



Important drivers of East African monsoon variability and improving rainy season onset prediction

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Abstract

Monsoon rain and its year-to-year variability have a profound influence on Africa's socio-economic structure by heavily impacting sectors such as agricultural and energy. This study focuses on major drivers of the east African monsoon during October–November–December (OND) which is the standard time window for the onset of the rainy season, be it unimodal or bimodal. Two drivers viz. Indian Ocean Dipole (IOD) and El Niño Southern Oscillation (ENSO) both separately indicate very strong positive connections with monsoon (OND) rain not only in the OND season with zero seasonal lag, but the signal is also present even taking IOD and ENSO a season ahead. A compositing approach is applied that can additionally identify strong signals when different combinations of ENSO and IOD phases act as confounding factors. Results of precipitation anomaly suggest that when IOD and ENSO are both on the same phase in July–August–September (JAS), a significant OND rainfall anomaly occurs around the east African sector: A deficit (excess) of OND monsoon rain occurs when both drivers are in a negative (positive) phase during JAS. A location Kibaha in Tanzania, for which station data are available, is considered for a more in-depth analysis. The uncertainty range in cumulative OND rainfall is also reduced to a large degree when IOD and ENSO phases are both negative in JAS. These results can be used for prediction purposes and interestingly, that criterion of IOD and ENSO being of same phase in JAS was again matched in 2022 (both negative) and hence it was possible to deliver early warnings for a deficit in rainfall a season ahead. Techniques to compute the monsoon onset as determined by meteorological services such as the Tanzania Meteorological Authority rely on various thresholds, which may also vary by country. To overcome some of the issues with thresholds-based techniques, other definitions of ‘onset’ take into account cumulative rainfall amount and such technique has also been tested and compared. In both approaches, late (early) onsets dominate in years when ENSO and IOD are both negative (positive) during JAS. In these cases, it is therefore possible to provide an estimation of cumulative rainfall and onset for OND in terms of average, median value, range and distribution of rainfall one season in advance. Such results have implications for optimizing agricultural, water and energy management, also mitigating possible severe production losses, which would impact the livelihoods of millions of Africans.

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Abbreviations

AT	Alternate Technique
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station
ENSO	El Niño Southern Oscillation
ERA5	ECMWF Reanalysis v5
ERA5L	ECMWF Reanalysis v5Land
GPCP	Global Precipitation Climatology Project
IOD	Indian Ocean Dipole
MERRA2	Modern-Era Retrospective analyses for Research and Applications Version 2
MSWEP	Multi-Source Weighted-Ensemble Precipitation
ST	Standard Technique
TMA	Tanzania Meteorological Authority

1 Introduction

Monsoon rainfall plays a crucial part in Africa's socio-economic structure. Its year-to-year variability has profound implications for agricultural, energy, and other societal sectors (World Bank 2022). Among African countries, East African countries are much more prone to climate vagaries and frequently impacted by severe droughts (Nicholson 2016) and floods (Li et al. 2016). Identification of any large-scale climate drivers, which contribute to the year-to-year fluctuations of monsoon seasonal rainfall in those regions of Africa and can be used to improve the quality of onset and rainfall amount predictions a few months ahead, would have enormous implications for the livelihood of millions of Africans.

Two possible large-scale drivers are discussed here as they are shown to be key to the South East (SE) African monsoon: the El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD). The ENSO is a periodic warming and cooling in the tropical Pacific and is usually measured by central to eastern tropical Pacific sea surface temperature fluctuations (Wang et al. 1999). Similarly, IOD is a periodic, see-saw kind of variation in the eastern and western sides of the Indian Ocean sea surface temperature (Saji and Yamagata 2003; Saji et al. 1999). ENSO and IOD are found to influence monsoons in other countries too (Roy 2021, 2018).

Earlier studies have discussed how African monsoon is impacted by ENSO (Lenssen et al. 2020), and IOD (Nicholson 2015). It is observed that ENSO and IOD, which may not be independent of each other, both have a very strong role in modulating the east African Monsoon rain in the October–November–December (OND) season (Black 2005). This season is the common period for both unimodal (from around October to May) and bimodal (typically October to December and March to May) rainy season onset. The date of monsoon onset, as well as the accumulated rainfall, is critical for large parts of east Africa's socio-economic activities due to the considerable interannual variability in rainfall patterns in the region (Hastenrath et al. 1993). The relative positioning of the Intertropical convergence zone (ITCZ), that separates northern hemisphere from southern hemisphere and its seasonal migration has an important role in this variability via changing direction of winds from north easterly to south easterly (Nicholson 2018). Many regions of east Africa experience two rainy seasons referred to as bimodal. The retreat of ITCZ southwards in the

southern hemisphere constitute the ‘short rainy’ season of OND, while northwards movement of ITCZ from the southern boundary constitutes ‘long rainy’ season of March–April–May (MAM) (Gamoyo et al. 2015).

Rainfall spatial variation patterns in SE Africa are well documented (Gamoyo et al. 2015; Stefanie and Mohr 2011), though it is noted that factors leading to short rainy seasons are very poorly understood (Nicholson 2016; Gamoyo et al. 2015). The short and long rainy seasons contrast in terms of many rainfall characteristics indicating major driving factors and influences in two seasons are different. For short rain, spatial coherence of rainfall over eastern Africa is much greater (Hastenrath et al. 2011; Moron et al. 2007), and the interannual variability of rainfall is much larger too (Nicholson 2017; Camberlin and Wairoto 1997). In terms of individual months, zonal winds at 850 mb show larger variability in each month of MAM to that from OND (Pohl and Camberlin 2011). Differences between short and long rainy seasons could be largely attributed to the phase of ENSO, as ENSO usually is of same sign throughout the OND season, though inconsistent and variable during the long rains (Indeje et al. 2000; Camberlin and Wairoto 1997).

Given the paramount role of rainy seasons in SE Africa economic activities, many studies have focused on the definition and calculation of their onset. Some onset definitions are based on accumulated precipitation, anomalies, and percentage cutoffs while others on a number of thresholds, which also typically vary from country to country (Zamperi et al. 2023; Gudoshava et al. 2022; Macleod et al. 2018; Fitzpatrick et al. 2015; Liebmann et al. 2012; Segele and Lamb 2005). For example, in Tanzania thresholds are defined by the country’s government official body Tanzanian Meteorological Authority (TMA), and some of them are different from its neighboring country Malawi.

The focus of this paper is mainly on identifying major drivers of short rainy season for SE Africa, which can subsequently improve prediction skill of accumulated rainfall and onset of the rainy season. Two different onset techniques are explored and compared. A retrospective outlook, a season ahead, is also provided and verified for 2022.

The structure of this paper is as follows. Section 2 covers the Data and Methodology part, where two different techniques for the onset rainy season are introduced. Results are presented in Sect. 3, which has a few sub-sections. Section 3.1 addresses cumulative rainfall and its variation as a function of ENSO and IOD for SE Africa. Analyses on onset are covered from Sect. 3.2 where the two techniques of onset are discussed and compared. Onset as a function of ENSO and IOD in both techniques is explored in Sect. 3.3. Finally, a discussion and conclusions are given in Sects. 4 and 5, respectively.

2 Data and methodology

Two commonly used precipitation datasets are considered here as the main reference: Global Precipitation Climatology Project (GPCP) data (Huffman et al. 2009) and Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data (Funk et al. 2015). Other precipitation datasets also used for comparison purposes are: ERA5 (ECMWF Reanalysis v5, <https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5>), ERA5L (ECMWF Reanalysis v5Land, <https://www.ecmwf.int/en/era5-land>), MERRA2 (Modern-Era Retrospective analyses for Research and Applications Version 2, <https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/>) and MSWEP (Multi-Source Weighted-Ensemble Precipitation, <https://www.gloh2o.org/mswep/>).

For ENSO, the Niño3.4 index is used. This is given by the average sea surface temperature (SST) over the region 5°N–5°S and 170°W–120°W. HadISST data (Rayner et al. 2003) are used for the Niño3.4 index, and its anomaly with respect to the 1981–2010 period is calculated (in °C). Data for Niño3.4 are available at: https://psl.noaa.gov/gcos_wgsp/Timeseries/Data/nino34.long.anom.data. The IOD index, also referred to as Dipole Mode Index, is defined as the anomalous SST gradient between the western equatorial Indian Ocean (50°E–70°E and 10°S–10°N) and the south eastern equatorial Indian Ocean (90°E–110°E and 10°S–0°N) (Saji and Yamagata 2003). Data for IOD are available at: https://psl.noaa.gov/gcos_wgsp/Timeseries/Data/dmi.had.long.data.

Two different rainy season onset techniques are discussed. The first is a threshold-based from TMA, hereafter referred to as Standard Technique (ST). The onset day for the (OND) season in ST is calculated based on the following thresholds: (a) the first occurrence with at least 20 mm rainfall in four consecutive days, (b) at least two wet days and (c) no dry spells of 10 days or more within the following 30 days. A wet day is defined when there is at least 1 mm of rainfall in the day; while a dry day records less than 1 mm of daily rainfall. The other technique we tested, hereafter referred to as Alternate Technique (AT), is based on cumulative anomaly of rainfall (Zampieri et al. 2023; Macleod et al. 2018; Liebmann et al. 2012). The two techniques are further elaborated in Sect. 3.2.

3 Results

Cumulative rainfall and onset in OND monsoon season, based on ENSO and IOD phase, are explored and two techniques of onset are discussed and compared. A location, Kibaha (38.96 °E, 6.83 °S), Tanzania, part of a case study of the EU FOCUS-Africa project¹, and for which station data are available, was considered for a more detailed assessment.

3.1 Cumulative rainfall as a function of ENSO and IOD

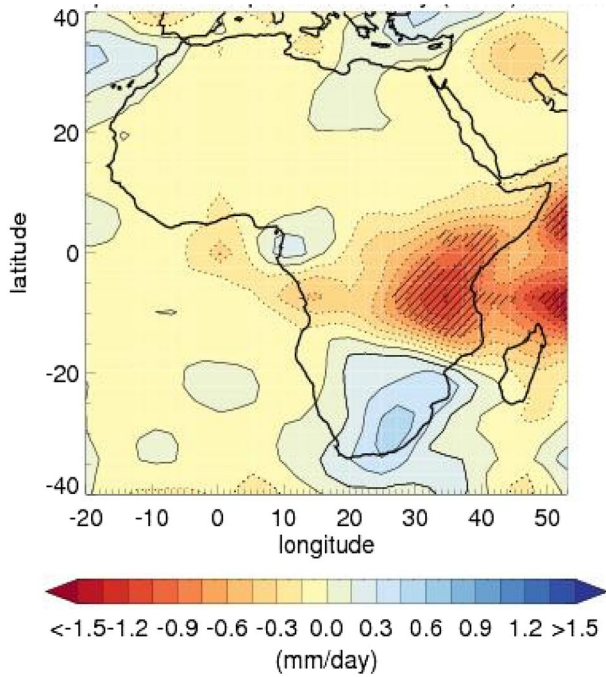
To explore cumulative rainfall and its connection with ENSO and IOD phases, we first investigate the spatial variations of seasonal rainfall in SE Africa, also identifying regions of influence of these two drivers. This is complemented by an assessment of rainfall data at the Kibaha meteorological station.

3.1.1 Spatial variation around SE Africa

Both ENSO and IOD separately indicate very strong positive correlations with monsoon OND rain in SE Africa. Not only is the correlation strong as a simultaneous relation, but a significant correlation is present even with a lead time of up to four months. This is because ENSO and IOD both usually change phase at around June-July and then maintain that phase for the ensuing few months. Such connection is also confirmed using various data sources, by detrending the data, using regression technique and considering either years of earlier time periods or recent time periods (Roy et al. 2023a). More specifically, analyses of precipitation data from ERA5, which are available since 1940, confirmed that the signal is similar for this longer period too (Roy et al. 2023a, 2023b).

¹ <https://focus-africaproject.eu>

Fig. 1 Precipitation composite anomaly (mm/day) for OND (compared to the average of recent near thirty years period), in years when IOD and ENSO are both negative in July-August-September (JAS) using GPCP data. In the whole season, a deficit of rain more than 100 mm from normal is noticed in regions of the SE African sector. Significant regions at 95% level are marked by hatching



In order to eliminate effects of confounding factors of ENSO and IOD, namely when they are in an opposite phase, the corresponding years are removed from the sample. The strongest connection between the SE Africa rainy seasons and the ENSO and IOD indices occurs when these two have the same sign. In the following section, we focus on years when this situation occurs. A deficit in rainfall in the regions of SE African sector covering Tanzania is noticed in OND when IOD and ENSO are both negative in July-August-September (JAS) (Fig. 1), and vice versa when both indices are positive. Results are shown here for GPCP data, but they are similar using CHIRPS and various other rainfall data sources too (not shown here). Years stratified according to ENSO and IOD phases, starting from JAS, are presented in Table 1. A total of six different cases are considered. The signal is only present around SE Africa when both drivers are in the same phase (either both negative, Case 1 and 2 or both positive, Case 3 and 4). A situation for Case 1 is shown in Fig. 1, where a significant deficit of rain is noted in the SE African sector (the signal is similar for Case 2).

3.1.2 Cumulative rainfall variation in Kibaha

Figure 2 shows the cumulative rainfall for the Kibaha station, where Case 1 and 2 are in pink and Case 3 and 4 in blue. Yellow indicates Case 5 and 6 situations. Average cumulative rain from 1st July to the end of December is shown, with uncertainty range of one standard deviation marked (Fig. 2a).

Cumulative rainfall is also presented in the form of boxplots indicating median values with ranges and distribution for various cases (Fig. 2b). There is a large deficit in rain for Case 1 and 2, while excess for Case 3 and 4. The uncertainty range is much reduced in Cases 1 and 2 from the rest Cases (Fig. 2).

Table 1 Six cases considered in this study, stratified according to the phases of ENSO and IOD, also indicating the years when the individual cases occurred, and the corresponding characteristics of total (accumulated) rain and onset. For SE Africa a signal in total rain and onset is present only when both drivers are in the same phase

Cases	Criteria	Years	Total rain (OND) in SE Africa	Onset date (OND) in SE Africa
Case 1	ENSO and IOD both negative in JAS and OND	1995,1996, 1998, 2001,2005,2010,2016	Deficit	Late
Case 2	ENSO and IOD both negative in JAS	1995,1996, 1998, 2001,2005,2010,2016, 2013, 2021	Deficit	Late
Case 3	ENSO and IOD both positive in JAS and OND	1994,1997,2002, 2006,2015, 2018,2019	Excess	Early
Case 4	ENSO and IOD both positive in JAS	1994,1997,2002, 2006,2015,2018,2019, 2012, 2003	Excess	Early
Case 5	Rest other years (ENSO and IOD in opposite phase in JAS)	1993,1999, 2000,2004, 2007,2008,2009, 2011, 2014, 2017, 2020	Not identified	Not identified
Case 6	All years together	1993–2021	Normal range	Normal range

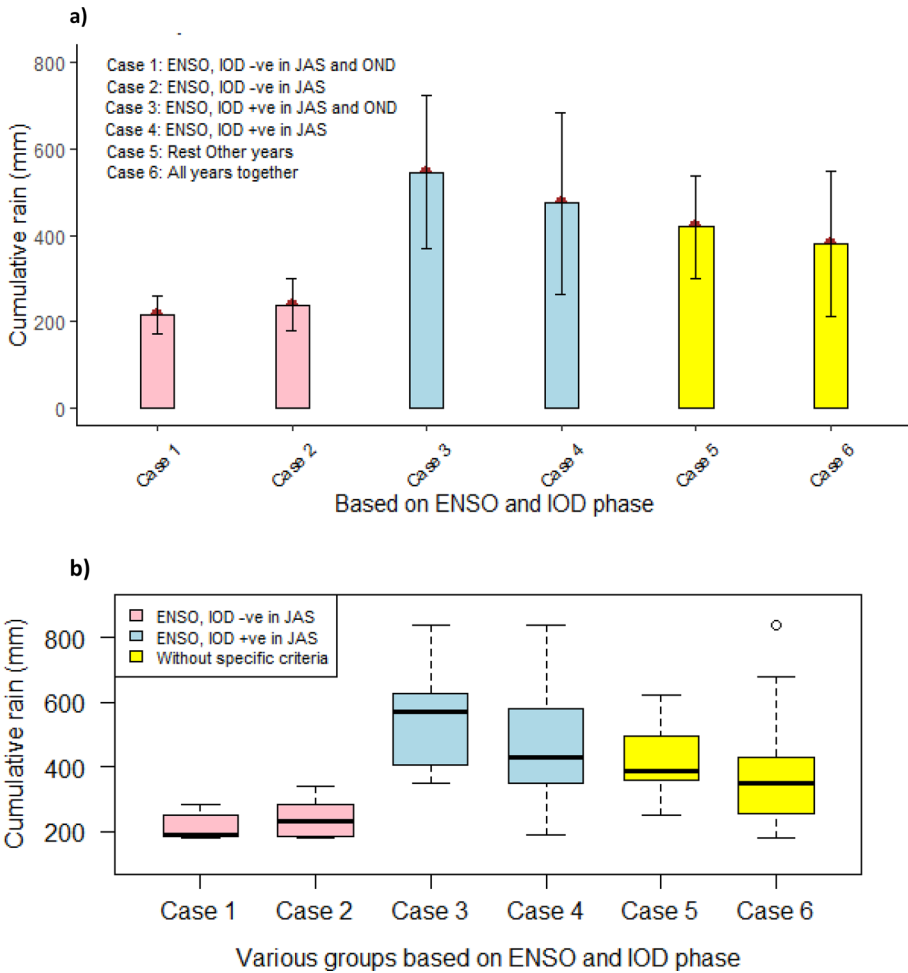


Fig. 2 Cumulative rain (mm) in Kibaha, Tanzania using CHIRPS data for 1993 to 2021, based on various ENSO and IOD phases. **a** Cumulative rain, average from 1st July to end of December with uncertainty range one standard deviation marked; **b** boxplot showing median values and variations of cumulative rainfall with range

3.2 Analyses on onset in Kibaha

For farmers, the onset of the monsoon season is of paramount importance (Mittal et al. 2021) and hence studies focused on improving the concept and definition of onset day tailoring farmers need (Macleod et al. 2018; Liebmann et al. 2012). The onset of the rainy season identified by the Standard Techniques (ST), and adopted by TMA, are based on various thresholds that vary according to the country (as discussed in Sect. 2). The use of fixed empirically-based thresholds in the definition of ST makes this technique difficult to apply in a general way. For example, there are instances when the ST definition is affected by long dry spells after an initial spur of precipitation, therefore indicating an earlier onset than when it actually occurs. Dry spells have major implications for agricultural crop failures and need to be accounted for too. For this reason, we have explored the use of another

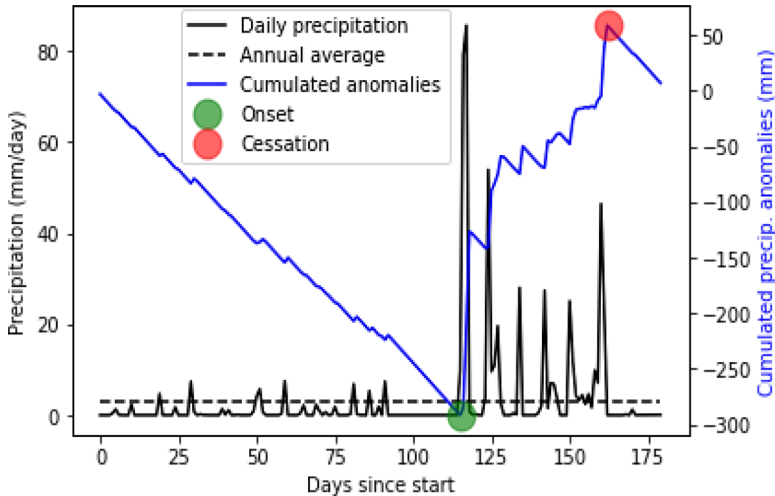


Fig. 3 Onset timing determination in 2017. A technique using cumulative rainfall, termed as Alternate Technique (AT) identified the onset, cessation and duration of monsoon (OND) in a location Kibaha, in Tanzania in 2017 using CHIRPS data

technique based on algorithms that can identify onset with no, or minimal, conditional statements based on arbitrary thresholds.

Such a technique, which we refer to as Alternate Technique (AT) mainly considers cumulative amounts of anomalous seasonal rainfall (Zampieri et al. 2023; Macleod et al. 2018; Liebmann et al. 2012) is tested for the location Kibaha (Fig. 3). The change in cumulative rainfall from the annual average (Y axis, right), shown in blue, is plotted over time from 1st July in the X axis. With this technique, onset is an absolute minimum of the (anomalous) cumulative rainfall (green dot in Fig. 3). Analogously, the absolute maximum is defined as the cessation date. Incidentally, this simple identification of the cessation, in addition to the onset, makes this technique even more appealing as cessation is not easily definable within the context of the ST. In this example, the AT onset is identified as 23rd Oct and cessation on 9th Dec and therefore the duration of the monsoon season is 47 days. It was a normal rainy season in 2017 and the day of onset in this method very closely matched the TMA's ST method.

3.2.1 Variation of onset date in ST using different data

Station data at Kibaha, which are available since 2008, are compared with gridded precipitation data sets for onset day variation using ST (Fig. 4). No consistency is present among different data sources. For a same year, some data suggest early onset, while some show late onset. In some years, there is even a 60-day difference in onset date among various data sources (e.g., 2016).

Figure 5 further compares various data for onset (ST) in Kibaha over similar period by applying the correlation technique. The correlation diagram suggests high resolution CHIRPS data has stronger correspondence with station data (correlation coefficient 0.85). Whereas, ERA5L has a reasonably good correlation with all other data.

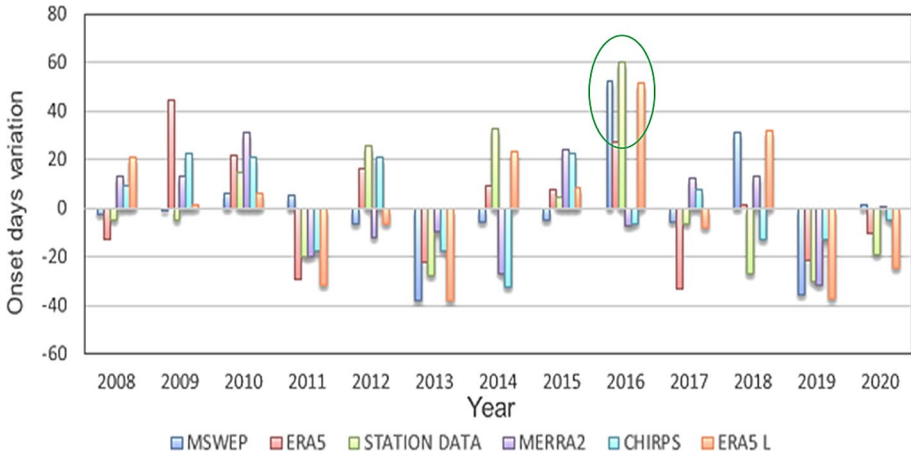


Fig. 4 Rainy season onset (OND) day variations in Kibaha during 2008–2020 using ST and various rainfall data. There is no consistency in onset day variation among different datasets and in some years, the difference can be more than 60 days as in 2016, as marked by the oval

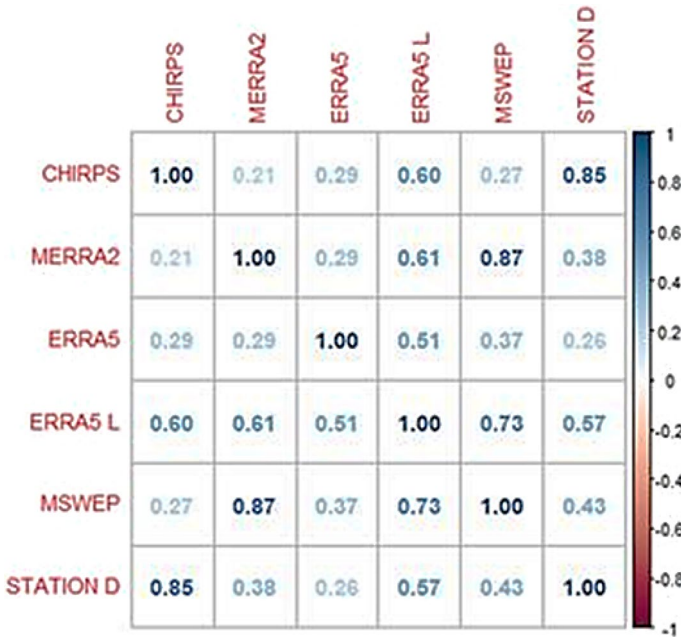


Fig. 5 Correlation coefficient between onset date using ST for Kibaha based on different rainfall datasets

As correlation for onset in ST with station data is found to be strongest using CHIRPS data compared to other datasets, more analyses are carried out here based on CHIRPS. Due to a stronger correspondence of CHIRPS with station data, most recent

Table 2 Comparison of onset days (starting from 1st January), based on two techniques: AT (using CHIRPS data) and ST (with various data, station data is available only from 2008). For AT, the actual onset date is also mentioned

Year	AT		ST					
	CHIRPS	Onset date	CHIRPS	ERA5	Station data	MERRA2	MSWEP	ERA5 L
2008	299	26th Oct	301	285	301	299	311	336
2009	340	5th Dec	314	342	301	299	313	316
2010	339	4th Dec	313	319	320	317	320	321
2011	309	4th Nov	274	268	286	266	319	283
2012	328	24th Nov	313	314	331	274	307	308
2013	327	22nd Nov	274	275	278	276	276	277
2014	303	29th Oct	259	307	338	259	308	338
2015	302	28th Oct	314	305	310	310	309	323
2016	360	26th Dec	285	325	366	279	366	366
2017	296	22nd Oct	299	264	299	298	308	307
2018	319	14th Nov	279	299	279	299	345	347
2019	275	1st Oct	279	276	276	254	278	278
2020	285	12th Oct	287	287	287	286	315	290
Average (Std. deviation)	314 (23)	9th Nov	292 (18)	297 (23)	306 (26)	286 (19)	313 (23)	315 (27)

studies in the African region have also adopted CHIRPS as the main rainfall dataset (Zamperi et al. 2023 among others).

3.2.2 Onset day in Kibaha: comparison of ST vs. AT

In Table 2, some comparisons of onset days based on two techniques, ST and AT are presented. ST.

considered various data (e.g., ERA5, Station data, MEERA2, MSWEP and ERA5 L) alongside CHIRPS, whereas AT only focused on CHIRPS. Results are usually comparable, though there are discrepancies among onset dates derived from various data sources and also between the two techniques using the same dataset. The average values of onset and the standard deviation, for each dataset and technique, are presented at the bottom of the table.

In some years, there is consistency among various datasets using ST, though results deviate for AT. For instance, in 2013, using ST, all dataset suggest the onset day to be around 275, though it is very different for AT (day 327). On the other hand, there are some years (e.g., 2019), when AT and ST suggest consistent results for onset.

3.2.3 Dry spells can make differences: ST vs. AT

Years with deficient rain are often associated with prolonged dry spells. Those situations usually happen when IOD and ENSO are in negative phase in JAS (Case 1 and 2). Some discrepancy between the two techniques (AT, ST) usually arises in rain deficit years. The

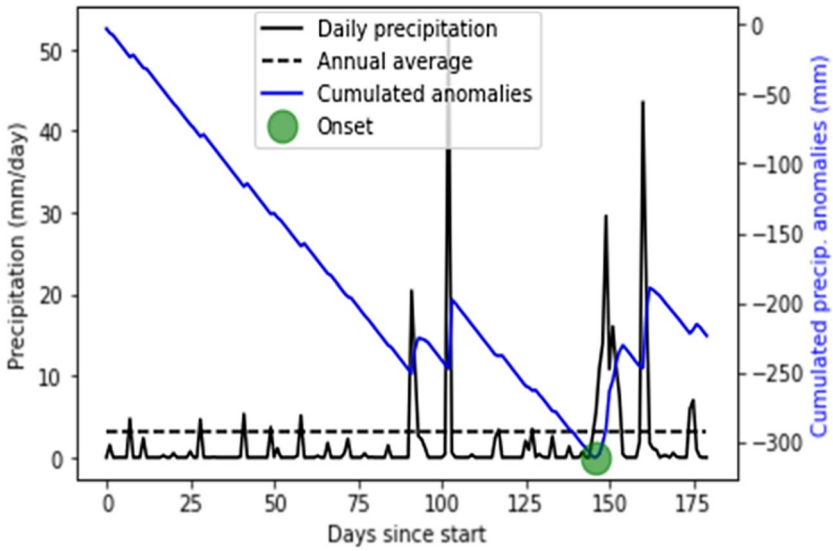


Fig. 6 Onset timing determination in 2013. Onset for Kibaha using CHIRPS in 2013, which is a rainfall deficit year. ST identifies onset at around 100 days (since start on 1st July); whereas, AT identifies onset near 150 days since the start, shown by green. Hence, around 50 days of difference between the two techniques

year 2013 is further discussed here, which is a Case 2 situation and accompanied by frequent prolonged dry spells (Fig. 6).

In that year, around 50 days difference in onset is noticed between two techniques, AT and ST (Table 2). In Fig. 6, onset using ST can be identified at around 100 days (since start from July) where a sudden surge of precipitation is observed only for a very few days. It satisfied all threshold criteria and hence even using various data sources, ST could identify that onset. Different data in ST suggested consistent result for 2013 onset (Table 2). However, after around 100 days, there was a prolonged dry spell of near 50 days, though definitions of ST did not account for such long dry spells. Long dry spells after the announced official onset in ST have severe consequences for agricultural purposes. AT can however overcome such shortcomings and identified the onset 50 days later than ST (around 150 days starting from July, marked by green in Fig. 6).

False onset, associated with a long dry spell afterward, which has major implications for agricultural crop failures seems to be eliminated in AT, though captured as true onset in ST.

3.3 Onset as a function of ENSO and IOD

Results of onset day using AT are compared with government adopted ST, when years are segregated based on IOD and ENSO phases (Table 1) and found to offer fair results (Figs. 7 and 8). Figure 7 depicts result as boxplot distribution, marking median values; whereas Fig. 8 presents mean value with uncertainty range (one standard deviation) marked. Late onset is identified in both techniques using AT or ST, when ENSO and IOD both are in a negative phase even one season ahead (JAS). Whereas, early onset dominates the years when ENSO and IOD

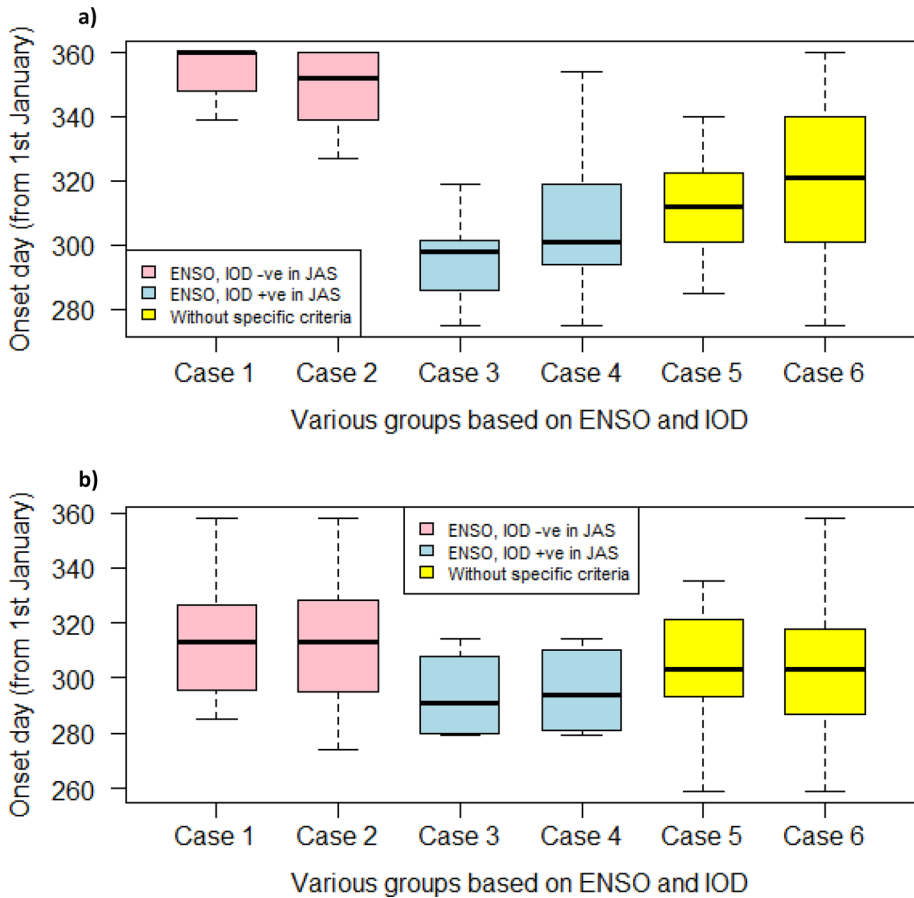


Fig. 7 Onset of monsoon (OND) in Kibaha, Tanzania using CHIRPS data for 1993 to 2021 based on ENSO and IOD phases in a form of boxplot. Onset days in two different techniques are presented: **a** based on the AT that focuses on cumulative rainfall; **b** based on the ST used by TMA. In 2022, we were in Case 1 situation and hence it was possible to deliver early warnings one season ahead

both are in positive phases during JAS season. Late onset for pink (Case 1 and 2) and early onset for blue (Case 3 and 4) are clearly distinct for both techniques and also mentioned in Table 1 (last column). The deviation in median values between pink and blue is larger for AT than ST, it is also true for mean values.

In almost all cases, IOD and ENSO continued with the same phase in OND as was observed in JAS and hence this knowledge can be useful for delivering an outlook and certain estimation relating to cumulative rainfall and onset one season ahead. It has implications for mitigation and losses, and optimization of agricultural production.

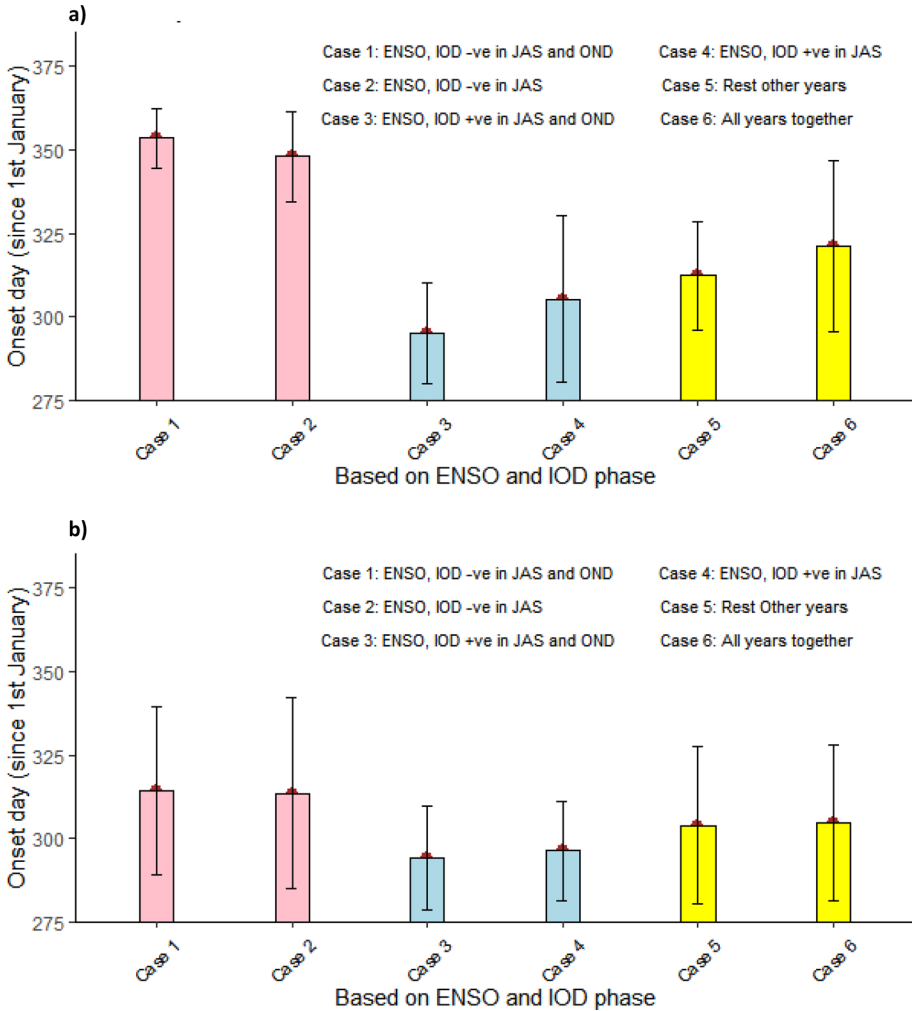


Fig. 8 Onset of monsoon (OND) in Kibaha, Tanzania using CHIRPS data for 1993 to 2021 based on ENSO and IOD phases. Average days are presented with the uncertainty range of one standard deviation marked, using two different techniques: **a** based on the AT that focuses on cumulative rainfall; **b** based on the ST used by TMA.

4 Discussion

Analyzing boxplots presented in Figs. 2 and 7, many useful estimations can be offered e.g., median value, range and distribution of data for each case (Case 1 to 6). Certain estimations of mean and standard deviation can also be made for accumulated rainfall (Fig. 2a) and onset day (Fig. 8) and discussed underneath. Outlook for the future can be given beforehand, one season ahead.

Cumulative amounts of precipitation in a rainy season play an important role and serve as a useful indicator for various sectors e.g., energy and agriculture among others.

For example, when IOD and ENSO are both negative in JAS and OND, a location like Kibaha (38.96 °E, 6.83 °S) in Tanzania, for which the station data is available, a total of around 216 mm cumulative rain on average was noted from 1st July until the end of the year (with one standard deviation of 44 mm), based on simple statistics of historical data, which is only 56% of the long-term mean (Fig. 2a, Case 1). The estimation of rain deficit from normal years is very similar for other surrounding locations of SE Africa too. Rain in JAS is minimal for all those African countries and major precipitation starts from October onwards, and hence results are similar if only the OND rainy season is considered. Interestingly, when IOD and ENSO are both positive in JAS and OND, the amount of total rain is on average more than doubled (546 mm) with a standard deviation of 210 mm (Fig. 2a, Case 3). However, normal amount of cumulative rain for 30 years in Kibaha is 381 mm with a standard deviation of 169 mm (Fig. 2a, Case 6). Results in the plot made use of CHIRPS data, as this dataset is the most consistent with station observations than others tested. By using the CHIRPS dataset it is therefore possible to compute accurate onset estimations for many other places (or average over an area).

Can such outlooks from JAS be used for future planning in optimizing agricultural and energy outputs, therefore mitigating severe consequences and losses due to an excess or deficit rain? Can we also take advantage of favorable weather situations when excess monsoon rains are likely to occur? Additional agricultural/energy related planning and mitigation strategies can be adopted for countries of SE Africa for the OND season, when IOD and ENSO are of the same phase in JAS to that from rest other years.

For onset, computation of mean and standard deviation is also done (Fig. 8) for each case (Case 1 to 6). The mean onset day, based on around 30-year average, identified by this technique of AT, following the technique of cumulative rainfall is 16th November (day 321 starting from 1st January, with a standard deviation of 26 days). For TMA's ST it is 31st October (day 305, standard deviation of 23 days). Both methods in general indicate late onset for rainfall deficit years, while early onset in years of excess rainfall. In years when IOD and ENSO are both negative in JAS, and this continues till OND season, the average onset day based on the cumulative rainfall's approach is around 19th December (day 354, with a standard deviation of 9 days). Thus, considering these different factors, our analysis, performed in September 2022, indicated a late onset in 2022. The ST also suggested a late onset, namely around 9th November (day 314, with a standard deviation of 25 days). In situations when both IOD and ENSO are negative, a large deviation in onset day may be observed between the two methods. Using the AT, when IOD and ENSO are both positive in JAS and OND, onset is identified much earlier, which is around 21st October (day 295), with a standard deviation of only 9 days. The date is also similar based on the ST though with a higher standard deviation (25 days).

In the recent near thirty year period (1993–2021), 9 years have both indices in their negative phase in JAS and all of them showed a deficit in rainfall in SE Africa. More recently, that criterion of IOD and ENSO being both negative was again matched in 2022, and it was the 2nd consecutive year. Based on the historical record, an early warning for a deficit in the monsoon OND rain for 2022, a season ahead, could be attempted. In 2022 OND season, most regions of SE Africa, as identified in Fig. 1, indeed experienced a deficit in rainfall (plots not shown here). Kibaha also suffered a deficit in rain with a total accumulated rain of only 220 mm. Moreover, it turned out that in the year 2022 a very late onset was noted in Kibaha in ST using two rainfall datasets, the local station rainfall data and CHIRPS data (both 22nd December), though long dry spells also occurred.

It remains to be investigated whether any local scale drivers or other large-scale modes of variability can also modulate the onset, with a view to further improve prediction.

Attention also needs to be placed on the onset day in rainfall deficit years. Announced onset dates in those years are likely to be associated with a long dry spell or nominal rain after that onset, which can be responsible for agricultural crop failures unless enough measures are taken to account for these likely dry spells.

5 Conclusions

Two important drivers of Monsoon rain during OND in Africa viz., ENSO and IOD are discussed and affected regions and countries around SE Africa are identified. Positive significant correlations noticed for rain (OND) with both ENSO and IOD, a season ahead. The compositing technique is applied to separate out years with confounding influence from ENSO and IOD, i.e., when both are in opposite phase. Compositing detected strong significant signals in regions of SE Africa covering Tanzania, Malawi, Kenya, etc., when both the drivers of IOD and ENSO are of the same sign starting in JAS. A significant deficit in OND rain is noticed when both drivers are negative in JAS and vice versa when both are positive. Hence future outlook is possible even in a season ahead.

A particular station Kibaha from Tanzania is further focused, where station data is available. Analyses on onset using two techniques are discussed. Correlation for onset using ST with station data is found to be strongest for CHIRPS compared to other data and hence more analyses are focused based on CHIRPS. An Alternate Technique (AT) for onset that can eliminate many biases of the official Standard Technique (ST) is tested and compared. It is based on cumulative rainfall anomaly and offers fair results and is comparable to ST as used by TMA. Dry spells after the onset of ST have severe consequences for agricultural purposes. False onset, associated with a long dry spell afterward, which has major implications for agricultural crop failures seems to be eliminated in AT, though captured as true onset in ST.

IOD and ENSO combined phases in JAS are not only good indicators for cumulative rain (OND), but also indicate about onset. Late (Early) onset in OND is observed when both drivers are negative (positive). Results suggested similar patterns even though two different onset techniques (ST, AT) are applied. Based on this analysis, it is possible to give a future outlook and estimation for onset day and cumulative rainfall in terms of average, median value, range and distribution of rain, one season in advance. Such results have implications for future planning in optimizing energy and agricultural outputs, mitigating severe consequences and losses, alongside taking advantage of favorable weather situations. The livelihoods of millions of Africans will be impacted.

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Declarations

Competing interests The Authors declare no Competing Financial or Non-Financial interests.

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