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Spatio-temporal Dynamics of the Onset and Cessation of OND Rainy Season across Bimodal Regions of Tanzania

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Keywords

Rainfall characteristics;
OND;
rainy season;
Intraseasonal variability;
Bimodal region;
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Abstract

This study investigates the temporal variability of the onset, cessation, and duration of the October-November-December (OND) rainy season in the bimodal rainfall region of Tanzania. Utilizing daily precipitation data from the Multi-Source Weighted-Ensemble Precipitation dataset for the period 2014–2023, the study employs the Accumulated Daily Index method to determine the onset and cessation of rains, with the seasonal duration computed as the difference between these dates. Variability in onset, cessation, and season length was quantified using the Coefficient of Variation. The findings highlight significant spatial variability in onset, with early rains in northwestern areas (e.g., Bukoba) and coastal zones, commencing as early as late September. Most regions experience onset between early October and late November, while cessation of rains is typically observed between mid-January and early February, with coastal and Lake Victoria Basin regions showing greater variability. The study identifies significant variations of the OND rainy season, particularly in the western and coastal areas, with shifts toward a November-December-January (NDJ) rainfall season in some regions. This suggesting a transition from OND to NDJ regime in some regions. These results underline the necessity for enhanced forecasting models to address the implications of altered rainfall regimes on agriculture, water management, disaster mitigation, and other socio-economic activities. This study provides critical insights into rainfall variability, aiding in the formulation of adaptive strategies to optimize socio-economic benefits while mitigating risks associated with climate variability.

Introduction

Rainfall is a critical climatic variable and a key resource for the development of socio-economic sectors in Africa, including industry, domestic use, agriculture, food security, energy, and water supply (Suleiman et al. 2023). Rainfall varies significantly in terms of quantity, spatial distribution, and temporal patterns, leading to variability (Dunning et al. 2016). Long-term shifts in these patterns introduce uncertainty in the agricultural sector, which is the backbone of socio-economic development in a large part of the world (Omay et al. 2023). In the East African region, including Tanzania, the frequency of rainfall season variations is increasing, with evidence linking these changes to long-term climate changes. (Mulamula et al. 2020). Such deviations from normal rainfall patterns have significant impacts on agriculture and other socio-economic activities (Chang'a et al. 2020).

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Understanding rainfall variables such as onset, cessation, and season duration is crucial for mitigating risks in rain-fed agriculture, property loss, and other socio-economic disruptions.

Intrannual variations in Tanzania rainfall are mostly linked to the sea surface temperature (SST) anomalies in the Indian and Pacific oceans included those associated with Indian Ocean Dipole (IOD) and El Niño-Southern Oscillations (ENSO). For instance, El Niño and positive IOD years are often associated with early onset and cessation during the October-December (OND) rainy season, whereas La Niña years exhibit the opposite trends (Yonah et al. 2023). Rainfall onset and cessation are critical for agricultural planning in the region, but their identification remains challenge (Camberlin and Okoola 2003, Suleiman et al. 2023). In addition, intra-annual variability is associated with low level moist and unstable wind from Congo basin which organizes and forms a confluent zone, inter tropical convergence zone (ITCZ) extending from Congo to northern sector of the country (Ame et al. 2021).

In Tanzania, rainfall variability manifests through unpredictability, shortages, increasing intensities, and prolonged droughts and floods, often resulting from variations in rainy season onset and cessation (Mulamula et al. 2020). Researchers have focused extensively on onset and cessation patterns, highlighting substantial inter-annual variability influenced by the pressure gradient between the Indian and Atlantic Oceans (Kabanda and Jury 1999, Camberlin and Okoola 2003). For instance, in Zanzibar, the OND rainy season typically begins between October 22nd and 25th and ends between December 10th and 12th, lasting approximately 55 to 60 days (Suleiman et al. 2023). Rainfall during this period is driven by atmospheric circulation anomalies such as sea surface temperature, wind patterns, relative humidity, and vertical velocity. Converging moist winds from the Congo Basin and the Indian Ocean play a key role in this process (Suleiman et al. 2023).

Onset variability is more pronounced than cessation, likely due to external forcing factors that are stronger during onset compared to cessation, where moist land surfaces provide positive atmospheric feedback (Camberlin et al. 2009). Forests, coastal areas, and transitional zones experience earlier onset and longer seasons, while savannah zones have later onset and shorter durations. The northern part of Tanzania experiences significant variations in seasonal rainfall patterns due to factors like ridging, moisture flux, and ENSO events, particularly during onset. Rainy season duration decreases from north to south and from east to west, with a 10-day variation in OND season length observed across regions. Rainfall amounts and the number of rain days are generally consistent (Hachigonta et al. 2008).

Certain areas, such as the northeastern highlands, parts of the northern coast, and unimodal regions, experience late rainfall onset accompanied by dry spells. These regions are influenced by the north-south movement of the ITCZ (Yonah et al. 2023). October rainfall is higher over the Lake Victoria Basin, northern Kigoma, and the northern coastal peripheries due to ITCZ movements. A strong temporal correlation exists between OND rainfall and the IOD, compared to ENSO. The OND rainy season typically begins in the Lake Victoria Basin and western areas before spreading to other bimodal regions. November is particularly wet in these regions (Ame et al. 2021). Emphasizing the timing of onset, cessation, and season length is essential for enhancing the accuracy of weather forecasting and addressing challenges related to rainfall variability. This study aims to analyze OND temporal variations in bimodal regions of Tanzania to improve forecasting and provide early warnings for agriculture and other socio-economic sectors affected by these variations.

Study area and data

This study was conducted over bimodal regions of Tanzania, which lie between latitudes of 3.4^{o} S and 6.8^{o} S and longitudes of 36.6° E and 39° E as depicted in Figure 1. These regions include the northern coast (Tanga, Dar es Salaam, north Morogoro, Pemba and Unguja islands), northeastern highlands (Kilimanjaro, Arusha and Manyara region), the Lake Victoria basin (Mara, Kagera, Simiyu, Shinyanga, Geita and Mwanza). This study employed daily rainfall data from the Multi-Source Weighted-Ensemble Precipitation (MSWEP) dataset, covering the September-February period from 2014 to 2023. MSWEP stands out as the first fully global precipitation dataset with a spatial resolution of 0.1° and a temporal resolution of 3 hours, achieved through the optimal merging of gauge, satellite, and reanalysis estimates (Hylke et al. 2019). These attributes make this dataset suitable for this study and differentiate it from other datasets typically used in Tanzania. The advantage of MSWEP includes its minimal root-mean-square error and its unparalleled global coverage, encompassing all land and ocean features which is not available in other datasets. Its high spatial and temporal resolution enhances the local relevance of precipitation estimates, making it a superior choice for capturing detailed rainfall patterns. The most recent decade (2014–2023) offers consistent and quality-assured daily records, particularly from MSWEP Version 2.8, which has been enhanced through the integration of more ground-based observations and improved satellite inputs in East Africa. Recently studies (e.g., Hylke et al. 2019, Dinku et al. 2022), have validated the suitability of MSWEP in East Africa for capturing extreme rainfall and daily variability, particularly in regions with sparse gauge networks including Tanzania. The dataset's inclusion of September, January, and February was essential for assessing variability in the OND rainy season. This approach ensured that onset dates occurring before October and cessation dates extending beyond December were accurately captured. Similar methodologies have been employed in other studies, such as Yonah et al. (2023), which incorporated September and January to determine onset during short rains across East Africa.

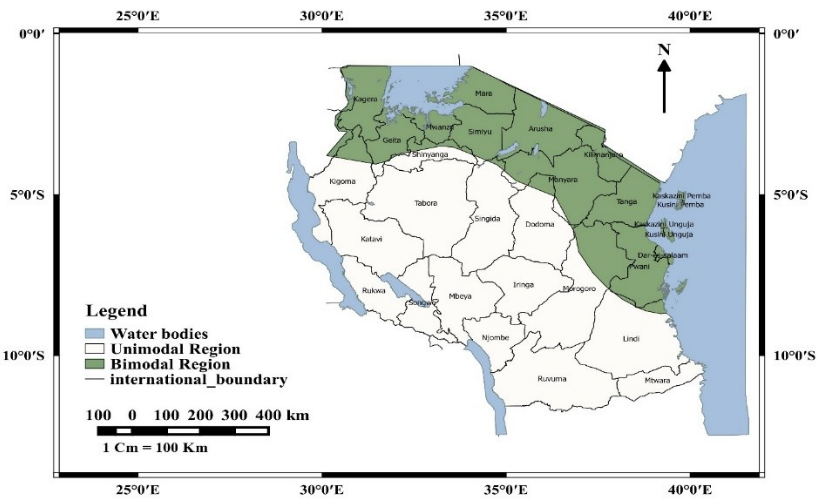

Figure 1: Location of the study region (shaded with green colour) in Tanzania

Methodology

Accumulated Daily Index

This method establishes rainfall thresholds to determine the onset and cessation of the rainy season in a specific region. The Accumulated Daily Index (ADI) method is particularly effective in capturing local climatic behaviors and is instrumental in analyzing rainfall variability (Valimba 2005, Dunning et al. 2016). This method has been applied on various studies to identifying the onset, cessation, and duration of the rainy season (Marteau et al. 2009, Ngetich et al. 2014, Mulamula et al. 2020). In this study, an ADI threshold of 20 mm, as defined by the Tanzania Meteorological Authority, was employed to identify the onset of the rainy season. Onset dates were determined as the first day with cumulative rainfall exceeding the ADI over four consecutive days, with at least two of those days being wet and no dry spell exceeding 10 days within the subsequent 30-day period (Maruatona and Moses 2022, Recha et al. 2012, Yonah et al. 2023). Cessation dates were defined as periods with less than 25 mm of accumulated rainfall over five days, with at least three of those days being dry, followed by a dry spell exceeding seven days (Adelekan and Adegebo 2014). The length of the rainy season was calculated as the interval between the onset and cessation dates (Valimba 2005).

Coefficient of variation

The variability in the onset, cessation, and duration of the rainy season was assessed using the Coefficient of Variation (CV), a statistical measure that quantifies the relative variability of a dataset around its mean and expressed in percentage. A higher CV indicates greater rainfall fluctuations, making predictions more challenging, while a lower CV suggests reduced fluctuations, facilitating more accurate predictions. Based on the classification proposed by Hare (2003) and Harka et al. (2021), variability is considered low when the CV is below 20%, moderate when the CV ranges between 20% and 30%, and high when the CV exceeds 30%. This study adopts the same interpretive framework. To compute the CV, the mean (μ¿ and standard deviation (σ¿ must first be calculated and can be computed as:

$$CV=\frac{\sigma}{\mu}\times 100 \qquad 1$$

Results and Discussion

Distribution of OND rainfall over bimodal regions

Normally, over a bimodal rainfall region of Tanzania, the short rainy season, known as the OND season, typically commences in October and concludes in December, as depicted in Figure 3. However, interannual variability occasionally leads to an earlier onset in late September or a delayed cessation in early January (Yonah et al. 2023). Observations indicate that the northwestern sectors of the bimodal regions, such as Bukoba, receive the highest precipitation totals, followed by coastal areas, including Pemba, Tanga, Zanzibar, and Dar es Salaam. Conversely, northeastern and central areas of the bimodal regions, such as Kilimanjaro, Arusha, Shinyanga, and Musoma, experience comparatively lower rainfall amounts (Figure 2). Elevated precipitation levels in the northwestern regions are primarily driven by abundant moisture fluxes associated with large water bodies like Lake Victoria and Lake Tanganyika. Similarly, the Indian Ocean significantly enhances moisture availability, resulting in higher rainfall along the coastal zones (Kavishe and Limbu 2020, Kebacho 2021, Makula and Zhou 2022).

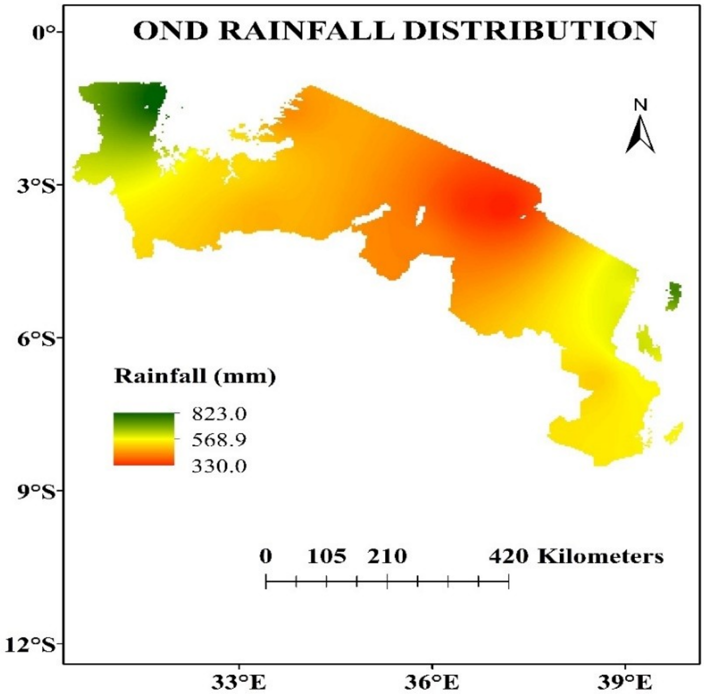

Figure 2: Spatial distribution of rainfall over bimodal regions

Throughout the OND rainy season, peak precipitation predominantly occurs in November across most bimodal regions, as illustrated in Figure 3. However, exceptions are noted in Manyara, Mwanza, Musoma, and Shinyanga, where maximum rainfall intensifies in December. These findings align with the studies conducted by Ame et al. (2021) and Kavishe and Limbu (2020). The observed precipitation patterns are primarily influenced by the migration and spatial positioning of the ITCZ. In November, the ITCZ is situated in the northern part of Tanzania, resulting in enhanced moisture flux and higher rainfall across the majority of bimodal regions. As the ITCZ gradually shifts southward, regions such as Manyara, Mwanza, Shinyanga, and Musoma experience their rainfall peaks in December. Additionally, the December precipitation maxima in these areas are significantly affected by topographical variations and the presence of large water bodies, including lakes (Borhara et al. 2020).

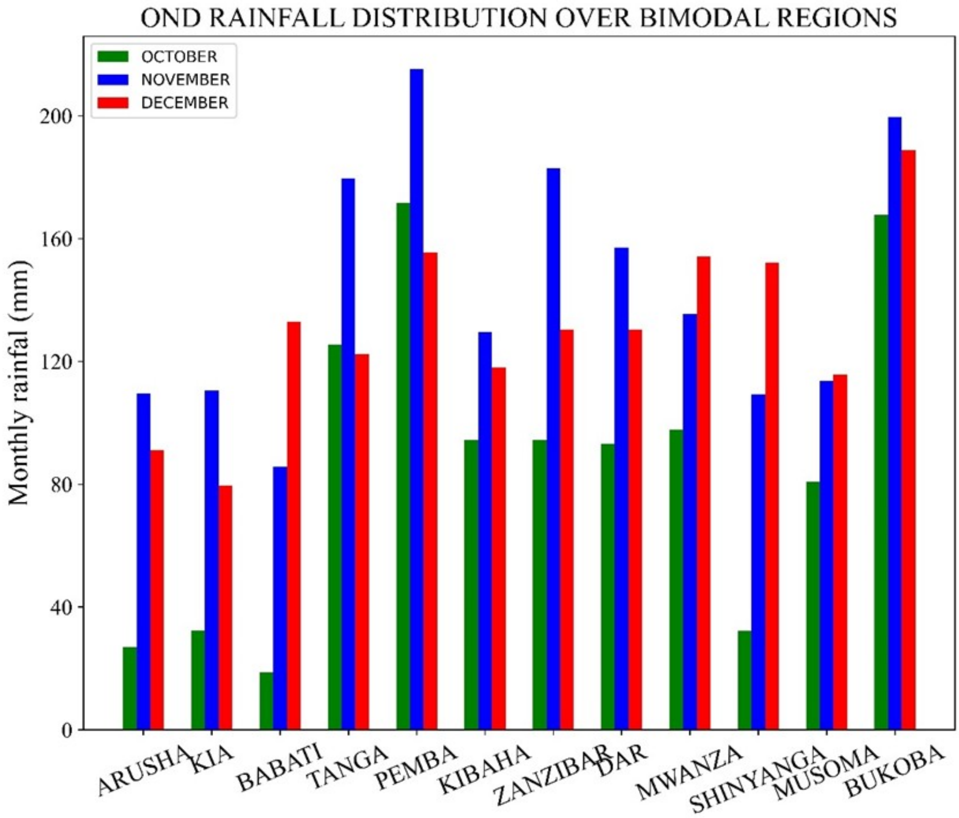

Figure 0: Distribution of rainfall amount over bimodal Region.

Onset and cessation of OND rainy season

Onset of OND season

The onset days for the bimodal regions in this study were quantified by designating 15 September as day one and 15 November as day 61 (Yonah et al. 2023). Earliest onset events typically occur in September, while average onset occurs in October, and late onset in November. Findings indicate spatial and temporal variability in the onset of the OND rainy season, with some areas experiencing earlier rainfall initiation and others encountering delays. Overall, the northwestern sector of Tanzania exhibits the earliest onset, followed by the coastal regions, and lastly, the central parts of the bimodal region (Figure 4). Additionally, rainfall onset commonly commences over the western bimodal zone and the Lake Victoria basin, progressing eastward as the season advances.

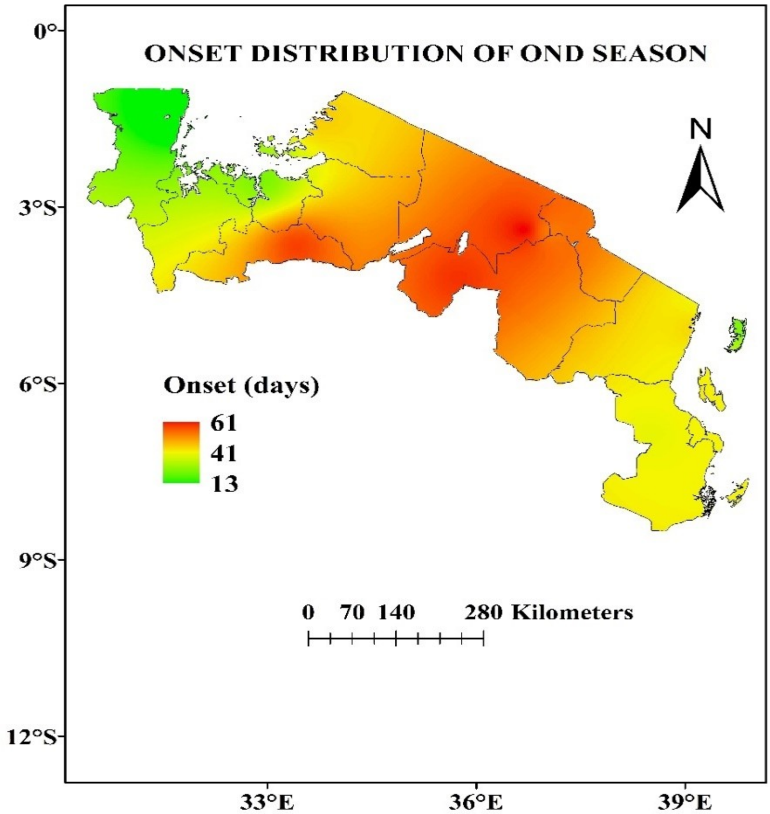

Figure 4: Onset rainfall distribution over bimodal region of Tanzania from 2014-2023

Moreover, the mean onset of rainfall across most bimodal regions occurs during the first and second weeks of October, with the exception of Bukoba, where the average onset is observed in the fourth week of September. Arusha, Manyara, and Shinyanga instead exhibit delayed onsets around the second and third weeks of November (Figure 5). The early onset in Bukoba is primarily governed by the migration of the ITCZ and moisture fluxes associated with the Congo air mass, which together influence rainfall onset, duration, and intensity (Dunning et al. 2016, Makula and Zhou 2022, Ongito and Limbu 2024). Along the coastal sectors of the bimodal region, the average onset is driven by large-scale atmospheric phenomena such as the IOD, ENSO, and the proximity of the Indian Ocean (Ame et al. 2021, Kebacho et al. 2024). In contrast, delayed onset in the northeastern areas is predominantly shaped by topographic barriers, notably Mount Kilimanjaro, which can impede moisture advection and subsequently alter rainfall patterns (Nyembo et al. 2020).

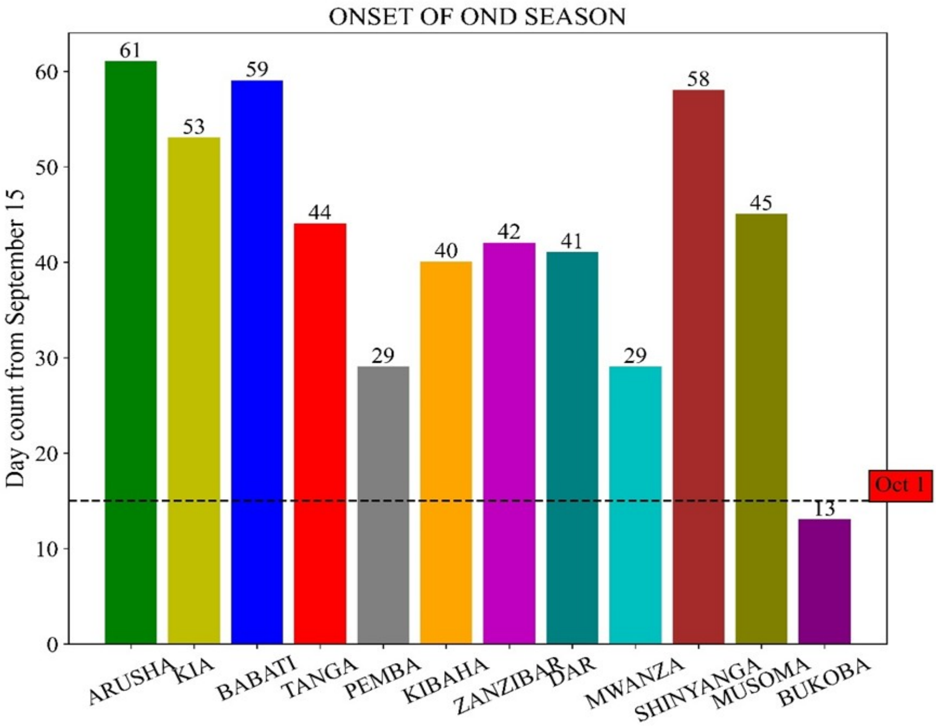

Figure 5: Average onset days over bimodal region

In some cases, a significant rainfall may appear to mark the beginning of the season, but is followed by an extended dry spell, this event is termed as false onset. False onset appears as if the rainy season has officially begun, while in reality, it has not fully established (Lisonbee et al. 2022, Roy et al. 2024). The false onset in this study was counted when the region had an accumulation of 20 mm of rainfall within four (4) days and followed by at least two (2) days of dry spell. The same methodology was used by Lisonbee et al. (2022). Within the study area, Mwanza and Musoma exhibited a higher frequency of false onsets compared to other bimodal regions between 2018 and 2023. Specifically, Mwanza recorded false onsets in 2019, 2020, 2021, and 2023, whereas Musoma recorded such events in 2021 and 2022 (Figure 6). On average, the temporal difference between false onset and actual onset was five days in Mwanza and ten days in Musoma. These discrepancies are influenced by convective activity around the Lake Victoria basin, which can trigger localized thunderstorms and rainfall episodes (Ame et al. 2021). Although these short-lived events may boost precipitation totals in Mwanza and Musoma, they do not necessarily indicate the sustained atmospheric circulation and moisture convergence required for the true establishment of the rainy season. Once these convective rains diminish and the subsequent dry spell ensues, it becomes evident that the broader meteorological mechanisms supporting seasonal rainfall have yet to fully develop—thereby confirming a false onset.

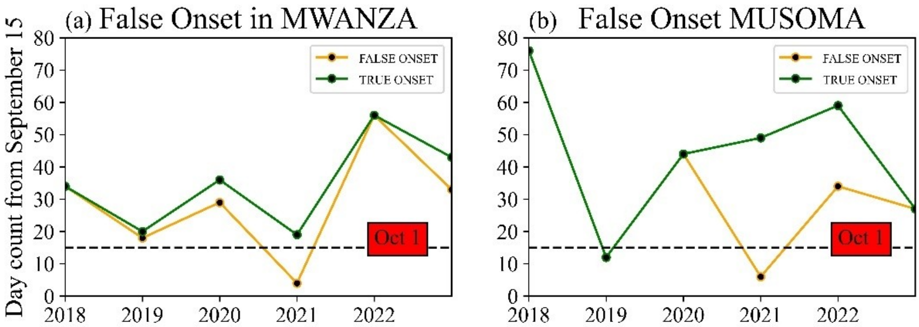

Figure 2: False onset over some regions in bimodal regions

Cessation of OND season

The cessation dates for the OND rainy season are quantified starting from 15th December as day one and extending to 15th February, which marks day 63. Early cessation is scientifically classified as the end of the rainy season prior to 31st December, while late cessation is characterized by the end of the season beyond 15th January. On average, the central and northeastern parts of the observed areas experience the earliest cessation, followed by the western sections of the bimodal rainfall region. In contrast, the coastal zones and the Lake Victoria Basin exhibit a delayed cessation of rainfall (Figure 7). The variability in cessation dates is primarily influenced by regional atmospheric dynamics. Early cessation in the central and northeastern regions is attributed to a rapid weakening of the IOD and the retreat of the ITCZ toward the southern hemisphere, which reduces the moisture influx and convective activity in these areas. Conversely, the late cessation observed in the coastal and Lake Victoria Basin regions is driven by the persistence of onshore moisture-laden winds and localized convection supported by lake-induced effects and prolonged ITCZ activity, which sustain rainfall into January and beyond.

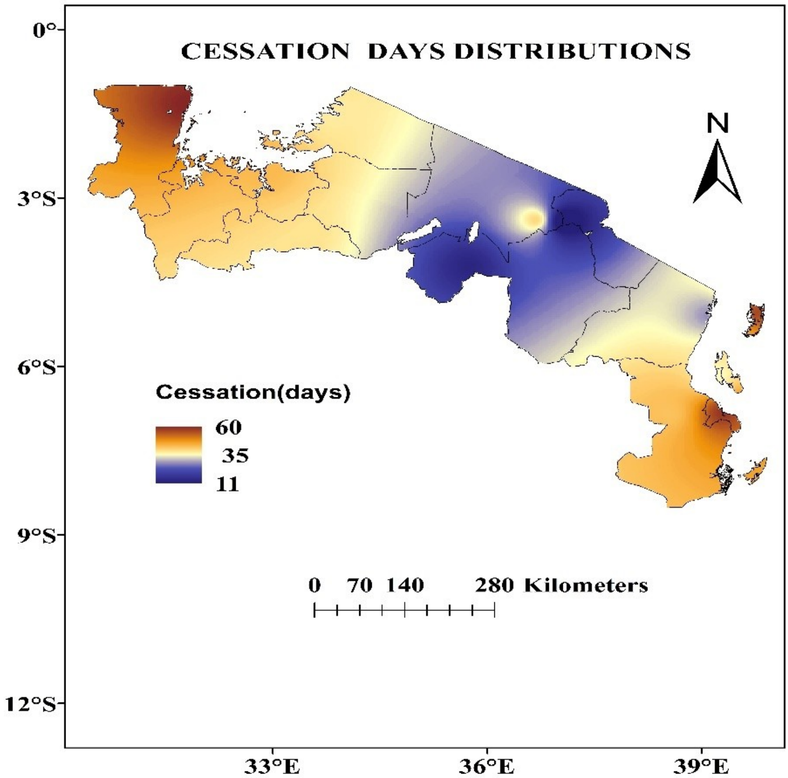

Figure 3: Spatial distributions of cessation days over bimodal regions

With the exception of the Kilimanjaro (KIA) region, where the OND rainy season typically concludes during the fourth week of December on average, all other areas within the bimodal rainfall regions exhibit cessation dates extending beyond December (Figure 8). The earlier cessation observed in the Kilimanjaro region is primarily attributed to its unique topographic characteristics, which significantly influence localized climatic conditions, including the timing and duration of the rainy season. This finding aligns with the conclusions of Amekduzi et al. (2015), who emphasized the impact of orographic features on regional precipitation patterns. In contrast, the delayed cessation observed in Bukoba is strongly influenced by the sustained moisture influx from the Congo Air Mass and the regulatory effects of Lake Victoria, which foster prolonged convective activity in the region. Similarly, the late cessation noted in Dar es Salaam and Pemba is closely associated with the persistent onshore flow of moisture-laden air from the Indian Ocean, which enhances precipitation during the latter part of the season. These dynamics underscore the critical role of geographic and atmospheric interactions in shaping the temporal variability of the OND rainy season across the bimodal regions.

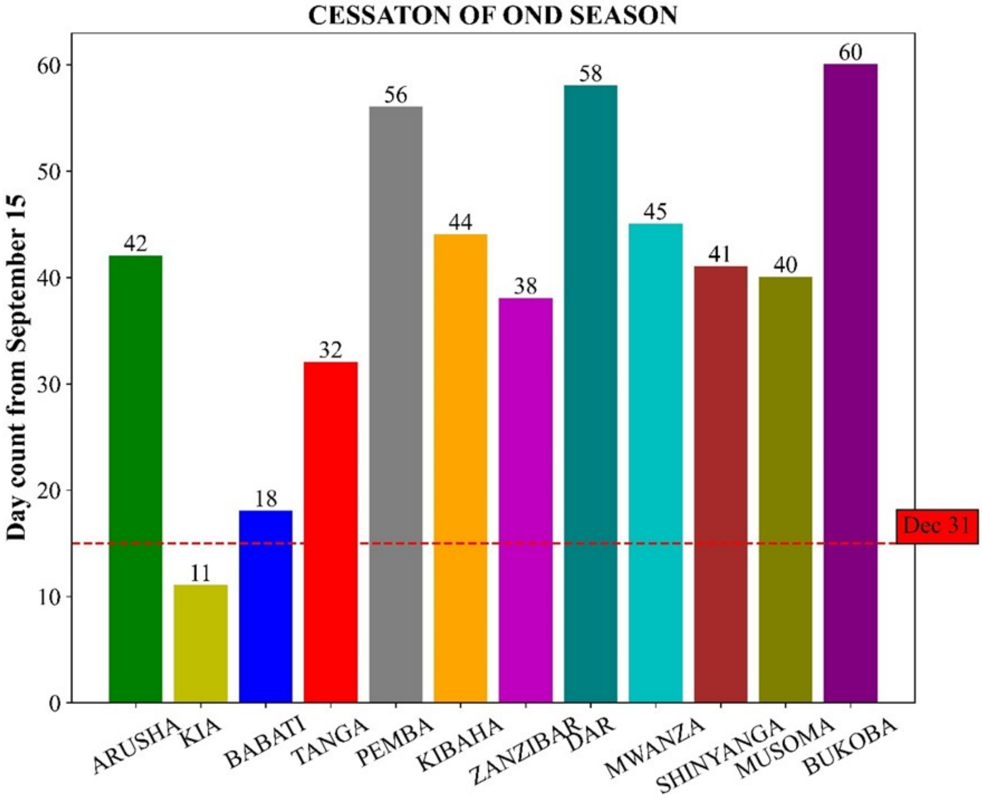

Figure 4: Average cessation days over bimodal regions

Length of the season

The results in Figure 9 illustrate significant spatial variability in the length of the OND rainy season across the bimodal regions in Tanzania, influenced by local climatic dynamics, atmospheric circulations, and topographical variations. Bukoba records the longest season at 138 days, primarily due to its proximity to Lake Victoria, where lake-induced convection enhances rainfall activity, resulting in early onset and late cessation of rains. The persistent activity of the ITCZ over this region also contributes to the prolonged season (Nicholson 2017). In contrast, KIA experiences the shortest rainy season of 49 days, attributed to the late arrival and early retreat of the ITCZ, combined with localized rain shadow effects caused by its high altitude. Additionally, the suppression of convective activity by subtropical anticyclones further limits the duration of rains in this region (Ogwang et al. 2014). Other regions, such as Zanzibar (87 days) and Pwani (95 days), have intermediate season lengths, reflecting the influence of maritime moisture from the Indian Ocean, which sustains rainfall activity. Mwanza (106 days) and Shinyanga (74 days) highlight the effects of both ITCZ movements and topographic variability, with Mwanza benefiting from Lake Victoria's proximity. The variability in onset and cessation dynamics is driven by the southward migration of the ITCZ, bringing moist winds from the Indian Ocean and the Congo Air Basin, while local factors like lake effects and orographic influences amplify the variability. The ENSO phases also play a critical role, with El Niño typically prolonging and intensifying rainfall over regions like Bukoba, while La Niña conditions suppress it (Camberlin and Okoola 2003, Mutai and Ward 2000). This spatial variability underscores the complex interaction between global, regional, and local climatic drivers in shaping rainfall patterns in Tanzania.

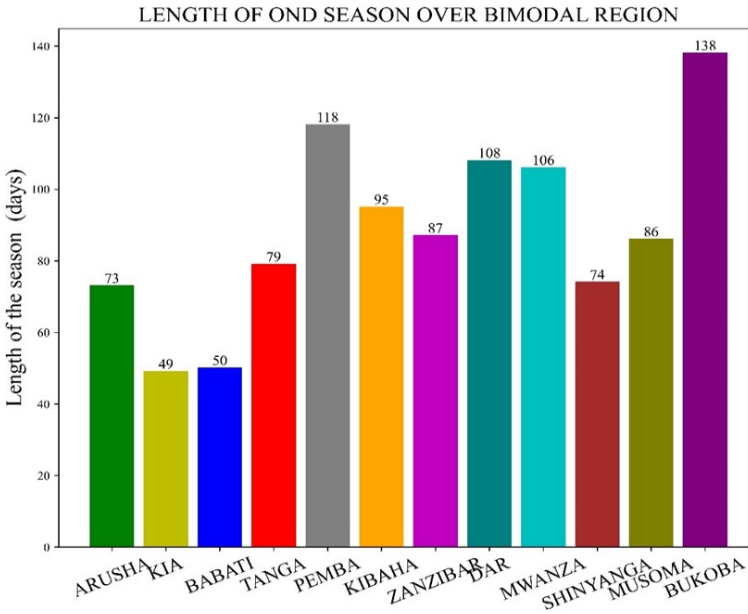

Figure 9: Average length of a season over bimodal regions

Temporal trends of onset and cessation

The results illustrated in Figure 10 highlight temporal trends in the onset and cessation of the OND rainy season across the bimodal regions of Tanzania. The results reveal a general increase in onset days (delayed onset) and a decrease in cessation days (earlier cessation). This trend results in a noticeable reduction in the length of the rainy season over the temporal scale of this study. The long-term mean onset for most bimodal regions typically occurs in October, as supported by Yonah et al. (2023), while the cessation is observed in January or February. However, the findings of this study show deviations, with a shift towards later onsets and earlier cessations, leading to shorter rainy seasons. The decreasing length of the OND rainy season has significant implications for agricultural productivity, water resources, and disaster risk management in Tanzania's bimodal regions. A shorter rainy season reduces the time available for soil moisture replenishment and crop maturation, which could lead to increased vulnerability to drought conditions. The results of this study, combined with previous findings, emphasize the need for robust climate adaptation strategies and a better understanding of interannual variability to mitigate the impacts of these trends.

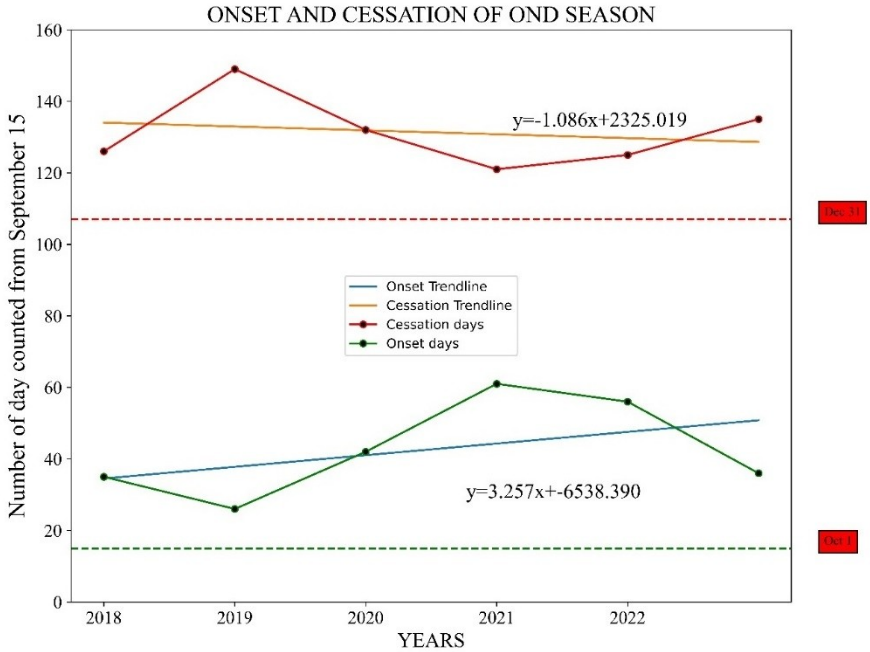

Figure 10: Onset and cessation trends for OND rainy season over bimodal region.

Onset and Cessation Variations of the OND rainy season

The variability in the onset, cessation, and duration of the OND rainy season across the bimodal region was analyzed using the Coefficient of Variation (CV). The results indicate spatial heterogeneity, with different parts of the bimodal region exhibiting distinct variations in the timing of onset and cessation, as well as the overall length of the OND rainy season.

Variation in the onset of OND rainy season

Figure 11 illustrates the spatial variability of rainfall onset dates across bimodal regions from 2014 to 2023. The central parts of the bimodal regions, including Kilimanjaro, Arusha, Manyara, as well as sections of Shinyanga and Simiyu, exhibit relatively low variability in rainfall onset dates, with a CV ranging from 13% to 31%. This limited variability enhances predictability in these areas. In contrast, the Lake Victoria zones display a higher variation in onset dates, ranging from 40% to 51%, indicating significant variability. Coastal regions (Pwani, Dar es Salaam and Tanga) exhibit the highest variability, with CV values exceeding 51%. Overall, regions near Lake Victoria and the coast have a high coefficient of variation in rainfall onset dates, posing challenges for accurate forecasting. The reduced variability in the central parts of the bimodal regions is primarily influenced by the dominance of topographic features such as Mount Kilimanjaro and surrounding valleys. These features exert a stabilizing effect on rainfall patterns during the OND season, including the timing of onset (Nyembo et al. 2020, Kavishe and Limbu 2020). Conversely, the high onset variability observed in coastal regions and the Lake Victoria zones is attributed to the dynamic southward migration of the ITCZ, the influence of the Lake Victoria basin, and variations in moisture influx from the Congo air mass. These factors contribute to year-to-year fluctuations in the timing of the rainy season in these regions (Ame et al. 2021, Kebacho 2021).

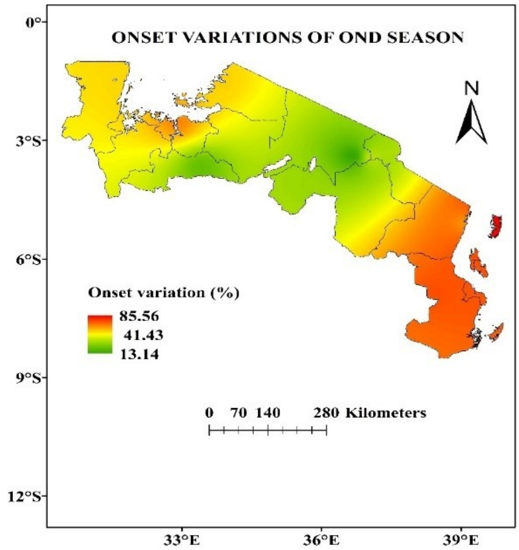

Figure 11: Spatial distribution in the variations of onset

Variation in the cessation of OND rainy season

Figure 12 illustrates the spatial variability of cessation dates across bimodal regions. The Lake Victoria zones and coastal regions exhibit a low CV, ranging from 14% to 37%, with the exception of the southern and eastern parts of the Lake Victoria basin, which show higher variability. This low variability in the cessation of the OND rainy season suggests that cessation dates in these regions are more consistent compared to onset dates, making them less challenging to predict. Regions such as Kilimanjaro, Arusha, Manyara, Tanga, and Geita demonstrate moderate variability in cessation dates, with a CV ranging from 37% to 47%. The southern and eastern parts of the Lake Victoria basin show higher variability, with CV values ranging from 47% to 57%, while Shinyanga and parts of Manyara exhibit very high variability, with CV values exceeding 57%. The observed low variability in cessation dates over the Lake Victoria zones and coastal regions is primarily attributed to the retreat of the ITCZ. The relatively stable movement of the ITCZ from year to year reduces variability in rainfall withdrawal, as the ITCZ plays a significant role in determining the onset and cessation of rainfall seasons. However, the high variability in cessation dates over the central parts of the bimodal regions, including areas near Mount Kilimanjaro, is largely influenced by topographic features. These features create localized climatic effects that disrupt the uniformity of the ITCZ retreat, thereby affecting the timing of rainfall withdrawal (Amekduzi et al. 2015). This spatial variability highlights the complex interplay between large-scale atmospheric circulations and local topographic influences on rainfall cessation patterns.

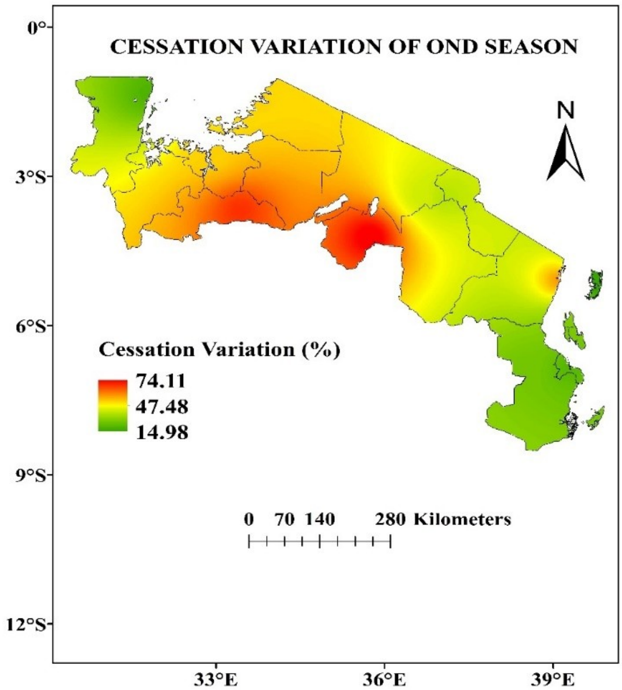

Figure 12: Spatial distribution in the variations of Cessation

Variation in length of OND rainy season

Figure 13 illustrates the spatial variation in the length of the OND rainy season across bimodal regions during the study period. Regions such as Bukoba, Pemba, and Dar es Salaam exhibit minimal variability in the length of the rainy season, with a CV ranging from 14% to 25%. This is followed by Geita, Mwanza, and Pwani, where the variability ranges from 25% to 33%. In contrast, the central parts of the bimodal regions display higher variability, ranging from 33% to 39%, with Shinyanga, Musoma, and the southern parts of Manyara experiencing the highest variability, with CV values exceeding 39%. These findings indicate that the variation in the length of the OND rainy season corresponds closely to the variability in its onset and cessation dates. Overall, the study shows that the variability in onset dates is greater than the variability in cessation dates. This disparity is largely influenced by the movement of the ITCZ, which has a stronger impact on the timing of rainfall onset, as supported by Yonah et al. (2023). Additionally, the lower variability in cessation dates can be explained by the positive feedback mechanism of a wetter land surface toward the end of the rainy season, which stabilizes atmospheric conditions and dampens externally forced variations. In contrast, rainfall onset is more influenced by external forcing and dynamic interactions, resulting in higher variability (Camberlin et al. 2009). These findings highlight the complex interplay between atmospheric dynamics, land surface conditions, and large-scale climatic drivers in shaping the length of the OND rainy season.

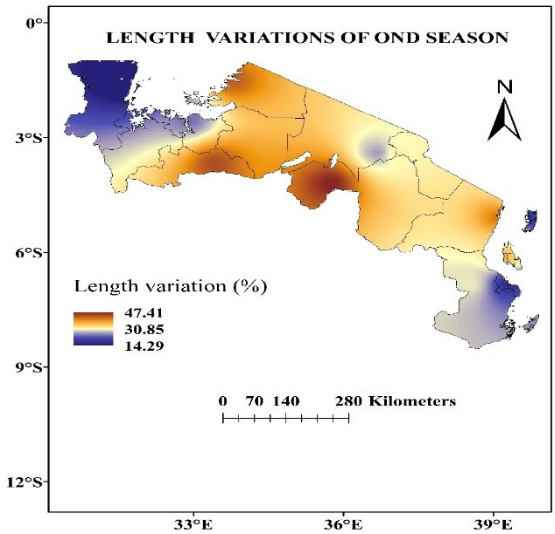

Figure 10: Spatial distribution in the variations of length of a season

Seasonal indices

The seasonality index (SI) is a critical rainfall characteristic used to quantify rainfall variability within a season for a specific region. A lower SI value signifies a more uniform distribution of rainfall intensity and timing, indicating less variability in the timing of rainfall for the region (Imteaz and Hossain 2022). Based on the findings of this study, as shown in Table 1, the SI varies significantly across the bimodal regions. Manyara demonstrates the highest average SI value of 0.77, followed by Arusha (0.7), Shinyanga (0.68), and Kilimanjaro (0.59). These elevated SI values reflect significant variability in rainfall timing or intensity within these regions (Imteaz and Hossain 2022). Conversely, regions such as Bukoba, Musoma, Pemba, Mwanza, Tanga, and Dar es Salaam exhibit lower SI values of 0.25, 0.37, 0.42, 0.43, 0.45, and 0.47, respectively. These lower SI values indicate a relatively uniform distribution of rainfall intensity and timing, signifying less variability in the onset and cessation of the OND rainy season. This uniformity suggests a more predictable rainfall pattern in these regions. The variation in SI across bimodal regions highlights differences in rainfall variability and distribution. High SI values are associated with significant shifts in rainfall timing or intensity, whereas low SI values correspond to regions with more consistent rainfall patterns. These variations in SI reflect the influence of both local and regional climatic factors on the distribution and variability of rainfall during the OND rainy season.

Table 1: The seasonality index for the bimodal regions of Tanzania

Station	SI_2014	SI_2019	SI_2020	SI_2021	SI_2022	SI_2023	Average
Arusha	0.574	0.500	0.667	0.651	0.930	0.894	0.703
Kilimanjar	0.318	0.377	0.658	0.681	0.700	0.832	0.594
o	0.835	0.629	0.740	0.915	0.742	0.759	0.770
Manyara	0.263	0.589	0.401	0.435	0.445	0.600	0.456
Tanga	0.159	0.497	0.333	0.664	0.243	0.649	0.424
Pemba	0.285	0.414	0.432	0.736	0.669	0.629	0.528
Pwani	0.278	0.420	0.619	0.725	0.457	0.788	0.549
Zanzibar	0.315	0.352	0.457	0.565	0.487	0.682	0.476
Dar	0.420	0.470	0.355	0.288	0.640	0.428	0.434
Mwanza	0.848	0.511	0.679	0.729	0.739	0.586	0.682
Shinyanga	0.629	0.210	0.394	0.214	0.456	0.360	0.377
Musoma	0.307	0.264	0.219	0.136	0.187	0.401	0.252
Bukoba							

Conclusion and recommendation

This study examines temporal variations in the onset, cessation, and duration of the OND rainy seasons over the bimodal rainfall region of Tanzania. The average daily intensity method was applied to determine the onset and cessation dates for OND rainfall from 2014 to 2023. The seasonal duration was derived as the difference between these dates. The CV was employed to quantify the variability in onset, cessation, and seasonal length. The findings indicate early onset dates in the fourth week of September for limited areas within the bimodal region, while most areas experienced onset between the second week of October and the fourth week of November. Notable spatial variability was observed, particularly in the coastal regions and western areas of the Lake Victoria Basin. The cessation of OND rains was recorded between the second week of January and the third week of February, with minimal variability in most areas but higher variability along the southern and eastern fringes of the Lake Victoria Basin. These temporal and spatial variations are largely influenced by atmospheric and oceanic drivers, including the ITCZ, Congo air mess, ENSO, and IOD. The study concludes that the OND rainy season exhibits significant variability in onset timing, especially in the western Lake Victoria Basin and coastal regions, ranging from early October to late November. In contrast, cessation dates show less variability, spanning from mid-January to late February. Furthermore, evidence suggests a seasonal shift from the traditional OND timeframe to NDJ framework in several parts of the bimodal region. This observed shift warrants further investigation to explain the underlying mechanisms. Such studies are essential to enhance understanding of onset and cessation of OND rainfall dynamics, optimize socioeconomic benefits, and mitigate potential adverse impacts associated with observed changes in the seasonal patterns.

Declaration of Competing Interest

The authors declare that there is no conflict of interest regarding this work.

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