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Hydroclimatic Analysis of the Unusual Wet Spell Observed in Senegal in July 2022

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Abstract

In July 2022, Senegal experienced an exceptional wet spell characterized by widespread flooding and anomalously high rainfall intensity. This study investigates the multi-scale hydroclimatic mechanisms underlying this event, focusing on the combined roles of sea surface temperature (SST) anomalies, African Easterly Waves (AEWs), and intraseasonal variability associated with the Madden-Julian Oscillation (MJO). We combine satellite-based precipitation products (IMERG, CHIRPS, and TAMSAT), ERA5 reanalysis fields, and daily SST data (OISST v2) to diagnose the large-scale and mesoscale processes involved. AEWs and mesoscale convective systems (MCSs) are objectively tracked to quantify their contribution to rainfall variability. The results show that the event coincided with a pronounced tropical Atlantic SST dipole, characterized by anomalous warming in the North Tropical Atlantic and cooling along the equatorial Atlantic. This configuration enhanced the meridional SST gradient, strengthened the low-level monsoon flow, and increased moisture availability over West Africa. During the same period, total column water vapor exceeded 59 mm over Senegal, while a sequence of long-lived and coherently propagating AEWs was observed. Moreover, this event occurred during an active MJO phase (phases 8 - 1), which is known to favor enhanced convection over West Africa. The MJO likely acted as an intraseasonal modulator, reinforcing large-scale ascent and moisture convergence, thereby amplifying convection triggered by AEWs. The extreme rainfall arose from a compound mechanism involving persistent AEW activity, a moisture-rich background state, and favorable intraseasonal conditions linked to the MJO. These results underscore the role of multi-scale interactions in shaping extreme rainfall over west Africa and offer valuable insights for improving subseasonal forecasting and early warning systems.

Keywords

Wet Spell, African Easterly Wave, Sea Surface Temperature, SST Index, MJO, Senegalese Rainfall

1. Introduction

West Africa and notably the Sahelian belt is characterised by high exposure and vulnerability to climate variability and change, due to the strong dependence of agricultural and socio-economic systems on rainfall patterns and the dynamics of the West African monsoon. These conditions amplify the risks associated with interannual and multi-decadal variability, with limited adaptive capacity in many communities [1]. Over recent decades, the region has experienced pronounced hydroclimatic fluctuations characterized by alternating drought periods and episodes of intense flooding, reflecting complex interactions between large-scale atmospheric circulation, oceanic forcing, and regional land-atmosphere feedback. These hydroclimatic extremes have significant impacts on agriculture, food security, public health, and disaster risk management across Sahelian countries, including Senegal.

Several studies have documented substantial changes in rainfall characteristics across West Africa since the late twentieth century. While persistent dry spells became more frequent during the late drought decades, more recent analyses indicate a partial recovery of Sahel rainfall since the 1980s, associated with changes in rainfall intensity, wet-spell frequency, and convective organization. At the national scale, Senegal exhibits marked multi-decadal variability, with increases in extreme rainfall intensity and shifts in the spatial distribution of precipitation regimes [2]. These long-term changes highlight the importance of understanding the physical mechanisms governing rainfall variability across temporal scales.

At intraseasonal timescales, convective activity over West Africa is strongly modulated by the Madden-Julian Oscillation (MJO), which alters large-scale circulation patterns, low-level moisture convergence, and vertical wind shear, thereby influencing the dynamical environment in which African Easterly Waves (AEWs) and mesoscale convective systems (MCSs) develop [3] [4]. Through its impact on atmospheric instability and moisture availability, the MJO can enhance both rainfall intensity and event persistence during active monsoon phases. In addition to the MJO, other equatorial wave disturbances particularly convectively coupled Kelvin waves contribute to the zonal redistribution of humidity and precipitation anomalies across the West African monsoon region. These waves can induce low-level convergence anomalies and reinforce humidity perturbations, effectively preconditioning the troposphere for enhanced deep convection [5] [6].

At the regional scale, the interaction between AEWs and thermodynamic features of the monsoon system further modulates convective organization. The Saharan Heat Low (SHL), a key thermal feature of the West African monsoon system, modulates meridional pressure gradients and low-level monsoonal inflow, thereby influencing convection and rainfall variability over the Sahel [7] [8]. Variability in SHL intensity affects the strength and position of the African Easterly Jet (AEJ), altering the dynamical support for AEW development and propagation. These processes regulate the initiation, propagation, and structural organization of MCSs, which account for a fraction of extreme rainfall events in the Sahel [9].

Despite growing evidence of these multi-scale influences, relatively few studies have examined how these mechanisms combine to produce extreme rainfall events at intra seasonal time scales over Senegal. This research gap is particularly relevant in the context of July 2022, when Senegal experienced widespread heavy rainfall and significant flooding impacts. The decadal rainfall maps provided by the Senegalese National Agency for Civil Aviation and Meteorology (ANACIM), shown in **Figure 1**, highlight a gradual strengthening and spatial expansion of positive rainfall anomalies across July 2022. During the first decade (1-10 July), precipitation amounts were already above climatological normal over central and southern Senegal, while localized deficits persisted in the northwest. During the second and third decades (11-20 July and 21-31 July), positive anomalies strengthened and expanded toward northeastern regions, resulting in widespread surplus conditions across most of the country. These episodes caused considerable socioeconomic damage, as documented in operational bulletins issued by the Senegalese National Agency for Civil Aviation and Meteorology (ANACIM).

Despite advances in understanding individual drivers of West African rainfall variability, limited attention has been given to how large-scale anomalies modulate the dynamical properties of African Easterly Waves (AEWs) including their persistence, propagation distance, and likelihood of reaching the western Sahel and how these changes translate into enhanced mesoscale convective system (MCS) frequency and rainfall intensity at the regional scale. It remains unclear whether extreme rainfall events result primarily from intensified convection within individual systems or from increased system occurrence under favorable synoptic conditions.

In this context, the present study investigates whether the extreme rainfall observed in July 2022 over Senegal was associated with anomalous large-scale conditions that enhanced AEW persistence and propagation toward the western Sahel, thereby increasing the frequency and intensity of organized MCS activity. By jointly analyzing AEW dynamical characteristics and daily MCS precipitation metrics, we assess whether the exceptional wetness of July 2022 resulted from a compound mechanism combining more frequent organized systems and stronger rainfall production per system.

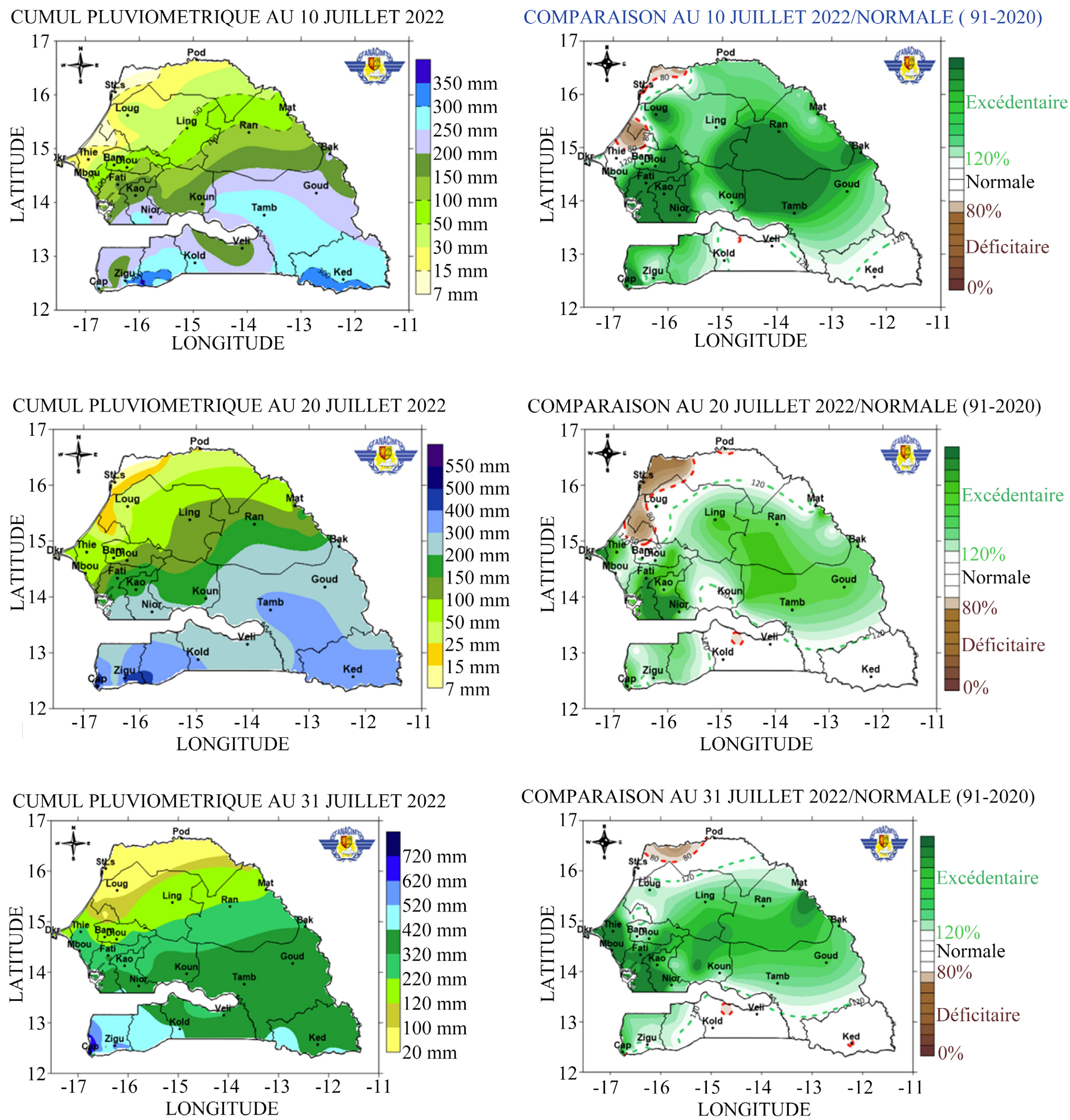

Figure 1. Accumulated rainfall (left panels) and precipitation anomalies relative to the 1991-2020 climatological normal (right panels) for each decade of July 2022 in Senegal. The first row corresponds to the period from 1-10 July, the second row from 11-20 July, and the third row from 21-31 July 2022. Rainfall accumulations are expressed in mm, while anomalies are shown as a percentage of the normal: excess (>120%), near normal (80% - 120%), and deficit (<80%). The figures are from the official reports of the Senegalese National Agency for Civil Aviation and Meteorology (ANACIM). The authors gratefully acknowledge ANACIM for providing these data and supporting their use in this study.

2. Data and Methodology

2.1. Data

The analysis draws on a multi-source observational framework that integrates geostationary satellite imagery, satellite-based and gauge-corrected precipitation estimates, atmospheric reanalysis, and oceanic surface temperature data. Each dataset was selected based on its documented performance in the West African monsoon region, its spatiotemporal resolution relative to the processes under investigation, and the availability of a sufficiently long climatological record to place the July 2022 event in its statistical context. The datasets and their specific roles in the analysis are described below.

2.1.1. Meteosat Second Generation SEVIRI Thermal Infrared Imagery

Cloud-top brightness temperatures were derived from the 10.8-μm thermal infrared channel of the Spinning Enhanced Visible and Infrared Imager (SEVIRI) aboard the Meteosat Second Generation (MSG) geostationary satellite. SEVIRI provides full-disk imagery at a native spatial sampling of ~3 km at the sub-satellite point and a repeat cycle of 15 min, giving a temporal resolution well suited to tracking the life cycle of organized convective systems at the mesoscale. Calibrated top-of-atmosphere radiances are converted to equivalent blackbody brightness temperatures (Tb) by inverting the Planck function at the central wavelength of the channel, following the procedures described in [10] and [11]. The resulting Tb fields serve as the primary input to the MCS detection and tracking algorithm detailed in Section 2.2.

2.1.2. Satellite-Derived Precipitation Estimates

The sparse and climatologically heterogeneous rain-gauge network across the Sahel precludes reliable areal-average rainfall estimation from *in-situ* observations alone. Three satellite-based precipitation products were therefore combined, each exploiting distinct retrieval strategies and offering complementary strengths with respect to spatial resolution, temporal depth, and algorithm performance in semi-arid tropical environments. Cross-comparison among products provides an internal consistency check and reduces the risk of dataset-specific biases propagating into the event-scale diagnostics.

Rainfall associated with tracked MCSs is quantified using the IMERG Final Run (version 06B) half-hourly product at 0.1˚ spatial resolution [12]. IMERG merges passive microwave precipitation retrievals from the GPM constellation with infrared-based estimates from geostationary sensors and applies monthly bias corrections using gauge analyses from the Global Precipitation Climatology Centre (GPCC). The Final Run product benefits from retrospective reprocessing and represents the highest-quality IMERG tier. IMERG observations are temporally collocated with MSG/SEVIRI imagery to ensure consistency between cloud-system identification and rainfall attribution. Over West Africa, IMERG demonstrates good skill in capturing the spatial organization and peak intensity of convective rainfall, particularly across the Sudano-Sahelian zone [13], though it tends to overestimate the frequency of light rain events and exhibits reduced daily skill in hyper arid subregions [14] [15]. At monthly and seasonal scales its performance is considerably more robust [16].

CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) [17] provides daily precipitation estimates at 0.05˚ resolution with a record extending back to 1981. The algorithm combines a high-resolution climatology derived from the CHPclim dataset with thermal infrared cold-cloud duration estimates and quality-controlled *in-situ* gauge observations. Over the Sahel, CHIRPS has been shown to reproduce the interannual variability of both moderate and heavy daily precipitation events, though satellite-based products including CHIRPS exhibit systematic biases in representing extreme daily accumulations compared to dense rain gauge networks [18] At the interannual scale, [19] used CHIRPS to demonstrate that Sahelian moderate and heavy daily rainfall respond to distinct SST teleconnection patterns, a finding directly relevant to the ocean-atmosphere framework adopted in the present study. At the national scale, CHIRPS has been validated against the Senegalese National Civil Aviation and Meteorology Agency (ANACIM) station data and used to characterize the spatiotemporal variability of rainy season onset and cessation [20]. Its long and spatially consistent archive makes it particularly well suited for computing the 1991-2020 climatological baseline and for quantifying daily precipitation anomalies during the July 2022 event.

TAMSAT (Tropical Applications of Meteorology using satellite and *in-situ* data; [21]) provides daily rainfall estimates at 0.0375˚ resolution, based on an empirically calibrated relationship between cold-cloud-top temperature duration (at a threshold of 235 K) and rainfall accumulation. Unlike global products calibrated against global gauge climatologies, TAMSAT employs Africa-specific calibration parameters derived from local gauge records, which makes it particularly adapted to the West African monsoon environment. It provides an independent check on the other products and has demonstrated reliable skill in monitoring wet-spell frequency, detecting intra-seasonal dry breaks, and characterizing organized convection associated with African Easterly Wave passages [22].

2.1.3. ERA5 Atmospheric Reanalysis

Large-scale dynamical and thermodynamical fields are obtained from the fifth-generation ECMWF atmospheric reanalysis ERA5 [23] [24]. ERA5 delivers hourly estimates of the global atmosphere on 137 hybrid sigma-pressure levels at ~31-km horizontal resolution, produced by a four-dimensional variational (4D-Var) data assimilation system that ingests an extensive and diverse observing network including satellite radiances, radiosondes, aircraft reports, surface synoptic observations, and scatterometer wind retrievals. Variables used in this study include the horizontal wind components, specific and relative humidity, total column water vapour (TCWV), and vertically integrated moisture flux. ERA5 has been extensively evaluated over West Africa and demonstrates strong skill in representing the kinematics and thermodynamics of the West African monsoon system at synoptic and intraseasonal timescales [23].

2.2. Methodology

The working hypothesis of this study is that the July 2022 extreme rainfall event was not solely the result of mesoscale convective variability but rather emerged from the modulation of AEW activity by large-scale environmental forcing. We therefore examine the extent to which sea surface temperature anomalies, MJO phase, and vertically integrated moisture transport influenced AEW dynamical characteristics (frequency, amplitude, propagation) and, subsequently, MCS occurrence and precipitation efficiency.

To test this hypothesis, we combine large-scale diagnostics with objective AEW and MCS tracking, allowing quantification of the dynamical pathway linking environmental forcing to rainfall anomalies.

2.2.1. Definition of the July 2022 Wet Spell

A rainy day was defined as a day with daily precipitation exceeding 1 mm. Following this criterion, a wet spell was identified as a period of at least seven consecutive rainy days. Daily precipitation was spatially averaged over Senegal using CHIRPS rainfall estimates.

Based on this definition, the period from 20 to 26 July 2022 was objectively identified as the most pronounced wet spell of July 2022. This period was characterized by the highest accumulated rainfall and persistent positive precipitation anomalies relative to the July climatology. In addition, operational reports issued by the Senegalese National Agency for Civil Aviation and Meteorology (ANACIM) documented widespread above-normal rainfall conditions across Senegal during this period.

2.2.2. SST Index Computing

Sea Surface Temperature (SST) data are derived from the Optimum Interpolation Sea Surface Temperature (OISST) product, which features a horizontal resolution of approximately 25 km and a daily temporal resolution, available from 1981 to the present. This dataset, also referred to as Reynolds SST, is constructed by merging observations from multiple platforms to produce a continuous, gap-free, and homogeneous field. Primary data sources include satellite sensors (AVHRR, AMSR), in situ measurements (ships, buoys), and sea ice concentration data [25] [26].

Daily SST anomalies are computed by removing the 30-year climatological mean. For the OISST version 2 product, this climatology is based on the 1971-2000 reference period [26] [27]. For a given grid point, the daily anomaly is simply the subtraction of this climatological value from the observed SST on the same day:

$$\mathrm{SSTA}(x,y,t)=\mathrm{SST}(x,y,t)-\overline{\mathrm{SST}}(x,y,day)$$

where SSTA is the SST daily anomalies, SST the observed SST, $\overline{\mathrm{SST}}$ the daily climatological SST, and x and y are spatial coordinates, and t is time (date). A positive anomaly indicates a warmer-than-normal sea surface relative to the climatological baseline, whereas a negative value indicates a cooler-than-normal sea surface.

To characterize large-scale oceanic forcing over the tropical Atlantic, two regional SST indices were computed from daily SST anomalies. The North Tropical Atlantic (NTA) index was calculated as the area-averaged SST anomaly over [14˚N - 18˚N, 25˚W - 15˚W], while the Equatorial Atlantic (EA) index was computed over [2˚S - 2˚N, 30˚W - 5˚W]. The Atlantic SST dipole index was then defined as:

$$\mathrm{SSTDI} = \mathrm{NTA} - \mathrm{EA}$$

Positive values of the SST dipole index (SSTDI) indicate anomalously warm conditions in the North Tropical Atlantic relative to the Equatorial Atlantic, whereas negative values indicate the opposite configuration. This index was used to quantify the development and evolution of the Atlantic meridional SST gradient during July 2022.

2.2.3. Tracking of AEWs and Mesoscale Convective Systems

A range of objective methodologies has been developed to automatically detect and track African Easterly Waves (AEWs), reflecting advances in dynamical diagnostics and feature-tracking algorithms. Early work established automated vorticity-centre tracking using reanalysis data [28], followed by streamfunction-based identification at 700 hPa [29] and object-oriented techniques applied to Hovmöller diagrams of curvature vorticity [30]. More flexible and scale-aware frameworks such as Tempest Extremes [31], as well as recent refinements based on convective coupling [32] and spectral discrimination of AEW modes [33], have strengthened the robustness and reproducibility of AEW climatologies.

Building on these developments, a dynamical-convective framework is adopted to analyse AEWs and their associated mesoscale convective systems (MCSs) over Senegal. AEWs are objectively detected across the broader domain (10˚N - 20˚N, 20˚W - 20˚E) using ERA5 700-hPa relative vorticity, a widely used diagnostic field for identifying AEW disturbances embedded within the African Easterly Jet [28] [34]. To isolate propagating synoptic-scale variability, the 700-hPa relative vorticity field is temporally band-pass filtered within the 2 - 6-day range, consistent with the characteristic timescales of AEW propagation [28]. Cyclonic anomalies exceeding 0.9×10^{-5} s^{-1} are identified as candidate AEWs and subsequently tracked in space and time following the objective methodology of [34]. A connectivity-based algorithm reconstructs complete wave trajectories, and only systems meeting minimum criteria of 2 days in lifetime and 500 km of westward propagation are retained. These criteria are intended to isolate coherent synoptic-scale AEWs while excluding short-lived, weakly propagating, or quasi-stationary vortical disturbances that are unlikely to contribute significantly to regional convective organization [28] [34].

Mesoscale convective systems are identified and tracked independently over Senegal using the open-source Python framework TAMS (Tracking Algorithm for Mesoscale Convective System) [11] [35], version 0.1.7. Convective cloud objects are detected using a brightness temperature threshold of 233 K. Successive cloud elements are linked through spatial overlap and propagation constraints, enabling reconstruction of full life cycles. Systems are retained as MCSs when their cold cloud shield exceeds a minimum area of 5000 km2 and persists consistently in time. For each tracked MCS, duration, cloud-top area, and associated precipitation are computed [36].

This combined dynamical-convective framework enables systematic examination of AEW structure, MCS occurrence, and rainfall contribution. The July 2022 event is analysed within a climatological baseline spanning 2000-2021, allowing comparison of AEW dynamical properties, MCS frequency, and rainfall intensity against their long-term July distributions.

2.2.4. MJO Analysis

The influence of the Madden-Julian Oscillation (MJO) on rainfall variability over West Africa is assessed using the Real-time Multivariate MJO (RMM) indices provided by NOAA [37] [38], following the methodology of [39]. These indices, based on a combined empirical orthogonal function (EOF) analysis of outgoing longwave radiation (OLR) and zonal winds at 850 hPa and 200 hPa, consist of two principal components (RMM1 and RMM2) that define the MJO phase space. Each day is classified into one of the eight canonical MJO phases, and days with an MJO amplitude greater than 1 are considered convectively active. Phase-based composites of rainfall are then computed to evaluate the modulation of convection and precipitation associated with the MJO over the region.

To establish a physical link between AEWs and convective activity over Senegal, an objective spatiotemporal matching procedure was applied between tracked AEWs and detected MCSs. For each AEW position, the distance between the AEW vortex center and MCS centroid was computed using the Haversine formula. An MCS was considered associated with an AEW when it occurred within 500 km and 24 h of the AEW position. When multiple AEWs satisfied these criteria, only the closest AEW was retained. Rainfall produced by these matched MCSs was subsequently classified as AEW-related rainfall.

3. Results and Discussion

3.1. Results

3.1.1. Eastern Atlantic SST Dipole as a Driver

The evolution of sea surface temperature (SST) anomalies over the tropical Atlantic during July 2022 reveals the progressive establishment and amplification of a meridional dipole pattern, characterized by anomalous warming in the North Tropical Atlantic (NTA) and cooling along the equatorial Atlantic (EA) (**Figure 2**). This configuration developed gradually during the second half of the month and reached its maximum intensity between 20 and 26 July, coinciding with the peak of the wet spell over Senegal.

At the onset of the event (around 20 July), positive SST anomalies were already present off the Senegalese coast, while cooler conditions prevailed along the equatorial Atlantic. This initial configuration indicates the emergence of an enhanced

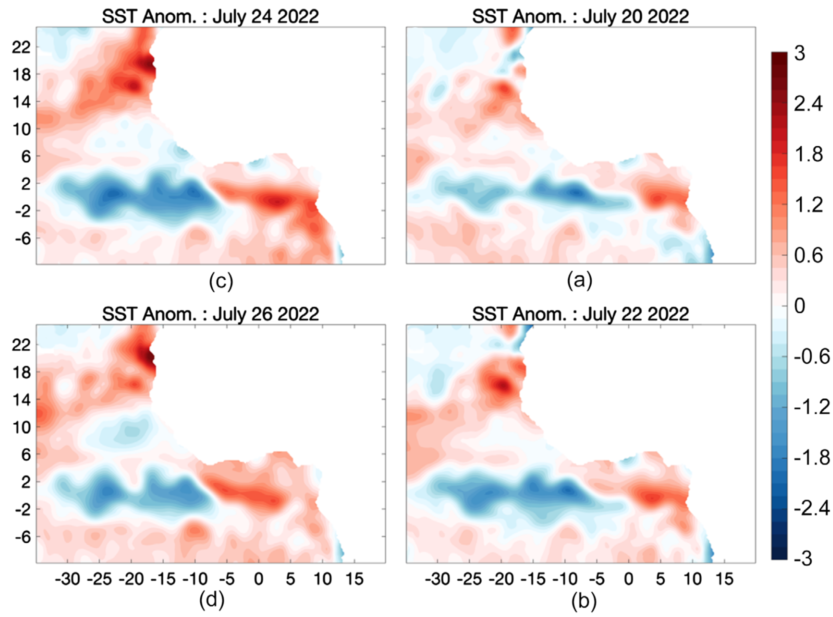

Figure 2. Daily anomalies of Sea Surface Temperature (SST) from July 20 to July 26, 2022.

zonal and meridional SST gradient. In the following days (22-24 July), the equatorial cooling intensified and extended westward, while warm anomalies persisted and expanded in the NTA, resulting in a strengthened meridional SST contrast. By 24-26 July, the dipole reached its maximum amplitude, with sustained warming in the northern basin and pronounced cooling near the equator, before slightly weakening toward the end of the event.

Such a dipole structure is known to enhance the meridional pressure gradient and strengthen the low-level monsoon flow toward West Africa. The associated intensification of southwesterly winds promotes increased moisture advection from the Atlantic into the Sahel, thereby creating a thermodynamically favorable environment for deep convection. The persistence of positive SST anomalies in the NTA further contributes to maintaining elevated surface fluxes and sustaining atmospheric instability over the region.

The temporal evolution of regional SST indices confirms this behavior, with sustained positive anomalies in the NTA and progressive cooling in the EA, leading to a peak in the SST gradient during mid-to-late July. This period coincides with the most intense rainfall episodes observed over Senegal, including the major event around 24 July. The synchronization between maximum SST contrast and rainfall intensity suggests a strong coupling between oceanic forcing and atmospheric response.

Overall, these results indicate that the eastern Atlantic SST dipole acted as a key large-scale preconditioning factor for the July 2022 event. Rather than directly triggering convection, the SST anomalies modulated the background atmospheric state by enhancing moisture availability and strengthening the monsoon circulation, thereby increasing the likelihood and efficiency of rainfall-producing systems over Senegal.

Figure 3 highlights the temporal evolution of sea surface temperature (SST) anomalies in the tropical Atlantic in July 2022. The top left panel shows the SST anomaly field on July 22, 2022, with two key regions delineated: the North Tropical Atlantic (NTA), outlined in red, and the Equatorial Atlantic (EA), outlined in blue. These boxes correspond to the domains used to compute the respective regional SST indices, as shown in the top right panel.

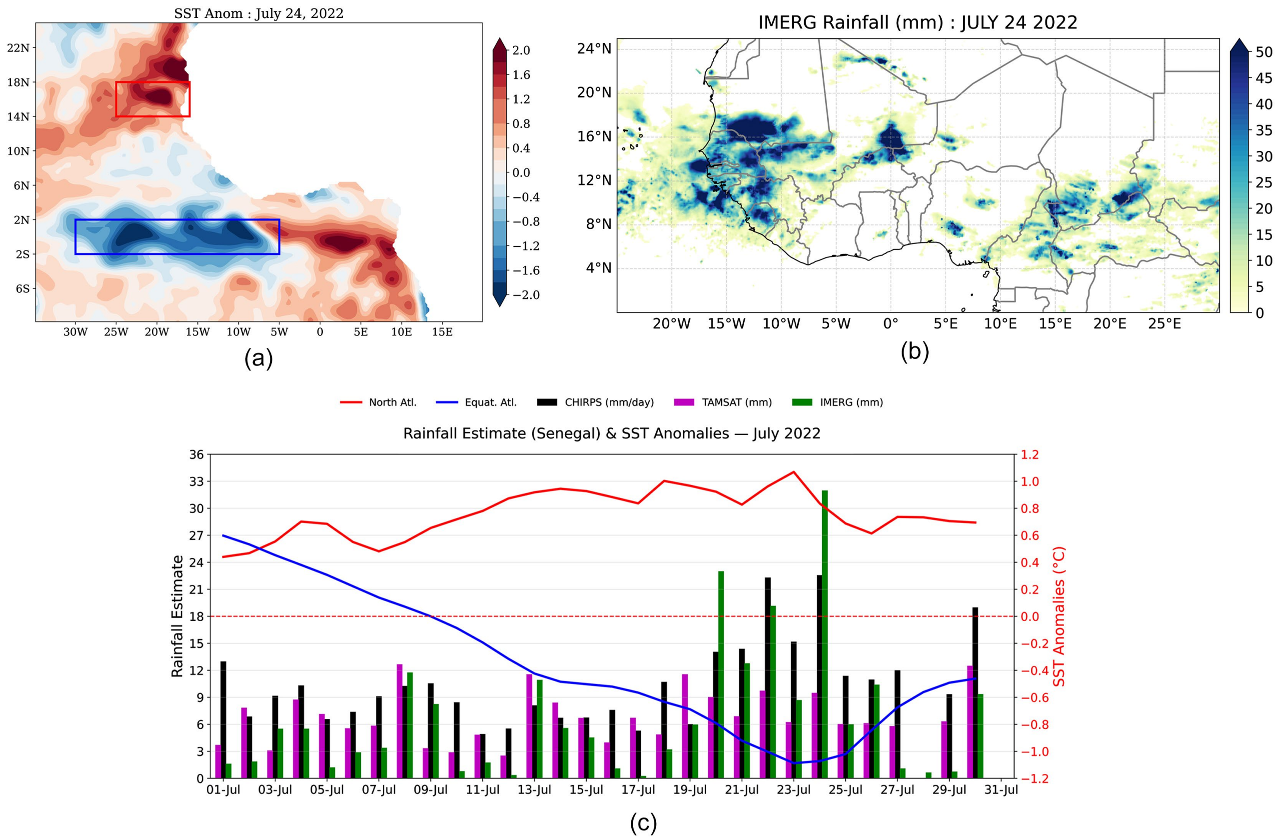

Figure 3. (a) panels: Sea Surface Temperature (SST) anomalies on July 24, 2022, highlighting the regions used to compute the indices for the North Tropical Atlantic (red rectangle) and the Equatorial Atlantic (blue rectangle). (b) panel: IMERG rainfall among (mm) over West Africa occurred on July 24, 2022. (c) panel: Averages rainfall estimates over Senegal (1-July 31, 2022) and SST anomalies: daily rainfall estimates from CHIRPS (black in mm/day), TAMSAT (magenta in mm), and IMERG (green in mm) are shown on the left axis, and, SST anomalies over the tropical Atlantic are shown on the right axis (˚C) for the North Tropical Atlantic (red) and the Equatorial Atlantic (blue).

Throughout July, the NTA region exhibited persistent positive SST anomalies, generally ranging between +0.5˚C and +1.0˚C, indicative of sustained surface warming in the subtropical northern basin. In contrast, the EA index revealed marked and progressive cooling, with anomalies intensifying from near-neutral conditions at the beginning of the month to values below −1.0˚C by July 24 before slightly recovering toward the end of the month. This contrasting behavior culminated in a pronounced meridional SST dipole, peaking in magnitude between mid- and late-July.

Rainfall estimates (bottom panel of Figure 3) revealed strong day-to-day variability, with four notable peaks occurring on July 3-July 5 7-July 9 13-15, and July 23-25. Among these, the event on July 24 stands out, with IMERG capturing nearly 35 mm/day and is moderately supported by CHIRPS and TAMSAT. The period of enhanced rainfall over Senegal (20-July 26) coincided with the strongest SST contrast between the warm NTA and cold EA, with the July 24 event occurring near the peak of this thermal dipole.

3.1.2. Moisture Transport and Precipitable Water

The evolution of moisture conditions during July 2022 reveals a coherent sequence of large-scale moistening, westward transport, and subsequent decay, closely aligned with the timing of the wet spell over Senegal (**Figure 4**). The joint analysis of total column water vapor (TCWV) and vertically integrated moisture transport highlights the central role of moisture advection and low-level convergence in sustaining deep convection during the event, consistent with previous studies emphasizing the importance of precipitable water in West African monsoon intraseasonal variability [40].

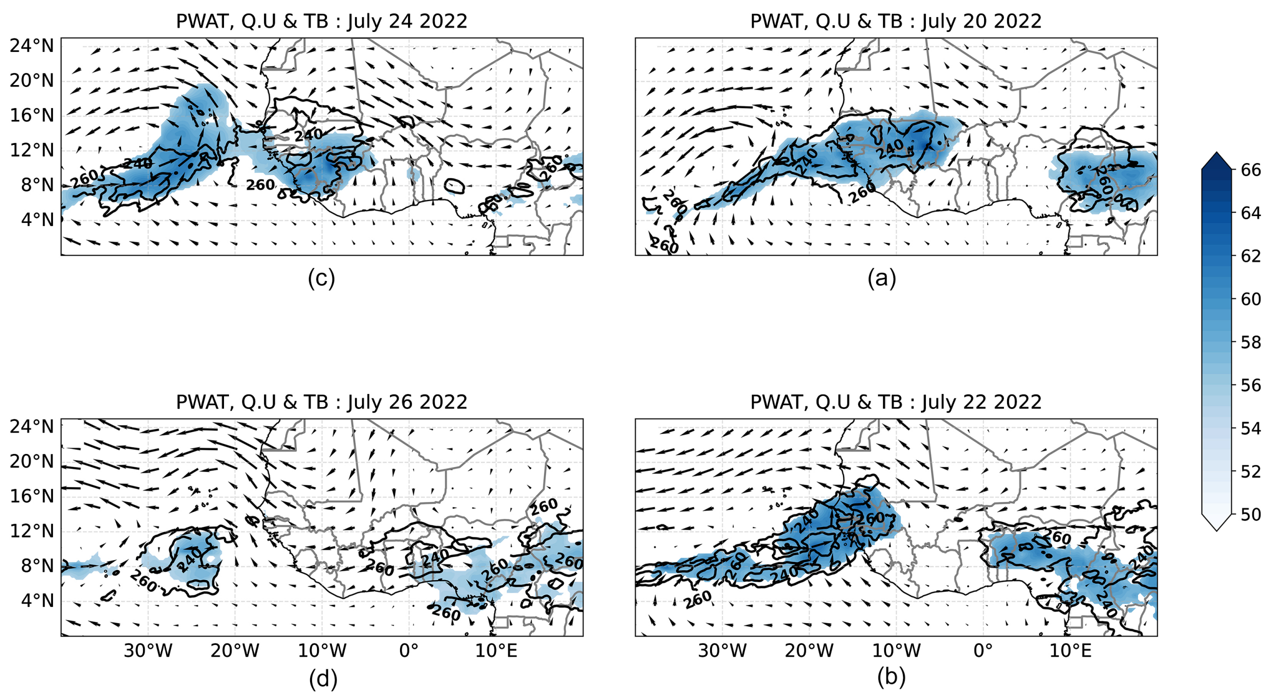

Figure 4. Total column precipitable water (PWAT, mm; shaded), vertically integrated moisture transport (vectors) between the surface and 850 hPa, and brightness temperature (TB in Kelvin; contours from 240 to 260 K with 10 K intervals) for 20 (a), 22 (b), 24 (c), and 26 (d) July 2022. The scale on the right indicates PWAT values (50 - 66).

At the onset of the episode, around 20 July, a well-defined moisture plume extended from the Gulf of Guinea toward the western Sahel, supported by a strengthened southwesterly monsoon flow. Elevated TCWV values over the region indicate enhanced moisture advection from the tropical Atlantic into continental West Africa. A secondary humid reservoir was also present farther east over central Africa, suggesting that the event developed within a broader large-scale moist environment favorable for organized convection.

Between 20 and 22 July, the primary moisture plume intensified and propagated westward in phase with an African Easterly Wave (AEW), reinforcing low-level convergence over Senegal and Gambia. This period corresponds to the peak of atmospheric moistening, with TCWV exceeding 59 mm over the region. Such values are indicative of a deeply saturated atmospheric column and therefore of conditions highly favorable for convective instability and efficient rainfall production [40]. The close alignment between enhanced moisture transport and AEW propagation points to a strong coupling between synoptic-scale disturbances and thermodynamic conditions, a feature commonly associated with intense convective episodes over West Africa [6] [41].

During the mature phase of the event, from 22 to 24 July, moisture convergence remained elevated over Senegal, maintaining conditions favorable for sustained deep convection. This interval coincides with the strongest rainfall episodes identified in the precipitation time series. The persistence of high TCWV values, together with continued low-level inflow, indicates that moisture availability did not constrain convection during this stage. Instead, the atmosphere remained continuously preconditioned for repeated triggering and organization of mesoscale systems, in agreement with studies showing that high-column moisture and persistent convergence strongly enhance convective efficiency in the Sahel [40] [42].

After 24 July, the moisture plume progressively weakened and shifted westward toward the Atlantic. TCWV values decreased over land, while low-level moisture transport weakened, signalling a transition toward less favorable convective conditions. By 26 July, most of the main moisture reservoir had moved offshore, marking the decay phase of the event and the end of the most intense rainfall period over Senegal.

This temporal sequence points to a persistent and dynamically organized moisture supply, in which enhanced monsoon inflow and AEW-related convergence jointly maintained a deep, moisture-rich atmospheric column over the region. Such conditions favored repeated convective development and likely contributed to the cumulative character of the extreme rainfall observed over Senegal, consistent with the multi-scale interpretation proposed for major West African rainfall extremes.

Figure 5 shows the vertical cross-sections of relative humidity (colour shading, %) and zonal wind (contours, $m \cdot s^{-1}$), averaged over the longitudes of Senegal, for July 20, 22, 24, and 26. The lower panels show the latitudinal profile of the SST index, defined as the difference between the North Tropical Atlantic (NTA) and Equatorial Atlantic (EA) SST anomalies (˚C) for the corresponding dates. On all four days, the lower and mid-troposphere (850 - 600 hPa) exhibited strong meridional gradients in relative humidity, with relatively dry air to the north between 15˚N and 25˚N and deep moist layers extending equatorward.

Relative humidity increased significantly on July 24th and 26th, when a deep, vertically continuous humid column developed at approximately 12˚N, consistent with an enhanced monsoonal inflow.

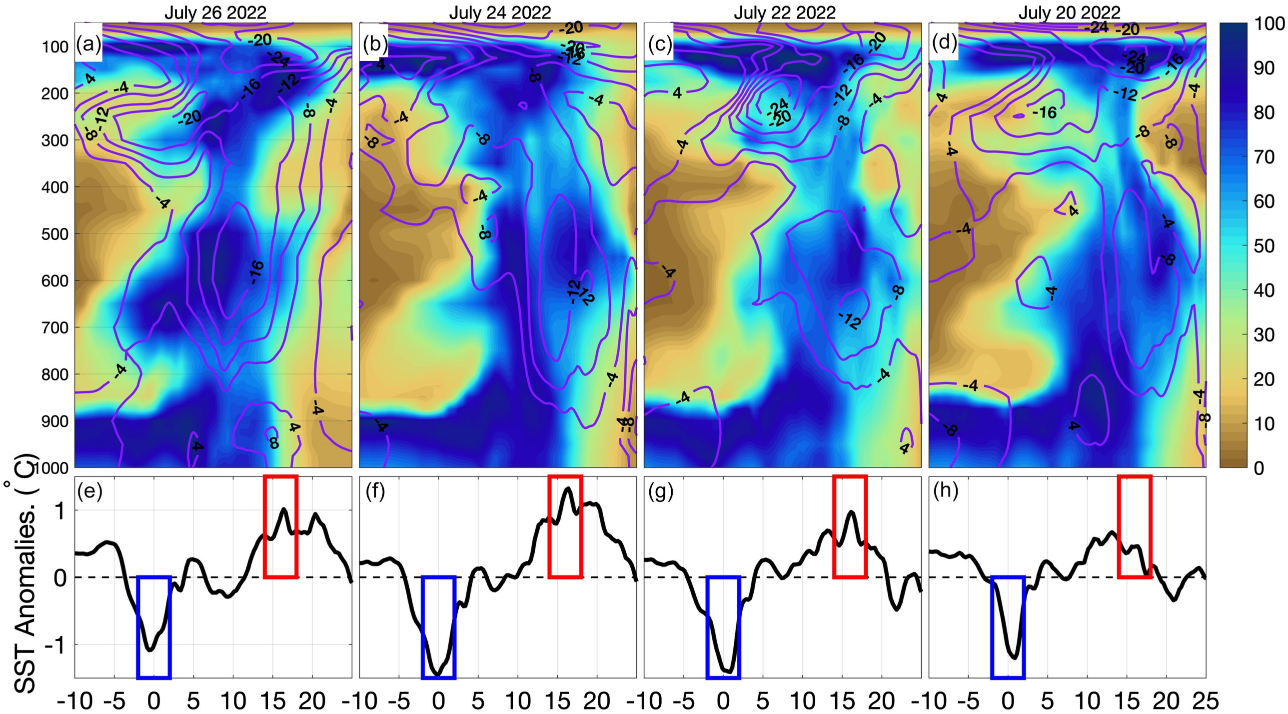

Figure 5. Top: vertical cross-section (latitude-altitude) of relative humidity (color, %) and zonal wind (contour, m/s) average over 6˚W-0˚W. Bottom: SST index (North tropical Atlantic minus Equatorial Atlantic anomalies), from right to left: July 20, 22, 24 and 26, 2022. Red and blue rectangles show north-eastern Atlantic and equatorial Atlantic latitude bands, respectively.

Superimposed zonal wind contours show the strengthening and vertical extension of the African Easterly Jet (AEJ), characterised by negative (easterly) wind maxima at approximately 600 - 700 hPa. The AEJ core was weaker and displaced northward on July 20 but became more intense and better defined by July 22-26. Enhanced easterlies in the mid-troposphere coincided with elevated humidity on the southern flank of the jet, suggesting improved dynamic support for deep convection. On 24 and July 26 the combination of a moister lower troposphere and intensified easterlies indicated a more favorable environment for convection and potential AEW development or amplification.

The lower panels show the latitudinal SST index (NTA minus EA SST anomalies). Negative values (blue boxes) indicate relative cooling of the NTA compared to the Equatorial Atlantic, whereas positive values (red boxes) correspond to a warmer NTA. The sign of the index alternated across the sequence, but a notable feature was the pronounced positive peaks on July 22 and 26. These warm NTA anomalies coincide with stronger humidity and an enhanced AEJ structure aloft, suggesting a possible ocean-atmosphere coupling: when the NTA is relatively warm, the monsoonal flow and mid-tropospheric easterlies appear to be strengthened, and the atmospheric column shows deeper moistening.

The figure highlights a consistent relationship between SST-driven meridional thermal contrasts, the AEJ structure, and atmospheric humidity modulation over Senegal during this period. Episodes of positive SST-index anomalies (warm NTA) align with a deeper moist layer and intensified AEJ, producing a more favourable environment for convection and potentially for the organisation or modulation of mesoscale systems in the region.

3.1.3. Role of African Easterly Waves and Mesoscale Convective Systems in the July 2022 Wet Spell

Figure 6 illustrates a longitude-time (Hovmöller) diagram of the 2 - 6-day band-pass-filtered relative vorticity at 700 hPa for July 2022, overlaid with African Easterly Wave (AEW) tracks. The diagram highlights a coherent succession of westward-propagating vorticity anomalies originating over continental West Africa and extending into the eastern tropical Atlantic, a hallmark of active AEW dynamics during the boreal summer season.

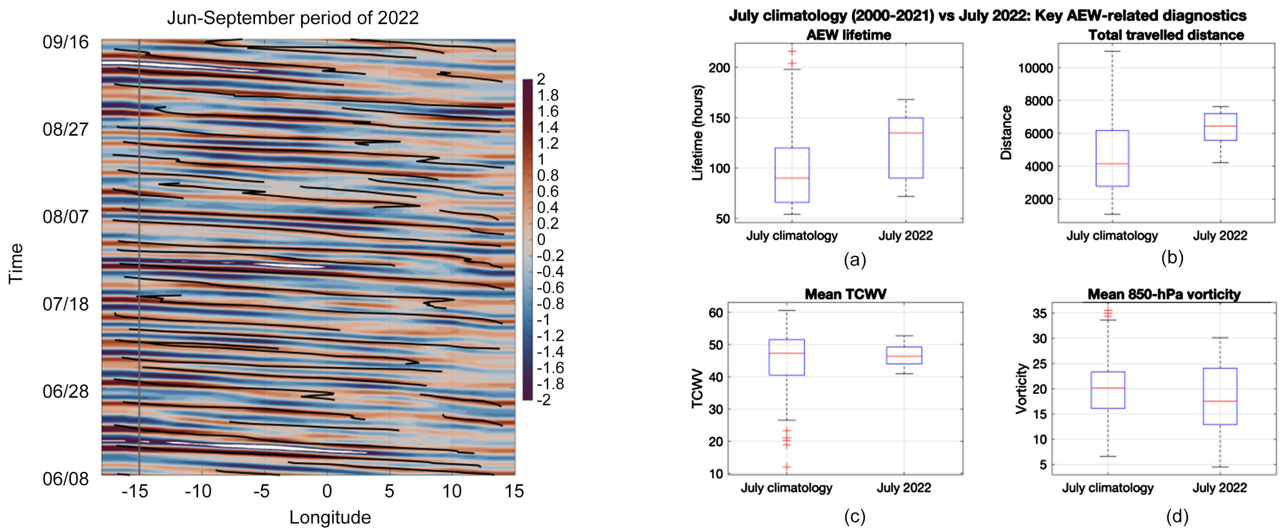

Figure 6. (Left) Hovmöller diagram of 700-hPa relative vorticity ($\times10^{-5}$ s^{-1}) averaged over the 5˚N - 15˚N West African band for July 2022, illustrating the westward propagation of African Easterly Waves (AEWs). Red (blue) shading indicates cyclonic (anticyclonic) vorticity anomalies. Black contours highlight selected AEW tracks, while vertical dashed line indicates the West African coastline. (Right) Comparison between July climatology (2000-2021; JJ) and July 2022 for key AEW-related diagnostics: (a) AEW lifetime (hours), (b) total travelled distance (km), (c) mean total column water vapor (TCWV; kg·m^{-2}), and (d) mean 850-hPa relative vorticity ($\times10^{-5}$ s^{-1}). Boxplots display the median (red line), interquartile range (box), whiskers (range), and outliers (red crosses). Vertical dashed lines separate the climatological distribution from the July 2022 case.

Alternating bands of cyclonic (positive) and anticyclonic (negative) relative vorticity were visible throughout the month, forming a quasi-periodic wave train. The consistent westward tilt of these bands indicates regular phase propagation with no prolonged interruptions, suggesting sustained AEW activity over the region in July 2022. The inferred propagation speed was comparable across successive waves, consistent with the climatological AEW phase speeds.

The detected AEW trajectories closely aligned with the cores of positive 700-hPa relative vorticity, demonstrating a strong coherence between the objectively tracked waves and the underlying dynamical signal. This correspondence confirms that the identified AEWs are associated with coherent mid-tropospheric cyclonic disturbances rather than transient or localized vorticity features.

Although the amplitude of the vorticity anomalies remained moderate, several cyclonic bands persisted over multiple days and spanned a large longitudinal range. In particular, from approximately 18 to July 26 successive AEWs exhibited enhanced temporal continuity, forming an almost uninterrupted sequence of westward-propagating disturbances. This period coincided with the peak of the wet spell over Senegal, as well as with the maximum values of total column water vapor and repeated rainfall peaks identified in the precipitation time series.

Overall, the Hovmöller analysis highlights that the exceptional rainfall observed over Senegal in July 2022 was associated with a sustained train of AEWs embedded within a persistently favorable large-scale environment, rather than with isolated, unusually intense wave events. The repeated passage of dynamically coherent AEWs likely contributed to the cumulative nature of the rainfall through the successive triggering and organization of mesoscale convective systems. These results suggest that the July 2022 wet spell was primarily driven by the persistence and repetition of AEW disturbances interacting with a moisture-rich background state, rather than by extreme enhancements in wave intensity.

The Hovmöller diagram highlights a sequence of well-organized, westward-propagating vorticity anomalies, with enhanced coherence and persistence during mid-to-late July 2022. This synoptic-scale signal is quantitatively reflected in panel (a), which shows a marked increase in AEW lifetime. Median lifetimes rise from approximately 90 h in the climatological distribution to about 135 h in July 2022, with a reduced overlap between the two distributions. This indicates that AEWs in July 2022 were not only more frequent in their expression along the longitude-time plane but also dynamically more persistent, consistent with the prolonged vorticity bands evident in the Hovmöller diagram.

Panel (b) further shows that AEWs in July 2022 travelled significantly longer distances than their climatological counterparts. The upward shift of the distribution suggests that the enhanced lifetime translated into longer westward propagation paths, supporting the interpretation of robust and sustained AEW activity across West Africa and into the eastern Atlantic. This behaviour is consistent with the continuous diagonal structures observed in the Hovmöller diagram, indicative of uninterrupted wave propagation.

To assess whether these differences are statistically significant, a Mann-Whitney rank-sum test was applied to compare July 2022 AEW characteristics with the July climatological distribution. The results indicate that AEW lifetime ($p = 0.0138$) and travelled distance ($p = 0.0037$) were significantly larger in July 2022 than in the climatology, confirming that AEWs persisted longer and propagated farther westward during the event. In contrast, differences in total column water vapour (TCWV; $p = 0.8349$) and mean 850-hPa relative vorticity ($p = 0.5712$) were not statistically significant. These results suggest that the exceptional nature of July 2022 was primarily related to enhanced AEW persistence and propagation rather than to unusually strong moisture content or stronger instantaneous wave intensity.

The thermodynamic environment associated with these AEWs is illustrated in panel (c). Although July 2022 was characterized by consistently moist atmospheric conditions, the TCWV distribution does not differ significantly from the climatological distribution (p = 0.8349). The relatively narrow spread of TCWV values suggests a more homogeneous moist environment, conducive to deep convection along AEW troughs. The coincidence of elevated moisture content with coherent vorticity maxima in the Hovmöller diagram supports the notion of strong coupling between AEW dynamics and moisture availability during the event.

In contrast, panel (d) shows that the mean 850-hPa relative vorticity associated with AEWs in July 2022 is comparable to, or slightly weaker than, climatological values. This indicates that the exceptional rainfall cannot be attributed solely to stronger instantaneous wave intensity. Rather, it is the combination of increased persistence, longer propagation distances, and a moisture-rich environment that appears to be critical.

In conclusion, the Hovmöller diagram and the statistical distributions in Figure 6 suggest that the July 2022 wet spell over Senegal was driven by long-lived, coherently propagating AEWs embedded in an anomalously moist large-scale environment, rather than by unusually intense vorticity amplitudes alone. This highlights the importance of AEW persistence and moisture coupling as key modulators of extreme rainfall events over West Africa.

Figure 7 shows a comparison between the July climatology (2000-2021) and July 2022 in terms of MCS-related precipitation and frequency. Panel (a) indicates that daily precipitation associated with MCSs exhibits a slight upward shift in July 2022, with higher median values and an increased occurrence of moderate-to-high rainfall amounts compared to the climatology. Although extreme outliers remain more frequent in the climatological distribution, the overall distribution in 2022 suggests more consistently elevated precipitation.

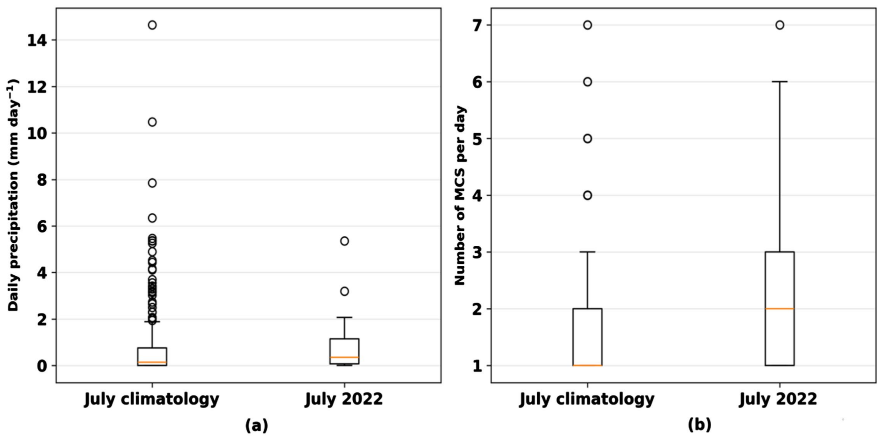

Figure 7. Comparison between July climatology (2000-2021) and July 2022 for mesoscale convective system (MCS) activity over the study region. (a) Daily precipitation associated with MCSs (mm/day). (b) Daily number of MCSs. Boxplots display the median (orange line), interquartile range (box), whiskers (range), and outliers (circles). July 2022 is characterized by a shift toward higher MCS frequency and enhanced daily precipitation compared to the climatological distribution, highlighting the anomalous convective activity during this period.

The comparison between July 2022 and the July climatology over the Dakar region reveals a coherent and physically consistent signal in both daily MCS precipitation intensity and system frequency. July 2022 stands out as an anomalously wet month, not only in terms of accumulated rainfall but also in the daily characteristics of convective activity.

The distribution of daily MCS-related precipitation exhibits a clear upward shift relative to the climatology. The median daily precipitation is higher, and the interquartile range is broader, indicating both more intense typical events and enhanced day-to-day variability. This suggests that MCSs in July 2022 were not only producing more rainfall on average, but also contributing to a more variable and intermittently intense precipitation regime.

In parallel, the daily number of MCSs is significantly increased compared to climatological conditions. The median frequency is higher, and the upper tail of the distribution reveals several days with unusually large numbers of systems. This points to enhanced convective activity and more frequent triggering of organized systems. Such an increase in MCS frequency is consistent with favorable large-scale conditions, including strengthened monsoon flow, enhanced low-level moisture convergence, and increased African Easterly Wave activity during active phases of the West African monsoon [43] [44].

The combined behaviour of these two variables highlights a compound mechanism underlying the exceptional wetness of July 2022. The rainfall anomaly results from both a higher occurrence of MCSs and increased rainfall production per system. This dual contribution is particularly relevant from a hydrological perspective: frequent MCS occurrences reduce soil infiltration capacity, while intense rainfall enhances surface runoff, thereby increasing flood risk in urban coastal environments such as Dakar. Similar compound processes have been identified as key drivers of extreme flood events across the Sahel and coastal West Africa [45].

Overall, these results indicate that July 2022 reflects a shift toward a regime characterized by more frequent and more intense organized convective systems, rather than a simple increase in background precipitation.

3.1.4. MJO Modulation of the July 2022 Extreme Rainfall Event over Senegal

The July 2022 prolonged wet spell that brought exceptional rainfall to Senegal naturally raised questions about what large-scale atmospheric patterns may have contributed to this extreme event. This analysis explores the possible role of the Madden-Julian Oscillation (MJO), a slow-moving tropical disturbance that travels around the globe and influences rainfall patterns across many regions. By tracing the MJO's path through its eight distinct phases and comparing its behavior with daily rainfall records over Senegal, we aim to determine whether the wet spell was merely a local anomaly or part of a larger, more predictable atmospheric rhythm. Together with the AEWs that often spark deep convection over the region, these large-scale and local phenomena appear to have conspired to produce the remarkable rains of late July 2022.

1) MJO phase evolution during July 2022

The phase-space diagram of the Madden-Julian Oscillation based on the Real-time Multivariate MJO (RMM) index of Matthew Wheeler and Harry Hendon illustrates the intraseasonal evolution of tropical convection during July 2022 (Figure 8). The trajectory of the RMM index in the RMM1-RMM2 phase space shows that MJO activity during the first half of the month was relatively weak, with most points located near or within the unit circle (amplitude < 1), indicating limited intraseasonal forcing.

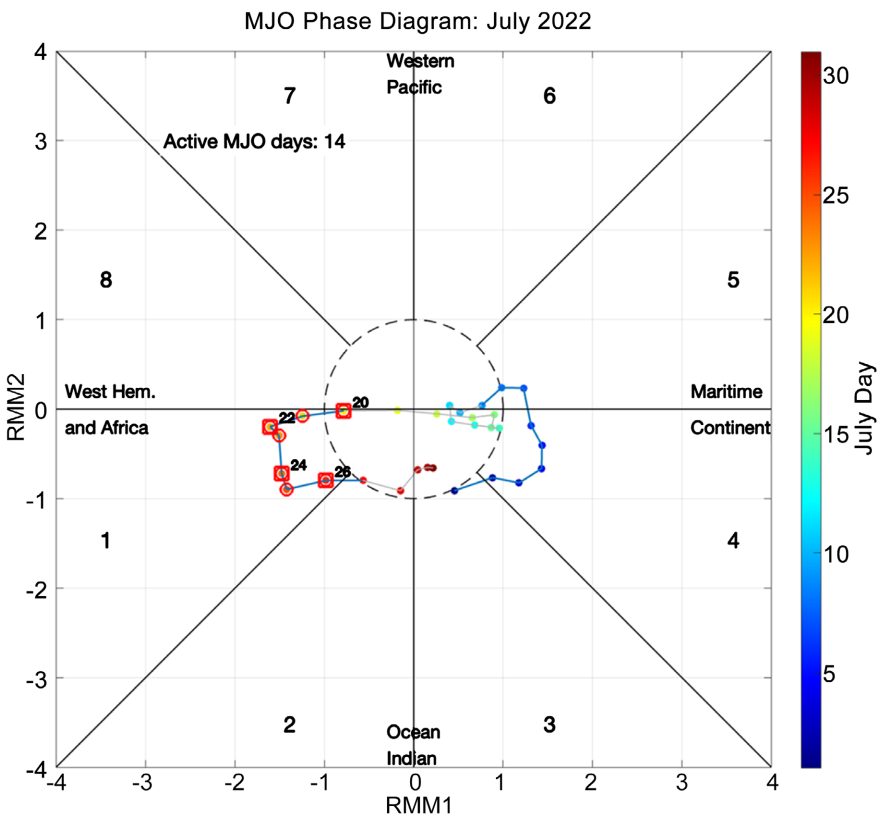

Figure 8. MJO phase diagram (RMM1 vs. RMM2) for July 2022. The gray dashed circle marks the unit amplitude (amplitude = 1). The trajectory is colored by day of the month (colorbar). Days with MJO amplitude > 1 (active MJO) are shown with bold symbols; the wet spell period (20-26 July) is highlighted by red circles, and the specific dates 20, 22, 24, and 26 are marked with black squares. Regional labels indicate the approximate geographical locations of enhanced convection associated with each quadrant. Phase numbers (1 - 8) are positioned around the unit circle according to the Wheeler-Hendon convention.

During the second half of July, the MJO signal strengthened and propagated westward from phases 6 - 7 toward phases 8 - 1, corresponding to the Atlantic-African sector. Approximately 14 days during the month exhibited amplitudes exceeding the unit threshold, indicating active MJO conditions. The main wet spell over Senegal (20-26 July) occurred when the MJO was primarily located in phases 8 - 1, a configuration typically associated with enhanced convection and large-scale ascent over West Africa.

2) MJO's role in driving the wet spell

Figure 9 shows daily rainfall over Senegal from the CHIRPS precipitation dataset together with the amplitude of the MJO derived from the RMM index of Matthew Wheeler and Harry Hendon. The dashed line marks the amplitude threshold of 1, separating active from weak MJO conditions. Rainfall during the first half of July was generally moderate while MJO activity remained weak or near the threshold. This period corresponds to relatively weak intraseasonal forcing, consistent with the limited rainfall variability observed during these days. A clear transition occurs after 19 July, when the MJO amplitude increases and remains above 1 for several days. This period coincides with the main wet spell over Senegal (20-26 July), including peaks exceeding 20 mm/day, during which several intense rainfall events were recorded.

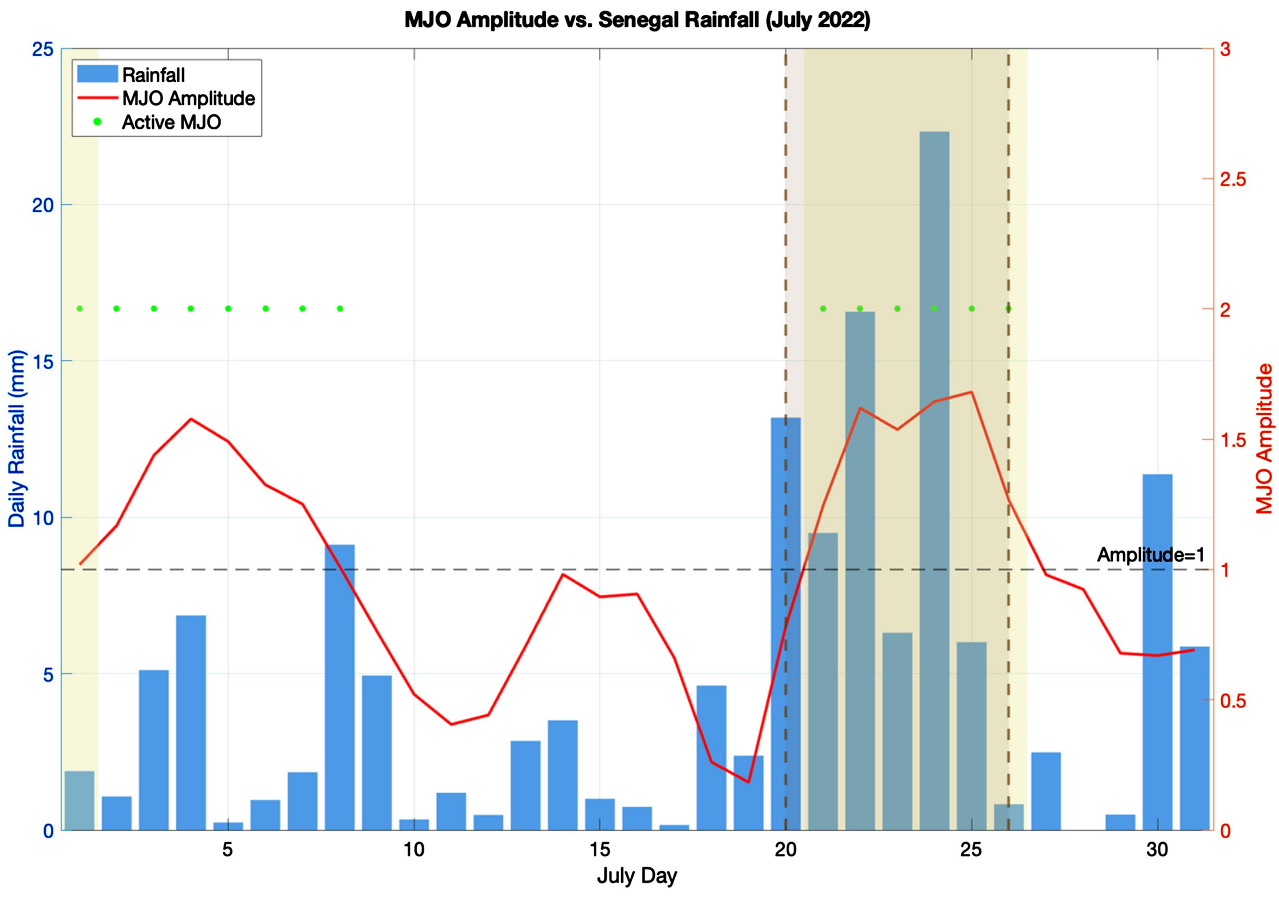

Figure 9. Time series of daily rainfall from Chirps datasets (over Senegal (CHIRPS; blue bars, left axis) and MJO amplitude (red line, right axis) over Senegal during July 2022. Here the green dots indicate active MJO days (amplitude > 1), scaled to a value of 2 for visibility). Yellow shaded areas mark days when the MJO was active and in phases 1-3 or 8, which are known to favor enhanced convection over West Africa. The 20-26 July shading highlights MJO phases favorable to convection (phases 1-3 and 8). The wet spell (20-26 July) is highlighted marked by vertical dashed brown lines and a light brown transparent fill. The wet spell shading and coincides with elevated enhanced MJO amplitude and active MJO days in conducive phases activity, suggesting a modulating role of the MJO in this rainfall event.

Most of these rainfall events occurred when the MJO was active and located from phases 8, 1 and 2 (yellow shaded intervals), which are typically associated with enhanced convection over the Atlantic-West African sector. This configuration likely strengthened monsoon moisture convergence and created favorable conditions for deep convection. The timing of the wet spell also coincides with increased African Easterly Waves activity, suggesting that the MJO acted as a large-scale modulator that enhanced the development of Mesoscale Convective Systems responsible for the extreme rainfall.

This intraseasonal configuration likely contributed to strengthening the monsoon inflow and increasing low-level moisture convergence over the region. The timing of the active MJO phase also coincided with enhanced AEWs activity identified earlier, suggesting that the MJO provided a favorable large-scale environment for the development and organization of MCS. Overall, the phase-space evolution indicates that intraseasonal variability likely contributed to the atmospheric conditions that favored the extreme rainfall event over Senegal in late July 2022.

In addition, the July 2022 wet spell over Senegal coincided with active MJO conditions in phases 1 - 3, the window known to favor enhanced convection over West Africa. During this period, the MJO likely strengthened the AEJ and deepened moisture convergence, creating a large-scale environment where passing AEWs could trigger sustained, organized rainfall. While the positive Atlantic SST dipole may have preconditioned the region earlier, the MJO provided the crucial intraseasonal boost that transformed an ordinary rainy stretch into an exceptional wet spell. These findings highlight the MJO's value as a forecasting tool: when active and positioned in phases 1 - 3, the risk of prolonged rainfall events across Senegal increases information that can support agriculture, water management, and disaster preparedness across the region.

4. Discussion

The July 2022 wet spell over Senegal provides a clear example of a multi-scale hydroclimatic event resulting from the interaction between oceanic forcing, synoptic dynamics, and intraseasonal variability. The results indicate that extreme rainfall in this case emerged from the constructive coupling of processes operating across different spatial and temporal scales.

This multi-scale behavior is consistent with previous studies over West Africa. In particular, [6] showed that the extreme rainfall event over Ouagadougou in 2009 resulted from the alignment of favorable conditions across large-scale oceanic forcing, synoptic disturbances such as African Easterly Waves (AEWs), and mesoscale convective organization. Their study emphasized that no single mechanism alone can explain extreme rainfall events, but rather the combination of processes across scales.

At the large scale, the presence of a pronounced tropical Atlantic SST dipole, characterized by anomalous warming in the North Tropical Atlantic (NTA) and cooling along the equatorial Atlantic (EA), played a key preconditioning role.

Such SST gradients are known to strongly influence rainfall variability over the Sahel through modulation of monsoon circulation and moisture transport. In particular, [46] demonstrated that warming in the northeastern tropical Atlantic induces a cyclonic circulation in the lower troposphere, enhances moisture transport toward West Africa, and increases precipitable water, thereby favoring deep convection, especially over the western Sahel and Senegal. This mechanism is consistent with the elevated total column water vapor observed during the July 2022 event and supports the interpretation of SST anomalies as a key driver of the favorable large-scale environment.

Superimposed on this thermodynamically favorable background, AEWs exhibited anomalous dynamical characteristics. Rather than showing increased instantaneous intensity, AEWs during July 2022 were characterized by enhanced persistence and longer propagation distances. This result aligns with previous work demonstrating that AEWs play a central role in organizing convection over West Africa through cyclonic troughs and wave-induced vorticity maxima, particularly when interacting with a moisture-rich monsoon flow and strong low-level convergence [47]. Recent case studies over Senegal further show that AEW-related cyclonic circulations can substantially enhance extreme rainfall when accompanied by high precipitable water and vertically integrated moisture transport [41].

In particular, the Dakar 2020 event analyzed by [41] demonstrated that successive AEW-like disturbances can prolong rainfall episodes by maintaining a continuous supply of moisture and sustaining convective instability. This mechanism highlights that AEW persistence and interaction with the background environment may be as important as wave intensity in controlling rainfall extremes. This interpretation is also consistent with regional analyses of extreme rainfall over Dakar and Ouagadougou, which emphasize the key role of atmospheric dynamics and organized convection in flood-producing events [42].

Accordingly, the sustained sequence of AEWs observed between 18 and 26 July 2022 suggests that wave persistence, rather than amplitude alone, was a key driver of cumulative rainfall over Senegal. In our case, the repeated westward propagation of AEWs within an anomalously moist environment likely promoted repeated triggering of organized convection, thereby increasing both mesoscale convective system (MCS) occurrence and rainfall production.

Unlike the Ouagadougou 2009 event described by [6], which was associated with a single intense mesoscale system, the July 2022 event over Senegal appears to reflect a persistence-driven regime in which successive AEWs repeatedly interacted with a favorable large-scale environment. This distinction suggests that extreme rainfall over West Africa can arise from at least two dynamical regimes: 1) isolated high-intensity events associated with mesoscale vortex development, and 2) prolonged wet spells driven by successive synoptic disturbances, as observed in this study.

At the mesoscale, the increased persistence of AEWs translated into both a higher frequency of MCSs and enhanced rainfall intensity per system. This compound behavior is consistent with previous studies indicating that extreme rainfall in the Sahel is often associated with organized convection and increases in both system frequency and intensity [1] [18]. The results therefore support the hypothesis that extreme events arise not only from stronger individual systems, but also from the repeated occurrence of organized convection under favorable large-scale conditions.

In addition to these large-scale and synoptic processes, intraseasonal variability associated with the Madden-Julian Oscillation (MJO) played a significant modulating role. The main wet spell (20-26 July) occurred during an active MJO phase (phases 8, 1, and 2), which is known to favor enhanced convection over West Africa through increased large-scale ascent and moisture convergence [3] [4]. While the MJO did not act as the primary driver of the event, it likely amplified the convective response by reinforcing the already favorable thermodynamic and dynamical conditions.

These findings support a conceptual framework in which extreme rainfall over Senegal results from the combined influence of three key mechanisms: 1) a thermodynamically favorable background state induced by SST anomalies, 2) persistent synoptic disturbances linked to African Easterly Waves (AEWs), and 3) intraseasonal variability associated with the Madden-Julian Oscillation (MJO). The interaction of these processes promotes a sustained and highly efficient convective environment, marked by frequent and intense mesoscale convective system (MCS) activity.

This multi-scale interaction has important implications for predictability. SST anomalies evolve relatively slowly and can provide a source of subseasonal predictability, while AEW activity and MJO phase offer additional dynamical constraints. In particular, periods characterized by persistent AEW activity combined with active MJO phases may represent windows of enhanced risk for extreme rainfall events in West Africa.

5. Conclusions

This study investigated the hydroclimatic mechanisms underlying the exceptional wet spell observed over Senegal in July 2022, with a focus on the interaction between large-scale oceanic forcing, synoptic disturbances, and mesoscale convective processes.

The results show that the event developed within a favorable large-scale environment associated with a pronounced tropical Atlantic SST dipole. This configuration enhanced the meridional SST gradient, strengthened the monsoon circulation, and increased atmospheric moisture availability over West Africa. Within this environment, African Easterly Waves exhibited enhanced persistence and longer propagation distances, leading to a sustained sequence of disturbances across the region.

At the mesoscale, this dynamical configuration resulted in both an increase in the frequency of mesoscale convective systems and enhanced rainfall production per system. The combined effect of these processes produced a cumulative amplification of rainfall, consistent with the observed extreme conditions.

The analysis further indicates that the exceptional nature of the event cannot be attributed to increased AEW intensity alone. Instead, the persistence of AEWs within a moisture-rich environment emerges as a key mechanism driving the prolonged and intense rainfall over Senegal. Intraseasonal variability associated with the Madden-Julian Oscillation likely contributed by reinforcing convection during its active phase, further amplifying the event.

These findings emphasize that extreme rainfall over West Africa results from the alignment of favorable conditions across multiple scales, rather than from isolated processes. This multi-scale perspective provides a more comprehensive framework for understanding and predicting extreme hydroclimatic events in the region.

Future work should focus on evaluating the predictability of such compound events using coupled modelling approaches and high-resolution regional simulations. Improving the representation of AEW persistence, moisture transport, and intraseasonal variability in numerical models will be essential for enhancing early warning systems and supporting climate risk management strategies in West Africa.

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Conflicts of Interest

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

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