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Changing Characteristics of Extreme Precipitation during Tanzania's Long Rain Season

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Abstract

The long rain season from March to May (MAM) is a critical contributor to water resources, agriculture, and ecosystem sustainability in Tanzania, yet it is increasingly characterized by high interannual variability, alternating between severe droughts and damaging floods. This study aims to examine the spatial and temporal variability of extreme precipitation during Tanzania's long rainfall season over the period 1981-2024 and to identify dominant modes of variability and large-scale climate drivers influencing these extremes. Daily rainfall data from the Climate Hazards Group InfraRed Precipitation with Stations dataset (CHIRPS) at 0.25˚ resolution were used to compute six precipitation extreme indices describing both wet and dry conditions. Climatological results show that consecutive dry days exceed 50 days in the western and southwestern highlands, while values below 40 days dominate the northern, eastern, and southern highlands. Total seasonal rainfall exceeds 200 mm in the northern regions, coastal areas, and southwestern highlands, but remains near 50 mm over the central and northeastern highlands, with maximum five-day rainfall totals exceeding 80 mm along the coast and in the southwestern highlands. Trend analysis reveals increasing consecutive dry days at rates of 0.2 - 0.6 in parts of central and northeastern Tanzania, while decreasing trends of −0.2 to −0.8 occur south of Lake Victoria. Total rainfall on wet days increases by more than 0.5 mm per year over most of the country, accompanied by increases in rainfall intensity and very heavy rainfall frequency. The leading mode of total rainfall explains 37.5 percent of the variance and shows a significant increase after 2000, while wet-spell persistence is significantly linked to the Indian Ocean Dipole with a correlation coefficient of 0.34. Overall, the results indicate a shift towards wetter but more unpredictable long rain seasons emphasizing the need for improved climate adaptation and disaster risk management strategies.

Keywords

Precipitation Extreme Indices, Long Rain Season, Spatial and Temporal Variability

1. Introduction

The urgency of climate change necessitates a global focus on extreme weather events, which represent a critical worldwide challenge driven by a complex interplay of atmospheric circulation, ocean-atmosphere interactions, and local geographical fact (Bobde et al., 2024). These events including intense rainfall, prolonged dry spells, and regional flooding significantly influence water availability, agriculture, and overall socio-economic stability, especially in regions where livelihoods depend on rain-fed agricultural systems, pastoralism and fishery which affect economic growth, and subsequently threatening the achievement of sustainable development among individuals, countries, and the region as a whole. (Mtewele et al., 2021; Chabaga et al., 2025). Extreme events are becoming increasingly pronounced and impactful, creating severe shocks to global human and natural systems

Africa is very vulnerable to extreme weather and climate which is exacerbated by its high exposure and low coping capacity whose precipitation extremes vary widely across regions (Niang et al., 2014; Kazora et al., 2025*)*. Africa's vulnerability to precipitation extremes is exacerbated by limited resources and infrastructure to mitigate climate risks, making it crucial to understand the atmospheric systems behind these changes (Mtewele et al., 2021). The spatial distributions in mean trends of extreme precipitation indices in the region have shown a tendency toward decreased extreme precipitation in North Africa, Sahel region, Central Africa and the Western part of South Africa. Conversely, West Africa, East Africa and the Eastern part of South Africa exhibit an inclination toward increased extreme precipitation (Habiyakare et al., 2024).

East Africa has already experienced climate-related challenges, such as frequent, longer, and more severe droughts in the last two decades, particularly the 2010-2011 East African drought when famine plunged several countries into a humanitarian crisis (Borhara et al., 2020) and plagued by frequent floods that have displaced many people and loss of lives (Mafuru & Guirong, 2018; Chang'a et al., 2017; Calvin et al., 2023).

In Tanzania the march-may (MAM) rainfall season is the dominant rains season (Masika) which contributes to significant portion of the annual rainfall which plays a great role in water retention and harvest, supporting crop growth and sustaining natural ecosystems (Chang'a et al., 2017). The MAM rainfall season provides the most significant rainfall amounts, particularly over coastal and northeast areas, while OND generally contributes less compared to MAM (King'uza et al., 2025). However, this crucial season is characterized by high interannual variability, frequently fluctuating between episodes of devastating floods and periods of severe drought (Chang'a et al., 2017; Kazora et al., 2025). The impacts of these extremes are already severe whereby the total volume of the (MAM) long rain season is observed to experiencing a significant decrease across the country though extreme precipitation events are observed to simultaneously increase in frequency and intensity (Chang'a et al., 2017; Chang'a et al., 2020b; Makula & Zhou, 2022).

While existing research such as (Borhara et al., 2020; King'uza & Limbu, 2019) focused on general annual, seasonal rainfall or drought indices, there is a critical lack of focused understanding on the interannual variation of precipitation extremes specifically during the long rains season. A significant knowledge gap exists concerning the detailed characteristics of these extremes, including their frequency, intensity, spatial distribution, and how these attributes change from year to year. This study systematically quantifies and compares the long-term trends and spatial variability of 6 diverse indices using the recommendations of the Expert Team on Climate Change Detection and Indices (ETCCDI) indices across Tanzania during long rains (MAM). The detailed comparative approach will provide a novel spatial distribution of extreme indices in different regions across Tanzania. The main research question focuses on how the spatiotemporal characteristics of precipitation extremes in Tanzania during long rain season MAM (March-April-May) including their distribution, frequency, and intensity? are there any observed statistically significant trends in interannual temporal patterns of the MAM precipitation extremes in Tanzania during 1981-2024?

2. Data and Methodology

2.1. Study Area

The study area for this research is the United Republic of Tanzania, situated in East Africa, spanning a significant area between approximately 1˚S and 12˚S latitude and 28˚E and 42˚E longitude (**Figure 1**). The climate of Tanzania is comprised of unimodal and bimodal regimes which, are characterized by strong spatial and temporal variability of rainfall with two distinct rainfall seasonal of MAM and October-December (OND) (Chang'a et al., 2010; Makula & Zhou, 2022; Kijazi & Reason, 2009; Chang'a et al., 2020a). The variability of rainfall is contributed by its diverse topography, including the East African Rift Valley, water bodies such as the Indian Ocean and major lakes, and high mountains like Mount Kilimanjaro (Luhunga et al., 2016). The bimodal regime includes Lake Victoria basin, northern eastern highlands and northern coastal regions, experiences two distinct rainy seasons, including the long rains of MAM and the short rain season of OND meanwhile, the unimodal regime, prevalent across the central, western, southwestern highlands and southern coast, which experiences a single, long rainy season from November to April (NDJFMA) (Chang'a et al., 2010; Chang'a et al., 2017). The predictability of the rains in Tanzania is highly linked with the large ocean atmospheric systems such as Intertropical convergence zone (ITCZ), Madden-Julian Oscillation (MJO), El Nino-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Tropical Cyclones (TC), Subtropical Anticyclones and Low-level jets (Chang'a et al., 2010; Kijazi & Reason, 2009; Kebacho & Chen, 2022). Analyzing the extreme precipitation indices across these geographical and climatical zones is essential in providing regionally tailormade precipitation information for climate sensitive sectors.

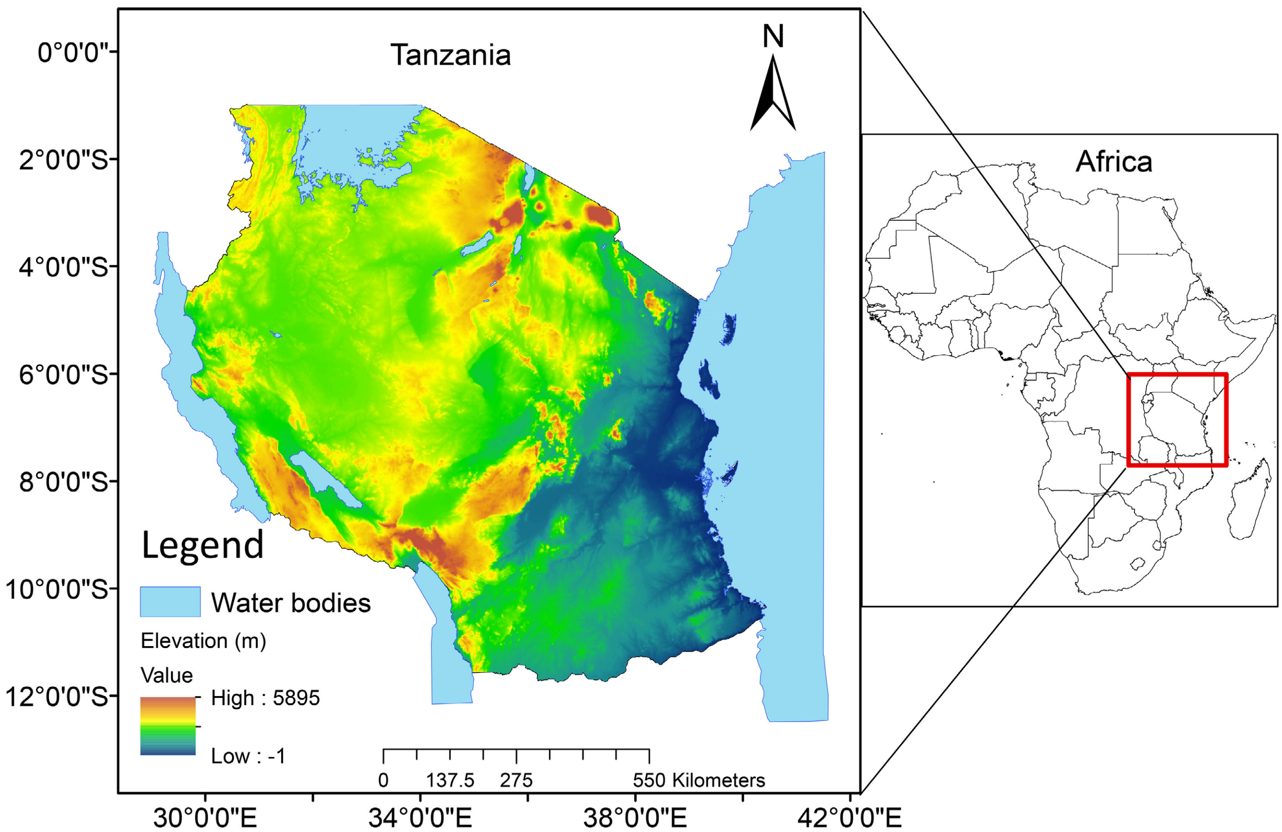

Figure 1. Topographical map of Tanzania showing elevation distribution over the country derived from digital elevation model (DEM).

2.2. Datasets

Daily data from Climate Hazards Group InfraRed Precipitation with Stations data (CHIRPS) are utilized to calculate precipitation extreme indices. The CHIRPS data consists of daily, gauge-calibrated, infrared precipitation estimates spanning from 1981 to 2024 with a resolution of 0.25˚ × 0.25˚ available over land. CHIRPS data are reliable and suitable for rainfall variability and extremes analysis due to its high spatial resolution and long records (Funk et al., 2015). Previous studies, (Camberlin & Okoola, 2003; Chang'a et al., 2020b) have validated its performance in comparison with observational data and recapture the rainfall peaks during MAM season in Tanzania.

In addition, the monthly series of the Pacific Decadal Oscillation (PDO), El

Nino-Southern Oscillation(ENSO), and Indian Ocean Dipole(IOD) indices are obtained from the U.S. National Oceanic and Atmospheric Administration Physical Sciences Laboratory (https://psl.noaa.gov). PDO is obtained through the leading principal component of monthly SST anomalies in the North Pacific Ocean (poleward of 20˚N). ENSO is monitored using the Nino 3.4 SST index which is the average SST anomalies over east-central Tropical Pacific SST (5˚S - 5˚N and 170˚ - 120˚W).The IOD is represented with the dipole mode index (DMI) which is the difference of the area mean SST anomalies in the western equatorial Indian Ocean (W-IO) (50˚ - 70˚ E and 10˚S - 10˚N) and the southeastern equatorial Indian Ocean (E-IO) (90˚ - 110˚ E and 10˚S - 0˚) (Saji et al., 2003).

2.3. Methodology

2.3.1. Calculation of Precipitation Extreme Indices

In this study, to quantify the long-term trends and spatial variability of the precipitation extreme indices, we selected 6 standardized ETCCDI indices (**Table 1**) to provide a balanced and comprehensive representation of both dry and wet conditions (Alexander et al., 2019). These indices are crucial for capturing the shifts in the hydrological cycle, ranging from drought stress to flood risk. These six indices were computed seasonally (MAM) at each year for each grid cell over Tanzania for the period 1981-2024. The ETCCDI definitions were applied directly to the daily datasets. Detailed information of ETCCDI can be accessed at (http://etccdi.pacificclimate.org/)

Table 1. Definitions and List of the six ETCCDI-recommended extreme precipitation indices used in this study.

Indices	Indices name	Definition	Units
PRCPTOT	Annual total precipitation on wet days	Precipitation from wet days (P ≥ 1 mm)	mm
CDD	Consecutive dry days	Maximum number of consecutive dry days (when PR < 1 mm/year)	days
CWD	Consecutive wet days	Maximum number of consecutive days with daily precipitation ≥ 1 mm/year	days
SDII	Simple daily intensity index	Daily PR intensity total PR divided by the number of wet days (when total PR ≥ 1 mm)	mm/day
RX5day	Max 5-day precipitation	maximum consecutive 5-day precipitation total	mm
R20mm	Number of very heavy precipitation days	Annual count of days when precipitation ≥ 20 mm	days

2.3.2. Empirical Orthogonal Function (EOF) Analysis

For purpose of investigating the spatial and temporal variability characteristics, we employed the Empirical Orthogonal Function (EOF) which involves calculating the parameters of the covariance matrix of data anomalies, with the variance (eigenvalue) associated with each Principal Components (PCs) providing a measure of the variability explained by that mode (Hannachi et al., 2007). EOFs represent the spatial patterns corresponding to the regions with the highest variability, while the associated scores, or Principal Components (PCs), provide the related time series.

2.3.3. Trend Analysis

In this study a linear regression statistical method is used to model the relationship between the PCs time series and time (years) same method used by (Fan et al., 2022) The slope derived from this regression indicates the rate of change of precipitation extremes, revealing whether the PCs exhibit a significant upward, downward or no trend observed over time. The Mann Kendal (MK) test (Mann, 1945; Kendall, 1955) was employed at ($p < 0.05$) and ($p < 0.01$) significant level to test the significance of both linear and spatial trend distribution respectively due to its reliability non-parametric nature, MK is not influenced by the non-normality of the data and exhibits low sensitivity to abrupt breaks in inhomogeneous series.

2.3.4. Correlation Analysis

Pearson correlation coefficient is used between the principal components of extreme indices and tropical oceanic systems underlying influences of oceanic factors on extremes during MAM season.

3. Results and Discussion

3.1. Climatological Means of Extreme Precipitations

The spatial distributions of the climatological means of extreme precipitation indices over Tanzania during the MAM season (1981-2024) are shown in **Figure 2**. The analysis indicates a significant regional contrast in moisture availability and drought risk. Specifically, the central, western, and southwestern parts of the country are more characterized by intense drought extremes compared to the northern, eastern, and southern highlands.

As shown in **Figure 2(a)**, values of CDD lower than 40 days are observed over the southern highlands and the northern and eastern parts of the country. In contrast, values greater than 50 days are dominant over the western and southwestern parts, with isolated areas in the northeastern highlands also exhibiting a longer range of dry spells. This spatial distribution of CDD suggests that while MAM is a primary rainy season, the interior regions are subject to higher intra-seasonal dry-spell persistence, which may be attributed to the rain shadow effect of the eastern escarpments and the semi arid nature of the central plateau.

The CWD shows an opposite spatial distribution whereas values greater than 3 days are observed over most parts of the country, with the highest persistence found in the north and relatively lower values over the central parts extending toward the northeastern highlands **Figure 2(b)**. This pattern of wet spell duration is further explained by the PRCPTOT depicted in **Figure 2(c)**. Here, the northern part of the country and the southwestern highlands extending toward the coastal areas show values exceeding 200 mm. These high totals are likely driven by the convergence of moisture from the Indian Ocean and Lake Victoria. Conversely, the central parts and northeastern highlands show lower accumulation, with values remaining above 50 mm.

The intensity of extreme events, represented by RX5day, shows that values greater than 80 mm are mainly concentrated along the coast and extend toward the southwestern highlands, with significant pockets in the northeastern highlands and areas around Lake Victoria Basin Figure 2(d). The central region, however, depicts lower intensity values. This spatial signature of intensity is reflected in the SDII Figure 2(e) and the frequency of very heavy precipitation days (R20mm) Figure 2(f). Interestingly, while the areas around Lake Victoria show high frequency and total rainfall, the SDII values there are slightly lower than the coastal areas, suggesting that rainfall in those areas is more frequent but potentially less on a daily basis than the coastal areas. These results overall highlight that the coastal and lake zones are the primary drivers of extreme precipitation variability in Tanzania during the MAM season.

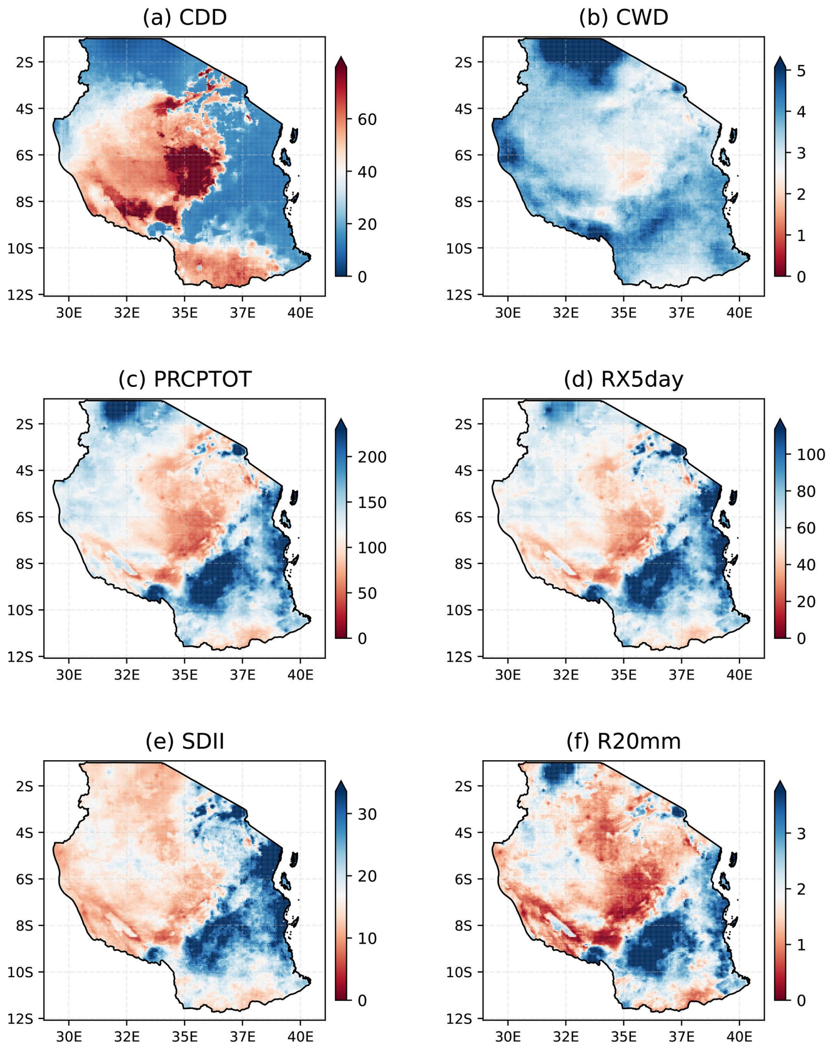

Figure 2. Spatial patterns of the climatological (1981-2024) mean for selected precipitation-based ETCCDI indices across Tanzania.

3.2. Trends of Extreme Precipitation

The linear trend distributions of precipitation extremes over Tanzania during the MAM season, represented by the coefficients of extremes indices regression on time, are displayed in **Figure 3**. The CDD shows a significantly increasing trend at a rate of 0.2 - 0.6 days per year over some few areas at the central and northeastern regions, indicating a tendency toward longer dry spells during the season. In addition, a more conspicuous decrease in CDD can be detected over the regions south of Lake Victoria extending through the center towards the southern areas of the country at a rate of −0.2 to −0.8 **Figure 3(a)**. This contrast suggests that while certain interior corridors are experiencing more frequent dry interruptions, a larger portion of the central-to-southern axis is seeing a reduction in the duration of dry intervals. In contrast, the CWD slightly decreases over the coastal belt and the southern border where significant trends greater than −0.02 are observed **Figure 3(b)**. Despite this slight reduction in the persistence of wet days in maritime-influenced zones, the overall moisture volume shows an upward trajectory. The PRCPTOT increases by values greater than 0.5 over most parts of the country, with statistically significant increases concentrated over the southwestern and northeastern highlands, the eastern coast, the center, and the northwestern areas **Figure 3(c)**.

A similar spatial pattern as that of PRCPTOT is observed for the intensity and frequency indices, specifically RX5day, SDII, and R20mm **Figures 3(d)-(f)**. The alignment of increasing trends across total rainfall and intensity-based indices justifies the conclusion that the long rains are becoming more concentrated into heavy events. Overall, during the study period, most parts of the country are getting wetter, a trend that subjects the region to more frequent and intense precipitation events, particularly in the high elevation and coastal sectors.

3.3. Spatiotemporal Characteristics

In this section, EOF with associated PCs were used to analyze the annual spatial and temporal distribution of extreme precipitation during the MAM season from 1981-2024 over Tanzania. This analysis identifies the dominant modes of climate variability, and the percentage of variance associated with each mode, providing a deeper understanding of how these extremes change over time and space.

Regarding the variability of dry spells, the first mode (EOF1) of the CDD accounts for 14.0% of the total variance. The spatial loading pattern **Figure 4(a)** shows positive values concentrated over nearly the entire study area, with very few negative loadings occurring over the central region and the northernmost parts. This widespread positive loading suggests a coherent interannual variability of dry spell duration across the country. The associated PC1 **Figure 4(b)** shows a decreasing trend, though it is not statistically significant. The second mode (EOF2) for CDD accounts for 9.5% of the variance **Figure 5(a)**, revealing a spatial dipole. It shows the strongest negative loadings over areas around Lake Victoria, the western regions, and patches over the central area. Conversely, positive loadings are concentrated along the coastal region, parts of the northeastern highlands, and the south-to-southwestern parts of the country. PC2 Figure 5(b) also shows a non-significant decreasing trend. For the CWD, the first mode (EOF1) explains 26.4% of the total variance Figure 4(c). The spatial pattern is characterized by negative loadings over most parts of the country, signifying that consecutive wet days are generally decreasing during the MAM season, with prominent loadings observed over the eastern Lake Victoria basin and the northeastern highlands. Interestingly, despite the negative spatial loadings, PC1 Figure 4(d) exhibits an increasing trend. EOF2 Figure 5(c) accounts for 13.2% of the variance, exhibiting a north-south opposition dipole mode with positive loadings over the northern part and negative loadings over the southern part of the country, while PC2 Figure 5(d) also shows an increasing trend.

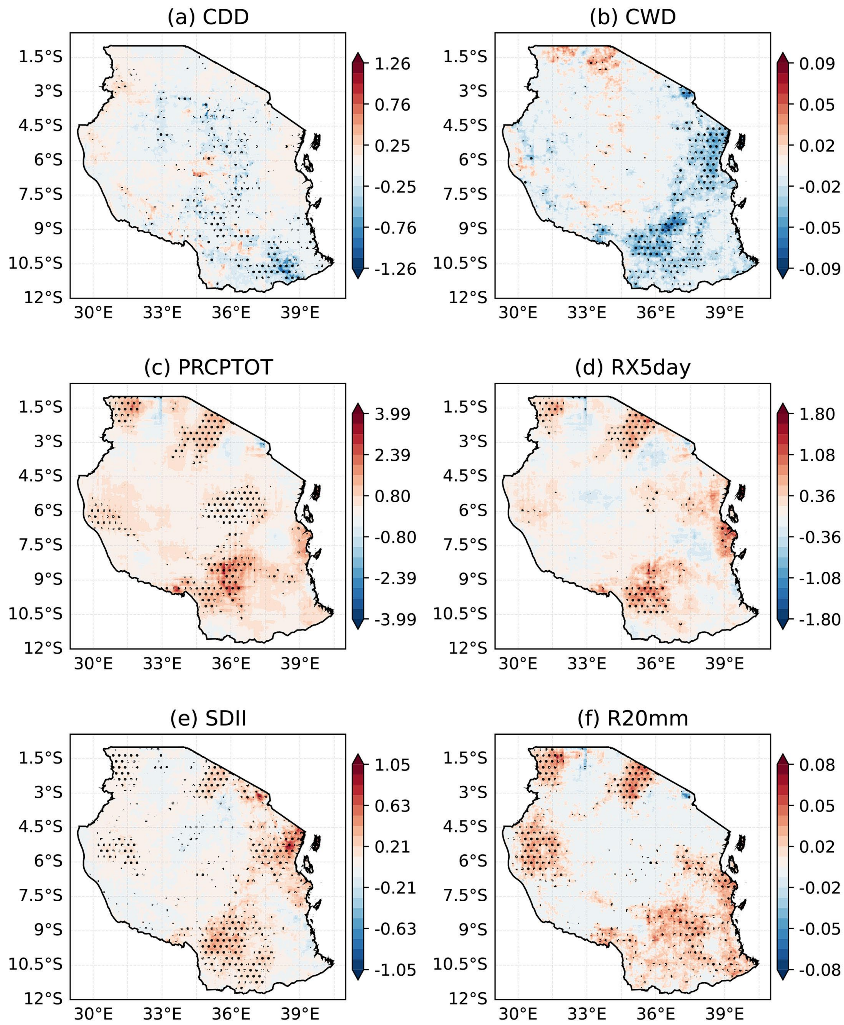

Figure 3. Spatial patterns of linear trends (1981-2024) in selected precipitation-based ETCCDI indices across Tanzania. Regions with statistically significant trends ($p < 0.01$) are indicated by stippling according to MK test.

The first dominant mode (EOF1) of the PRCPTOT index represents 37.5% of the total variance, showing positive loadings over most parts of the country Figure 4(e). This shows that most part of the country are experiencing signal toward more wet day precipitation. The associated PC1 Figure 4(f) shows a statistically significantly increasing linear trend on a decadal scale starting from 2000, supporting the overall wetting trend. The second mode (EOF2) accounts for 14.1% of the variance Figure 5(e), presenting a dipole mode with positive loadings over the southern regions extending to the southwestern highlands, the center, and western parts of Lake Victoria. PC2 Figure 5(f) shows a slight increasing trend. The analysis of intensity and frequency indices further elucidates these changes. The first mode (EOF1) of RX5day accounts for 23.5% of the total variance. Its spatial loadings cover almost all parts of the country with negative values Figure 4(g), and PC1 Figure 4(h) exhibits a decreasing trend. The second mode (EOF2) accounts for 11.7% of the variance Figure 5(g), with positive values localized over the northern coasts and negative loadings dominating the remaining parts of the country. PC2 Figure 5(h) shows almost no trend.

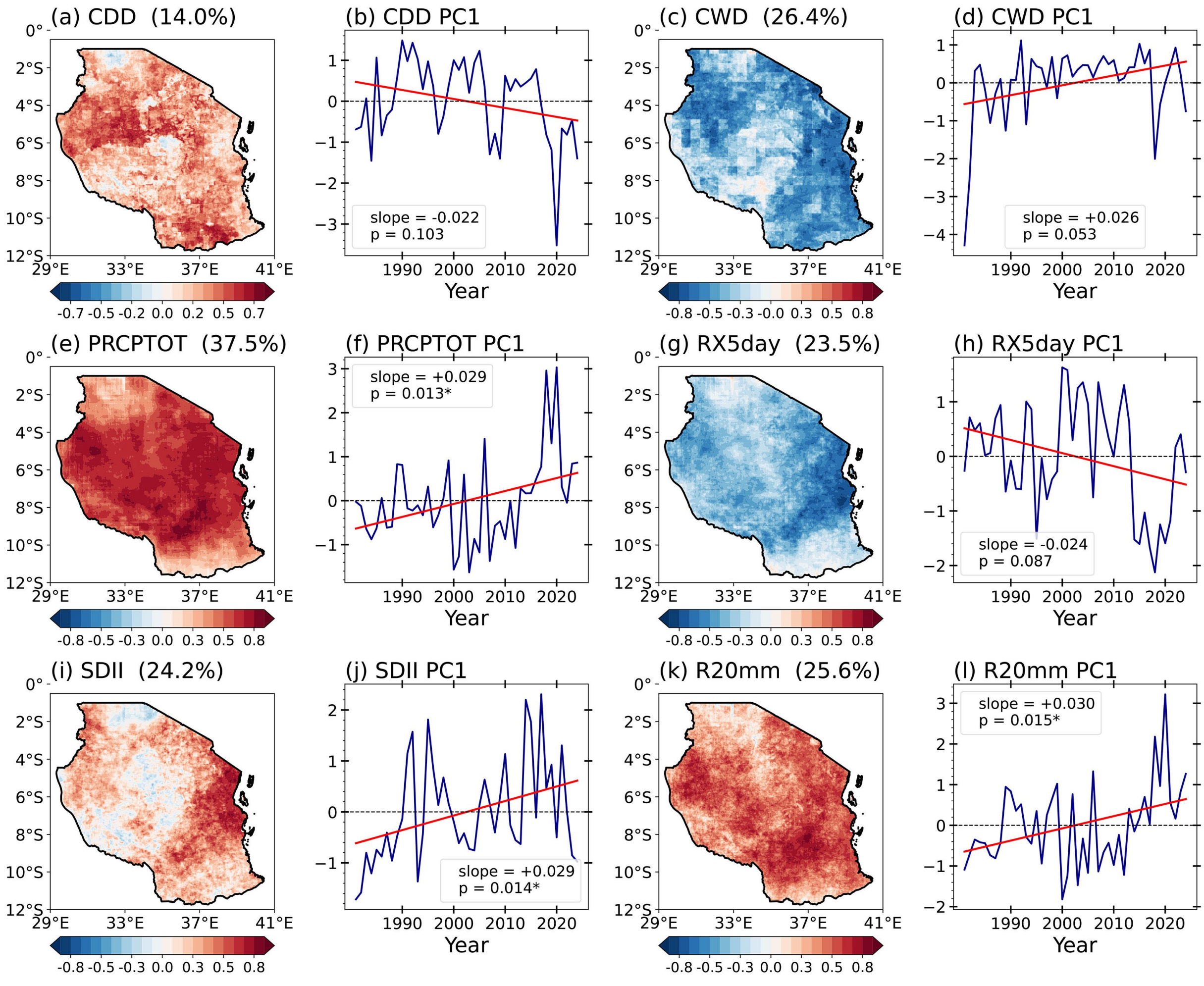

Figure 4. Spatial patterns of the first leading EOF (EOF1) mode and the time series of the first principal component (PC1) of the selected precipitation-based ETCCDI indices across Tanzania during 1981-2024. The asterisks * indicated in *p*-values represent that the trend of the time series is significant at $p < 0.05$ significance levels according to MK test.

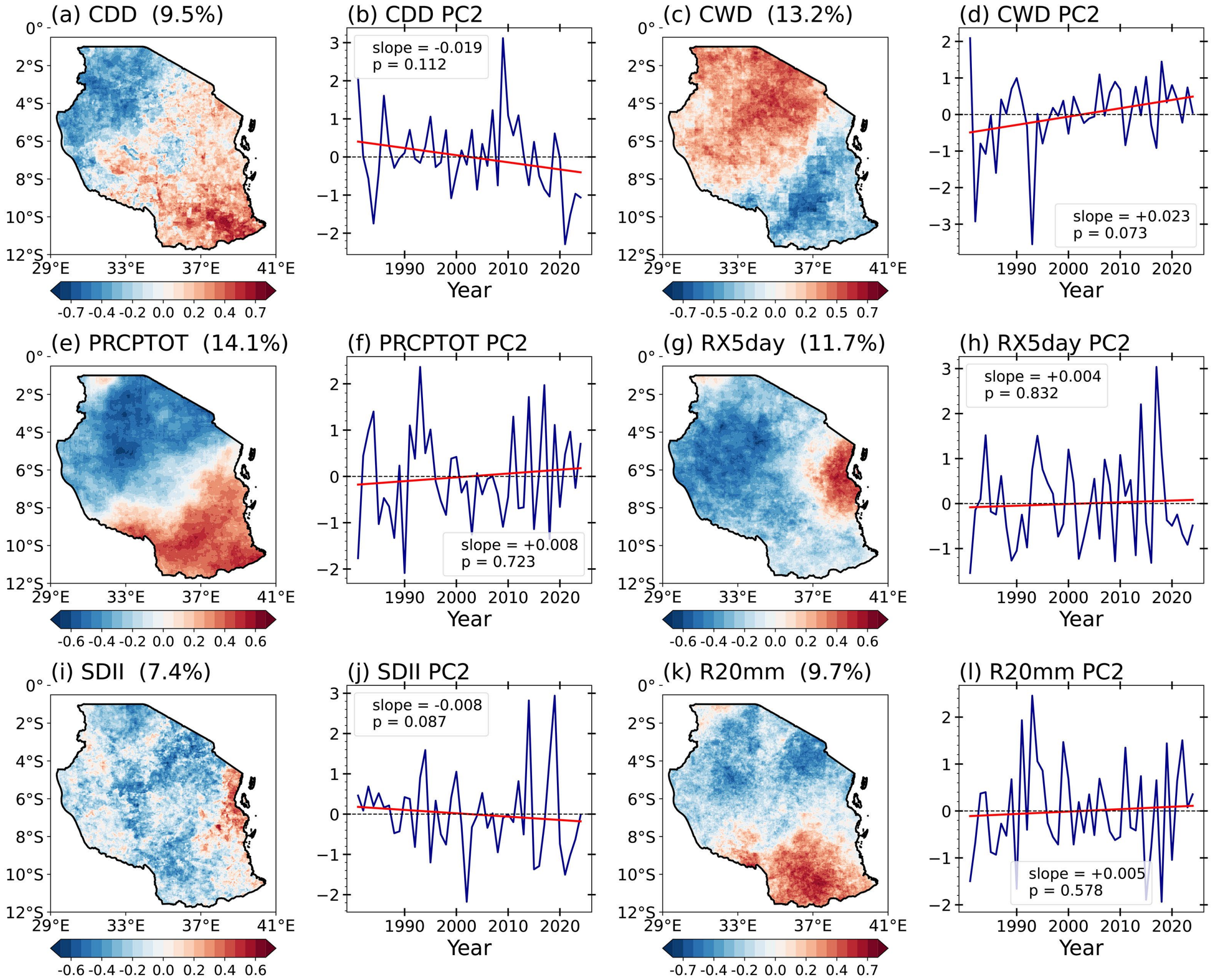

Figure 5. Spatial patterns of the second leading EOF (EOF2) mode and the time series of the second principal component (PC2) of the selected precipitation-based ETCCDI indices across Tanzania during 1981-2024.The trend of time series is non-significant at $p < 0.05$ significant level according to MK test.

For the SDII, EOF1 Figure 4(i) is the dominant pattern, explaining 24.2% of the total variability. Strong positive loadings over the coastal region indicate that areas where SDII is consistently higher experience more intense rainfall. On the other hand, negative loadings are observed mostly over the eastern Lake Victoria basin and the central part extending to the southwestern highlands. PC1 Figure 4(j) shows a clear, strong long-term upward trend over the decades from 1981 to 2001, indicating that the intensity pattern shown in EOF1 has been strengthening over time. The second mode (EOF2) Figure 5(i) accounts for 7.4% of the variance, with strong positive loadings concentrated largely over the coastal region, while PC2 Figure 5(j) shows a non-significant decreasing trend.

Finally, the first dominant mode (EOF1) Figure 4(k) of the R20mm index accounts for 25.6% of the total variance, with positive loadings over most parts of the country, mirroring the PRCPTOT pattern. The first PC1 Figure 4(l) of R20mm shows a statistically significant increasing trend, highlighting a rise in the frequency of very heavy rainfall events. The second mode (EOF2) Figure 5(k) accounts for 9.7% of the variance, with positive loadings over the southern regions extending to the southwestern highlands and localized areas around Lake Victoria. PC2 Figure 5(l) shows no significant trend, suggesting that the primary driver of very heavy rain frequency is the national-scale mode (EOF1).

3.4. Possible Impacts from Oceanic Systems

To further explore the physical mechanisms underlying the spatiotemporal variations of precipitation extremes over Tanzania during the MAM season, the correlation coefficients between the first two PCs of the extreme indices and dominant climate modes specifically ENSO, IOD, PDO, Tropical Northern Atlantic (TNA), and Tropical Southern Atlantic (TSA) were calculated (Table 2). These results illustrate how the thermal states of the surrounding oceans modulate the variability of extremes.

Table 2. The results of Correlation coefficients of the detrended MAM PC1 and PC2 of the selected precipitation-based ETCCDI indices across Tanzania during 1981-2024.

Extreme indices	ENSO	DMI	PDO	TNA	TSA
PC1					
CDD	0.09	0.29	0.09	−0.06	−0.22
CWD	0.15	0.34*	0.09	0.007	0.12
PRCPTOT	0.08	0.04	−0.06	−0.13	0.11
RX5day	−0.22	−0.07	−0.27	0.19	−0.02
SDII	0.21	0.02	0.30	−0.20	−0.06
R20mm	0.18	−0.10	−0.14	0.09	0.13
PC2					
CDD	0.13	0.28	0.07	−0.002	−0.008
CWD	−0.21	−0.09	−0.15	0.07	−0.06
PRCPTOT	0.12	0.05	0.09	−0.12	0.10
RX5day	−0.02	0.23	0.28	−0.03	0.02
SDII	−0.01	0.18	0.15	−0.21	−0.04
R20mm	−0.09	0.04	−0.19	−0.15	0.13

*Significant at the $p < 0.05$ significance level.

The correlation analysis reveals that the IOD is likely a primary driver of wet spell persistence in Tanzania. As shown in Table 2, the CWD (PC1) exhibits a statistically significant positive correlation (r = 0.34, $p < 0.05$), (r = 0.34) with the DMI. This indicates that during a positive IOD phase, characterized by warmer-than-average sea surface temperatures in the western Indian Ocean, there is enhanced moisture transport and atmospheric convergence toward East Africa, leading to more persistent wet spells. This aligns with the spatial findings in EOF1 of CWD, which highlighted significant variability in the lake and coastal zones.

Furthermore, CDD (PC1 and PC2) show relatively positive correlations with the DMI (0.29 and 0.28, respectively), suggesting that the Indian Ocean also influences the duration of dry intervals within the season.

The influence of ENSO on the primary modes of variability (PC1) appears less dominant than the IOD during the MAM season, with weak positive correlations for CWD (0.15) and R20mm (0.18). This supports the notion that while ENSO is a major driver of the short rains (OND), its impact on the long rains MAM) extremes is more complex and potentially modulated by other regional factors. Additionally, the Pacific Decadal Oscillation (PDO) shows a moderate positive correlation with SDII (PC1, 0.30) and RX5day (PC2, 0.28), suggesting that lower-frequency Pacific variability may influence the daily intensity and 5-day maximum totals of precipitation.

The influence of the Atlantic Ocean, the Tropical Southern Atlantic (TSA) shows a negative correlation with CDD (PC1, −0.22), indicating that warmer SSTs in the South Atlantic may be associated with a reduction in the duration of dry spells. Conversely, the TNA exhibits a weak negative correlation with PRCPTOT (PC1, −0.13) and SDII (PC1, −0.20). While the study identifies the role of oceanic indices during MAM season, the correlation coefficients across all oceanic indices in **Table 2** remain relatively low which likely indicates that while large scale oceanic teleconnections have been identified as drivers of MAM seasonal precipitation in Tanzania as revealed by Kebacho & Chen, (2022); Chang'a et al. (2010), they explain a limited fraction of contribution to the total extreme events. In addition to that, the relative low correlation shown by the oceanic indices suggest that the MAM seasonal extremes are likely influenced by regional and local scale forcing which have been revealed to plays part in both spatial and temporal characteristics of MAM rainfall in Tanzania (Zorita & Tilya, 2002). These regional and local forcings include complex topography features such as mountains, Lakes (Victoria, Tanganyika and Nyasa); MJO; TC, ITCZ, subtropical anticyclones, Congo air mass, low level jet to mention a few (Makula & Zhou, 2022; Kijazi & Reason, 2005; Kijazi & Reason, 2009; Kebacho & Chen, 2022; King'uza et al., 2025; King'uza & Limbu, 2019) which enhances the modulation of precipitation extremes in Tanzania.

4. Conclusion

The analysis of extreme precipitation indices from 1981 to 2024 reveals a significant shift in the characteristics of long rain season in Tanzania toward wetter and more unstable conditions. While the central regions remain prone to persistent dry spells, a widespread increasing trend is observed in total precipitation (PRCPTOT) and very heavy rainfall frequency (R20mm), particularly in the northern areas and southwestern highlands. EOF analysis confirms that these changes are driven by large-scale regional modes, with the first principal components of PRCPTOT (37.5%) and R20mm (25.6%) showing significant decadal strengthening since 2000, aligns with projections of enhanced rainfall intensity under a warming climate (Calvin et al., 2023). These results indicate that despite a reduction in the duration of individual wet spells (CWD), the intensity of daily rainfall (SDII) has risen sharply, concentrating seasonal moisture into more unstable and potentially damaging extreme events.

However, the increasing trend in consecutive dry days (CDD) in climatically sensitive areas like the northeastern highlands and parts of the coast is particularly alarming. This suggests a tendency toward more prolonged intra-seasonal droughts even within a season that may be getting wetter on average. The increasing rainfall intensity alongside longer dry spells poses severe challenges for agriculture and water management (Mtewele et al., 2021). It increases the risk of both flash floods and soil moisture deficits, a dual threat that has been noted in other parts of East African Countries (Ongoma et al., 2018). The observed increasing trend of extreme indices is supported by (Tibangayuka et al., 2025) that this may be due to region's recovery from the severe droughts of the 1970s and 1980s by analyzing SPI-6 and SPI-12 which indicated a trend towards wetter conditions especially over Lake Victoria Basin.

Results from correlation analysis reveal a significant positive correlation between IOD and CWD during MAM season, which is consistent with the previous findings (King'uza & Limbu, 2019; Chang'a et al., 2020b) that IOD is the primary predictor of MAM precipitation distribution in both spatial and temporal timescale in Tanzania. It has been found that a positive IOD phase establishes anomalous warming in the western Indian Ocean, which enhances low-level atmospheric instability and deep convection directly over Tanzania, which provides a continuous source of moisture and upward motion, supported by the localized modification of Walker Circulation thereby sustaining wet spells over the domain (Chang'a et al., 2020b; Mafuru & Guirong 2018, 2019; Ogega et al., 2023). Meanwhile, ENSO exhibits a spring predictability barrier and decaying signal strength during the MAM season, whereas, the IOD facilitates a sustained low-level westerly convergence, advection of moisture from the Indian Ocean which efficiently allowing the residing of the ITCZ over the region for extended periods (Mafuru & Guirong, 2019; King'uza & Limbu, 2019). Moreover, the findings of Marchant et al. (2007), enhances the findings that, the local SST gradients in the Indian Ocean exert a more direct influence on East African rainfall duration thereby complementing the IOD more than ENSO.

Moreover, Tanzania's climate is not uniform across the country due to its size and varied topography with seasons defined by rainfall rather than temperature (Mwinuka & Uiso, 2017). Due to its diversity of topography, it influencing the spatial variability of extreme rainfall events such as presence of Lake Victoria basin likely drives convection currents in the eastern part, whereas the higher elevations in the west influence airmass movement from the lake and the Indian Ocean (Ongoma et al., 2018). Presence of highlands over the northeastern and southwestern regions influences local occurrences of extremes compared to other areas. Changes in extreme precipitation indices significantly affect multiple sectors such as agriculture, which are particularly vulnerable, as rain-fed farming practices are highly susceptible to both droughts and excessive rainfall especially during MAM season.

This research has analytically quantified the spatial and temporal characteristics of MAM precipitation extremes in Tanzania over four decades. However, the long rains season is undergoing a significant transformation, some regions experience declining rainfall, while others show increasing trends (Kebacho & Chen, 2022) with greater temporal concentration and spatial variability**.** This is shown by more intense heavy rainfall events (Tibangayuka et al., 2025) alongside a tendency for longer dry spells in key region, thereby amplifying the risk of both floods and agricultural drought within the season. It can be evidenced by the most recent severe floods of 2006, 2009, 2010, 2011, 2012, 2014, 2016, and 2017 events, meanwhile the most devastating and recurrent droughts recorded in the country's history include those of 2003, 2005, 2011, 2014, and 2016 events (Kijazi & Reason 2012; Chang'a et al., 2017). Periods of longer dry spells (CDD) occurring during MAM season, combined with likely rising temperatures, might accelerate evapotranspiration and soil evaporation which influences a reduction in soil moisture, a tendency toward more prolonged intra-seasonal droughts even within a season that may be getting wetter on average (Mtewele et al., 2021; Mkonda & He, 2018). The occurrence of rainfall intensity with presence of longer dry spells pose severe challenges for rain-fed agriculture and water scarcity for irrigation, leading to impairing plant growth (Zita, et al., 2025) exacerbating crop failure and low yields of cereal staple food crops such as maize, paddy rice, and beans (Mkonda & He, 2018; Tibangayuka et al., 2025). Additionally**,** high rainfall intensity increases the risk of flash floods which increases surface runoff and likely causing soil erosion, and related hydrometeorological hazards (TMA, 2024). Therefore, these findings underscore the urgent need for climate sensitive sectors and improved climate adaptation strategies on enhanced disaster risk management, especially in high-sensitivity zones across the coastal belt, northeastern highlands and the Lake Victoria basin. Moreover, further investigation should be done regarding to the causes of the increase trends of extremes precipitation indices in terms of frequency and intensity over Tanzania during long rain season by analyzing the large-scale atmospheric circulation.

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Conflicts of Interest

The authors confirm that there are no conflicts of interest associated with the publication of this paper.

References

Alexander, L. V., Fowler, H. J., Bador, M., Behrangi, A., Donat, M. G., Dunn, R. et al. (2019). On the Use of Indices to Study Extreme Precipitation on Sub-Daily and Daily Timescales. *Environmental Research Letters, 14,* Article 125008. https://doi.org/10.1088/1748-9326/ab51b6

Bobde, V., Akinsanola, A. A., Folorunsho, A. H., Adebiyi, A. A., & Adeyeri, O. E. (2024). Projected Regional Changes in Mean and Extreme Precipitation over Africa in CMIP6 Models. *Environmental Research Letters, 19,* Article 074009. https://doi.org/10.1088/1748-9326/ad545c

Borhara, K., Pokharel, B., Bean, B., Deng, L., & Wang, S.-Y. S. (2020). On Tanzania's Precipitation Climatology, Variability, and Future Projection. *Climate, 8,* Article 34. https://doi.org/10.3390/cli8020034

Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W. et al. (2023). *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* IPCC.

Camberlin, P., & Okoola, R. E. (2003). The Onset and Cessation of the "Long Rains" in Eastern Africa and Their Interannual Variability. *Theoretical and Applied Climatology, 75,* 43-54. https://doi.org/10.1007/s00704-002-0721-5

Chabaga, C. M., Asenga, G., & Ndabagenga, D. (2025). Intraseasonal Variability of Rainfall over Tanzania during March-April-May (MAM) Season of 2022. *Atmospheric and Climate Sciences, 15,* 218-247. https://doi.org/10.4236/acs.2025.151011

Chang'a, L. B., Kijazi, A. L., Luhunga, P. M., Ng'ongolo, H. K., & Mtongor, H. I. (2017). Spatial and Temporal Analysis of Rainfall and Temperature Extreme Indices in Tanzania. *Atmospheric and Climate Sciences, 7,* 525-539. https://doi.org/10.4236/acs.2017.74038

Chang'a, L. B., Kijazi, A. L., Mafuru, K. B., Kondowe, A. L., Osima, S. E., Mtongori, H. I. et al. (2020a). Assessment of the Evolution and Socio-Economic Impacts of Extreme Rainfall Events in October 2019 over the East Africa. *Atmospheric and Climate Sciences, 10,* 319-338. https://doi.org/10.4236/acs.2020.103018

Chang'a, L. B., Kijazi, A. L., Mafuru, K. B., Nying'uro, P. A., Ssemujju, M., Deus, B. et al. (2020b). Understanding the Evolution and Socio-Economic Impacts of the Extreme Rainfall Events in March-May 2017 to 2020 in East Africa. *Atmospheric and Climate Sciences, 10,* 553-572. https://doi.org/10.4236/acs.2020.104029

Chang'a, L. B., Yanda, P. Z., & Ngana, J. O. (2010). Spatial and Temporal Analysis of Recent Climatological Data in Tanzania. *Journal of Geography and Regional Planning, 3,* 44-65.

Fan, Y., Li, J., Zhu, S., Li, H., & Zhou, B. (2022). Trends and Variabilities of Precipitation and Temperature Extremes over Southeast Asia during 1981-2017. *Meteorology and Atmospheric Physics, 134,* Article No. 78. https://doi.org/10.1007/s00703-022-00913-6

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S. et al. (2015). The Climate Hazards Infrared Precipitation with Stations—A New Environmental Record for Monitoring Extremes. *Scientific Data, 2,* Article ID: 150066. https://doi.org/10.1038/sdata.2015.66

Habiyakare, F., Jiang, T., Yahaya, I., Ndabagenga, D., Kagabo, J., & Su, B. (2024). Spatial Variation and Trend of Extreme Precipitation in Africa during 1981-2019 and Its Projected Changes at the End of 21st Century. *Journal of Geoscience and Environment Protection, 12,* 192-221. https://doi.org/10.4236/gep.2024.123012

Hannachi, A., Jolliffe, I. T., & Stephenson, D. B. (2007). Empirical Orthogonal Functions and Related Techniques in Atmospheric Science: A Review. *International Journal of Climatology, 27,* 1119-1152. https://doi.org/10.1002/joc.1499

Kazora, J., Zhu, W., Oo, K. T., Akimana, D., Paul, K. J., Ayugi, B. O. et al. (2025). Evaluation of CMIP6 Models for Rainfall Simulation in Central Eastern Africa Using Extreme Precipitation Indices. *Discover Atmosphere, 3,* Article No. 40. https://doi.org/10.1007/s44292-025-00066-2

Kebacho, L. L., & Chen, H. (2022). The Dominant Modes of the Long Rains Interannual Variability over Tanzania and Their Oceanic Drivers. *International Journal of Climatology, 42,* 5273-5292. https://doi.org/10.1002/joc.7532

Kendall, M. G. (1955). Further Contributions to the Theory of Paired Comparisons. *Biometrics, 11,* 43-62. https://doi.org/10.2307/3001479

Kijazi, A. L., & Reason, C. J. C. (2005). Relationships between Intraseasonal Rainfall Variability of Coastal Tanzania and Enso. *Theoretical and Applied Climatology, 82,* 153-176. https://doi.org/10.1007/s00704-005-0129-0

Kijazi, A. L., & Reason, C. J. C. (2009). Analysis of the 2006 Floods over Northern Tanzania. *International Journal of Climatology, 29,* 955-970. https://doi.org/10.1002/joc.1846

Kijazi, A. L., & Reason, C. J. C. (2012). Intra-Seasonal Variability over the Northeastern Highlands of Tanzania. *International Journal of Climatology, 32,* 874-887. https://doi.org/10.1002/joc.2315

King'uza, P. H., & Limbu, P. T. S. (2019). Inter-Annual Variability of March to May Rainfall over Tanzania and Its Association with Atmospheric Circulation Anomalies. *Geographica Pannonica, 23,* 147-161. https://doi.org/10.5937/gp23-22430

King'uza, P. H., Zhou, B., Okrah, A., Joan, B., & Limbu, P. (2025). Contribution of Very Heavy Rainfall Events to MAM and OND Rainy Seasons in Tanzania and Their Linkages to IOD and ENSO Events. *Theoretical and Applied Climatology, 156,* Article No. 580. https://doi.org/10.1007/s00704-025-05815-2

Luhunga, P., Botai, J., & Kahimba, F. (2016). Evaluation of the Performance of CORDEX Regional Climate Models in Simulating Present Climate Conditions of Tanzania. *Journal of Southern Hemisphere Earth Systems Science, 66,* 32-54. https://doi.org/10.1071/es16005

Mafuru, K. B., & Guirong, T. (2018). Assessing Prone Areas to Heavy Rainfall and the Impaction of the Upper Warm Temperature Anomaly during March-May Rainfall Season in Tanzania. *Advances in Meteorology, 2018,* 1-17. https://doi.org/10.1155/2018/8353296

Mafuru, K. B., & Guirong, T. (2019). The Influence of ENSO on the Upper Warm Temperature Anomaly Formation Associated with the March-May Heavy Rainfall Events in Tanzania. *International Journal of Climatology, 40,* 2745-2763. https://doi.org/10.1002/joc.6364

Makula, E. K., & Zhou, B. (2022). Linkage of Tanzania Short Rain Variability to Sea Surface Temperature over the Southern Oceans. *Frontiers in Earth Science, 10,* Article ID: 922172. https://doi.org/10.3389/feart.2022.922172

Mann, H. B. (1945). Nonparametric Tests against Trend. *Econometrica, 13,* 245-259.

https://doi.org/10.2307/1907187

Marchant, R., Mumbi, C., Behera, S., & Yamagata, T. (2007). The Indian Ocean Dipole—The Unsung Driver of Climatic Variability in East Africa. *African Journal of Ecology, 45,* 4-16. https://doi.org/10.1111/j.1365-2028.2006.00707.x

Mkonda, M. Y., & He, X. (2018). Climate Variability and Crop Yields Synergies in Tanzania's Semiarid Agroecological Zone. *Ecosystem Health and Sustainability, 4,* 59-72. https://doi.org/10.1080/20964129.2018.1459868

Mtewele, Z. F., Xu, X., & Jia, G. (2021). Heterogeneous Trends of Precipitation Extremes in Recent Two Decades over East Africa. *Journal of Meteorological Research, 35,* 1057-1073. https://doi.org/10.1007/s13351-021-1028-8

Mwinuka, P., & Uiso, C. B. S. (2017). Prediction of Rainfall in the Southern Highlands of Tanzania. *Tanzania Journal of Science, 43,* 36-46.

Niang, I., Ruppel, O. C., Abdrabo, M. A. et al. (2014) *Africa Climate Change 2014: Impacts, Adaptation and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1199-1266). Cambridge University Press.

Ogega, O. M., Scoccimarro, E., Misiani, H., & Mbugua, J. (2023). Extreme Climatic Events to Intensify over the Lake Victoria Basin under Global Warming. *Scientific Reports, 13,* Article No. 9729. https://doi.org/10.1038/s41598-023-36756-3

Ongoma, V., Chen, H., & Omony, G. W. (2018). Variability of Extreme Weather Events over the Equatorial East Africa, a Case Study of Rainfall in Kenya and Uganda. *Theoretical and Applied Climatology, 131,* 295-308. https://doi.org/10.1007/s00704-016-1973-9

Saji, N. H., Yamagata, T., Res, C., Saji, N. H., & Yamagata, T. (2003). Possible Impacts of Indian Ocean Dipole Mode Events on Global Climate. *Climate Research, 25,* 151-169. https://doi.org/10.3354/cr025151

Tibangayuka, N., Mulungu, D. M. M., & Izdori, F. (2025). Analysis of Spatial Variability and Temporal Trends in the Extreme Rainfall of Kagera Sub-Basin, Tanzania. *Meteorological Applications, 32,* e70076. https://doi.org/10.1002/met.70076

TMA (2024) Statement on the Status of the Tanzania Climate in 2023(Issue 1130). https://www.meteo.go.tz/uploads/documents/en-1758111343-Tanzania%20Climate%20Statement%202024.pdf

Zita, L. E., Justino, F., Gurjão, C., Adamu, J., & Talacuece, M. (2025). Spatiotemporal Characteristics of Climate Extremes in Sub-Saharan Africa and Potential Impact of Oceanic Teleconnections. *Atmosphere, 16,* Article 86. https://doi.org/10.3390/atmos16010086

Zorita, E., & Tilya, F. (2002). Rainfall Variability in Northern Tanzania in the March-May Season (Long Rains) and Its Links to Large-Scale Climate Forcing. *Climate Research, 20,* 31-40. https://doi.org/10.3354/cr020031