RAINFALL AND WIND VARIABILITY IN BASSE, THE GAMBIA: TEMPORAL TRENDS, EXTREME EVENTS, AND INTER-VARIABLE RELATIONSHIPS (2000-2025)

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ABSTRACT

Empirical analyses that integrate rainfall and wind variability remain scarce in The Gambia, despite the country's high climate sensitivity. This study examined temporal trends, seasonal variability, extreme events, and intervariable relationships between rainfall and near-surface wind speed in Basse, Upper River Region, The Gambia (2000–2025) using NASA POWER (MERRA-2) monthly reanalysis data. Mann–Kendall trend tests, Sen's slope estimator, P90/P10 percentile thresholds, standardized anomaly index (SAI), and Spearman rank order correlation were applied to 312 monthly observations per variable. Annual rainfall exhibited a significant positive trend (+15.36 mm yr^{-1}; MK τ = +0.280, p = 0.047), consistent with Sahelian monsoon recovery, whereas wind speed showed no significant change (−0.005 m s^{-1} yr^{-1}; p = 0.269), reflecting the stability of the Harmattan West African Monsoon (WAM) alternation. Extreme wet years clustered in 2020–2022 and extreme dry years in 2000–2002, confirming a bimodal hydrometeorological regime shift. A strong inverse relationship between annual rainfall and wind speed (Pearson r = −0.73; Spearman ρ = −0.66; $p < 0.001$) identified monsoon Harmattan antagonism as the dominant atmospheric driver, with June being the only month with significant monthly coupling (r = −0.655, $p < 0.001$). These findings provide evidence-based insights into climate adaptation, agricultural planning, and disaster risk reduction in the Sudano-Sahelian zone.

Keyword: Rainfall Variability, Wind Speed Trends, NASA POWER, Basse, Sudano-Sahelian Climate

Introduction

Climate variability and the rise of extreme weather events have become a major global environmental issue due to their wide-ranging impacts on ecological systems, socio-economic development, agricultural productivity, and human livelihoods [1]. Over the past few decades, the precipitation regimes, atmospheric circulation patterns, and wind regimes have changed significantly across the globe, mainly due to anthropogenic climate change and increasing concentrations of greenhouse gases in the atmosphere [2]. These climate changes have exacerbated the frequency of hydro-meteorological extremes such as extreme rainfall, droughts, storms, and abnormal winds [1,3]. Extreme rainfall events often lead to flooding, soil erosion, destruction of infrastructure, and contamination of water resources, and strong wind events lead to environmental degradation, crop damage, and disruptions to socio-economic activities [4]. Thus, knowledge of the

temporal characteristics and variability of these climatic extremes has become essential for adaptation planning for climate change, disaster risk reduction, and sustainable environmental management [5].

The sub-Saharan region is one of the most climate change-vulnerable areas due to its reliance on rain-fed agriculture, low adaptive capacity, and growing environmental pressures [6]. In the region, significant climate variations have been observed since the severe Sahelian droughts of the 1970s and 1980s [7]. Such changes include variations in seasonal precipitation patterns, intensification of rainfall, delays in starting and ending seasonal precipitation, and greater atmospheric instability [8]. Climate variability in West Africa has been reported to have caused recurrent floods, prolonged dry spells, reduced agricultural production, and increased food insecurity [9]. Moreover, the variability in wind patterns has a great influence on the evapotranspiration processes, atmospheric moisture transport, erosion intensity, and local conditions [10]. These developments in combination pose a challenge to environmental sustainability and socio-economic resilience in the region [11].

The Gambia is situated in the Sudano-Sahelian climate zone of West Africa, which is highly vulnerable to climate perturbations due to its limited geographical size and reliance on climate-sensitive sectors such as natural resource utilization (NRU) and agriculture [12]. The climate of The Gambia is tropical with two distinct seasons: the rainy season, predominantly from June to October, and the dry season from November to May [13]. Variability in the amount, duration, intensity, and nature of precipitation has direct impacts on crop production, water availability, and food security [14]. In addition, wind dynamics affect all processes such as dust transport, vegetation, soil moisture conditions, and land degradation, particularly in the interior of the region with weak ecological systems [15]. Basse, in the Upper River Region of The Gambia, is one of the significant agricultural and socio-economic centres of the country, where livelihoods are highly vulnerable to seasonal climate conditions [16]. The increasing irregularities in rainfall patterns and wind conditions have led to concerns about the sustainability of agricultural activities, environmental stability, and climate resilience in the region [17].

Despite the risks associated with climate change being increasingly recognized in West Africa, the local-scale spatial dynamics of extremes have not been fully understood in The Gambia. In Basse, agricultural productivity, the management of water resources, and the livelihoods of the rural population have been impacted by a rise in the frequency of irregular rainfall regimes, delayed rainfall onset, short-duration heavy rainfall, and variable wind patterns [18]. Heavy rainfall can lead to flooding and soil erosion, nutrient losses, crop destruction, and infrastructure damage, while high wind speeds cause soil erosion, loss of vegetation, and environmental degradation [19]. These climate changes are a major risk to the sustainability of development and food security in the region [6]. Scarcity of continuous long-term meteorological records, however, narrows and limits understanding of the evolution of rainfall and wind conditions. In many regions of The Gambia, existing meteorological observations are often incomplete, with gaps and poor spatial representativeness, which hinders comprehensive evaluation of climatic conditions and evidence-based adaptation planning [20].

Moreover, most previous studies relied on limited meteorological observations from station data, which may have limited spatial coverage and were poorly monitored due to data gaps and irregularities, especially in rural areas like Basse. Station observations are useful for localized measurements, but cannot be used reliably on extended temporal scales, where long-term climatic analyses are needed [21]. Nevertheless, the Gambia context remains under-studied with respect to the interaction between rainfall and wind speed variability, despite its critical role in providing insights into atmospheric dynamics and the behaviour of extreme weather events [22].

The opportunities for climate monitoring and climate variability studies have been enhanced by satellite and reanalysis data, particularly in areas where such data are less available [23]. Of these datasets, the National Aeronautics and Space Administration Prediction of Worldwide Energy Resources (NASA POWER) database can provide the meteorological information required for long-term climatic studies that is continuous and easily accessible [24]. Due to the temporal consistency, extensive spatial coverage, and reliability in geographical areas with low observation density, NASA POWER datasets have been increasingly used in climatological, hydrological,

and environmental studies [25]. Such datasets can be used to determine climatic trends, seasonal variability, and extreme weather events in extended time series with enhanced spatial and temporal continuity [26]. However, few investigations have used NASA POWER data to fully explore the joint dynamics of rainfall and wind variability in Basse, The Gambia. In West Africa, several studies have examined climate variability, but gaps remain in understanding long-term and localized patterns of extreme rainfall and wind events in The Gambia. Furthermore, previous studies have not combined rainfall and wind analyses within a single framework to examine temporal trends, variability characteristics, or periods of extreme events [27-29]. Empirical knowledge of the temporal variability of rainfall and wind extremes in Basse from 2000 to 2025 is therefore inadequate, and there is no adequate knowledge of the relationship between the temporal variability of rainfall and wind speed for the region.

Accordingly, the present study aims to analyse the temporal trends, variability, and extreme characteristics of rainfall and wind events in Basse, The Gambia, between 2000 and 2025 using NASA POWER meteorological datasets. Specifically, the study seeks to: (I) assess the temporal trends of rainfall and wind patterns in Basse, The Gambia, from 2000 to 2025, (II) evaluate the monthly and annual variability of rainfall and wind events during the study period, (III) identify and characterize periods of extreme rainfall and wind events in Basse between 2000 and 2025, and (IV) examine the relationship between rainfall variability and wind speed variability in the study area.

This study will make a significant contribution to the existing literature on climate variability in the following ways: 1. It offers a localized long-term analysis of rainfall and wind extreme conditions in Basse, which is a region that is not adequately represented in Gambia's climatic research. 2. The coupling of rainfall and wind analysis provides a better overview of the variations of the atmosphere and their interactions with hydro-meteorological processes in the Sudano-Sahelian environment. 3. The use of NASA POWER meteorological data shows the value of satellite-derived data for climate assessment in data-sparse areas. 4. The results will contribute significantly to scientific knowledge and information for climate adaptation, disaster risk reduction, agricultural management, and sustainable natural resource governance for The Gambia and other semi-arid regions in West Africa.

Methodology

Study area

The study was carried out in Basse, the administrative capital of the Upper River Region (URR) of The Gambia, situated between 13.34°N and 13.40°N latitude and 14.19°W and 14.23°W longitude, and at an average elevation of 38.52 m above sea level (m asl), based on the MERRA-2 topographic reference as shown in Figure 1. The delineated study domain covers an area of approximately 28.9 km² (about 6.7 km north–south by 4.3 km east–west) and lies within the broader Basse Local Government Area (coterminous with the Upper River Region), which spans approximately 2,069.5 km². Basse is in the Sudano-Sahelian climatic zone of West Africa, which has a distinct bi-seasonal nature, with June-October as the wet season and November-May as the long dry season [30]. The region is largely agro-dependent and rural, and livelihoods rely heavily on seasonal rainfall distribution and near-surface atmospheric dynamics. Basse is an ecologically sensitive study area with respect to hydro-meteorological extremes and is underrepresented in the country's existing climatological literature, as well as a centrally located, strategic socio-economic hub in the Upper River Region [16].

Data Source and Acquisition

Data were obtained from a global gridded climate variables database from the National Aeronautics and Space Administration (NASA) Prediction of Worldwide Energy Resources (POWER) database for meteorological variables, version 2.6.2 (NASA POWER v2.6.2); this reanalysis product is a Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) reanalysis [31]. This study has relied on the NASA POWER dataset because it is temporally consistent, spatially continuous, and has been proven to be reliable for climate assessments in data-sparse sub-Saharan regions [32]. The monthly aggregated data were provided for 26 years, from January 2000 to December 2025, and cover 312 monthly data points per variable. The original dataset did not contain any data with a sentinel value of –999; however, during quality inspection, no missing values were found across all the retrieved parameters, which ensured the analytical integrity of the dataset, eliminating the need for imputation procedures [33].

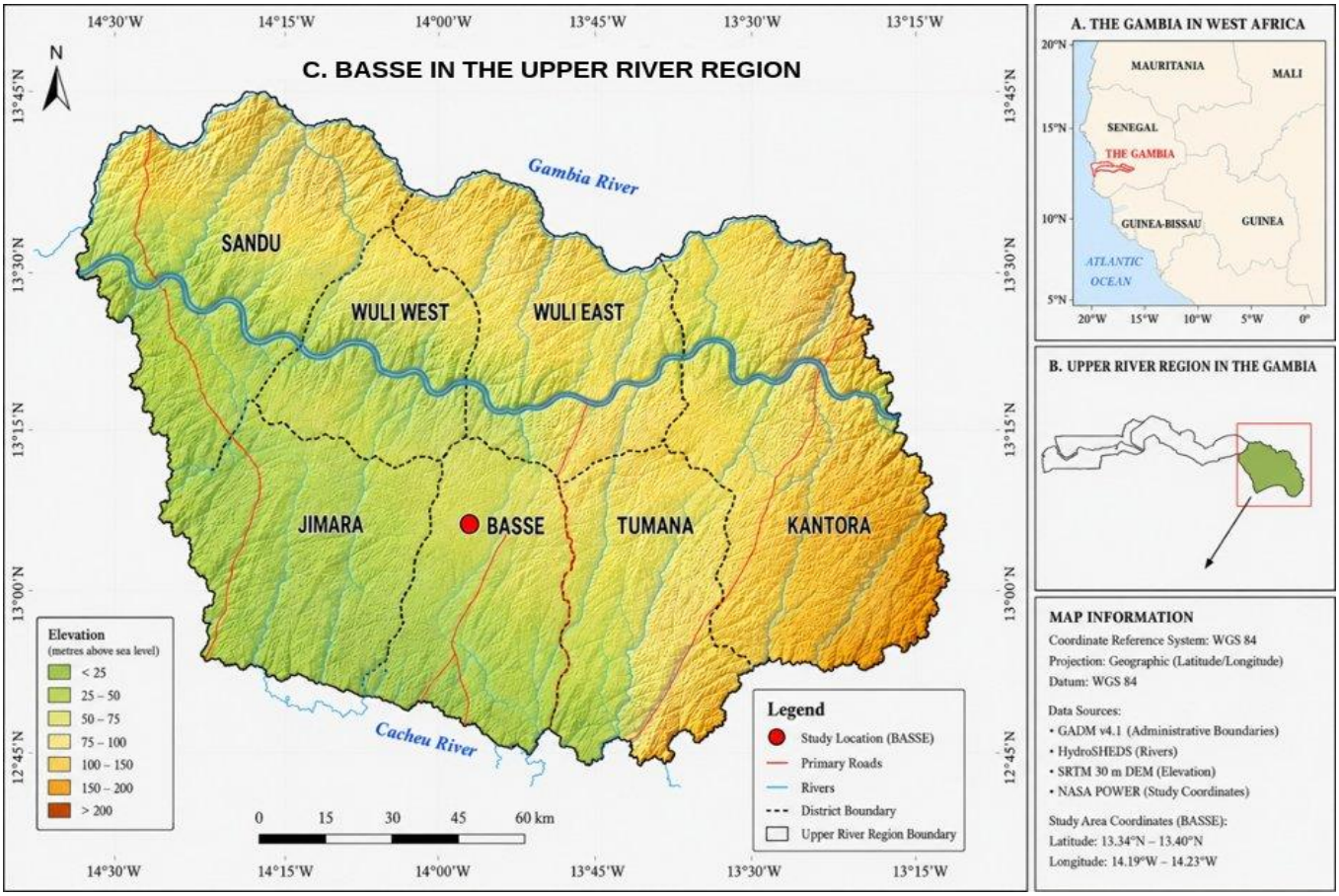


Figure 1. Study area:(A) The Gambia in West Africa, (B) Upper River Region in The Gambia, and (C) Basse in the Upper River Region.

Four meteorological variables were obtained at two geographically close coordinate nodes for the Basse study area.

The following four variables were retrieved for the node at Latitude 13.342°N and Longitude 14.187°W: (i) Mean Air Temperature at 2 Metres (T2M; °C); (ii) Relative Humidity at 2 Metres (RH2M; %); (iii) Precipitation (PRECTOTCORR; mm/month); and (iv) Wind Speed at 2 Metres (WS2M; m/s), where the latter represents the MERRA-2 bias-corrected accumulated monthly precipitation. All the variables are climatologically representative of the same spatial domain of the atmosphere, as the two nodes of the coordinate system are in the same approximately 0.5° × 0.625° MERRA-2 grid cell, which is approximately 7.3 km apart [34].

Data Processing

Data preprocessing and statistical analyses were carried out using Python (Version 3.11.7), with the pandas library used for data ingestion, transformation, and tabular manipulation [35] and the SciPy library used for inferential statistical computations [36]. The tabular data were preceded by a structured ten-line metadata header that was not part of the data but was instead programmatically removed from the file when the data was imported using the pandas read_csv function with the skiprows parameter. Both datasets were organized in a wide format, with rows denoting each year, and columns denoting calendar months (from January to December) and the annual total value (ANN). The data were then pivoted (melted) to long format, creating tidy temporal series with indices for year and month. Two datetime indices were built to order the data chronologically and to disaggregate the data seasonally. All variables were kept in their original measurement units as described in the NASA POWER v2.6.2 metadata documentation [31].

Descriptive Variability Analysis

Monthly climatological and annual descriptive statistics for each meteorological variable were calculated as arithmetic mean, standard deviation (SD), minimum, maximum, and coefficient of variation (CV) with the DataFrame.describe method and added custom aggregation functions. The coefficient of variation (CV) (SD/Mean × 100) was used as a

dimensionless measure of relative inter-annual variability, which allows comparison of relative variability across variables regardless of units of measurement [37]. The intra-annual seasonal cycle for each variable was characterized by averaging each calendar month over the 26-year record to yield monthly climatological means. The Standardised Anomaly Index (SAI) was computed for each year of precipitation and wind speed, using the difference between the annual data and the historical long-term mean divided by the standard deviation of the historical long-term data ($SAI = [Xi - \bar{X}] / \sigma$), to normalise the data for the identification of years of anomalously high or low conditions when compared to the historical baseline period [18].

Trend Analysis

A non-parametric monotonic trend test was used to evaluate the inter-annual trends in all four meteorological variables using the pymannkendall Python package [38-39]. The Mann-Kendall test was chosen instead of parametric tests due to its resistance to non-normal frequency distributions, lack of sensitivity to outliers, and proven suitability for hydro-meteorological time series that often exhibit skewness and heteroscedasticity [40]. For each test, the null hypothesis was a lack of monotonic trend, and the alternative hypothesis was the presence of a trend (either positive or negative) that was statistically significant at the conventional significance level of $\alpha = 0.05$ [41]. Where a statistically significant trend was found, the magnitude was calculated using Sen's non-parametric slope estimator [42], which was implemented using the scipy.stats.theilslopes function. Sen's slope gives a good indication of the linear rate of change per year, and its 95% confidence interval was reported to be within the range of estimation uncertainty. The Mann-Kendall test statistic (τ) and the associated p-value were reported for each variable for both annual and seasonal time scales [43].

Extreme Event Identification and Characterisation

Extreme rainfall and wind events were selected by using a percentile-based threshold approach that follows the methodological convention of the World Meteorological Organization (WMO) Expert Team on Climate Change Detection and Indices (ETCCDI) [44]. Precipitation events exceeding the 90th and 95th percentiles of the long-term monthly distribution were considered as extreme and very extreme precipitation events, respectively [45]. Monthly wind speed values above the 90th percentile of their long-term distribution were classified as anomalously high wind events [46]. The pronounced seasonal heteroscedasticity typical of Sahelian precipitation regimes was considered by computing percentile thresholds independently, by calendar month, from the full 26-year record, using the function numpy.percentile [47]. The occurrence of extreme events was then tabulated and analyzed for temporal clustering, frequency, and inter-annual variation, including any decadal patterns and direction of change in extreme events over the study period [48].

Correlation and Bivariate Association Analysis

Assessment of the strength and statistical significance of the inter-annual rainfall variability to wind speed variability association was done using Spearman's rank-order correlation coefficient (ρ) through scipy.stats.spearmanr function [49]. The Spearman's correlation was used over the Pearson product-moment correlation because the trend detection framework used was non-parametric, and the rainfall-wind relationship may not be linear in the Sahelian atmospheric environment [50]. Correlation analyses were conducted at an annual time scale and at a seasonal time scale, namely the wet season (June–October) and dry season (November–May), to determine if there are any differences between the rainfall-wind relationship in different atmospheric regimes, which are climatological [51]. Furthermore, bivariate correlations were calculated between relative humidity and precipitation, and between temperature and wind speed, to gain a complete picture of the interdependencies of the meteorological variables used [52]. The analysis of all correlation coefficients was done at $\alpha = 0.05$ and interpreted in the context of the dynamics of West African monsoon circulation and seasonality of Harmattan winds [53].

Significance and Reproducibility

To ensure methodological transparency and computational replicability, all the analytical procedures were carried out in the same reproducible scripting environment (Python 3.11.7) [36]. All tests were performed at the 95% level of confidence ($\alpha = 0.05$), and the p-values, test statistics, and effect size measures were reported in full to satisfy the inferential reporting expectations of climatological research [40]. The analytical approach used in this research, from trend detection and quantification of variability, through identification of extremes to

bivariate correlation, is in line with the methodological framework that has been used in most climatological and hydro-meteorological studies found in the literature [54], making it possible to compare with similar studies that have been carried out in the different West African sub-regions and across the Sahelian climatic zone.

Result and Discussion

Inter-Annual Trend Analysis of Rainfall and Wind Speed

Annual rainfall showed a statistically significant positive trend of +15.36 mm yr^{-1} (R^2 = 0.259, p = 0.008; MK τ = +0.280, p = 0.047), confirming a monotonic increase at α = 0.05 (Table 1). The R^2 is 0.259, indicating that a moderate proportion of the interannual rainfall variance is explained by the linear trend and highlighting the high background variability of Sahelian rainfall regimes. In contrast, annual wind speed showed a weak, non-significant negative trend (−0.005 m s^{-1} yr^{-1}; R^2 = 0.086, p = 0.147; MK τ = −0.156, p = 0.269), indicating no directional change over the study period. As shown in Figure 2, rainfall was lowest in 2001–2002, then remained relatively stable between 2003 and 2018, and increased rapidly in 2019–2022, while wind speed fluctuated only slightly from a long-term average of ~2.4 m s^{-1}. This decoupling increased precipitation, but no change in near-surface flow indicates increased West African Monsoon (WAM) moisture flux without a shift in near-surface circulation.

Monthly and Seasonal Climatological Variability

The rainfall and wind speed showed clear opposing seasonal cycles associated with the alternation of the West African Monsoon (WAM) and Harmattan north-easterly system (Table 2, Figure 3). Rainfall was concentrated in the June–October wet season, peaking in August (mean = 295.09 mm, SD = 88.07 mm, CV = 29.8%), followed by September (212.73 mm) and July (187.48 mm). Average rainfall was near zero during the dry seasons (November-April), with February having the lowest mean (0.11 mm, CV = 460.1%), an extreme CV attributable to stochastic variations in out-of-season extreme events rather than meaningful climatological variability. The Wind speed was at its lowest in October (1.34 m s-1, CV = 12.7%) with the ITCZ moving northwards, while at its highest in February (3.20 m s-1, CV = 9.6%) and January (3.01 m s-1, CV = 11.7%) during the Harmattan dominance. The wind speed CVs were also low across all months (6.0–14.0%), indicating relatively high inter-annual consistency of circulation compared to rainfall. Yearly maps of the same wind intensity (Figure 2, lower panels) confirm that more wet than average seasons occurred in 2020–2022, and that wind intensity, relative to the dry seasons, was relatively uniform over the years, with higher wind speeds during the wet seasons being associated with the drier early 2000s.

The mean air temperature was bimodal in the pre-monsoon, with a peak during May (33.6 °C) and during April (33.1 °C), and dropped in the wet season to 26.8–28.1 °C (July–September; Figure 4). Rainfall was mirrored by relative humidity (RH) that was lowest during February (19.0%) and highest during August–September (85.2–86.1%), with the rapid increase from May (31.9%) to June (54.6%) indicating monsoon onset and decrease from October (79.7%) to November (60.7%) indicating Harmattan re-establishment. Temperature CVs were low (1.6–6.0%) during all months and were much higher during the dry season (January: 32.4%; February: 28.5%; December: 30.3%) than during the wet season (4.0% in September; Figure 5). These supplementary variables complement the coherent and WAM-controlled full meteorological system.

Identification and Characterization of Extreme Events

Three extreme wet years (2020, 2021, 2022) were observed when comparing to the P90 threshold of 1,129.2 mm, and three extreme dry years (2000, 2001, 2002) were observed when comparing to the P10 threshold of 590.5 mm (Table 3, Figure 6). The concentration of extreme wet years in 2020-2022 is consistent with the positive trend found in Inter-Annual Trend Analysis of Rainfall and Wind Speed, suggesting that the upward trend occurs, in part, as a rise in extreme wet year frequencies. The early 2000s dry cluster is a period of rainfall deficiency that was observed throughout the Sudano-Sahelian region before the partial recovery from WAM. The P90 value for wind speed was 2.52 m/s, and the P10 was 2.28 m/s; extreme high wind years (2001, 2002, 2007) were in the early-to-mid period, with extreme low wind years (2008, 2010, 2021, 2023) distributed throughout the middle-to-later record.

Table 1. OLS regression and Mann–Kendall trend test results for annual rainfall and wind speed, Basse, The Gambia (2000–2025), $p < 0.05$.

Variable	OLS Slope	R^2	p (OLS)	MK τ	p (MK)
Annual Rainfall (mm)	+15.36 mm yr^{-1}	0.259	0.008	+0.280	0.047
Annual Wind Speed (m s^{-1})	−0.005 m s^{-1} yr^{-1}	0.086	0.147	−0.156	0.269

OLS = Ordinary Least Squares; MK = Mann–Kendall; τ = Kendall rank correlation coefficient.

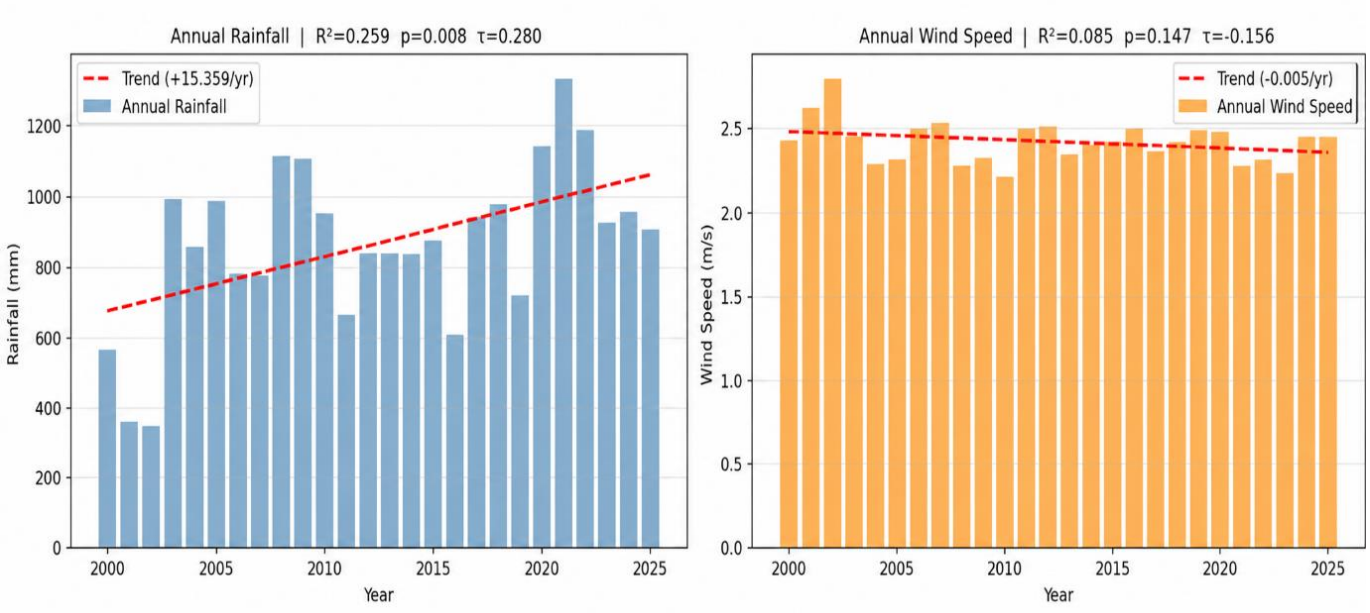


Figure 2. Inter-annual time series of annual total rainfall (mm; left) and annual mean wind speed (m s^{-1}; right), Basse, The Gambia (2000–2025). Red dashed lines show OLS trend lines. MK τ and R^2 statistics are annotated in panel titles.

Table 2. Mean monthly rainfall and wind speed with standard deviation and coefficient of variation, Basse, The Gambia (2000–2025).

Month	Rain Mean (mm)	Rain Std (mm)	Rain CV (%)	Wind Mean (m s^{-1})	Wind Std (m s^{-1})	Wind CV (%)
JAN	0.41	1.47	359.3	3.01	0.35	11.7
FEB	0.11	0.52	460.1	3.20	0.31	9.6
MAR	0.56	1.72	310.2	2.86	0.28	9.9
APR	0.19	0.48	252.4	2.82	0.21	7.3
MAY	8.42	10.35	122.9	3.00	0.18	6.0
JUN	91.02	45.03	49.5	2.88	0.24	8.3
JUL	187.48	65.45	34.9	2.31	0.22	9.4
AUG	295.09	88.07	29.8	2.01	0.20	9.9
SEP	212.73	82.30	38.7	1.57	0.16	10.4
OCT	72.55	33.80	46.6	1.34	0.17	12.7
NOV	2.75	4.75	172.8	1.67	0.21	12.8
DEC	0.42	1.95	461.0	2.44	0.34	14.0

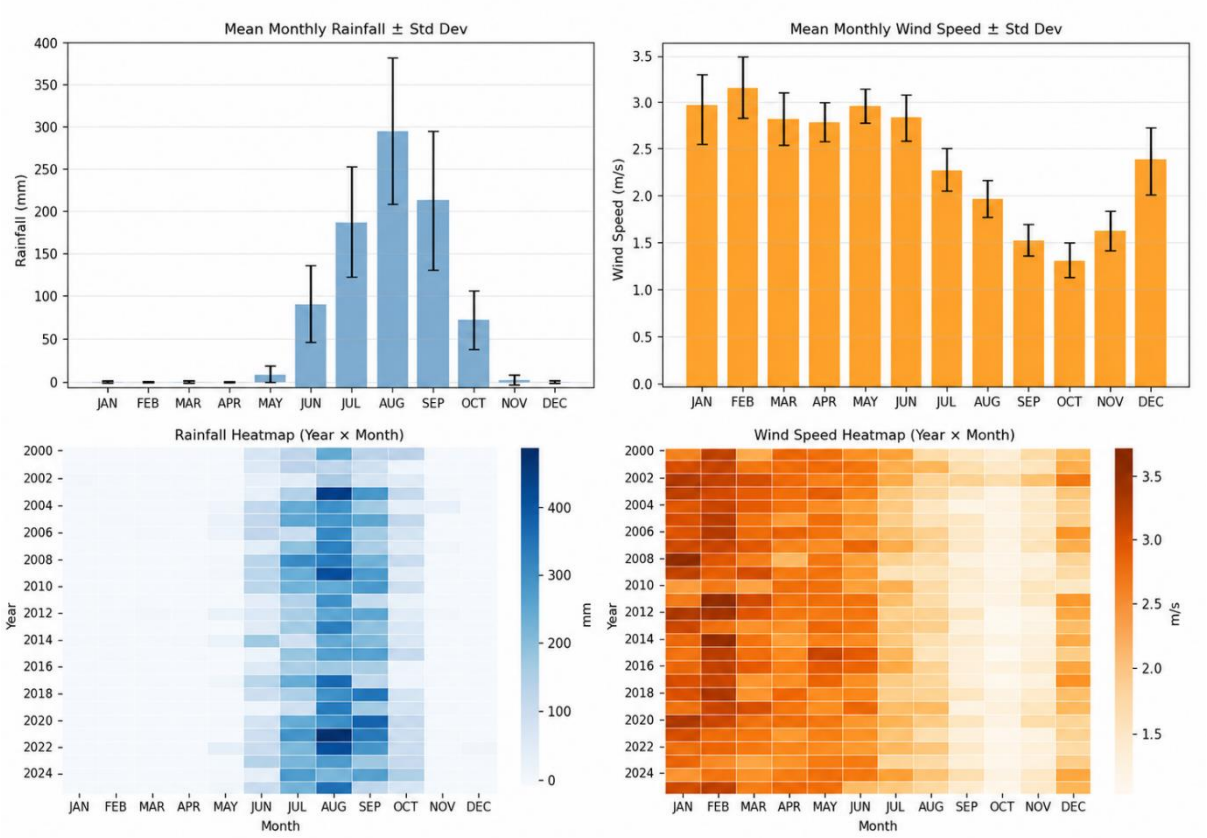


Figure 3. Monthly climatological variability of rainfall and wind speed, Basse (2000–2025). Upper panels: mean monthly values (±1 SD). Lower panels: year-by-month heatmaps of rainfall (mm; left) and wind speed (m s^{-1}; right).

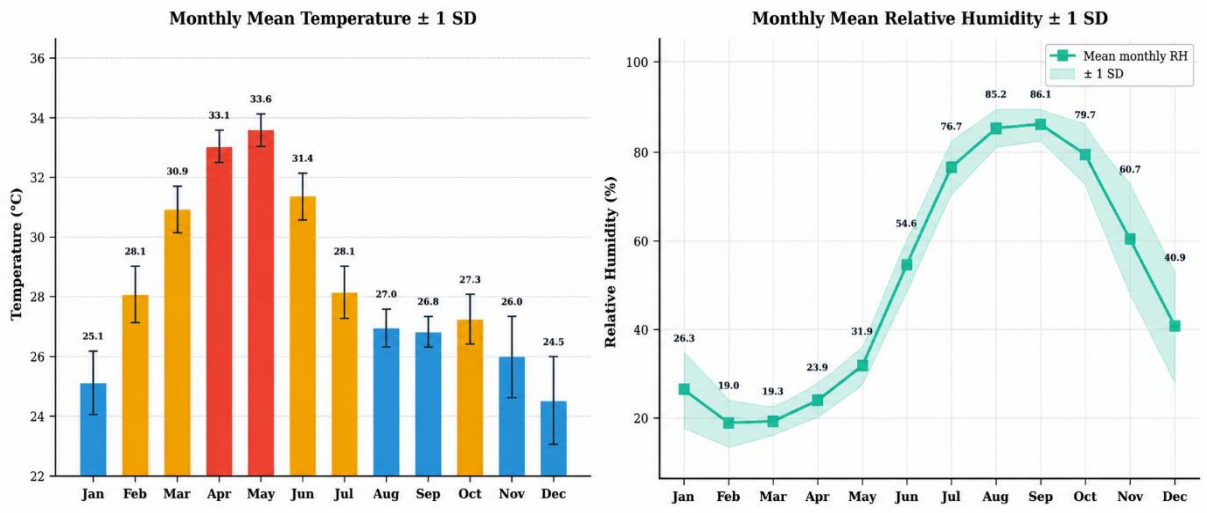


Figure 4. Monthly climatological means (±1 SD) of mean air temperature at 2 m (T2M; °C; left) and relative humidity at 2 m (RH2M; %; right), Basse, The Gambia (2000–2025).

The convergence of extreme dryness with high wind in 2001-2002 agreed with the dominance of the Harmattan, which had led to the suppression of monsoon penetration.

On the other hand, 2021 is both in extreme wet and in extreme low wind, indicating a very strong monsoon season, a correlation which will be discussed in (Bivariate Association Between Rainfall and Wind Speed Variability). The resulting bimodal temporal structure (early dryness and high winds versus recent wetness and low winds) is a directionality change in the hydro-meteorological regime, which is consistent with Sahelian monsoon recovery.

Bivariate Association Between Rainfall and Wind Speed Variability

The Pearson ($p<0.001$, $r = -0.73$) and Spearman ($p<0.001$, $\rho = -0.66$) correlations at the annual scale confirmed a strong inverse relationship with a very high level of significance between rainfall and wind speed, which was statistically significant (Figure 7). There was also a systematic relationship between higher rainfall years and lower wind speeds, and vice versa: during intense monsoon phases, southwesterlies bring moisture, whereas during weaker monsoon phases, north-easterlies (Harmattan) persist, increasing wind speed; and during weaker monsoon phases, southwesterlies are weak, and north-easterlies are strong during intense monsoon phases, decreasing wind speed. There was also a systematic relationship between higher rainfall years and lower wind speeds, and vice versa. During intense monsoon years, southwesterlies bring moisture, whereas during weaker monsoon years, north-easterlies (Harmattan) persist, increasing wind speed; and during weaker monsoon years, southwesterlies are weak, and north-easterlies are strong during intense monsoon years, lowering wind speed. Only June had a statistically significant correlation at the monthly time scale (Table 4) ($r = -0.655$, $p < 0.001$). June is the most dynamic transition month in the Upper River Region, with the ITCZ moving between the north and south, intensifying WAM flow, and Harmattan between the north and south moving most intensely; thus, the inter-annual variability in June rainfall is closely linked to the strength of monsoon onset, which also controls surface wind conditions. Within-month rainfall–wind coupling has been muted by the dominance of the atmospheric regime (either dry season or mature wet season) in all other months. The identified complementary relationships between RH and rainfall (positive) and between temperature and wind speed (positive in the dry season) are consistent with this integrated WAM–Harmattan framework and indicate that the negative rainfall–wind relationship observed is not independent or stochastic but is controlled by a single dominant driver in the atmosphere.

Increasing Rainfall Trend and Sahelian Monsoon Recovery

Annual rainfall in Basse increased at a statistically significant rate of +15.36 mm yr^{-1} (MK $\tau = +0.280$, $p = 0.047$) between 2000 and 2025, which reflects the regional Sahelian monsoon recovery trend observed over the West African Sudano-Sahelian belt in general. This recovery, which is generally explained by the general increase in moisture flux associated with the warming of the Atlantic and Mediterranean Sea surface temperatures, has been confirmed to enhance rainfall intensities as well as to increase the intermittency and convective intensities of precipitation events [55]. The results from Basse are in a parallel trend to the findings by [56], who demonstrated that Sahel rainfall has been increasing significantly in the past 30 years as a result of an increase in Vertical Integrated Moisture Flux Convergence (VIMFC), and future warming scenarios predict further increases in rainy days in the region. In addition, the study by [57] on long-term rainfall variability in West Africa identifies significant differences in hydro-climatic signals across the region, some with rainfall recovery and others with ongoing decrease or increasing rainfall variability. Their results, based on long time series of mean rainfall and trend analyses, stress the significant spatial variability of rainfall over West Africa and the need for specific studies, like the present investigation, to cover the sub-regional hydro-climatic behaviour.

The two clusters of extreme wet years in 2020-2022 (all above the P90 threshold of 1,129.2 mm) and of extreme dry years in 2000-2002 (below the P10 threshold of 590.5 mm) confirm the bimodal temporal nature of hydro-meteorological regimes in the Sahel region highlighted by [58] and reinforced by other recent studies about the intensification of extreme events during recovery years. The moderate R^2 value (0.259) highlights the well-documented high inter-annual variability of rainfall in the Sahel region, with climatological expectations of large deviations from the trend [55,59]. The IMF has explicitly explained that frequent floods and droughts are a key development risk in The Gambia, noting that the frequency of rainfall, not the overall amount of rainfall, is the biggest threat to the rain-fed agricultural sector and the food security situation in the country [60]. The current findings provide quantitative evidence substantiating this institutional assessment.

Wind Speed Stationarity and Atmospheric Circulation Stability

Compared to the considerable rainfall trend, annual wind speed in the 2000–2025 period showed a statistically insignificant and marginal negative tendency (-0.005 m s^{-1} yr^{-1}; MK $\tau = -0.156$ and $p = 0.269$, respectively).

Table 3. Extreme event thresholds (P90 and P10) and identified extreme years for annual rainfall and wind speed, Basse, The Gambia (2000–2025).

Variable	P90 Threshold	P10 Threshold	Identified Extreme Years
Annual Rainfall (mm)	1,129.2 mm	590.5 mm	Wet: 2020, 2021, 2022 | Dry: 2000, 2001, 2002
Annual Wind Speed (m s^{-1})	2.52 m s^{-1}	2.28 m s^{-1}	High: 2001, 2002, 2007 | Low: 2008, 2010, 2021, 2023

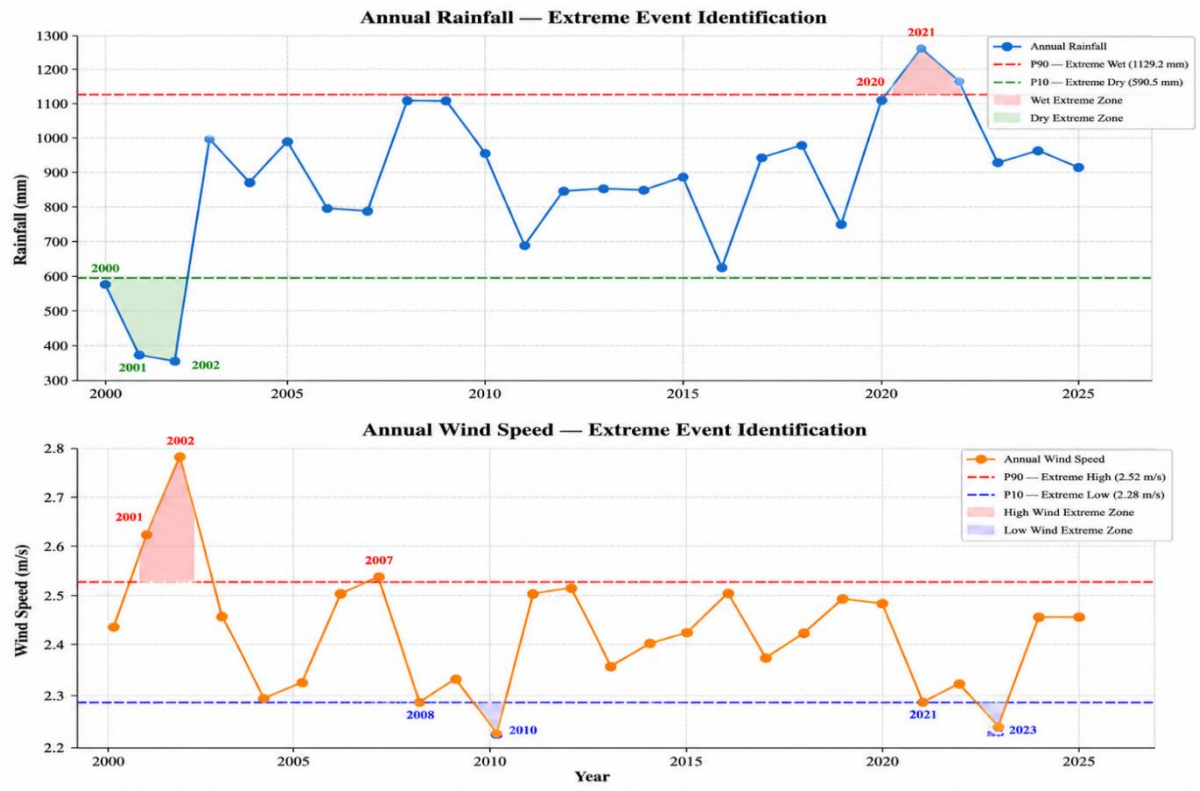


Figure 6. Annual extreme event identification for rainfall (upper panel) and wind speed (lower panel), Basse (2000–2025). Red/green dashed lines indicate P90/P10 thresholds. Shaded zones and annotated labels mark identified extreme years.

The decoupling between the positive trends in precipitation and the negative trends in near-surface wind circulation is physically understandable in the context of the dynamics of the West African Monsoon (WAM)-Harmattan system. The enhanced WAM moisture flux that led to the rainfall recovery is not necessarily associated with any discernible surface wind speed but rather occurs through middle-tropospheric circulation and moisture convergence [56,61,62]. The low coefficients of variation (6.0–14.0%) of wind speed for all months, when compared with the high coefficients of variation (29.8–460.1%) of rainfall, indicate that surface circulation of Harmattan alternation is relatively stable while monsoon air masses are changing in their thermodynamic content.

The seasonal cycle in the wind speed, which peaks in January–February (3.01–3.20 m s-1) when the influence of the Harmattan is strongest and is lowest in October (1.34 m s-1) when the Intertropical Convergence Zone (ITCZ) has moved south, agrees with previous characterisations of the wind climate over West Africa [62,63].

The interaction between high winds and dry conditions in 2001–2002, in contrast with low winds and wet conditions in 2020–2021, is closely compatible with the cause-and-effect monsoon-Harmattan antagonism. Years with high winds and dryness near the surface are characterised by an antagonistic interaction between strong Harmattan circulation and little penetration by the monsoon,

Table 4. Monthly Pearson correlation coefficients between rainfall and wind speed, Basse, The Gambia (2000–2025). $p < 0.001$.

Month	r	p-value	Month	r	p-value	Significant
JAN	+0.314	0.118	JUL	−0.317	0.114	No
FEB	+0.081	0.693	AUG	−0.193	0.344	No
MAR	+0.192	0.348	SEP	−0.154	0.453	No
APR	−0.053	0.799	OCT	−0.248	0.223	No
MAY	−0.211	0.300	NOV	−0.026	0.898	No
JUN	−0.655	0.000	DEC	−0.223	0.273	Yes

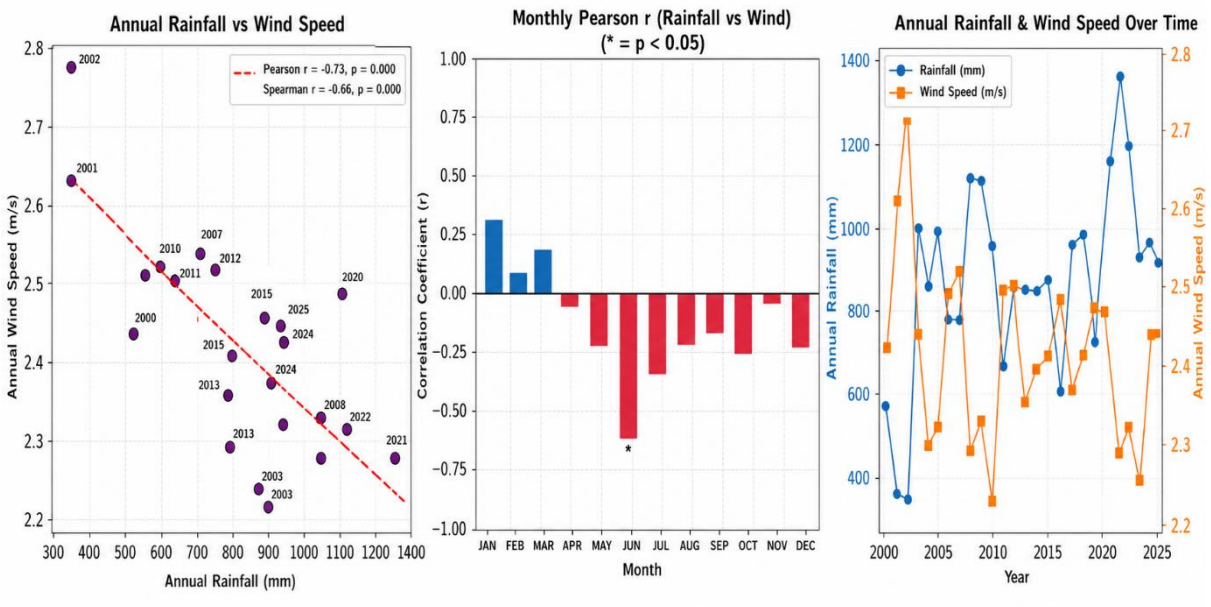


Figure 7. Bivariate rainfall–wind speed analysis, Basse (2000–2025). Left: annual scatter plot with OLS trend line (red dashed); Pearson r and Spearman ρ annotated. Centre: monthly Pearson r bar chart; = $p < 0.001$ (June only). Right: dual-axis annual co-evolution of rainfall (blue) and wind speed (orange), 2000–2025.

while years with strong monsoon onset are associated with little Harmattan flow and lower surface wind speeds [48,64].

The analysis of the pattern supported the hypothesis of regime-controlled near-surface wind dynamics, which agrees with the interpretation of Harmattan/harmattan alternation with West African Monsoon (WAM) as the dominant forcing of the wind regime in Basse, with no tendency toward independent directional change.

Extreme Event Characteristics and Temporal Clustering

The identification of distinct temporal clusters of extreme events in Basse, with dry extremes clustered in the early 2000s and wet extremes in 2020–2022, is generally consistent with the Sahelian drought-to-recovery trajectory in recent climate observations [48,55,58,65]. The clustering is not a mere statistical phenomenon, but the actual rain behaviour that proposed a transition from a rainfall deficiency to enhancement of monsoon activity in the Upper River Region of The Gambia, in addition to the strengthening of Harmattan influence. The empirical evidence for the mechanistic linkage between the monsoon strength and suppression of surface winds provided by the extreme dryness and the related high wind speed in 2001–2002, and the high wetness and surface wind suppression in 2021, supports the opposing relationship between rainfall and wind [66].

This applied perspective is particularly relevant for planning disaster risk reduction in Basse, as the wet years of the last three years (2020-2022) were clustered together. The IMF (2025) Climate Policy Diagnostic for The Gambia also mentions that the country's exposure to flood events is growing because rainfall intensity is rising, leading to losses in agricultural infrastructure and livelihoods. The present analysis quantitatively provides sub-national

evidence at the level of Basse (Upper River Region) that these flood-prone extremes are not random, but rather temporally coherent, consistent with the intensification of WAM, which can have direct implications for early warning system calibration and adaptive planning.

Rainfall-Wind Coupling and the WAM-Harmattan Framework

The negative correlation between annual mean rainfall and annual mean wind speed (−0.73; $p < 0.001$) and (−0.66; $p < 0.001$) of Pearson and Spearman is one of the most important analytically significant results of this study. This relationship shows the opposing effects of two dominant flows: moisture-laden, such as the Southwest Indian Monsoon (WAM), and dry, such as the Harmattan. While the strong monsoon years effectively hinder Harmattan penetration through south-westerly moisture advection, the weaker monsoon years keep surface winds high due to Harmattan dominance but keep precipitation low. This mechanistic explanation is substantiated by the available West African literature on atmospheric dynamics for the region, as well as more recent research, which established that WAM moisture transport is not related to variations in surface wind speed magnitude at the inter-annual scale [55,56].

A negative coupling between positions at the monthly timescale for June is the only one that is found to be statistically significant ($r = −0.655$, $p < 0.001$). June is a critical transition window in the Upper River Region for the Intertropical Convergence Zone (ITCZ), as the variability in whether the monsoon happens on time or early/late between years has the largest influence on both the amount and conditions of rain and surface winds. During the wet and dry seasons, when the climate is climatologically stable, the atmospheric regimes are homogenized, so the rainfall-wind covariance is masked. The result is consistent with that of Dunning et al. (2016), who found that variability of monsoon onset is a mechanism by which the signals propagate through the Sahelian region, and it has implications for seasonal agricultural planning in Basse as a tool to provide an early suggestion about the overall nature of the wet season [8].

Numerous studies have validated NASA POWER (MERRA-2) for capturing these dynamics. The use of NASA POWER has repeatedly proven to be beneficial in sub-Saharan Africa, where temporal consistency and continuity given by the model cannot be achieved by ground-based stations in rural areas like Basse, and is impossible in environments with few or no station data [31,34,67]. Because the dataset has no missing values and covers the entire 312-month record examined in this study, the integrity of the dataset is further supported.

Conclusion

This study characterized the temporal variability, trends, extreme events, and inter-variable relationships of rainfall and wind speed in Basse, The Gambia, over the 2000–2025 period using NASA POWER (MERRA-2) monthly datasets. Four key conclusions emerge from the analysis:

The annual rainfall in Basse showed a significant positive trend (+15.36 mm yr-1; $p<0.05$), which indicates the partial recovery of the West African Monsoon system over the Sudano-Sahelian region. This recovery is reflected in a rise in mean annual rainfall totals and in the temporal clustering of extreme wet years (2020–2022), indicative of higher chances of high rainfall events, which would have implications for flood risk and water resource management.

There was no statistically significant directional change in the annual wind speed, with a long-term mean wind speed of approximately 2.4 m s^{-1}. Throughout, the seasonal modulation of the atmospheric circulation by Harmattan dry and low-wind conditions (November-April) and WAM wet conditions (June-October) was the most persistent feature in the system, with few indications of appreciable inter-annual variability.

From the above, we observed a good and statistically significant inverse relationship between annual rainfall and wind speed ($r = −0.73$, $\rho = −0.66$, $p < 0.001$), thereby confirming monsoon-Harmattan antagonism as the main causative factor of hydro-meteorological variability in Basse. The coupling is the most pronounced during the transition period from June into the season, and this coupling has physical meaning as a predictor of the nature of the wet season and is directly useful for agriculture and disaster risk management planning.

A successful analytical application of NASA POWER reanalysis data was used to assess the climatology for a period of 50 years in a region with few ground-based observation stations, further confirming the utility of satellite-based reanalysis products in climate science

with limited ground station coverage in sub-Saharan regions.

These findings contribute to the evidence base for climate adaptation data in The Gambia, where increased variability in rainfall over time and a growing frequency of extreme events have become a major threat to rain-fed agriculture, water security, and rural livelihoods. Future analyses and studies should expand this approach using high spatiotemporal resolution modelling, multi-station ground validation, and future climate projections of the CMIP6 suite to inform evidence-informed national-level climate adaptation planning in the Upper River Region and beyond.

Conflict of Interest

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

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