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The Inter-Annual Variability of Rainfall Onset and Its Implication on Crop Planting in Selected East Africa Countries

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Abstract

The inter-annual variability of rainfall onset and crop replanting in East Africa (EA) was assessed using daily estimated rainfall data from climate hazard group infrared precipitation (CHIRPS Ver2.0) and monthly Sea Surface Temperature (SST) indices [Indian Ocean Dipole (IOD) and El-Niño Southern Oscillation (ENSO) at NINO3.4 region] from the National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). The data covered a period of 40 years from1981 to 2020. The methods of cumulative of daily mean rainfall, percentage of onset date departure (PODD), Mann-Kendall (MK) trend test, student t-test, and correlation were applied in the analysis. The results showed that early onset with dry spell (WDS) consideration frequently occurs in Uganda between the first and second dekads of September, while late rainfall onset WDS occurs in the first and second dekads of December over central and Northern Kenya as well as in the Northeastern highlands, parts of the northern coast and unimodal regions in Tanzania. Rainfall onset with no dry spell (WnDS) portrayed an average of 10 days before the occurrence of true onset WDS, with maximum onset departure days (ODD) above 30 days across the Rift Valley area in Kenya and the Northeastern highlands in Tanzania. The high chance of minimum ODD is seen over entire Uganda and the area around Lake Victoria. However, few regions, such as Nakuru (Kenya) Gulu and Kibale (Uganda), and Gitega (Burundi), revealed a slight positive linear trend while others showed negative trend. Significant positive patterns for correlation between onset WDS and SST indices (IOD and NINO 3.4) were discovered in Northern and Northeastern Kenya, as well as areas along the Indian Ocean (over Tanzania's Northern Coast). Inter-annual relationship between onset dates WDS and

IOD (NINO3.4) indices exhibits a high correlation coefficient r = 0.23 (r = 0.48) in Uganda and r = 0.44 (r = 0.36) in Kenya. On the other hand, a negative correlation was revealed over Burundi and Tanzania (over a unimodal region). A high percentage of PODD was observed, ranging from 40% to 70% over the Rift Valley in Kenya and at the Northeastern highlands in Tanzania. However, a strong PODD above 70% was observed over Tanga and the Northern Pwani Region in Tanzania. These findings will help farmers to understand the appropriate time for crop planting, as well as help other socio-economic activities that strongly depend on rainfall.

Keywords

Inter-Annual Variability, Rainfall Onset, Crop Planting, East Africa

1. Introduction

Rainfall is a major source of soil moisture and the most important determinant of the start of the crop growing season over much of the East African region (Atiah et al., 2021; Liu et al., 2022). The October, November, December (OND) and the November, December, January, February, March, April (NDJFMA) rainfall season have been described as unreliable and variable from season to season (Mahoo et al., 1999). At the regional scale, inter-annual variations in the onset date of the rainy season have the biggest impact on the seasonal rains, which are less dependent on within-season variations in both the number of rainy days and daily rainfall intensity (Camberlin et al., 2009). The rainy season in East Africa experiences frequent variability caused by multiple factors including El-Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) events manifested in the Western Indian Ocean (Saji et al., 2003; Mapande & Reason, 2005; Nicholson, 2017; Japheth et al., 2021); and moisture from the Congo basin, as well as the proximity to Lake Victoria and Mount Kilimanjaro (Mubiru et al., 2012; Chang'a et al., 2020). Moreover, the observed extreme and prolonged OND rainy season mostly are influenced by strong positive IOD itself although historically some of them coupled with El-Niño events as observed in 1982 and 1997 (Wainwright et al., 2020). Generally, Vengateswari et al. (2017) found that most of the El-Niño and positive IOD years were related to early-onset and late cessation during OND rainy season, while the opposite was true during La-Niña years.

The rainy season can be characterized by rainfall distribution (amount and time), the start and cessation of rains, dry spells, and the time of planting (Yonah et al., 2006). The onset and cessation dates, and the temporal distribution of rainfall during the rainy season are extremely important. However, for the OND rainy season, the onset is more decisive than the cessation, while the different intra-seasonal descriptors of the rains are more strongly interrelated (Camberlin et al., 2019).

Planting is usually successful if it is not followed by a long dry period or false start because the occurrence of a dry spell in the region can severely impact on agricultural productivity (Ocen et al., 2021). In areas like East Africa where farmers largely rely on rain-fed agriculture, variability of the growing season has caused frequent crop failure and forced the society to live under the threat of famine (Kijazi & Reason, 2011; Ocen et al., 2021).

Rainfall seasonal performance may be influenced by late onset and early cessation of rains (Atiah et al., 2021). Late onset and early cessation of the rainy season in East Africa usually affect rainfall dependent socio-economic activities as it has been elaborated by Dunning et al. (2016) that the failure of the rains and subsequent humanitarian disaster are associated with shorter as well as weaker rainy seasons. Dunning et al. (2016) further urged that, cessation of the short rains over East Africa region is 7 days later in El-Niño and 5 days earlier in La-Niña years with only a small change in onset date. The late planting, occurrence of dry spells, early cessation of rainfall reduces the length of the growing season which in turn reduces crop yields (Yonah et al., 2006), as established by Lomas (1998) who found that a delay of planting by 10 days may lead to yield loss of 20%.

Rainfall onset and cessation have been defined in a number of publications (Omotosho et al., 2000; Kijazi & Reason, 2005; Stern et al., 2006; Marteau et al., 2009; Amekudzi et al., 2015; Mensah et al., 2016; Ojo & Ilunga, 2018). For example; according to Ojo and Ilunga (2018), the start of rains is the first occurrence of any specified rainfall amount (20 mm) in 1 or 2 consecutive days with no dry spell of 10 days or more within the next 30 days. According to Omotosho et al. (2000), rainfall onset is the beginning of the first 10 days period with cumulative rainfall of 20 mm, above one of which is 10 mm, or above, followed by another two 10-days period each with 50% or more of the minimum dekadal crop water requirement; and the cessation is any day after which there are 21 or more consecutive days of rainfall less than 50% of the dekadal crop water requirement. The word dekad has been used in this study referring to every month has three dekads, such that the first two dekads have 10 days (i.e., 1 - 10, 11 - 20), and the third is comprised of the remaining days of the month which vary from 8 - 11 days, depending on the length of the month (Joyce et al., 2004). Planning on agriculture activities from land preparation, seed selection and planting, is rainfall dependent (Guido et al., 2020). The variability in rainfall onset and cessation threatens food security, induce poverty, and affects the transmission of vector borne diseases (Amekudzi et al., 2015). Presence of reliable onset dates will greatly assist on-time preparation of farmlands, mobilization of agriculture inputs, manpower and equipment and also reduce the risks that may involve due to planting too early or too late (Odenkunle, 2004).

This paper seeks to 1) access the distribution and variability of onset dates of rains in EA, 2) assess the relationship between inter-annual onset dates variations and large-scale climate features, specifically El-Niño, La-Niña, and the Indian Ocean Dipole (IOD) and lastly 3) access the risk of dry spell after planting.

The findings from this study could be used in planning for agriculture operations during the crop growing seasons (OND and NDJFMA) and for improving crop productivity through timely planting and appropriate choices of crop variety suitable for the area.

2. Methodology

2.1. Description of the Study Area

This study focuses only on selected five EA countries, namely; Tanzania, Kenya, Uganda, Burundi and Rwanda which are located between Latitude 5˚N and 12˚S and Longitude 29˚E and 42˚E (Figure 1). The climate pattern of the region particularly its rainfall distribution is characterized by stronger spatial and temporal

Figure 1. East Africa (EA) region with spatial distribution of regions/provinces used in this study particularly in analysis of percentage of onset date departure (PODD) (with yellow dots).

variations amplified by significant differences in relief and vegetation cover (Chang'a et al., 2020). Large areas within the region (including the Northern parts of Tanzania and Southern parts of Kenya, Rwanda and Uganda) receive bimodal rainfall pattern with long rains in March, April, and May (MAM) and the short rains during OND associated with the North-South seasonal movement of the main rain belt, the Inter-tropical Convergence Zone (ITCZ) (Nicholson, 2017). The ITCZ usually migrates southwards through Tanzania during OND, reaching the southern parts of Tanzania in January and February and returning northwards during MAM. The Southwestern highlands (SWH), southern region, Southern coastal areas, Western and Central parts of the Tanzania experience uni-modal rainfall pattern that normally starts from November and ends in April subsequent year. In Uganda, the short rainy season starts a month earlier running from September to October (Nsubuga et al., 2014), and from January to February in Rwanda while some areas around the Lake Victoria Basin and Eastern regions of the Rift Valley experience tri-modal rainfall regime that peaks in June, July, and August (JJA).

2.2. Data

2.2.1. Data Sources and Data Type

This study utilized satellite-blended daily precipitation data and monthly Sea Surface Temperatures (SST) Indices for the time interval of 40 years from 1st January 1981 to 31st December 2020. The data sets covered the East Africa region; Tanzania, Kenya, Uganda, Burundi, and Rwanda as displayed in **Figure 1**. The blended precipitation was obtained from the climate hazards group infrared precipitation with the station (CHIRPS) which has a 0.05˚ × 0.05˚ grid resolution (Funk et al., 2015). The data was downloaded at http://iridl.ldeo.columbia.edu/SOURCES/.UCSB/.CHIRPS/.v2p0/.daily-improved/.global/.0p05/.prcp/datafiles.html. The validation of CHIRPS rainfall estimates over EA demonstrates a high correlation ($r = 0.73$) with gauge-based or observed data (Muthoni et al., 2019). Furthermore, CHIRPS data was utilized in the analysis of onset dates and results were correlated with SST indices. Additionally, monthly SST indices data with the time range of 40 years (from January to December 1981-2020) from the National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) as cited by Kalnay et al. (1996) were utilized to assess the relationship between rainfall onset dates and SST indices mainly El-Niño/La-Niña Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). The ENSO data was collected from central Pacific Ocean over Nino3.4 region (5˚N-5˚S, 120˚W-170˚W). IOD indices were collected over the Western Indian Ocean (WIO) at (50˚E-70˚E, 10˚S-10˚N) and Eastern Indian Ocean (EIO) confined at (90˚E-110˚E, 0˚-10˚S).

2.2.2. Data Preparation

Precipitation datasets were converted into R-Data format (RDS) ready for analysis of rainfall onset dates. The IOD indices were computed by subtracting area average SST data at the Western Indian Ocean (50˚E-70˚E, 10˚S-10˚N) to that collected at the Eastern Indian Ocean at (90˚E-110˚E, 0˚-10˚S). The indices were anomaly standardized to improve data consistency. Furthermore, four-month average SST indices (IOD and NINO3.4) for the months of August, September, October and November were computed. The months were casted back to include the slow heat effect of seawater before the start of OND and NDJFMA rainfall season. Lastly, country area average onset dates were extracted and then correlated with the monthly average IOD/NINO3.4 indices.

3. Methodology

Climate Data Tools (CDT) was effectively utilized in the determination of the rainfall onset dates for the selected period over the EA region. This tool is an open-source R package, developed and maintained by the International Research Institute for Climate and Society (IRI), Columbia University. The CDT can be used for data organization, quality control, combining station data with satellite and reanalysis data, evaluating merged and inputs datasets, performing an array of analyses, handling Network Common Data Format (NetCDF) and visualization (Dinku et al., 2022). All functions in CDT are available freely in graphical user interface (GUI) mode (Acharya et al., 2020; Dinku et al., 2022).

In this study, two rainfall onset criteria were considered during the analysis. The first criterion was based on the number of rainy days and dry spells. The second criterion was based only on number of rainy days. Thus, the threshold of 1.0 mm of rainfall in a day has been used as a rainy day in which below the value was termed as a dry day (Ojara et al., 2020). The onset criteria were defined as the day from 1st September with a running total of at least 20 mm of rainfall in 4 consecutive days with at least 2 days being wet and no dry spell length of more than 10 days in the next 30 days. The criteria were modified from authors (Stern et al., 2006; Marteau et al., 2009; Recha et al., 2012). However, 1st of September was used as the earliest possible date to ensure those few onset dates that occur before October are not missed out when determining the onset of rains during OND rainy seasons. A point to note in this paper is that the rainy season onset dates were determined based on two criteria: onset dates that consider dry spells "with dry spells" (WDS) and onset dates that do not consider dry spells "with no dry spells" (WnDS).

The series of onset dates of each region (**Figure 1**) were presented in the time-series graphs against years (1981-2020). Thereafter, the dates series were then tested by Mann-Kendall (MK) trend test at a 95% confidence level (Mann, 1945). This statistical test detects a monotonic trend whether is a linear or non-linear time series. The test is among of powerful non-parametric tests commonly used in climate data analysis particularly in meteorology, environment, and water management (Longobardi & Villani, 2010; Bekele et al., 2017). The main advantage of this test is that, it can be used for normal data distribution such as annual and seasonal data for several weather parameters such as rainfall

(Modarres & Sarhadi, 2009).

Pearson correlation analysis was used to determine the linear relationship between onset dates and SST indices (IOD and NINO3.4) for the time range of 40 years (1981-2020). The series of the average onset dates per region boundary were correlated with SST indices (IOD and NINO3.4) and results were presented in temporal graphs and spatial maps. Thereafter, the spatial results were tested by student t-test at 95% significant level to reveal the areas that were much influenced with the effect of IOD and NINO3.4 indices. The techniques recently have been used much over East Africa countries in examining the relationship of rainfall and SST indices by several researchers (King'uza & Tilweba, 2019; Chang'a et al., 2020; Kavishe & Limbu, 2020).

A new technique, known as "Percentage of Onset Dates Departure" (PODD) was invented and applied to examine the risk of crop replanting, whereby onset dates from selected regions (**Figure 1**) were interpolated by the Inverse Distance Weighting (IDW) method. The technique was used in the determination of areas with a high risk of crop replanting. The results from this analysis help farmers understand risks associated with dry spells after planting a crop, and how many times the first rains were not effective for planting and if farmers had planted with these rains they would have to replant. The concept developed from the successful sowing date(s) was taken when the correspondent series of date X minus date Y, equal to zero while the risk of replanting increases when X is greater than Y. Therefore, successfully crop planting without risk of dry spells occurs when the number of onset days in X is approximate close to number of onset days in Y. Contrary, X-Y termed as Onset Departure Days (ODD) which should be greater or equal to zero. The onset date departures in Days (ODD) and Percentages (PODD) were computed by using Equations (1) and (2) respectively.

$$\text{ODD} = X_i - Y_i \tag{1}$$

$$\text{PODD} = \frac{\sum_{i=1}^{n}\left(X_i > Y_i\right)}{\sum_{i=1}^{n} X_i} \times 100\% \tag{2}$$

where;

X stands for number of onset WDS, Y stands for onset WnDS and PODD is the percentage of onset date departure (crop replanting percentage). For this method to be valid the value of X should be greater or equal to that of Y ($X \geq Y$). Also, the letter i stands for yearly onset dates (annual onset iteration), n is the number of the onset dates within the series.

4. Results and Discussion

4.1. Spatial Patterns of Average Rainfall Onset Dates

Normally, over a bimodal regime, rainfall starts in October over most parts of EA countries except the Southern, Southern coast, and Southwestern highlands of Tanzania which experience unimodal rainfall pattern that start in November and December. The spatial map of the onset dates (**Figure 2(a)**) shows that early onsets occur on the first dekad of September in the Northwestern portion of Uganda and in some parts of Western Kenya and Rwanda. Furthermore, early onset was observed in the Southern part of Tanzania over unimodal regime between the third dekad of October and the first dekad of November, over most of the Western and Southwestern highland regions adjacent to Lake Tanganyika. Generally, failure of capturing onset WDS has been seen over Turkana in Kenya and few a spots of extreme late onset patterns over bimodal areas are revealed across Arusha and Manyara regions in Tanzania as well as in the provinces of Samburu and Marsabit in Kenya. Most of these areas experience rainfall onset between 20th December to 19th January, which may not be useful for OND cropping season.

The average onset WnDS consideration, as displayed in **Figure 2(b)**, exhibits early onset dates between 10 to 20 days before the actual onset WDS, particularly over much of Tanzania and Kenya, while less than 20 days in Uganda, Rwanda, Burundi, and across Lake Victoria regions in Tanzania. However, a significantly longer ODD (**Figure 2(c)**) of about 20 to 40 days has been observed in most parts of the Southern coast, Northern coast, and Northeastern highlands in Tanzania. Additionally, extreme ODD of more than 40 days is depicted across the southwestern part of Kenya over the Rift Valley and a few areas over the Northern part of Tanzania including Mara and Arusha regions.

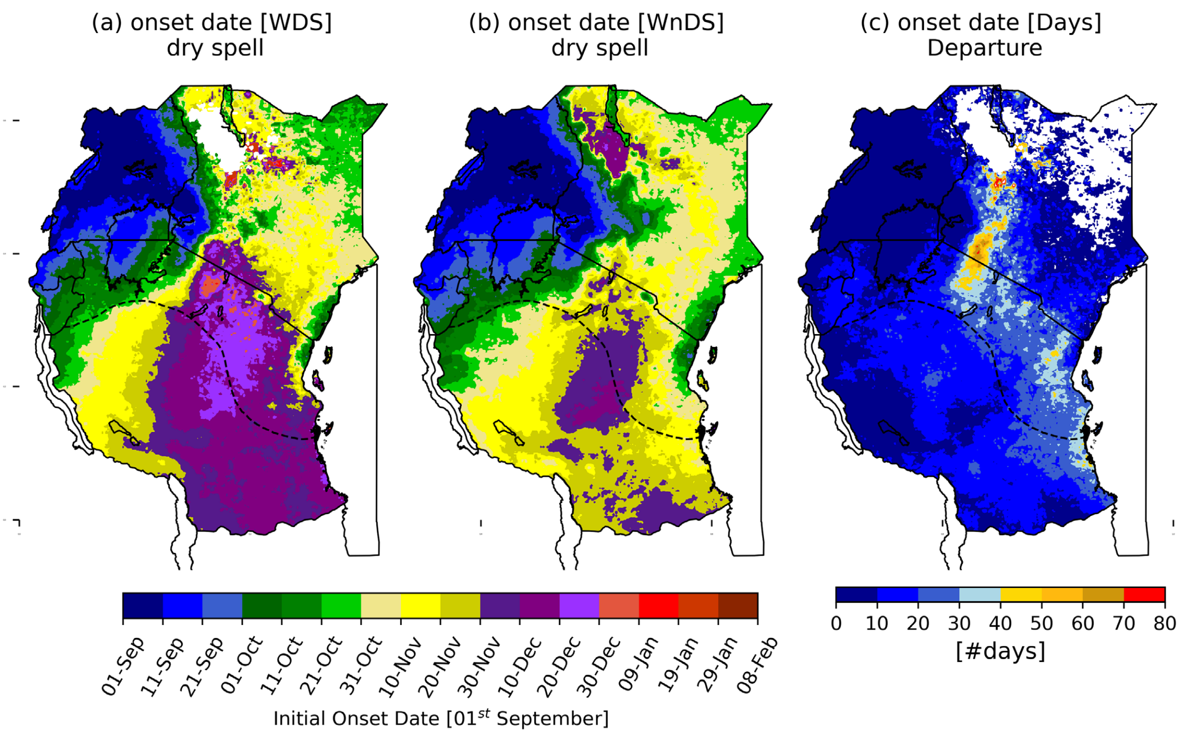

Figure 2. Rainfall onset spatial patterns (a) Rainfall onset dates with 10 days or more dry spells (onset WDS), (b) Rainfall onset dates with no risk of dry spell (onset WnDS), and (c) Rainfall onset departure days (ODD). The dotted black line is a boundary that separates areas that experience two rainy seasons (bimodal at the top) and one rainy season (unimodal at the bottom).

4.2. Inter-Annual Variability of Rainfall Onset Dates

Inter-annual variability of onset dates WDS were determined yearly using time-series graphs. Four to nine regions were selected randomly from each country, and then years with early or late onset dates were identified. Many regions in Tanzania (TA) display high variability in onset WDS with a negative decrease in trend line. The analysis (**Figures 3(a)-(e)**) shows that, over the area of bimodal rainfall regime in Tanzania, the early onset occurred in 1999 (Tanga on September 08), 2005 (Arusha on September 04th, Simiyu on September 12th, and Mwanza on September 19th), and 2013 (Dar es Salaam on September 01st), Most of these regions depicted the Long Term Mean (LTM) onset in the month of October except for the Arusha and Simiyu regions that revealed the LTM rainfall onset at the beginning of November. However, the latest onset was observed in Tanga region on the 06th of January 2001 and 2007; and Dar es Salaam on January 22nd, 2007. For the unimodal rainfall regime (**Figures 3(f)-(i)**), the earliest onset was observed in Mtwara region on September 11th, 1981, and 2020; Mbeya on November 07th, 1982; Iringa on October 08th, 2020; and Tabora on October 30th, 2000. In the meantime, late onset was depicted in Iringa on the 07th of January 2016 with LTM onset at the end of November and beginning of December over many regions.

Furthermore, as shown in **Figures 4(a)-(i)**, many regions in Uganda (UG) and Kenya (KE) show the earliest onsets at the beginning of September, while the late-onsets occur at the end of October. Meanwhile, the LTM onset date is observed in October, except in Nakuru province, where it occurred on 4th of October. However, inter-annual variability of onset dates is high in many regions in Kenya with exceptional of Marsabit which depicted slight variability in onset dates from year to year with strong delaying on 1997 where the rains started on October 29th. Moreover, in Uganda rains start earlier on August to the beginning of the September therefore, as displayed in (**Figures 4(f)-(i)**) the country experiences a slight change in inter-annual onset variation between years. Strong onset variations, have been seen in Kampala (**Figure 4(h)**) with late onset on 2016 around 28th October and followed by Kasese (**Figure 4(i)**) where recorded late onset on the 03rd of October 2002. Generally, many regions in Uganda and Kenya depicting decrease of onset trendline with less decrease at Marsabit, and less increase at Nakuru and Gulu.

The western part of EA, particularly Burundi (BU) and Rwanda (RW), observed the earliest rainfall onset in many regions during the first dekad of September, with the exception of Makamba (**Figure 5(i)**), where the earliest onset occurred in the third dekad of September. Moreover, rainfall onset has started earlier in recent years in several places like Byumba, Kibaye, Bujumbura, and Makamba. Additionally, most of the regions display significant variation in inter-annual onset patterns except for the Kibaye (**Figure 5(d)**) region which revealed an exceptional late-onset on October 27th, 1993. However, the regions like Byumba and Kibaye in **Figure 5(a)** and **Figure 5(d)** display LTM onset on the

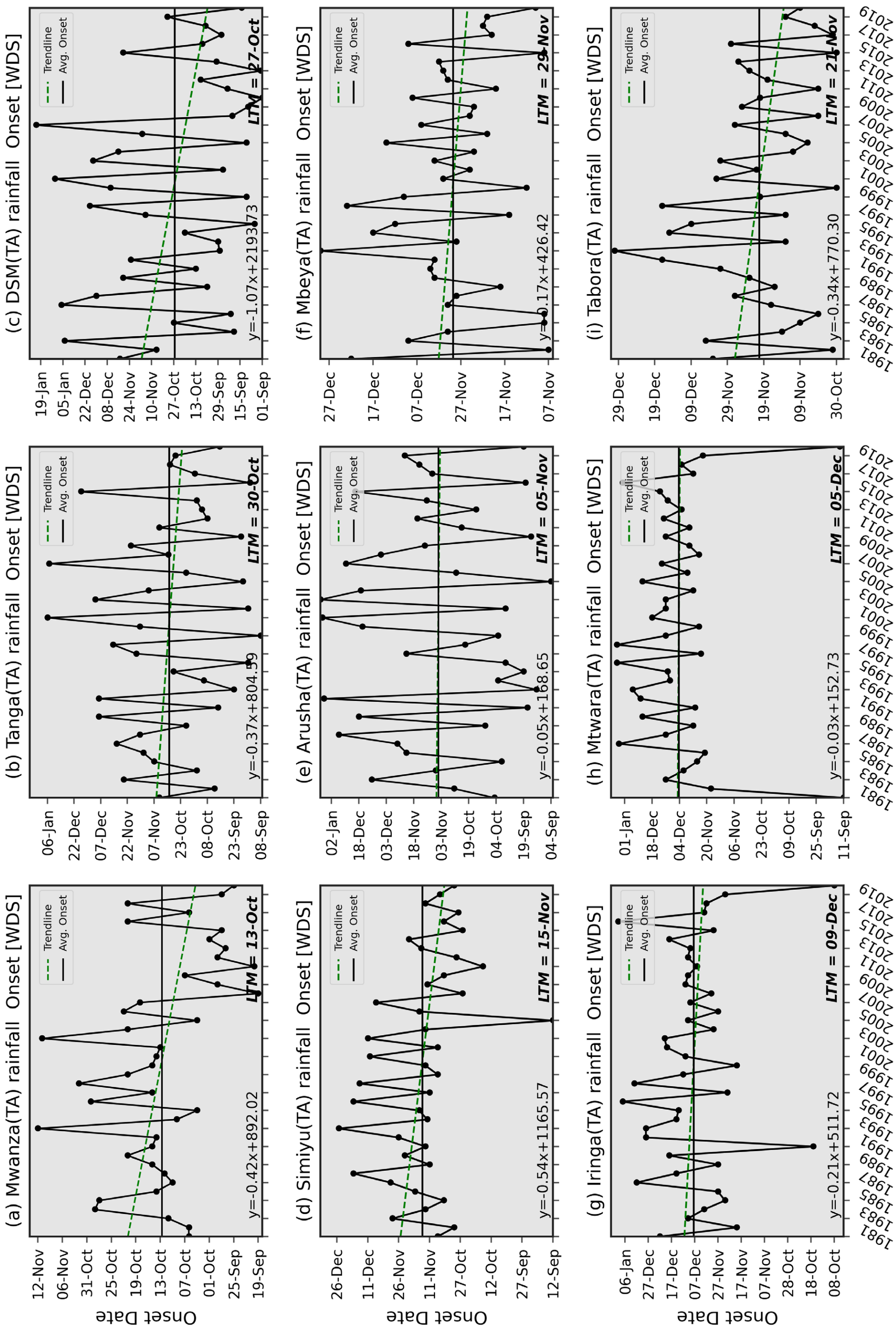

Figure 3. Inter-annual variability time series (1981-2020) of onset dates WDS between September and January (including OND and NDJFMA seasons) over the Tanzania regions (unimodal and bimodal). (a) Mwanza region, (b) Tanga region, (Dar es Salaam (DSM) region, (d) Simiyu region, (e) Arusha region, (f) Mbeya region, (g) Iringa region, (h) Mtwara region, and (i) Tabora region. Where the dotted green line represents the linear trend for the rainfall onset dates while the black straight line shows the LTM onset date whereby the value is displayed on the light side of the graphs.

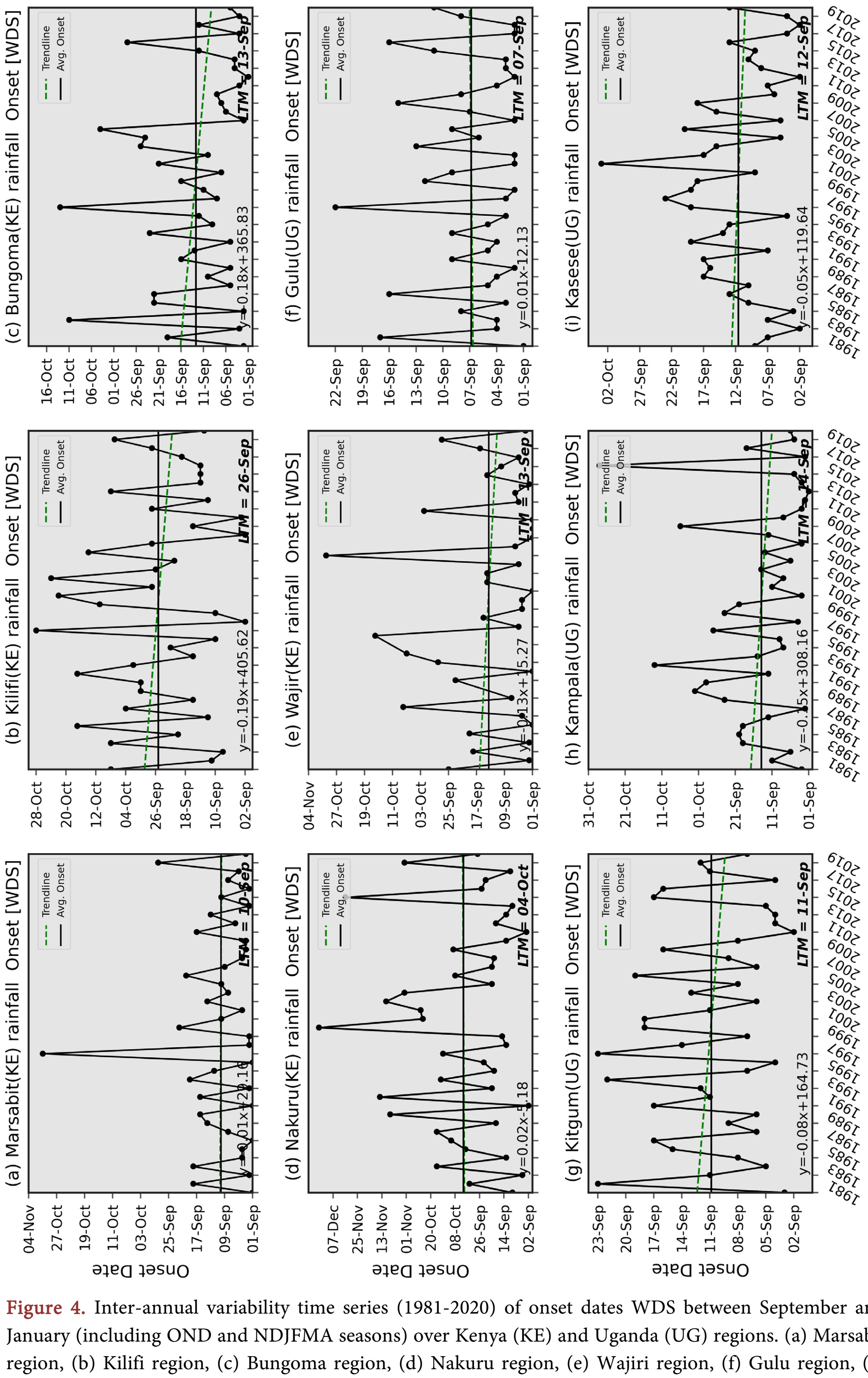

Figure 4. Inter-annual variability time series (1981-2020) of onset dates WDS between September and January (including OND and NDJFMA seasons) over Kenya (KE) and Uganda (UG) regions. (a) Marsabit region, (b) Kilifi region, (c) Bungoma region, (d) Nakuru region, (e) Wajiri region, (f) Gulu region, (g) Kitgum region, (h) Kampala region, and (i) Kasese region. Where the dotted green line represents the linear trend for the rainfall onset dates while the black straight line shows the LTM onset date whereby the value is displayed on the light side of the graphs.

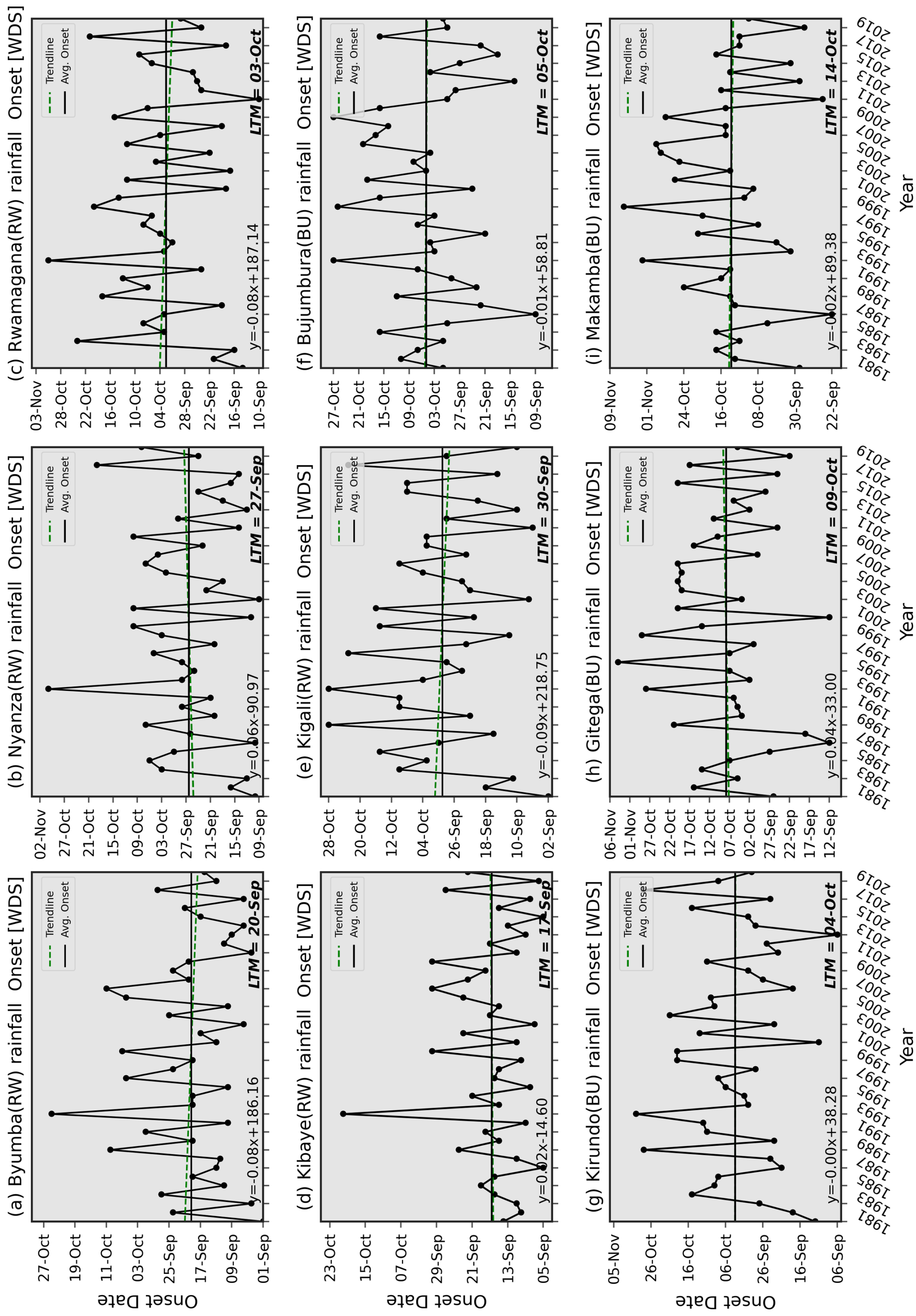

Figure 5. Inter-annual variability time series (1981-2020) of onset dates WDS between September and January (including OND and NDJFMA seasons) over the Rwanda (RW) and Burundi (BU) regions. (a) Byumba region, (b) Nyanza region, (c) Rwamagana region, (d) Kibaye region, (e) Kigali region, (f) Bujumbura region, (g) Kirundo region, (h) Gitega region, and (i) Makama region. Where the dotted green line represents the linear trend for the rainfall onset dates while the black straight line shows the LTM onset date whereby the value is displayed on the light side of the graphs.

second dekad of September, while Nyanza and Kigali in Figure 5(b) and Figure 5(e) show LTM onset on the third dekad of September. Similarly, delay of onset (LTM) has been observed in Rwamagana, Kirundo, Bujumbura, Gitega, and Makamba in the first dekad and second dekad of October. On the other hand, most of the regions exhibit a negative trendline with a negative slope, except for the Gitega-Burundi, as well as Nyanza and Kibaye in Rwanda, where a slight increase in trendline was detected.

4.3. Mann Kendall Trend Test Analysis of Rainfall Onset Dates

The Mann Kendall (MK) method was used to test the series of the onset dates WDS and onset dates WnDS at a 95% confidence level for the selected regions/provinces and the results are presented in Table 1. Therefore, most of the selected regions are characterized by no significant trend ($p > 0.05$) for both onset WDS and onset WnDS except for Mwanza and Simiyu regions in Tanzania. These two regions are characterized by a significant decrease in the onset for both WDS ($p = 0.03$) and WnDS (Mwanza, $p = 0.02$ and Simiyu, $P = 0.04$). On the other hand, trend test results for Mwanza and Simiyu agree well with the linear trend depicted in Figure 3(c) and Figure 3(d). However, some regions, such as Dar es Salaam (Tanzania), Kampala (Uganda), and Nakuru (Kenya) are characterized by negative slopes with negative linear trends which are not statistically significant ($p > 0.05$) for both WDS and WnDS onset dates as shown in Table 1.

4.4. Relationship between Inter-Annual Variability of Rainfall Onset Dates and SST Indices (IOD and NINO3.4)

This section highlights on the relationship between inter-annual onset dates WDS and SST indices depicted from maps and time-series graphs. The results presented in spatial maps were tested using the student t-test at a 95% confidence level (shown in cross hatching boxes). In East Africa, onset is better defined than cessation and is strongly affected by SST variations. However, it has been seen that IOD and NINO3.4 have a strong influence on EA rains during the OND season (Kavishe & Limbu, 2020). Thus, this paper explores the influence of SSTs on the start of rain over selected countries in EA region. The results (Figure 6(a)) show a significant positive correlation coefficient ranging from r = 0.2 to r = 0.4 between onset dates and Nino3.4 in the Northern coast and Northeastern highlands of Tanzania. The correlation value increases in the Eastern and Northern parts of Kenya with the correlation coefficients of about r = 0.2 to r = 0.8. On the other hand, a negative correlation with significant patterns was revealed over much of Uganda and some parts of Northwestern Kenya. Furthermore, the negative and positive patterns of correlation coefficients ranged from r = -0.2 to r = 0.2 with no significant boxes displayed in Tanzania over the Southwestern highlands and some parts of the Lake Victoria Basin.

Figure 6(b) shows the correlation patterns and areas with significant levels at a 95% confidence level for the onset dates correlated with IOD. A significant

Table 1. Mann Kendall trend test at 95% confidence level for the rainfall onset dates (WDS and WnDS).

Country	Region	Mann Kendall trend test of rainfall onset dates (WDS)		Mann Kendall trend test of rainfall onset dates (WnDS)	
		Trend test	P-value	Trend test	P-value
Tanzania	Mwanza	Decreasing	0.0316	Decreasing	0.0157
	Tanga	No trend	0.3820	No trend	0.2834
	Dar es Salaam (DSM)	No trend	0.0867	No trend	0.1688
	Simiyu	Decreasing	0.0273	Decreasing	0.0368
	Arusha	No trend	0.9907	No trend	0.2828
	Mbeya	No trend	0.3158	No trend	0.4767
	Iringa	No trend	0.2991	No trend	0.2884
	Mtwara	No trend	0.8978	No trend	0.2481
	Tabora	No trend	0.1074	No trend	0.1023
Burundi	Bujumbura	No trend	0.8519	No trend	0.3815
	Kirundo	No trend	0.8887	No trend	0.1721
	Gitega	No trend	0.9721	No trend	0.7793
	Makamba	No trend	0.9256	No trend	0.2628
Rwanda	Byumba	No trend	0.7086	No trend	0.1829
	Nyanza	No trend	0.6576	No trend	0.2527
	Wamagana	No trend	0.9257	No trend	0.8701
	Kibaye	No trend	0.8609	No trend	0.2924
	Kigali	No trend	0.5753	No trend	0.4484
Uganda	Gulu	No trend	0.9906	No trend	0.5235
	Kitgum	No trend	0.4269	No trend	0.5197
	Kampala	No trend	0.0585	No trend	0.0756
	Kasese	No trend	0.6072	No trend	0.6319
Kenya	Marsabit	No trend	0.7789	No trend	0.4696
	Kilifi	No trend	0.3942	No trend	0.9257
	Bungoma	No trend	0.3097	No trend	0.5195
	Nakuru	No trend	0.9349	No trend	0.0886
	Kakamega	No trend	0.2121	No trend	0.2924

positive correlation coefficient ranging from r = 0.2 to r = 0.4 was observed over the Northeastern highlands in Tanzania and become strong (r = 0.4 to r = 0.8) over the Northeastern parts of Kenya. Moreover, negative correlation with significant patterns has been observed in the unimodal region in Tanzania, especially over the Western, Southwestern highlands, and Southern regions. It seems that episodes of strong positive IOD conditions are associated with early onsets

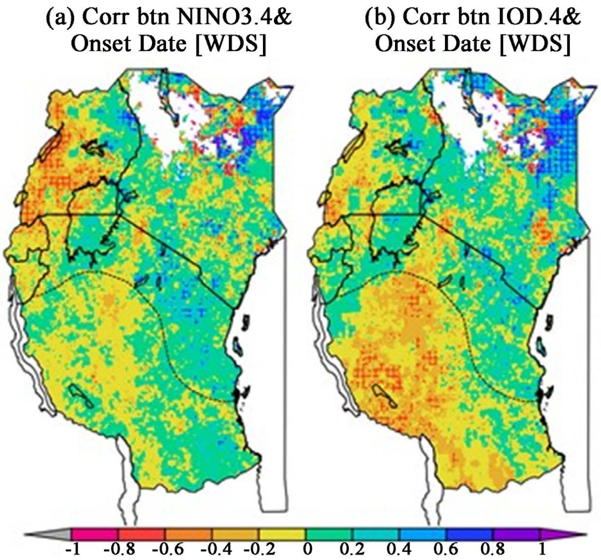

Figure 6. The maps show the correlation between rainfall onset dates WDS and SST indices (NINO3.4 and IOD). (a) Correlation between the NINO3.4 index and the onset date WDS, and (b) Correlation between the IOD index and the onset date WDS. Where rectangular cross-hatching indicates areas tested by student t-test at a 95% significant level. The red cross-hatching is significant area with the negative correlation values, while the blue cross-hatching is significant area with the positive correlation values. The white patches in the maps (in northern Kenya) mean failure of capturing onset.

of rains and vice-versa. Generally, IOD strongly influences rainfall onset over EA region. On the other hand, NINO3.4 SSTs indices have displayed a slight positive correlation with rainfall onsets in many areas of EA region, except for the Western Uganda, which has shown significant negative correlation patterns. Moreover, a clear negative correlation with significant patterns between onset WnDS and NINO3.4 has been found over northwestern Kenya, and with a slight change for IOD, indicating that in this region the more the NINO3.4 SSTs anomalies become positive the early the onset of rains and less risk of dry spells and vice-versa.

The time series correlation coefficients were computed between inter-annual onset dates per area average or county administrative boundaries and SST indices (NINO3.4 and IOD) and the results are portrayed in **Figure 7**. The mean onset date in the unimodal region of Tanzania (**Figure 7(a)**) occurs around November 26th, and the region revealed negative inter-annual correlation values for both IOD (r = −0.45) and NINO3.4 (r = −0.16). Years with high peaks of SSTs anomalies such as 1991, 1993, 1997 and 2015 were characterized by an early onset, while years with low peaks such as 1992, 1996, 1998, and 2016 were characterized by a delayed onset. However, in recent years, 2017, 2018, 2019, and beyond, the patterns of rainfall onset date responded only slightly to SST indices. For the bimodal region (**Figure 7(b)**), the average onset date was observed on the 2nd of November since the occurrence of rainfall onset was influenced positively by both IOD (r = 0.02) and NINO3.4 (r = 0.11) despite the correlation coefficient being small. Inter-annual variability is well defined before 2019; when most of the

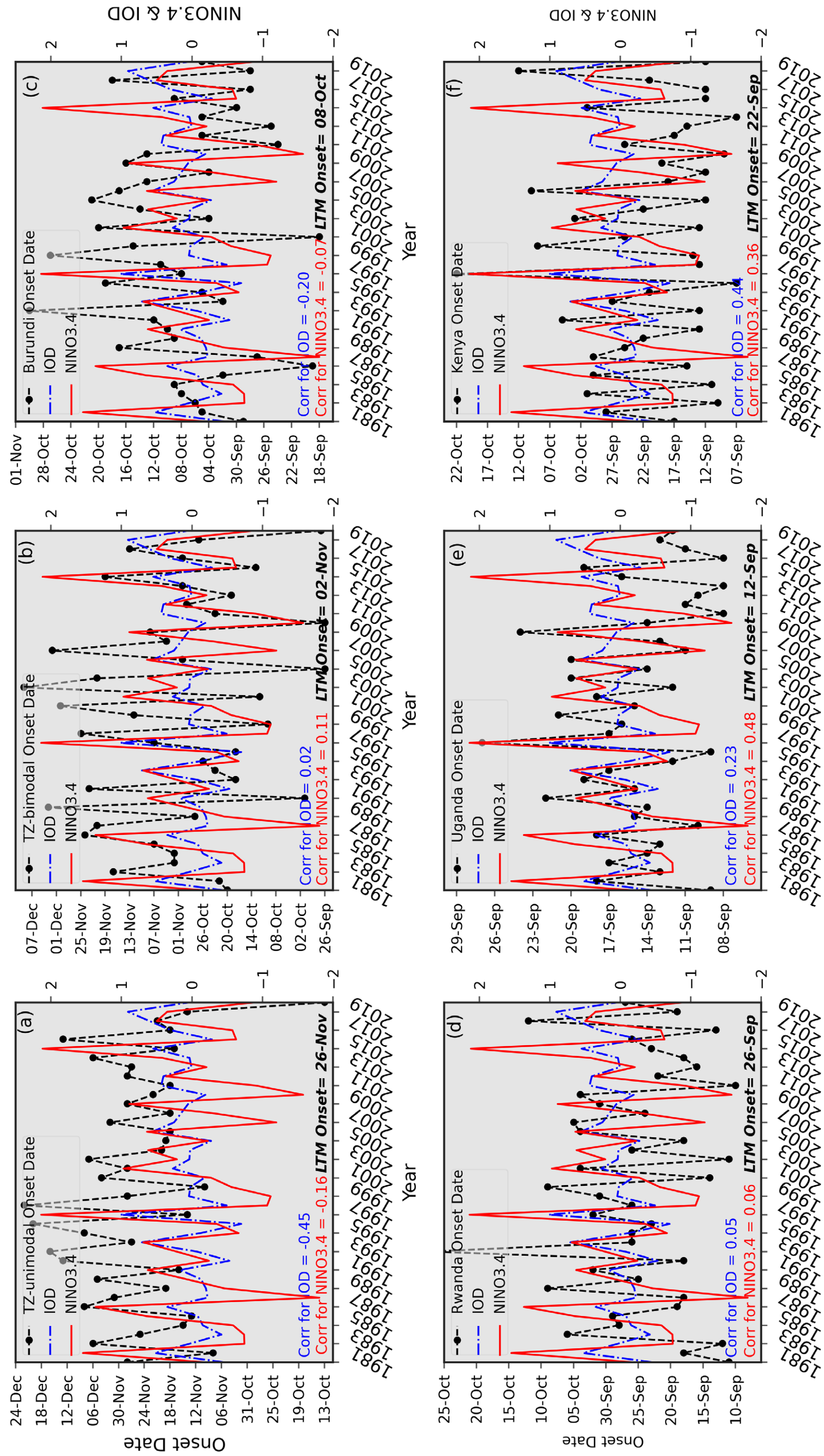

Figure 7. Temporal correlation coefficients of rainfall onset date against NINO3.4 SST and IOD indices during the OND and NDJFMA seasons. (a) Tanzania (unimodal domain), (b) Tanzania (bimodal domain), (c) Burundi, (d) Rwanda, (e) Uganda, and (f) Kenya. The rainfall onset dates were computed based on the country's administrative boundary, except for Tanzania, where onset dates were computed based on the bimodal and unimodal regions separately. The graphs also include the country's average of the rainfall onset date (LTM onset).

years experienced SST indices with high peaks (with positive anomalies) correspond with early onset dates and vice versa for the years with low peaks.

The negative correlation coefficients were also discovered over Burundi (**Figure 7(c)**), in which IOD had r = −0.20 and NINO3.4 had r = -0.07. This implies that rising SSTs in the Western Indian Ocean and central Pacific Ocean have less impact on the occurrence of earlier rainfall onset. However, the earliest rainfall onsets were observed in 1987 and 2001 around 18th and 19th September, while the latest rainfall onset dates were observed in 1993 and 1999 around 30th and 27th October, respectively. Moreover, the influence of NINO3.4 is slightly higher than that of IOD. A slight influence has been seen on the SSTs across the central Pacific Ocean. The LTM onset date over this region was experienced on October 08th, almost at the beginning of the OND rainy season.

Furthermore, in Rwanda (**Figure 7(d)**) the late onset was observed on 25th October, 1993 and early onset dates on 10th September, 2011 (**Figure 7(d)**). Generally, Rwanda experiences LTM onset around 26th September and the occurrence of onset is slightly influenced by IOD (r = 0.05) and SSTs over NINO3.4 region (r = 0.06). Either, **Figure 7(e)** depicts a significant correlation coefficient between the IOD (r = 0.23) and NINO3.4 (r = 0.48) over Uganda, both of which have significant influence in occurrence of rainfall onsets. The region is distinguished by a slight change in inter-annual patterns in terms of departure from the earliest and late onset. Therefore, the earliest onset date was observed on the 9th September in 2011, 2014, 2017 and the late onset on 27th September in 1997. This country had an earlier onset than other EA countries, with LTM onset around September 12th, as shown in **Figure 7(e)**. However, in Kenya, LTM begins on September 22nd, as shown in **Figure 7(f)**, and IOD has slight greater influence on the start of rains than NINO3.4. Thus, the high value of correlation that observed for IOD was r = 0.44 which is greater compared to NINO3.4 (r = 0.36). Generally, these SST indices have positive effects on the rainfall onset over Uganda and Kenya, while a slight effect is observed in Tanzania (over the bimodal region) and Rwanda.

4.5. Risk of Dry Spells at Planting Days during OND and NDJFMA Seasons

The risk associated with dry spells after planting dates indicates how many times the first rains were not effective for planting, and if farmers had planted with these rains, they would have to replant (Yonah et al., 2006; Mwongera et al., 2014). Therefore, proper crop plating happens when the onset WnDS is equal to the onset WDS. **Figure 8** shows areas with high risk of replanting (about 40 to 80% probability) are located along the Northeastern highlands, Northern coast, central, and Southern coast as well as in the Southern region of Tanzania. The scenario extends to Kenya across the Rift Valley areas (including some parts of Turkana, Marsabit, Nakuru, and Bungoma) and the Southeastern parts of Garisa province. Moreover, large patterns of crop replanting that range from 70% to 80% have been observed in Southern Tanga and Northern part of Coast region

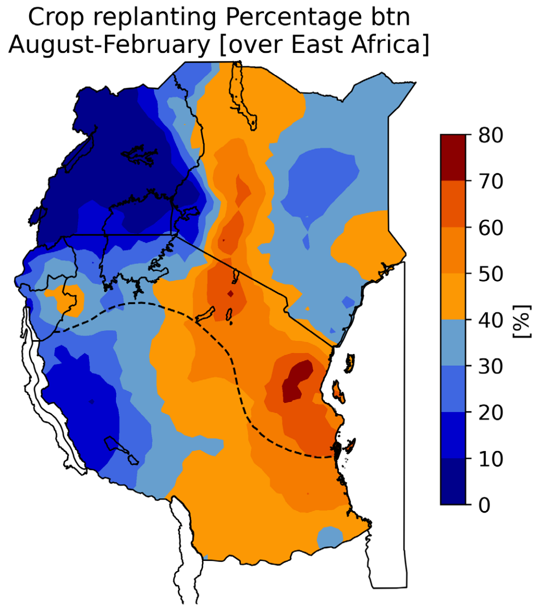

Figure 8. The risk of crop replanting percentage (PODD) has been computed from the number of onset dates WDS when they are greater than onset dates WnDS. The dotted black line is a boundary which separates areas that experience two rainy seasons (bimodal in the north) and a single rainy season (unimodal in the south).

in Tanzania. These are areas where probably farmers experience crucial crop seed replanting during the OND and NDJFMA seasons that are caused by the occurrence of long dry spells after the first rains. The scenario is different over much of the Western part of EA, especially over the Southwestern highlands of Tanzania, and the areas around Lake Victoria Basin, Uganda, Rwanda, Burundi and Eastern Kenya, where less than 40% is found. In these areas, most farmers are more confident in planting after the occurrence of the first rain.

The results for monthly PODD (**Figure 9**) clearly show high percentage of crop replanting risk over most parts of the EA. The fraction of replanting risk tends to weaken from September through December, as indicated whereby NDJFMA season has a lowest risk compared to the OND season. **Figure 9(a)** and **Figure 9(b)** shows that most areas in the unimodal region experienced more than 80% of PODD which attributed much to false start of rainfall onset before the "*Msimu*" rainy season in November. This scenario probably led farmers to replant crops in the affected areas. However, between 50% and 70% of PODD were observed in September and October in Northeastern Kenya, some areas of Western Uganda, and the Northern Kigoma region of Tanzania. Less PODD, between 10% and 50%, was observed in Western Kenya and some regions of Eastern Uganda along Lake Victoria. It seems that, the meridional arm of the ITCZ has a significant impact on these rains, which typically start between September and November. In fact, a few weeks after October, the ITCZ and Congo Air Boundary (CAB) lead to the occurrence of rain belts over the Northwestern side (across the equator) of EA (Diem et al., 2019). The effect has been clearly displayed in **Figure 9(c)** and **Figure 9(d)** whereby the number of dry spells and false start

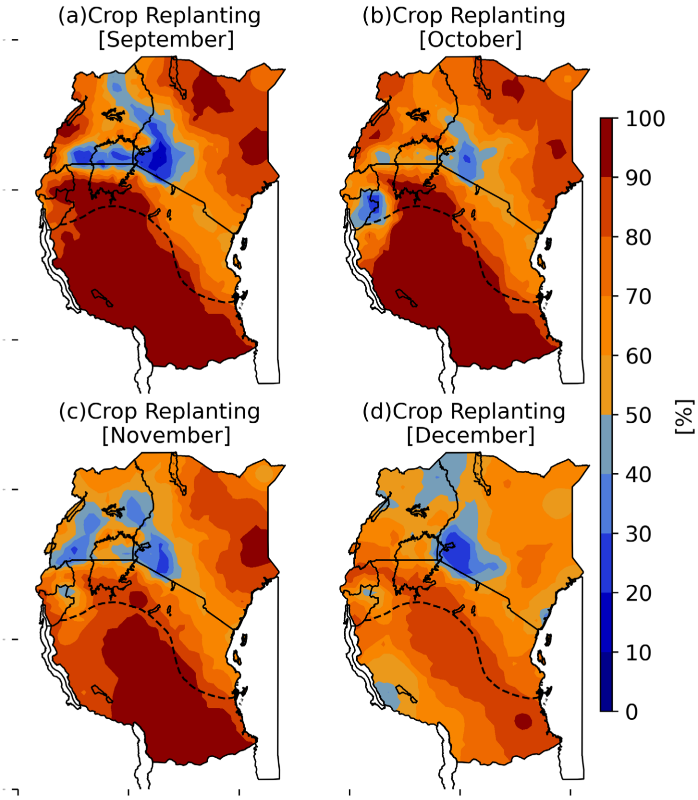

Figure 9. Monthly risk for crop replanting percentage (PODD) during (a) September, (b) October, (c) November, and (d) December. The dotted black line is a boundary which separates areas that experience two rainy seasons (bimodal in the north) and a single rainy season (unimodal in the south).

onsets decrease lead to the PODD percentage decreasing significantly in the Southern and Southwestern highlands of Tanzania (over the unimodal region). Therefore, farmers are likely to be safer to plant crops in November and December in most parts of EA.

5. Conclusion

This paper applied cumulative daily mean rainfall, percentage of onset date departure (PODD), Mann-Kendall (MK) trend test, student t-test, and correlation methods in an assessment of rainfall onset date distribution and variability over selected EA countries, the risk of a dry spell after planting, and the relationship between inter-annual onset date variations and large-scale climate features, specifically El-Niño, La-Niña, and the Indian Ocean Dipole (IOD). The following conclusions can be drawn from this study:

1) Early onset with dry spell (WDS) consideration frequently occurs in Uganda between the first and second dekad of September, while late rainfall onset WDS occurs in the first and second dekads of December over central and Northern Kenya as well as in the Northeastern highlands, parts of the Northern coast and over unimodal regions in Tanzania. This is much by the North-South movement of the ITCZ (Nicholson, 2017).

2) Most of EA regions, with the exception of the Mtwara region in Tanzania and the Marsabit region in Kenya, showed distinct patterns of inter-annual variability. While the earliest LTM onset was seen over the Gulu region of Uganda around September 7th, the late-onset WDS was first noticed over the Iringa region of Tanzania on December 9th. With the exception of those in Burundi's Gitega, Rwanda's Kibaye, and Kenya's Nakuru and Gulu, the majority of the selected regions were characterized by negative slope values and a decrease in linear trends. Only two regions, Simiyu and Mwanza in Tanzania had a notable significant decrease in the onset trend. Thus, the occurrence of early rainfall onset across the EA region during this study period is highly influenced by SST indices such as IOD and NINO3.4, as revealed in (Dunning et al., 2016; Vengateswari et al., 2017).

3) The significant correlation coefficients between onset dates and both IOD and NINO3.4 in spatial coverage, were found in the North and Northeastern Kenya as well in the Northeastern highlands of Tanzania and Eastern Uganda. These SST indices highly influence early rainfall onset occurrence in areas characterized by a bimodal rainfall season, with less influence in unimodal areas. Temporarily, IOD influences onset positively over Kenya, Uganda, Rwanda, and Tanzania, particularly in the bimodal regions, and vice versa over the remaining regions. Similarly, patterns have also been seen after onset dates correlated with the NINO3.4 index. In general, the IOD index has a much greater influence on the onset of rainfall in most East African countries than the NINO3.4 index.

4) The percentage of crop replanting (PODD) ranged from about 40% to 70%. This was revealed over the Southern coast, central, Northern coast, the Northeastern highlands, and some parts of Eastern Lake Victoria in Tanzania and along the Rift Valley area in Kenya. In Tanzania, PODD increased to 80% over Tanga and the northern Pwani region. Therefore, farmers have to take this high percentage into consideration; otherwise they would probably suffer from severe crop seed replanting and crop loss due to the false onset of rainfall.

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Conflicts of Interest

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

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