

Temporal and Spatial Variation Characteristics of March-April-May Precipitation in Tanzania and Its Relationship with SST

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Abstract

This study examines the temporal and spatial variation characteristics of March-April-May (MAM) rainfall over Tanzania and its relationship with Sea Surface Temperature (SST) anomalies using data from 1981-2024. Results reveal a strong north-south rainfall gradient, with enhanced precipitation over the northern, coastal, and Lake Victoria regions, influenced by the Intertropical Convergence Zone (ITCZ), Indian Ocean moisture transport, and local topography. Trend analysis indicates an overall increasing pattern of MAM rainfall, particularly in the southern highlands, central plateau, and coastal areas, while localized declines appear in the Lake Victoria Basin. The Empirical Orthogonal Function (EOF) analysis identifies three dominant modes explaining about 61% of the total rainfall variance, representing widespread, dipole, and zonal variability patterns. Composite circulation analysis shows that wet MAM years are associated with strong low-level moisture convergence, upper-level divergence, and enhanced vertical motion, while dry years display subsidence and reduced moisture inflow. Additionally, global SST anomalies—notably from the Central Pacific ENSO, Western Indian Ocean Dipole (IOD), and Northern Pacific variability—exert significant teleconnection influences on Tanzania's MAM rainfall. Overall, the findings highlight that Tanzania's MAM rainfall variability is strongly modulated by SST anomalies and atmospheric circulation systems, providing a scientific foundation for seasonal forecasting, water management, agriculture, and climate adaptation strategies.

Keywords

March-April-May (MAM) Rainfall, El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Pacific Decadal Oscillation (PDO)

1. Introduction

Rainfall during Tanzania's MAM "long rains" season plays a central role in sustaining the country's agriculture, water resources, and overall socio-economic development. Given that approximately 25% of the national GDP is generated through agriculture and over 75% of the population depends on rain-fed farming systems, rainfall variability in this season has far-reaching implications for food security and poverty reduction (URT, 2017). However, rainfall during this period exhibits significant spatial and temporal variability, often driven by large-scale ocean-atmosphere interactions such as sea surface temperature (SST) anomalies in the adjacent Indian Ocean and distant Pacific and Atlantic Oceans. Notably, studies have identified the Indian Ocean Dipole (IOD) and the El Niño-Southern Oscillation (ENSO) as critical contributors to this variability (Mafuru & Guirong, 2018; Nkunzimana et al., 2020). While numerous studies have explored East African climate variability, most have focused on annual rainfall patterns or the October-December "short rains" (Nicholson, 2017; Ingeri et al., 2024), leaving the MAM season in Tanzania relatively underexamined. Existing research often lacks the spatial detail necessary to capture sub-national variations in climate influences (Alupot et al., 2024) and has tended to treat sea surface temperature (SST) impacts as static over time, overlooking the potential for warming-induced shifts in the strength or positioning of climate drivers (Luhunga et al., 2019). Recent observational records reveal growing unpredictability in Tanzania's rainfall, with more frequent droughts and extreme wet events increasingly linked to intensified global climate phenomena, underscoring the dynamic interplay between Sea Surface Temperature (SST) anomalies and regional rainfall mechanisms. Despite this recognition, understanding remains limited regarding how MAM rainfall varies across Tanzania's diverse topography and climate zones, and how these variations are connected to SST patterns in different ocean basins (Reason, 2001). This gap not only constrains the accuracy of seasonal forecasts but also hinders efforts to strengthen climate resilience in critical sectors such as agriculture and water resource management.

Moreover, there is a notable lack of understanding regarding how atmospheric and oceanic circulation patterns specifically influence the monthly breakdown of MAM rainfall. While some efforts have been made to understand these dynamics in northern Tanzania (Zorita & Tilya, 2002), their work examined the relationship between rainfall variability in northern Tanzania and large-scale ocean-atmosphere interactions, particularly highlighting the influence of ENSO and the Indian Ocean SST anomalies on seasonal rainfall fluctuations. Their study found that March-May (MAM) precipitation exhibits distinct characteristics compared to the October-December (OND) season, with MAM rainfall being less persistent within the season and linked to intraseasonal variations in large-scale patterns of surface temperature, sea-level pressure, and wind circulation. However, their analysis was spatially limited to northern stations and covered a time period (1963-1998). A comprehensive study covering the entire country is still in-

quate, specifically the influence of PDO on MAM rainfall characteristics. Questions such as what types of circulation anomalies are associated with the interannual variability of MAM rainfall, and whether these anomalies are consistent across different regions, remain inadequately answered. This study, therefore, seeks to fill this crucial gap by investigating monthly rainfall anomalies and the corresponding atmospheric circulation patterns on a national scale, providing an integrated and detailed assessment of the mechanisms driving MAM rainfall variability in Tanzania.

The main objective of this study is to conduct an in-depth analysis of the temporal and spatial variation characteristics of MAM rainfall over Tanzania and examine its relationship with atmospheric circulation and SST anomalies. Specifically, the research seeks to: 1) analyze long-term trends and spatial distribution patterns of MAM rainfall over the past four decades; 2) determine the oceanic regions whose SST anomalies have the most pronounced influence on Tanzanian rainfall; and 3) assess the relative contribution of dominant climate drivers such as IOD and ENSO. It is hypothesized that increasing SST anomalies in the western Indian Ocean have had a growing influence on the variability of MAM rainfall in recent decades.

The study holds both academic and practical importance. From an applied perspective, an improved understanding of SST-rainfall relationships is essential to enhancing seasonal forecasting capabilities and ensuring effective climate adaptation strategies. Farmers can benefit from early warnings on likely rainfall patterns for better crop planning, while water managers can optimize reservoir and irrigation planning based on more accurate climate projections. At a broader level, the study also contributes to ongoing scientific discussions on tropical rainfall variability under climate change, particularly in under-studied regions of East Africa.

The structure of this paper is organized as follows: Section 2 outlines the study area, data utilized, and the methodological framework. Section 3 explores the key characteristics of interannual variability in MAM rainfall. In Section 4, the general atmospheric circulation patterns corresponding to monthly rainfall are analyzed. Section 5 delves into the sea surface temperatures linked to variations in monthly rainfall. Finally, Section 6 presents the main conclusions drawn from the study.

2. Study Area, Data, and Methodology

2.1. Study Area

The United Republic of Tanzania, located in East Africa between approximately 1° - 12° S latitude and 28° - 42° E longitude (**Figure 1**), features a highly diverse landscape shaped by the western and eastern branches of the East African Rift Valley and characterized by significant topographical and climatic heterogeneity. Its physiography ranges from coastal lowlands to high-altitude regions such as the northeastern highlands, home to Mount Kilimanjaro (5895 m a.s.l.), Mount Meru, the volcanic ranges, and the Eastern Arc and Southern Highlands, all of which exert strong orographic influences on regional rainfall patterns, creating steep gra-

dients that intensify rainfall, particularly during the MAM long rains. Tanzania's rainfall regime displays pronounced spatial and temporal variability, shaped by the interplay of complex topography, large water bodies, and dynamic atmospheric-oceanic interactions. Two dominant patterns exist: a bimodal regime in the northern and coastal regions, where the long rains occur in MAM and the short rains in October-December (OND), and a unimodal regime across southern, southwestern, central, and western areas, where rainfall typically peaks between November and May (NDJFMAM). In bimodal zones such as the Lake Victoria basin, northern highlands, and Zanzibar Islands, January and February act as transitional months, while June to September is generally dry nationwide. The migration of the Intertropical Convergence Zone (ITCZ) governs these seasonal cycles, with its southward passage triggering the OND rains and its northward return bringing the MAM rains. Long-term records reveal that the rainfall regime can shift between unimodal and bimodal distributions in response to interannual and decadal climate variability (Nicholson, 2017; Diem et al., 2021; Arame et al., 2023).

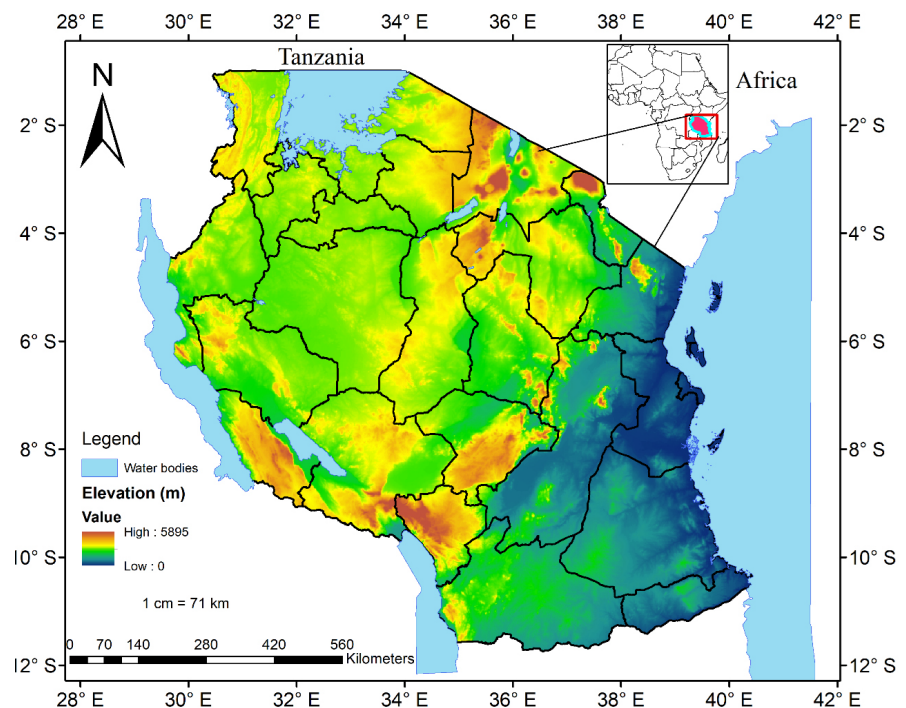


Figure 1. Elevation map of tanzania with major water bodies and geographical location.

Large-scale climate drivers, including the ENSO and the IOD, strongly modulate these patterns by influencing moisture transport and convection, while regional features such as Lake Victoria, Lake Tanganyika, Lake Nyasa, and the Indian Ocean play additional roles. For instance, Lake Victoria generates lake-land breezes that trigger localized thunderstorms, and moist easterly winds from the Indian Ocean enhance precipitation in coastal and adjacent highland regions, par-

ticularly during MAM. Conversely, interior regions often experience reduced rainfall due to rain-shadow effects and distance from major moisture sources. Understanding this intricate spatial and temporal rainfall variability, supported by data from Tanzania's synoptic and agrometeorological station network, is essential for investigating the links between SST anomalies and seasonal rainfall, making the country an ideal natural laboratory for studying mechanisms that drive variability in the climatologically significant MAM and OND seasons (Nicholson, 2017; Dunning et al., 2016; Kebacho, 2022; Ndabagenga et al., 2023).

2.2. Data

This study employed monthly precipitation data from the Climate Hazards Group Infrared Precipitation with Station (CHIRPS) version 2.0, which provides global coverage between 50° S and 50° N at a spatial resolution of 0.05° × 0.05° from 1981 to the present (Funk et al., 2015). CHIRPS combines high-resolution satellite-based infrared cold cloud duration (CCD) observations, in-house climatology (CHPclim), and ground-based station data to produce a consistent gridded rainfall time series. This integration minimizes the biases typically found in datasets derived solely from either satellite estimates or station measurements, thereby improving accuracy for both long-term climate analysis and seasonal monitoring. The dataset, covering a climatological period of over four decades (March-May (MAM) 1981 to March-May (MAM) 2024), is particularly valuable for detecting interannual and decadal rainfall variability, extreme precipitation events, and hydrometeorological trends across Tanzania.

For atmospheric circulation analysis, this study utilized reanalysis data from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) Reanalysis I, which provides a horizontal resolution of 2.5° × 2.5° and 17 pressure levels ranging from 1000 hPa to 10 hPa (Kalnay et al., 1996). Variables extracted include zonal and meridional wind components, vertical velocity (omega), geopotential height, specific humidity, and mean sea level pressure, with a temporal resolution of six hours. These datasets facilitate the assessment of how large-scale circulation anomalies influence MAM rainfall variability over Tanzania.

To investigate ocean-atmosphere interactions, the study employed the Extended Reconstructed Sea Surface Temperature dataset version 5 (ERSSTv5) from the National Oceanic and Atmospheric Administration (NOAA), which offers a spatial resolution of 2.0° × 2.0° and spans from 1854 to the present (Huang et al., 2017). For this research, the period 1981-2024 was selected to align with the atmospheric and precipitation datasets. SST data are essential for identifying large-scale climate drivers, such as ENSO and the Indian Ocean Dipole, and for exploring their role in modulating regional rainfall during the MAM season. Together, the CHIRPS precipitation records, reanalysis atmospheric circulation variables, and ERSSTv5 SST data provide a robust and coherent framework for examining the relationships between oceanic conditions, atmospheric dynamics, and sea-

sonal rainfall variability in Tanzania.

2.3. Methodology

This study uses the following methods to investigate the temporal and spatial variability of MAM precipitation over Tanzania and its relationship with sea surface temperature (SST): Empirical Orthogonal Function (EOF) analysis, composite analysis, statistical significance testing, and correlation analysis. These methods provide a comprehensive framework for examining rainfall variability, associated atmospheric circulation patterns, and the influence of large-scale ocean-atmosphere interactions.

2.3.1. Empirical Orthogonal Function (EOF) Analysis

EOF analysis was applied to extract dominant spatial and temporal modes of rainfall variability across Tanzania. This method decomposes rainfall anomalies into spatial patterns (eigenvectors) and temporal variations (principal components), allowing identification of coherent modes linked to large-scale climate drivers (Hannachi et al., 2023; Wilks, 2016).

The general form of EOF decomposition is:

$$X(t, s) = \sum_{i=1}^k PC_i(t) \cdot EOF_i(s) + \varepsilon(t, s) \quad (1)$$

where $X(t, s)$ is the rainfall anomaly at time t and location s , PC_i represents the principal component time series, $EOF_i(s)$ is the spatial loading, and $\varepsilon(t, s)$ denotes the residual variability. EOF analysis has been widely employed to capture dominant variability patterns of precipitation in East Africa and their teleconnections with global SST anomalies (Nicholson, 2017).

2.3.2. Composite Analysis

Composite analysis was used to evaluate circulation and SST anomaly patterns during wet and dry MAM years. Positive and negative rainfall years were identified based on standardized rainfall anomalies exceeding ± 1 standard deviation. By averaging anomalies of geopotential height, wind vectors, mean sea level pressure, vertical velocity (omega), and moisture divergence during these contrasting years, circulation structures associated with enhanced or suppressed rainfall were identified (Wainwright et al., 2021).

Anomalies were calculated as:

$$A'(t, s) = A(t, s) - \bar{A}(s) \quad (2)$$

where $A(t, s)$ is the observed variable, and $\bar{A}(s)$ represents its climatological mean.

2.3.3. Statistical Significance Testing

To assess whether the composite differences and correlation results were robust, a two-tailed Student's t -test was applied at the 95% confidence level (Wilks, 1997). The t statistic was computed as:

$$t = \frac{(-)}{\sqrt{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)}} \quad (3)$$

where \bar{X}_1 and \bar{X}_2 are the sample means of wet and dry years, s_1^2 and s_2^2 their variances, and n_1 and n_2 their respective sample sizes. This procedure ensured that the observed differences in rainfall, circulation, and SST fields were statistically significant and not due to random variability.

2.3.4. Correlation Analysis

Correlation analysis was conducted to quantify statistical relationships between Tanzanian (MAM) rainfall variability and global SST anomalies. The Pearson correlation coefficient was used (Deser et al., 2018; McPhaden et al., 2020), expressed as:

$$r_{xy} = \frac{\sum_{\Sigma}^{i=1} (n_{(x,i)})(\bar{x}_{(y,i)})}{\sum_{\bar{y}} (\sqrt{\Sigma} i = 1\bar{n})^{(x)} i \sum_{\bar{x}} (\bar{x})_2 \sqrt{\Sigma}^{i=1}} \quad (4)$$

where x_i and y_i denote rainfall and SST anomalies, respectively, and \bar{x} and \bar{y} their means. This analysis highlights the role of teleconnections, particularly ENSO, the Indian Ocean Dipole (IOD), and Pacific Decadal Oscillation in shaping Tanzanian rainfall variability.

3. Results and Discussion

3.1 Climate Characteristics of MAM Precipitation in Tanzania

The MAM rainfall season, widely recognized as the long rains, represents one of the most critical climatological periods in Tanzania. **Figure 2** illustrates the rainfall climatology during this season, highlighting the spatial distribution across March, April, and May, together with cumulative MAM totals. Using a color scale ranging from dark blue (<80 mm) to dark red (>640 mm), the maps reveal strong spatial and temporal variability shaped by large-scale atmospheric circulation, the seasonal migration of the Intertropical Convergence Zone (ITCZ), local topography, and proximity to moisture sources such as the Indian Ocean and Lake Victoria.

March (**Figure 2(a)**) marks the uneven onset of the long rains, with much of the central plateau and southern regions, particularly Dodoma, Singida, and the southern highlands, remaining relatively dry (<160 mm). In contrast, wetter conditions dominate the coastal strip and eastern highlands, where totals often exceed 320 mm, reflecting the transitional influence of the ITCZ's northward migration and mesoscale processes like coastal convergence.

April (**Figure 2(b)**) emerges as the wettest month of the season, with widespread rainfall concentrated in northern and northeastern Tanzania. The Lake Victoria Basin, Kilimanjaro, Arusha, and Manyara frequently record >480 mm, with localized maxima surpassing 560 mm due to orographic uplift, ITCZ convection, and lake-land interactions. Coastal regions, including Dar es Salaam and

Tanga, also receive substantial rainfall (320 - 480 mm), while the central plateau and southwest remain drier (<240 mm). This pattern reinforces the north-south rainfall gradient characteristic of MAM, shaped by regional circulation features such as the Mascarene High (semi-permanent subtropical anticyclone over the southwest Indian Ocean that drives southeasterly flow toward East Africa), Somali Jet (a low-level southwesterly jet that enhances moisture advection from the Indian Ocean), and Congo Air Boundary (the convergence zone between moist westerlies from the Congo Basin and easterlies from the Indian Ocean).

By May (**Figure 2(c)**), rainfall declines sharply, signaling the retreat of the ITCZ and the onset of the austral winter dry season. Central and southern regions register <160 mm, while northern areas, particularly the Lake Victoria Basin and northeastern highlands, continue to receive moderate rains (160 - 240 mm) linked to residual ITCZ activity and lake-induced convection.

The cumulative MAM distribution (**Figure 2(d)**) underscores the dominance of northern and coastal Tanzania as rainfall hotspots. Seasonal totals often exceed 480 mm in the Lake Victoria Basin, northern highlands (Kilimanjaro, Arusha, Meru), and the northeastern corridor, while coastal areas typically record 320 - 400 mm. In contrast, the central plateau and southern regions remain comparatively dry (<240 mm) due to semi-arid conditions and limited exposure to moisture-laden winds.

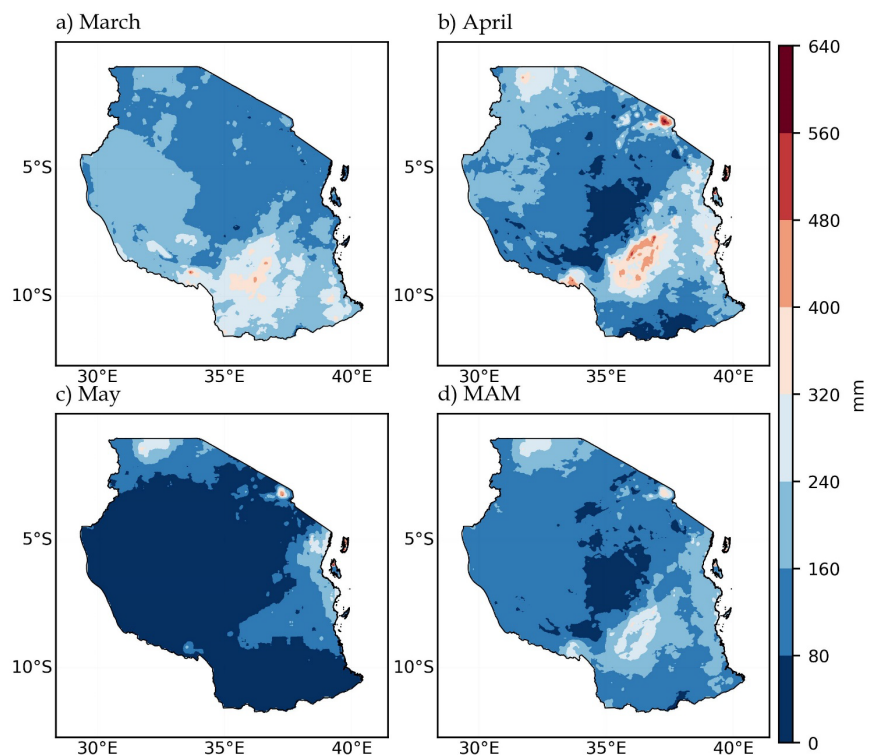


Figure 2. shows the climatological mean rainfall (mm) over Tanzania during March (a); April (b); May (c); and (d) the seasonal average, the climatology was computed from 1981-2024.

Overall, the figure demonstrates a distinct north-south rainfall gradient, with wetter conditions in northern and coastal regions and drier conditions in central and southern Tanzania. These patterns reflect the seasonal migration of the ITCZ, the role of topography, and mesoscale processes such as orographic uplift and lake-land circulation. The rainfall climatology of the MAM season thus highlights pronounced temporal and spatial variability: March as the onset, April as the peak, and May as the retreat. Understanding this behavior is crucial for water resource management, agricultural planning, and disaster preparedness, given Tanzania's reliance on the MAM rains for food security, livelihoods, and socio-economic stability.

Figure 3 displays the annual area-averaged rainfall over Tanzania during the MAM season from 1981 to 2024. The blue bars represent annual rainfall values, whereas the red dashed line denotes the trendline, indicating a general increase in MAM rainfall over time. The slope of the trendline, 1.58 mm per year, suggests a gradual rise in rainfall amounts over the study period. Despite the increasing trend, rainfall exhibits significant interannual variability, with notable fluctuations in different years. Some years, such as the late 1990s and early 2000s, show lower rainfall values, whereas the late 2010s and early 2020s experience some of the highest rainfall amounts in the dataset. There are instances of sharp increases in rainfall, particularly around 2018 and 2020, where values exceed 500 mm. Conversely, drier years, such as the early 2000s, show rainfall levels below 350 mm. The variability in rainfall suggests alternating wet and dry periods, which may have significant implications for agriculture, water resources, and climate-related risks. The R^2 value of 0.127 indicates that while there is an increasing trend, the variability in rainfall is influenced by other climatic and environmental factors.

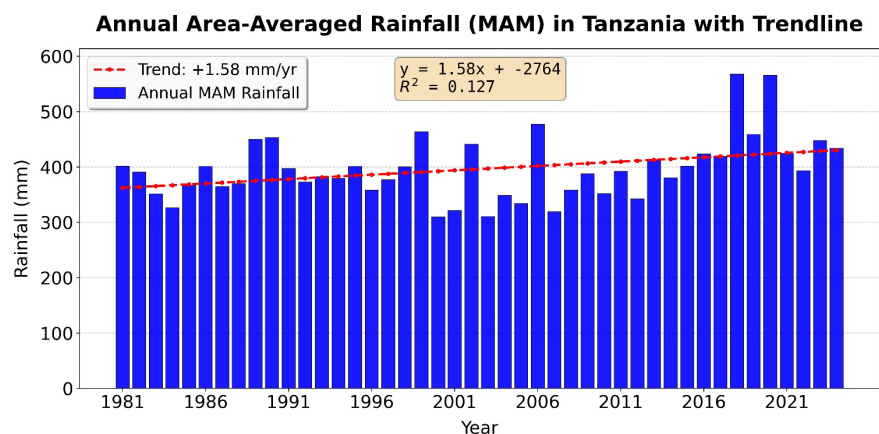


Figure 3. Annual area-averaged MAM rainfall time series over Tanzania from 1981-2024. The blue bars represent the annual rainfall amounts (in mm), while the red dashed line indicates the linear trend.

The presence of both wetter and drier years highlights the unpredictability of seasonal rainfall patterns. The increasing trend suggests a possible shift towards

wetter conditions in recent decades, which may be linked to broader climatic changes. While the trendline provides an overall positive slope, some periods show declining or stagnant rainfall levels. The years 2010 to 2024 show relatively high rainfall compared to the earlier decades, with some peaks reaching unprecedented levels. The variability in the dataset indicates that extreme wet years are becoming more frequent in recent decades. Overall, the figure reveals that while rainfall during the MAM season shows an increasing trend, variability remains a defining characteristic of Tanzania's climate.

The spatial distribution of MAM rainfall trends in Tanzania from 1981 to 2024 (**Figure 4**) reveals a predominantly positive trajectory with clear regional contrasts. Using a scale from -3.6 to $+3.6$ mm per season per year, the maps show widespread increases in rainfall, particularly across the southern highlands, eastern coast, and central plateau, while localized declines appear around the Lake Victoria Basin, the far southwest, and parts of the southern coast. Statistically significant areas, marked by black dots, confirm that many of these changes represent persistent shifts rather than short-term fluctuations.

The southern highlands, including Iringa, Njombe, Mbeya, Ruvuma, and Morogoro, emerge as the strongest rainfall hotspots, with positive trends of $+1.2$ to $+3.6$ mm per year, supported by dense clusters of significance markers. Similarly, the eastern coastal belt—covering Dar es Salaam, Pwani, and Tanga—shows consistent wetting, with trends between $+1.2$ and $+2.4$ mm per year. The central regions of Dodoma, Singida, and Manyara also demonstrate notable increases, representing a major shift for historically drier areas of the plateau.

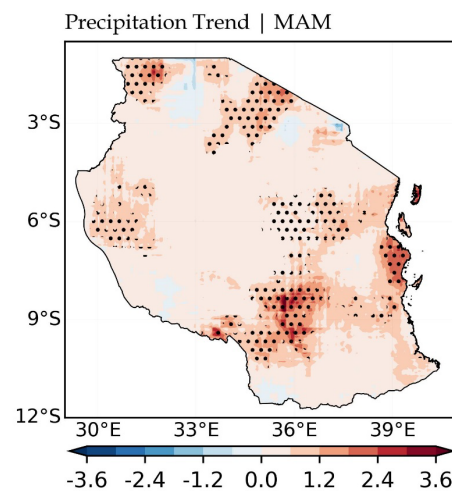


Figure 4. Precipitation Trend|MAM (March, April, May in mm) spatial distribution over Tanzania 1981-2024 statistically significant at the 95%.

In contrast, the Lake Victoria Basin, including Mwanza, Kagera, Shinyanga, and Geita, records declines ranging from -1.2 to -2.4 mm per year, with localized patches approaching -3.6 mm. These reductions, though spatially limited, are sig-

nificant due to the basin's reliance on rainfall for agriculture, fisheries, and water resources. Smaller areas of drying are also evident in Rukwa, Katavi, Lindi, and Mtwara, but these signals are weaker and less spatially extensive compared to the dominant wetting patterns elsewhere.

Taken together, the trends illustrate a clear northwest-southeast gradient: drying or neutral conditions in the northwest contrast with widespread and statistically robust rainfall increases across the central, southern, and eastern regions. This heterogeneous evolution of MAM rainfall highlights both intensification and localized drying, underscoring the importance of regional-scale analysis for water resource planning, agriculture, and climate adaptation in Tanzania.

3.2. The Spatial and Temporal Variation Characteristics of MAM Precipitation in Tanzania

The Empirical Orthogonal Function (EOF) analysis of MAM rainfall over Tanzania highlights major modes of spatial and temporal variability. The first three EOF modes together explain 61% of the total variance, with EOF1, EOF2, and EOF3 accounting for 37%, 14%, and 10%, respectively.

EOF1 (**Figure 5(a)**) represents the dominant mode, characterized by strong positive loadings across central, western, and eastern Tanzania. Positive PC1 phases correspond to widespread above-average rainfall, while negative phases indicate suppressed rainfall, particularly in northern and southern regions. The PC1 time series shows a marked transition from drier conditions during the 1980s-1990s to wetter conditions from the early 2000s onward, with several prominent wet years in the 2010s and 2020s.

EOF2 (**Figure 5(b)**) reveals a north-south dipole, where enhanced rainfall in the south and east coincides with deficits in the north and west, and vice versa. The PC2 time series reflects strong interannual variability, highlighting alternating wet and dry years. This pattern is often linked to shifts in sea surface temperature anomalies in the western Indian Ocean and changes in the positioning of the Intertropical Convergence Zone (ITCZ).

EOF3 (**Figure 5(c)**) captures zonal contrasts, with positive PC3 phases bringing wetter conditions to western and southwestern Tanzania while suppressing rainfall along the eastern coast, including Dar es Salaam. Negative PC3 phases reverse this pattern, with enhanced rainfall in the east and deficits in the west. The PC3 time series indicates decadal-scale fluctuations, particularly stronger western rainfall during the early 2000s and late 2010s, influenced by land-sea gradients, topography, and mesoscale systems such as coastal convergence zones.

These EOF modes underscore the complexity of Tanzania's MAM rainfall, which is shaped by both large-scale drivers and regional dynamics. The observed shift toward wetter conditions in recent decades, reflected in PC1 and PC2, may signal broader climate change impacts, including Indian Ocean warming and heightened variability. Moreover, the contrasting rainfall signals in EOF2 and EOF3 highlight the uneven distribution of rainfall, where some regions experience

excesses while others face deficits, posing critical challenges for water resource management, agriculture, and disaster preparedness.

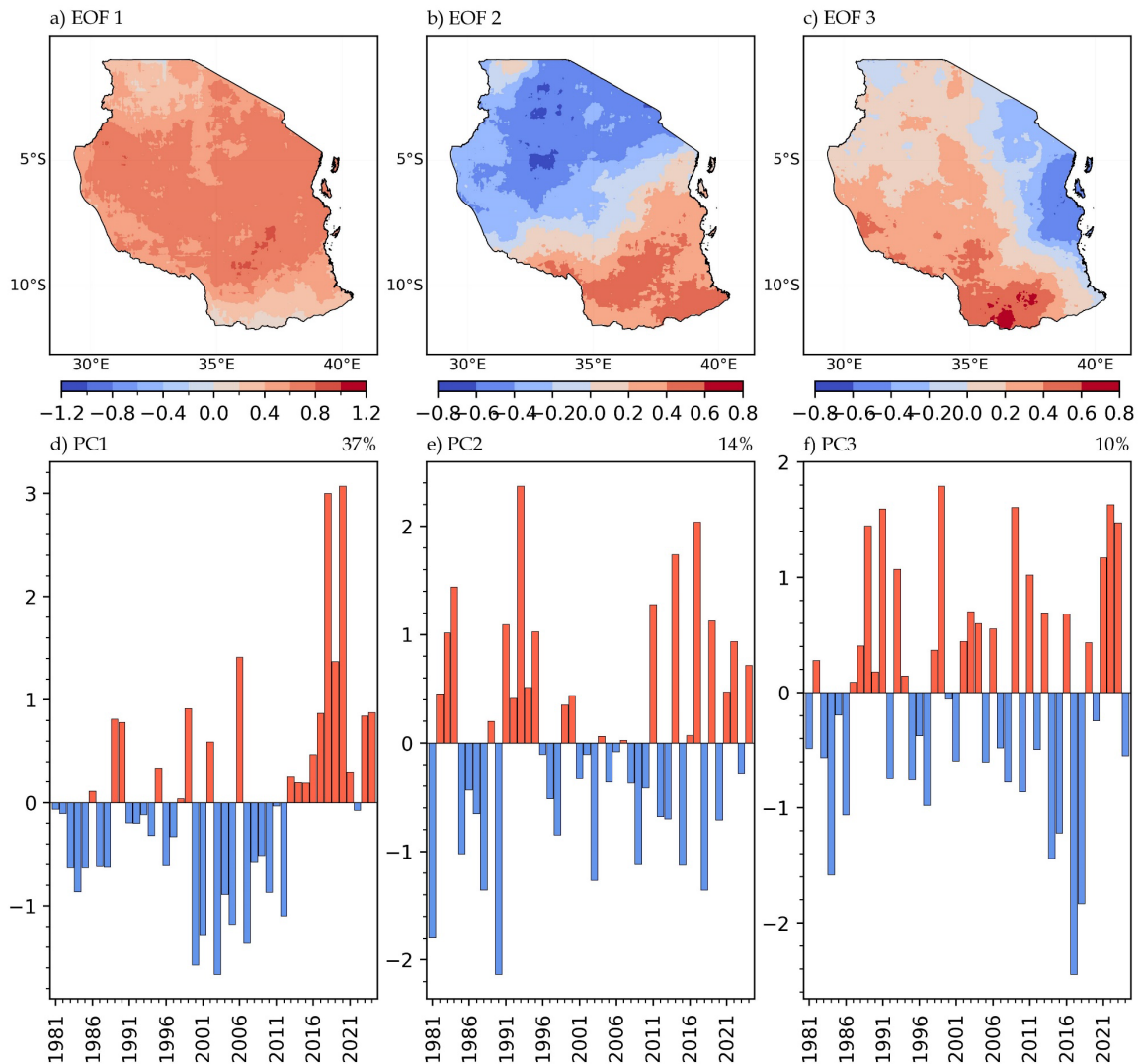


Figure 5. shows the Empirical Orthogonal Function (EOF) analysis of MAM rainfall over Tanzania for the period 1981–2024. Panels (a); (b); and (c) display the spatial patterns of the first three leading EOF modes: EOF1, EOF2, and EOF3. Panels (d); (e); and (f) show the corresponding time series of principal components (PC1, PC2, and PC3), representing the temporal evolution of each EOF mode. Positive values indicate wet years, while negative values indicate dry years across the identified dominant spatial zones.

3.3. The Interdecadal Variations of MAM Precipitation in Tanzania

Understanding long-term precipitation variability is essential for climate studies, and Principal Component Analysis (PCA) effectively captures this by isolating dominant spatial patterns. The first principal component (PC1), which explains the largest variance, highlights two phases: negative PC1 years (1981–2012) with anomalously dry conditions and positive PC1 years (2013–2024) with anomalously wet conditions. Composite analyses and their differences reveal regions

with significant rainfall changes, offering insights into interdecadal shifts and the evolving spatial distribution of rainfall across Tanzania.

MAM precipitation during positive PC1 years (**Figure 6(a)**), indicating widespread wet anomalies (blue shades) along the eastern coast (Dar es Salaam, Pwani, Tanga), the Lake Victoria Basin (Mwanza, Kagera, Geita), and parts of the southern highlands (Iringa, Njombe, Mbeya) with values exceeding +140 mm. Conversely, dry anomalies (red shades) dominate the central plateau (Dodoma, Singida, Tabora) and parts of the western interior (Kigoma, Katavi), suggesting moisture suppression in these areas.

The negative PC1 years (**Figure 6(b)**), revealing an opposite pattern where dry anomalies (red shades) prevail in the north, northeast, and coastal zones (Kilimanjaro, Arusha, Tanga, and Dar es Salaam), while wet anomalies (blue shades) appear over the southern highlands, central interior, and western regions, indicating a southward shift of rainfall during these years.

The difference map (**Figure 6(c)**), emphasizing a clear north–south rainfall dipole. Positive differences (blue shades, up to +72 mm) dominate the eastern coast, Lake Victoria Basin, and southern highlands, signifying higher rainfall during positive PC1 years. In contrast, negative differences (red shades) over the central plateau and northern regions indicate reduced rainfall in positive years compared to negative ones.

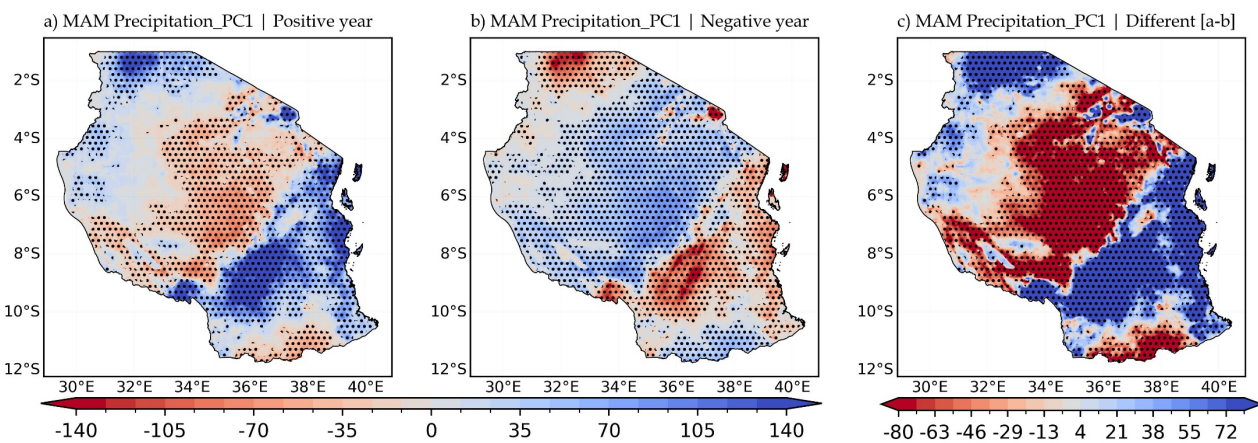


Figure 6. Composite rainfall anomalies during March–April–May (MAM) season for Tanzania over the period 1981–2024: (a) precipitation anomalies in positive years (PC1); (b) precipitation anomalies in negative years (PC1); and (c) difference in rainfall anomalies between positive and negative years [a–b]. Black dots indicate areas significant at the 95% confidence level.

3.4. Composite Analysis of Atmospheric Circulation and Moisture Dynamics Associated with PC1 and MAM Rainfall Variability over Tanzania

Following the examination of PC1, a composite analysis of atmospheric circulation variables of geopotential height highlights how positive, negative, and difference patterns at multiple pressure levels shape MAM rainfall variability in Tanzania.

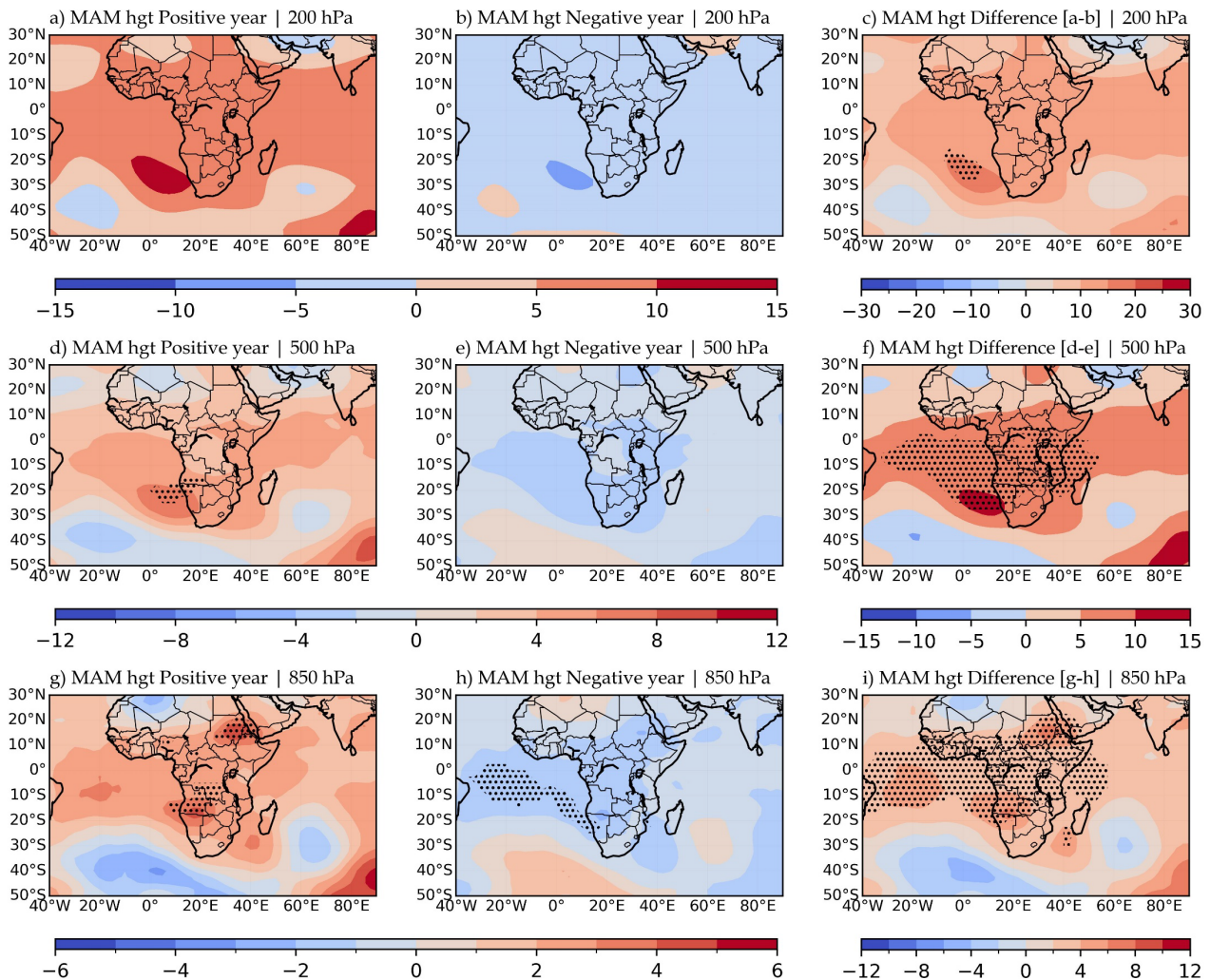


Figure 7. shows geopotential height anomalies (units: m) at 200 hPa (top row), 500 hPa (middle row), and 850 hPa (bottom row) averaged for March-April-May (MAM) over Africa. Panels (a, d, g) show composites during positive rainfall years (2013-2024); panels (b, e, h) represent negative rainfall years (1981-2012); and panels (c, f, i) show the differences (positive minus negative). Statistically significant regions (95% confidence level from a two-tailed Student's t-test) are stippled in the different panels.

At 200 hPa, positive years (**Figure 7(a)**) show widespread positive geopotential height anomalies over East Africa and the western Indian Ocean, indicating upper-level divergence and enhanced convection, while negative years (**Figure 7(b)**) display negative anomalies linked to convergence and suppressed convection; the difference map (**Figure 7(c)**) confirms statistically significant positive anomalies over the western Indian Ocean and eastern equatorial Africa. At 500 hPa, wet years (**Figure 7(d)**) exhibit positive anomalies over the Congo Basin and southwestern Tanzania, consistent with mid-level ascent and thermal low development, whereas dry years (**Figure 7(e)**) show widespread negative anomalies across southern and eastern Africa, indicating subsidence; the difference map (**Figure 7(f)**) reveals a strong dipole with positive anomalies centered over Tanzania and the Congo Basin. At 850 hPa, positive years (**Figure 7(g)**) are marked by anoma-

lies over the Mascarene High that weaken southeasterly trade winds, enhancing west-to-east moisture advection into Tanzania, while negative years (**Figure 7(h)**) intensify easterly flow and block westerly transport; the difference map (**Figure 7(i)**) highlights a positive anomaly over central and eastern Africa, emphasizing the role of low-level circulation. Together, these results identify three key centers of action—an upper-level high over the western Indian Ocean, a mid-level ridge over the Congo Basin, and modulation of the Mascarene High at 850 hPa—demonstrating that wet years are characterized by divergence aloft, mid-level ridging, and favorable low-level inflow, while dry years display the opposite, with the difference maps confirming vertically coherent tropospheric anomalies as central to MAM rainfall variability in Tanzania.

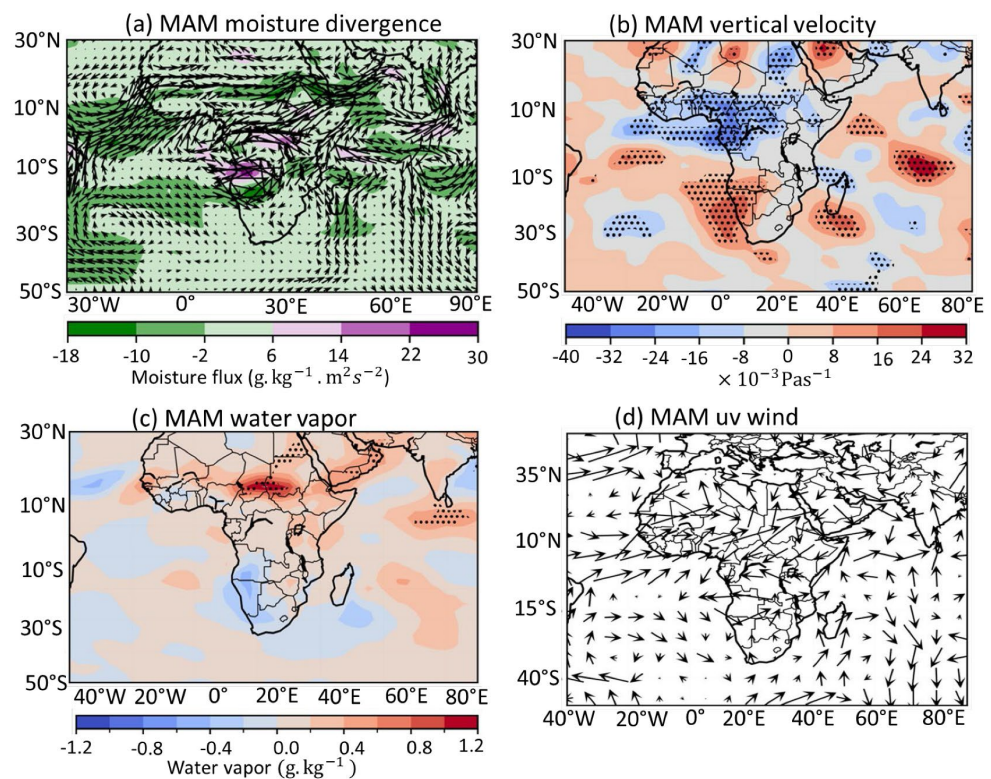


Figure 8. Spatial patterns of (a) moisture divergence and flux vectors; (b) vertical velocity (ω , Pa s^{-1}); (c) water vapor (g kg^{-1}); and (d) horizontal wind ($u-v$) at 850 hPa during the March-April-May (MAM) season from 1981-2024, showing key atmospheric features influencing rainfall variability over Tanzania.

The spatial distribution of moisture divergence (**Figure 8(a)**) reveals strong convergence over central and northern Tanzania, indicating enhanced inflow of moist air from the Indian Ocean through prevailing southeasterly winds. This convergence supports upward motion and convective cloud development, consistent with regions experiencing above-average MAM rainfall, while divergence over southern Tanzania corresponds to reduced precipitation. The moisture flux vectors emphasize the dominant east-west transport aligned with the seasonal mi-

gration of the Intertropical Convergence Zone (ITCZ). The vertical velocity pattern (**Figure 8(b)**) shows pronounced upward motion (negative ω , blue shading) over northern and central Tanzania, signifying enhanced convection favorable for rainfall, while positive ω values (red shading) over southern and western regions indicate subsidence and suppressed rainfall. The spatial coherence between ascending motion and rainfall maxima confirms that vertical circulation strongly controls the intensity and

Spatial distribution of MAM precipitation. The water vapor distribution (**Figure 8(c)**) exhibits high moisture content over northeastern Tanzania, reflecting strong oceanic moisture advection, while negative anomalies over the south coincide with drier conditions. This pattern highlights the role of warm western Indian Ocean SSTs in supplying moisture that sustains rainfall over northern and coastal zones. The horizontal wind field (**Figure 8(d)**) displays easterly and southeasterly flows converging over Tanzania, reinforcing low-level moisture transport inland and intensifying convection. Divergent flow in the southern sector coincides with descending motion and dry conditions. Collectively, these results demonstrate that MAM rainfall variability over Tanzania is primarily governed by low-level moisture convergence, vertical ascent, and strong ocean-atmosphere moisture coupling driven by regional wind dynamics.

3.5. Relationship between March-April-May (MAM) Rainfall Variability in Tanzania and Sea Surface Temperature (SST) Anomalies Across Key Ocean Basins

We investigate the relationship between MAM precipitation variability over Tanzania and global SST patterns (1981 to 2024) using pointwise correlation analysis. Three key oceanic regions show statistically significant SST-rainfall linkages as seen in (**Figure 9**). The Northern Pacific Ocean (50° N - 60° N, 170° W - 150° E) displays mixed positive (0.2 - 0.6) and negative (-0.2 to -0.4) correlations, reflecting modulation of East African rainfall via SST anomalies, the Aleutian Low, and large-scale modes such as the PDO and ENSO. The Central Equatorial Pacific Ocean (5° N - 5° S, 180° - 150° W) exhibits strong positive correlations (0.4 - 0.8), indicating central Pacific El Niño events as the dominant teleconnection driver of Tanzania's MAM rainfall by enhancing deep convection, altering Walker circulation, and redistributing moisture. The Western Indian Ocean (10° S - 20° S, 40° E - 60° E) shows moderate positive correlations (0.2 - 0.4), linked to IOD phases that enhance convection, strengthen moisture inflow, and reinforce monsoonal circulations over East Africa. Together, these regions highlight a coupled global-regional SST-rainfall system, with the central equatorial Pacific exerting primary control, the northern Pacific modulating through multi-decadal variability, and the western Indian Ocean acting as a regional amplifier. These findings emphasize the role of SST teleconnections in shaping Tanzania's rainfall and underscore their importance for seasonal prediction, agricultural planning, and climate risk management.

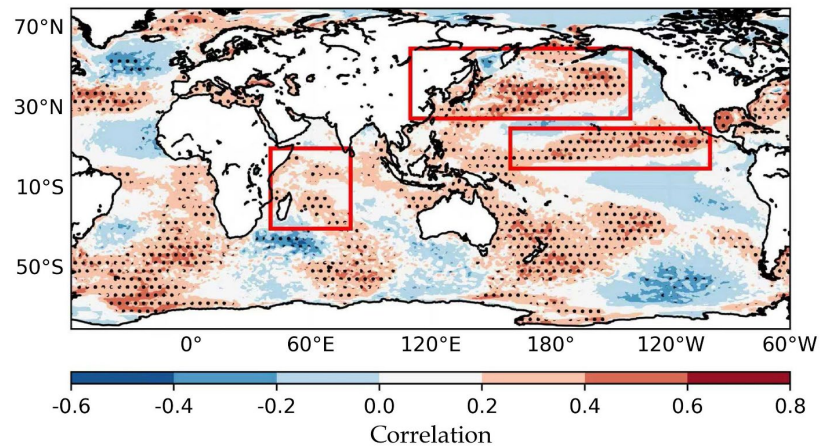


Figure 9. Correlation analysis between MAM precipitation over Tanzania and global SST anomalies for the period 1981-2024. Values represent Pearson correlation coefficients (r), with warm (cool) colors indicating positive (negative) relationships. Statistically significant areas ($p < 0.05$) are marked with stippling (if applicable). Key SST regions influencing Tanzanian rainfall are labeled.

Analysis of SST anomalies from 1981 to 2024 highlights the roles of the Western Indian Ocean (WIO), Northern Pacific Ocean, and Central Pacific Ocean in modulating Tanzania's MAM rainfall. In the WIO (**Figure 10(a)**), SST anomalies range from -0.6°C to 0.6°C , with positive phases during 1997-1998 and 2015-2016 linked to positive IOD events that enhance evaporation, moisture flux, and ITCZ shifts toward East Africa, increasing rainfall. Negative anomalies in the early 1990s and 2010-2011 coincide with negative IOD phases, which weaken moisture convergence and reduce rainfall. The Northern Pacific (**Figure 10(b)**) shows anomalies between -0.4°C and 0.6°C , peaking in 2014-2016 and 2020-2022, reflecting PDO shifts and Aleutian Low variability. ENSO primarily governs interannual rainfall variability through modulation of equatorial Pacific SSTs, while the PDO exerts a broader, decadal influence that can enhance or suppress ENSO effects depending on its phase. During positive PDO phases, Tanzania tends to experience amplified ENSO-driven anomalies, particularly in the northern and coastal regions. Although remote, this region modulates rainfall indirectly through atmospheric wave propagation and subtropical jet adjustments, serving as a secondary influence when coupled with tropical Pacific signals. The Central Pacific (**Figure 10(c)**) displays anomalies from -0.6°C to 0.8°C , with strong positive phases during major El Niño events (1982-1983, 1997-1998, 2015-2016) that enhance convection, weaken the Walker Circulation, and shift the ITCZ east-southward, thereby strengthening moisture convergence over Tanzania. Conversely, La Niña years (1988-1989, 2010-2011) suppress convection and reduce rainfall. Overall, the Central Pacific ENSO system emerges as the primary global driver of Tanzania's MAM rainfall variability, the WIO acts as a regional modulator through IOD phases, and the Northern Pacific serves as a supportive regulator via large-scale circulation influences. These results underscore the value of multi-basin SST

monitoring for improving seasonal prediction and guiding climate risk management in Tanzania.

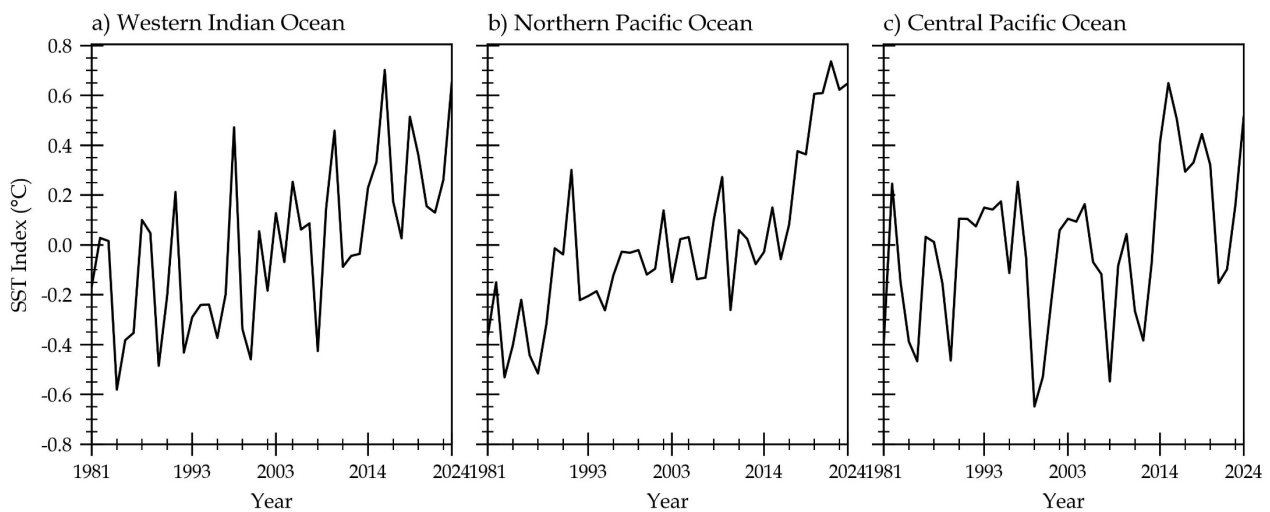


Figure 10. shows the time series of Sea Surface Temperature (SST) anomalies ($^{\circ}\text{C}$) from 1981-2024 for (a) the Western Indian Ocean; (b) the Northern Pacific Ocean; and (c) the Central Pacific Ocean.

The correlation maps (**Figure 11**) demonstrate how global SST anomalies shape MAM rainfall variability across Tanzania, with color gradients from -0.8 to $+0.8$ representing correlation strength and black dots marking statistically significant regions. In the Western Indian Ocean (**Figure 11(a)**), correlations are spatially heterogeneous: negative values over northwestern and southwestern Tanzania indicate that cooler SSTs, typical of negative IOD phases, reduce rainfall by weakening monsoon flows and moisture transport, whereas positive correlations along the eastern seaboard reflect warmer SSTs that enhance evaporation, local convection, and rainfall, albeit inconsistently across regions. The Northern Pacific (**Figure 11(b)**) shows predominantly positive correlations, strongest in central and southeastern Tanzania, suggesting that PDO-related warming modifies upper-tropospheric circulation and promotes low-level moisture convergence, illustrating how remote SST anomalies influence rainfall through atmospheric teleconnections such as jet stream shifts and planetary wave propagation. The Central Pacific (**Figure 11(c)**) exerts the most consistent and widespread influence, with positive correlations dominating northeastern, eastern, and central Tanzania, consistent with El Niño-driven weakening of the Walker Circulation, enhanced Pacific convection, and increased moisture inflow toward East Africa. Weak negative correlations in the southwest align with La Niña conditions that suppress rainfall. Collectively, the results highlight the Central Pacific ENSO system as the dominant driver of Tanzania's MAM rainfall, followed by the Northern Pacific and Western Indian Ocean, underscoring the importance of multi-basin SST monitoring for improving seasonal rainfall forecasts and informing agricultural planning, water resource management, and climate risk mitigation.

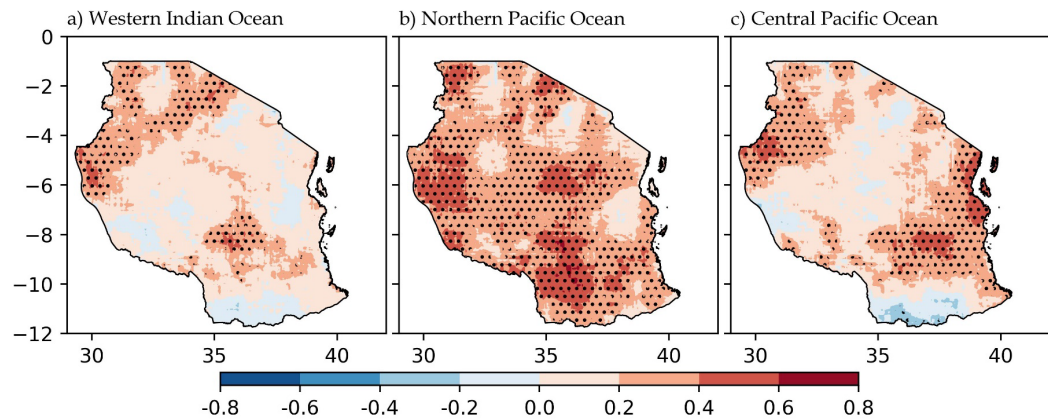


Figure 11. Spatial distribution of correlation coefficients between MAM rainfall over Tanzania and SST indices from (a) the Western Indian Ocean; (b) the Northern Pacific Ocean; and (c) the Central Pacific Ocean, based on data spanning 1981-2024.

4. Conclusion and Summary

In conclusion, the findings of this study reveal that the variability of MAM rainfall over Tanzania is primarily governed by the combined effects of local atmospheric circulation and large-scale oceanic influences. Spatially, a distinct north-south rainfall gradient is evident, with enhanced precipitation over the northern, northeastern, and coastal regions, while the central plateau and southern highlands experience relatively drier conditions. Temporally, a gradual increasing rainfall trend since the 1980s is observed, particularly over the southern highlands, coastal areas, and central plateau, suggesting a transition toward wetter conditions in recent decades. The EOF and composite circulation analyses confirm that rainfall variability is controlled by vertically coherent atmospheric structures—upper-level divergence, mid-tropospheric ridging, and low-level moisture convergence—that enhance convection during wet years, whereas subsidence and weakened inflow dominate during dry phases, suppressing rainfall. Furthermore, global SST anomalies linked to ENSO, IOD, and PDO exert significant teleconnection effects that modify regional atmospheric dynamics and moisture transport pathways, influencing the spatial and temporal distribution of MAM rainfall across Tanzania. During positive PDO phases, Tanzania tends to experience amplified ENSO-driven anomalies, particularly in the northern and coastal regions.

While these findings offer crucial insights into the mechanisms driving rainfall variability, some limitations remain, including the reliance on reanalysis datasets and the focus on linear relationships, which may overlook non-linear interactions and localized feedback processes. Future research should therefore utilize high-resolution regional climate models, longer time-series data, and coupled ocean-atmosphere simulations to better capture the complex interactions shaping rainfall variability. Overall, this study enhances the scientific understanding of MAM rainfall dynamics in Tanzania and provides a strong foundation for improving seasonal rainfall prediction, optimizing water resource management, guiding ag-

ricultural planning, and supporting climate adaptation and disaster preparedness efforts across the country.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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