9&dq=Abramowitz+%26+Stegun,+1965+&ots=-HTNSmP5Gj&sig=gHvuOgljQaftR3bybIvv_Wk_Iew)
- Ali, A., Amani, A., Diedhiou, A., & Lebel, T. (2005). Rainfall Estimation in the Sahel. Part II: Evaluation of Rain Gauge Networks in the CILSS Countries and Objective Intercomparison of Rainfall Products. *Journal of Applied Meteorology*, 44, 1707-1722.  
<https://doi.org/10.1175/jam2305.1>
- Ayugi, B., Eresanya, E. O., Onyango, A. O., Ogou, F. K., Okoro, E. C., Okoye, C. O. et al. (2022). Review of Meteorological Drought in Africa: Historical Trends, Impacts, Mitigation Measures, and Prospects. *Pure and Applied Geophysics*, 179, 1365-1386.  
<https://doi.org/10.1007/s00024-022-02988-z>
- Biasutti, M. (2013). Forced Sahel Rainfall Trends in the CMIP5 Archive. *Journal of Geophysical Research: Atmospheres*, 118, 1613-1623. <https://doi.org/10.1002/jgrd.50206>
- Bodian, A., Diop, L., Panthou, G., Dacosta, H., Deme, A., Dezetter, A. et al. (2020). Recent Trend in Hydroclimatic Conditions in the Senegal River Basin. *Water*, 12, Article 436.  
<https://doi.org/10.3390/w12020436>
- Cerpa Reyes, L. J., Ávila Rangel, H., & Herazo, L. C. S. (2022). Adjustment of the Standardized Precipitation Index (SPI) for the Evaluation of Drought in the Arroyo Pechelín Basin, Colombia, under Zero Monthly Precipitation Conditions. *Atmosphere*, 13, Article 236. <https://doi.org/10.3390/atmos13020236>
- Chukwuma Sr, D. C. (2025). Invariance of Extreme Hydrologic Events and Climate Change in the Risk Reduction on Environment and Health. *Greenfort International Journal of Applied Medical Science*, 3, 92-102. <https://doi.org/10.62046/gijams.2025.v03i02.011>

- Daku, E. K., Salack, S., Worou, O. N., & Ogunjobi, K. (2022). Maize Response to Temporary Floods under Ambient On-Farm Conditions of the West African Sahel. *Environmental Research Communications*, 4, Article ID: 045004. <https://doi.org/10.1088/2515-7620/ac6073>
- Descroix, L., Guichard, F., Grippa, M., Lambert, L. A., Panthou, G., Mahé, G. et al. (2018). Evolution of Surface Hydrology in the Sahelo-Sudanian Strip: An Updated Review. *Water*, 10, Article 748. <https://doi.org/10.3390/w10060748>
- Edwards, D. C. (1997). *Characteristics of 20th Century Drought in the United States at Multiple Time Scales*. <https://apps.dtic.mil/sti/html/tr/ADA325595/>
- Faye, C. (2022). Comparative Analysis of Meteorological Drought Based on the SPI and SPEI Indices. *HighTech and Innovation Journal*, 3, 15-27. <https://doi.org/10.28991/hij-sp2022-03-02>
- Faye, M. (2023). *Evolution de la fréquence des flux d'harmattan et hausse de la température à l'extrême nord du Sénégal de 1991 à 2020: La station de Saint-Louis et de Podor*. <https://rivieresdusud.uasz.sn/handle/123456789/2081>
- Gaye, D., & Sow, S. A. (2019). Variabilité pluviométrique au Sahel sénégalais: Évaluation du retour progressif vers la normale. *Revue Ivoirienne des Sciences et Technologie*, 33, 84-105. [https://revist.net/REVIST\\_33/REVIST\\_33\\_6.pdf](https://revist.net/REVIST_33/REVIST_33_6.pdf)
- Govoeyi, B., Tignégré, J. D. L. S., Badolo, F., Zaato, P. A., Sanogo, K., & Birhanu, B. Z. (2022). Perceptions on Sack Gardening in Rural Areas: The Case of Vegetable Stakeholders in Koutiala and Bougouni, Mali. *Sustainability*, 14, Article 14896. <https://doi.org/10.3390/su142214896>
- Gupta, S. (2022). *Climate Migration to the Global Gateway*. <https://dspace.cuni.cz/handle/20.500.11956/177428>
- Haile, B. T., Bekitie, K. T., Zeleke, T. T., Ayal, D. Y., Feyisa, G. L., & Anose, F. A. (2022). Drought Analysis Using Standardized Evapotranspiration and Aridity Index at Bilate Watershed: Sub-Basins of Ethiopian Rift Valley. *The Scientific World Journal*, 2022, Article ID: 1181198. <https://doi.org/10.1155/2022/1181198>
- Halimatou, T., Nouhoun, Z., Kalifa, T., & Nicholas, K. (2016). Farmers' Perceptions on Climate Variability and Adaptation Strategies to Climate Change in Cinzana, Mali. *Journal of Agricultural Studies*, 4, 13-36. <https://doi.org/10.5296/jas.v4i3.9331>
- Hargreaves, G. H., & Samani, Z. A. (1985). Reference Crop Evapotranspiration from Temperature. *Applied Engineering in Agriculture*, 1, 96-99. <https://doi.org/10.13031/2013.26773>
- Haslinger, K., Koffler, D., Schöner, W., & Laaha, G. (2014). Exploring the Link between Meteorological Drought and Streamflow: Effects of Climate-catchment Interaction. *Water Resources Research*, 50, 2468-2487. <https://doi.org/10.1002/2013wr015051>
- Holleman, C., Rembold, F., Crespo, O., & Conti, V. (2020). *The Impact of Climate Variability and Extremes on Agriculture and Food Security: An Analysis of the Evidence and Case Studies*. <https://ageconsearch.umn.edu/record/309365/>
- Kumar, R., Kumar, A., & Saikia, P. (2022). Deforestation and Forests Degradation Impacts on the Environment. In V. P. Singh, S. Yadav, K. K. Yadav, & R. N. Yadava (Eds.), *Environmental Degradation: Challenges and Strategies for Mitigation* (pp. 19-46). Springer International Publishing. [https://doi.org/10.1007/978-3-030-95542-7\\_2](https://doi.org/10.1007/978-3-030-95542-7_2)
- Labudová, L., Labuda, M., & Takáč, J. (2017). Comparison of SPI and SPEI Applicability for Drought Impact Assessment on Crop Production in the Danubian Lowland and the East Slovakian Lowland. *Theoretical and Applied Climatology*, 128, 491-506. <https://doi.org/10.1007/s00704-016-1870-2>

- Lebel, T., Panthou, G., & Vischel, T. (2018). *Au Sahel, pas de retour à la normale après la «grande sécheresse»*. [https://horizon.documentation.ird.fr/exl-doc/pleins\\_textes/2024-01/010079165.pdf](https://horizon.documentation.ird.fr/exl-doc/pleins_textes/2024-01/010079165.pdf)
- Legg, S. (2021). IPCC, 2021: Climate Change 2021: The Physical Science Basis. *Interaction*, 49, 44-45. <https://search.informit.org/doi/abs/10.3316/informit.315096509383738>
- Li, Y., Liu, W., Feng, Q., Zhu, M., Yang, L., & Zhang, J. (2022). Quantitative Assessment for the Spatiotemporal Changes of Ecosystem Services, Tradeoff-Synergy Relationships and Drivers in the Semi-Arid Regions of China. *Remote Sensing*, 14, Article 239. <https://doi.org/10.3390/rs14010239>
- Mann, H. B. (1945). Nonparametric Tests against Trend. *Econometrica*, 13, 245-259. <https://doi.org/10.2307/1907187>
- Mganga, K. Z. (2022). Agricultural Land Degradation in Kenya. In P. Pereira, M. Muñoz-Rojas, I. Bogunovic, & W. Zhao (Eds.), *Impact of Agriculture on Soil Degradation I* (pp. 273-300). Springer International Publishing. [https://doi.org/10.1007/698\\_2022\\_929](https://doi.org/10.1007/698_2022_929)
- Mohammed, S., Alsafadi, K., Enaruvbe, G. O., Bashir, B., Elbeltagi, A., Széles, A. et al. (2022). Assessing the Impacts of Agricultural Drought (SPI/SPEI) on Maize and Wheat Yields across Hungary. *Scientific Reports*, 12, Article No. 8838. <https://doi.org/10.1038/s41598-022-12799-w>
- Monerie, P., Pohl, B., & Gaetani, M. (2021). The Fast Response of Sahel Precipitation to Climate Change Allows Effective Mitigation Action. *npj Climate and Atmospheric Science*, 4, Article No. 24. <https://doi.org/10.1038/s41612-021-00179-6>
- Morsy, M., Moursy, F. I., Sayad, T., & Shaban, S. (2022). Climatological Study of SPEI Drought Index Using Observed and CRU Gridded Dataset over Ethiopia. *Pure and Applied Geophysics*, 179, 3055-3073. <https://doi.org/10.1007/s00024-022-03091-z>
- Nguru, W., & Mwongera, C. (2022). *Évaluation de la vulnérabilité climatique de certaines cultures au Sénégal*. <https://cgspace.cgiar.org/items/925001cf-c6ec-4319-b4eb-57f5b337b892>
- Noguera, I., Vicente-Serrano, S. M., Domínguez-Castro, F., & Reig, F. (2022). Assessment of Parametric Approaches to Calculate the Evaporative Demand Drought Index. *International Journal of Climatology*, 42, 834-849. <https://doi.org/10.1002/joc.7275>
- Nouaceur, Z. (2020). La reprise des pluies et la recrudescence des inondations en Afrique de l'Ouest sahélienne. *Physio-Géo*, 15, 89-109. <https://doi.org/10.4000/physio-geo.10966>
- Orlandi, M. (2023). *The Relationship between Natural Resources and Conflicts in Africa-Deconstructing Malthus through the Political Ecology Approach*. <https://unitesi.unive.it/handle/20.500.14247/14085>
- Padgham, J., Abubakari, A., Ayivor, J., Dietrich, K., Fosu-Mensah, B., Gordon, C., Habtezion, S., Lawson, E., Mensah, A., & Nukpezah, D. (2015). *Vulnerability and Adaptation to Climate Change in the Semi-Arid Regions of West Africa*. <https://idl-bnc-idrc.dspacedirect.org/bitstream/handle/10625/58627/IDL-58627.pdf>
- Panigrahi, S., & Vidyarthi, V. K. (2024). Assessing the Suitability of Mckee et al. (1993) Drought Severity Classification across India. *Natural Hazards*, 120, 13543-13572. <https://doi.org/10.1007/s11069-024-06762-3>
- Pettitt, A. N. (1979). A Non-Parametric Approach to the Change-Point Problem. *Applied Statistics*, 28, 126-135. <https://doi.org/10.2307/2346729>
- Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S. I., Lambin, E. et al. (2009). Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society*, 14, Article 32. <https://doi.org/10.5751/es-03180-140232>

- Sanogo, S. (2022). *Observations et modélisation des extrêmes de précipitation aux échelles saisonnière à interannuelle au Sahel*. Master's Thesis, Institut National Polytechnique de Tou-louse-INPT. <https://hal.science/tel-04124637/>
- Sarr, B., Atta, S., Ly, M., Salack, S., Ourback, T., Subsol, S., & George, D. A. (2015). Adapting to Climate Variability and Change in Smallholder Farming Communities: A Case Study from Burkina Faso, Chad and Niger. *Journal of Agricultural Extension and Rural Development*, 7, 16-27. <https://doi.org/10.5897/jaerd14.0595>
- Sarra, M., Traore, S., Sarr, T., & Soumare, M. (2022). Manifestations de la variabilité et du changement climatique perçues par les producteurs de basfond dans la commune rurale de Doumanaba au Mali. *African Scientific Journal*, 3, 141-159. [https://www.academia.edu/download/123571361/N12-8-Manifestations\\_20of\\_20climate\\_20variability\\_20and\\_20change\\_20perceived\\_20by\\_20lowland\\_20producers\\_20in\\_20the\\_20rural\\_20commune\\_20o.pdf](https://www.academia.edu/download/123571361/N12-8-Manifestations_20of_20climate_20variability_20and_20change_20perceived_20by_20lowland_20producers_20in_20the_20rural_20commune_20o.pdf)
- Sen, P. K. (1968). Estimates of the Regression Coefficient Based on Kendall's Tau. *Journal of the American Statistical Association*, 63, 1379-1389. <https://doi.org/10.1080/01621459.1968.10480934>
- Siddha, S., & Sahu, P. (2022). Impact of Climate Change on the River Ecosystem. In S. Madhav, et al. (Eds.), *Ecological Significance of River Ecosystems* (pp. 79-104). Elsevier. <https://doi.org/10.1016/b978-0-323-85045-2.00014-5>
- Smart, C. (2017). *Rainfall Variability and Drought in the Central and Northern KwaZulu-Natal Drakensberg: 1955-2015*. <https://search.proquest.com/openview/bc39438d04fd639550669445fc69a884/1?pq-origsite=gscholar&cbl=2026366&diss=y>
- Sylla, M. B., Nikiema, P. M., Gibba, P., Kebe, I., & Klutse, N. A. B. (2016). Climate Change over West Africa: Recent Trends and Future Projections. In J. Yaro, & J. Hesselberg (Eds.), *Adaptation to Climate Change and Variability in Rural West Africa* (pp. 25-40). Springer International Publishing. [https://doi.org/10.1007/978-3-319-31499-0\\_3](https://doi.org/10.1007/978-3-319-31499-0_3)
- Tall, M., Sylla, M. B., Dajuma, A., & Koubodana Houteta, D. (2022). *Drought Hotspots and Recent Changes in Their Characteristics across the African Continent during the Historical Period (1928-2017)*. <https://ui.adsabs.harvard.edu/abs/2022AGUFMGC55G0313T/abstract>
- Tefera, A. S., Ayoade, J. O., & Bello, N. J. (2019). Comparative Analyses of SPI and SPEI as Drought Assessment Tools in Tigray Region, Northern Ethiopia. *SN Applied Sciences*, 1, Article No. 1265. <https://doi.org/10.1007/s42452-019-1326-2>
- Traore, L., Bello, O. D., Balogoun, B., Chabi, F., Issifou, M. Y., Yabi, Y. et al. (2022). Variabilité Intra-saisonnière des Pluies et Production du Sorgho en Zones Soudanienne et Sahélienne du Mali. *European Scientific Journal ESJ*, 9, 44-68. <https://doi.org/10.19044/esjpreprint.9.2022.p44>
- Zerbe, S. (2022). Global Land-Use Development Trends: Traditional Cultural Landscapes under Threat. In S. Zerbe (Ed.), *Restoration of Multifunctional Cultural Landscapes* (pp. 129-199). Springer International Publishing. [https://doi.org/10.1007/978-3-030-95572-4\\_4](https://doi.org/10.1007/978-3-030-95572-4_4)
- Zhou, Y., Li, Y., Li, W., Li, F., & Xin, Q. (2022). Ecological Responses to Climate Change and Human Activities in the Arid and Semi-Arid Regions of Xinjiang in China. *Remote Sensing*, 14, Article 3911. <https://doi.org/10.3390/rs14163911>
- Zittis, G., Almazroui, M., Alpert, P., Ciaia, P., Cramer, W., Dahdal, Y. et al. (2022). Climate Change and Weather Extremes in the Eastern Mediterranean and Middle East. *Reviews of Geophysics*, 60, e2021RG000762. <https://doi.org/10.1029/2021rg000762>