Identifying important drivers of East African October to December rainfall season

Indrani Roy\textsuperscript{a,}\textsuperscript{*}, Alberto Troccoli\textsuperscript{b}

\textsuperscript{a} University College London (UCL), UK
\textsuperscript{b} World Energy and Meteorology Council (WEMC), UK

HIGHLIGHTS

- Two important drivers of Monsoon (OND) in East Africa with affected regions identified.
- Positive significant correlation between rain (OND) and ENSO or IOD, a season ahead.
- Results are confirmed by various data, earlier/later years, detrending data before.
- Compositing: significant rain (OND) deficit (excess), if both drivers -ve(+ve) in JAS.
- Future outlook of rain possible a season ahead and Walker circulation plays role.

GRAPHICAL ABSTRACT

ABSTRACT

Monsoon rainfall plays a crucial part in Africa's socio-economic structure and its year-to-year variability has profound implications for agricultural, energy, and other societal sectors. The current study focuses on two of the major climate drivers of the east African rainy season during October-November-December (OND), which is when the season starts for a large portion of east Africa (e.g. Tanzania and Malawi). Such drivers could be different in early austral summer from the rest of the year, due to the relative positioning of the Intertropical convergence zone, which passes through this region - hence regions of east Africa and OND season are the focus here.

The two drivers of Monsoon viz. El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) are considered: both independently indicate strong connections with monsoon OND rain. Not only is there a strong significant positive correlation in the OND season as a simultaneous relation, but the signal is also there even with the lag of a few months. This has been tested using various data sources, detrending data beforehand, analysing either recent time periods or earlier time periods - covering two decades each, and using regression analyses. To further strengthen the results, a compositing approach is applied that can additionally identify

\textsuperscript{*} Corresponding author.
E-mail address: Indrani.roy@ucl.ac.uk (I. Roy).

https://doi.org/10.1016/j.scitotenv.2023.169615
Received 18 June 2023; Received in revised form 18 November 2023; Accepted 21 December 2023
Available online 29 December 2023
0048-9697/© 2023 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
1. Introduction

Monsoon rainfall and its interannual variability have an enormous impact on Africa’s socio-economic structure. There are two distinct circulations comprising the African monsoon; the first one is the west African monsoon, which prevails during the northern hemisphere summer, and the second one is the east African monsoon producing precipitation in the spring (March to May) and autumn (October to December) (Nicholson et al., 2018). However, east African countries are affected more by the high level of variability in seasonal monsoon rain. Out of the seven most flood-prone countries in Africa, five are in eastern Africa (Li et al., 2016). One common feature of eastern African countries comprises the frequent occurrence of severe drought too (Nicholson, 2016). The livelihood of millions of east Africans can be improved if any significant influence of large-scale climate drivers is identified ahead of time.

Two large-scale climate drivers, the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), are explored in this regard for early austral summer (Oct-Nov-Dec, OND) monsoonal rain in the eastern Africa. Studies previously discussed the influence of ENSO and IOD on east African monsoon (ENSO; Lenssen et al., 2020, Dezfuli and Nicholson, 2013; IOD: Nicholson, 2015, Blau and Ha, 2020). Both drivers have a strong role in modulating the east African monsoon rain in OND season, even if they are not independent of each other (Black, 2005). Though ENSO positive phases are usually associated with excess rain in eastern Africa, two strong El Niño years, 1983 and 1992, were accompanied by significant drought episodes in east African countries (Mason and Tyson, 2000; Ibebuchi, 2021). Kenya was one of the worst affected countries in the drought of 1983 (Shisanya, 1990). The 1992 drought episode in the African countries, south of equator was in fact distinguished as one of the most severe on record (Ibebuchi, 2021; Glantz et al., 1997; Mason and Tyson, 2000). It severely impacted the agricultural sector and food security, which resulted in the demand for increased efficiency in the management of drought episodes in African countries (Bruiwer, 1993). The most affected country of 1992 drought was Zimbabwe (Eldridge, 2002). The impact of ENSO was known at that time but IOD was a completely new phenomenon and the influence was unknown to people. Subsequently, when this new mode of variability, the IOD in the Indian Ocean, was identified during 1999 (Saji et al., 1999), it was found that apart from ENSO, IOD plays a crucial role in modulating the east African rainy seasons too. Interestingly, IOD was in a negative phase in those two years (1983, 1992). In this work, we will explore how the combined influence of ENSO and IOD can play a key role in controlling various monsoon related features in east African sectors in OND, from even a season ahead (July–August-September, JAS).

The focus here is on OND, in particular, because it is the season that has the common onset for both rainy seasons, unimodal (regions experience one rainy season: typically from October to May) and the bimodal (regions experience two rainy seasons: typically October to December and March to May). Moreover, in this particular season, various monsoon-related features (e.g. onset date, total accumulated rainfall, etc.) affect large parts of east Africa’s socio-economic activities due to a larger degree of interannual variability (Nicholson, 2017; Hastenrath et al., 1993). The relative positioning of the Intertropical convergence zone (ITCZ, a belt of low pressure system crossing around the equator and separates the northern hemisphere from southern hemisphere) and its seasonal meridional migration has an important role in this variability via changing direction of winds. Many regions of eastern Africa experience two rainy seasons; the retreats of ITCZ southwards in the southern hemisphere constitute the ‘short rainy’ season of OND, while northwards movement of ITCZ to that from the southern boundary constitutes ‘long rainy’ season of March-April-May (MAM) (Gamoyo et al., 2015; Nicholson, 2017). The terminology ‘short’ is often used against ‘long’ as OND season is usually shorter than the MAM rainy season.

Detailed discussions on rainfall spatial variation in Africa relating to bimodal and unimodal patterns are well documented (Stefanie and Mohr, 2011; Gamoyo et al., 2015; Palmer et al., 2023). Studies further discussed that the factors leading to drought in east Africa, especially during the short rains, are very poorly understood (Gamoyo et al., 2015) that included continuation of droughts through several rainy seasons (Nicholson, 2016). Interestingly, the long and short rainy seasons exhibit strong contrasts in rainfall characteristics. For example, the spatial coherence of rainfall over eastern Africa is much greater during the short rains than during the long rains (Moron et al., 2007; Hastenrath et al., 2011). The two seasons also contrast in terms of inter-annual variability too, which is much greater during the short rains (Nicholson, 2017; Camberlin and Wairoto, 1997). The zonal winds at 850 mb are more variable in OND than at any other time of year (Pohl and Camberlin, 2011). However, when the focus is on individual months rather than annual variation, months of MAM show larger variability. The time series of interannual variability of 850 mb zonal wind for the months of March, April, and May are mutually uncorrelated, while those for October and November are strongly correlated throughout eastern Africa (Nicholson, 2017). Such differences between two seasons, MAM and OND, were discussed largely related to the phase of ENSO, as ENSO usually is of same sign throughout the OND season, though variable and inconsistent during the long rains (Camberlin and Wairoto, 1997; Indeje and Semazzi, 2000).
discussed that circulation fields played crucial roles (Ibebuchi, 2021). Other studies also found that the short rains are strongly coupled to a zonal vertical circulation cell in the central equatorial Indian Ocean, which is related to the Walker circulation (Hastenrath et al., 2011; Mutai et al., 2012). It has been demonstrated that the most important physical mechanism in the variability of the short rains is the intensity of the Walker cell, where the westerlies at low-level play a fundamental part in modulating this circulation. For coastal stations, the correlation between these low-level westerlies and rainfall area averaged over 1958 to 1997 is −0.85 (Hastenrath et al., 2011); though the connection extends throughout a much larger sector of eastern Africa. For coastal stations, seven locations were considered from Kenya e.g., Lamu, Malindi, Mombasa, Voi, Tanga, Bagamoyo and Dar es Salaam (Hastenrath et al., 2011). Convergence of moisture from ocean towards landmass first crosses coastal stations and hence likely to induce more rains over the coasts than from the interior. Direction of change in lower level winds from ocean towards land, consistent with the change in direction of the Walker circulation and subsequent moisture convergence, are reflected in the negative sign of correlation. For the regions of east Africa (e.g., Kenya, Tanzania and Uganda) with a bimodal rainy season, the correlation is still −0.74, for over 100 years period (1874 to 2012) (Nicholson, 2015). In spite of decadal variability, the zonal winds in that study (Nicholson, 2015) indicated most consistent and strongest relationships with October–November precipitation than other variables they analysed such as 200 mb zonal wind, Niño 3.4 and the IOZM (Indian OceanZonal Mode/Dipole). An additional point to note is that the short rains are more strongly modulated by the low-level winds over the Indian Ocean than by ENSO, indicating the stronger role of IOD (Nicholson, 2015; Hastenrath et al., 2011; Bergonzini et al., 2004).

For farmers, the onset of the monsoon season has of enormous importance and hence research also focused on improving the definition and concept of onset day tailoring farmers’ requirements (MacLeod, 2018; Zampieri et al., 2023). A recent study discussed two independent onset techniques and compared those in regions of east Africa for OND monsoon season (Roy et al. 2023b). The first onset definition is official method adopted by the government of east African countries that depends on a number of thresholds, which also typically vary from country to country; whereas, another method was tested that is based on accumulated precipitation and anomalies (Zampieri et al., 2023; MacLeod, 2018; Liebmann et al., 2012). The OND onset day is shown heavily modulated in both techniques when years are segregated based on IOD and ENSO phases (Roy et al., 2023a, 2023b).

The coupling of various large-scale drivers (e.g., ENSO, QBO, polar annular modes, etc.), decadal signature involving atmosphere-ocean coupling and teleconnection among various surface parameters including monsoon, were previously discussed with sufficient details (Roy, 2018, 2014, 2020). Those indeed raised issues of complexities in various teleconnection features involving large-scale drivers and indicated why prediction is difficult and associated with uncertainties. Eastern African countries are not the exception and recent studies raised issues that skilful seasonal forecasts in east African countries are still very poor, especially for precipitation, which varies by country, season, and sometimes by model (Hannah and Klingaman, 2020). Decadal signature on rainfall, in specific, for south Africa is discussed focusing on period 1920–2014, and noted significant associations between short-term droughts with decadal variability (Malherbe et al., 2016). Decadal connection on various indices (e.g., zonal winds at the surface and at 200 mb, the central equatorial Indian Ocean, Niño 3.4 and the Indian Ocean Zonal Mode/dipole (IOZM) and rainfall in OND season are also detected for east African countries for over an 139 year record (Nicholson, 2015). It discussed that the relationships with these indices are not only time dependent, but the relationships among the indices also changed on a decadal timescale, which are consistent with regime shifts as discussed by other studies. For e.g., the links were very weak roughly between 1920 and 1960, when apparently the Walker circulation over the Indian Ocean was very weak but was particularly strong over the Pacific Ocean. During those decades, ENSO appeared to control most of the variability of Oct-Nov rain; while interannual variability was weak, with seasonal rain below long term average during most of that period (Nicholson, 2015). After 1961, the total rain and interannual variability increased markedly.

Southern Annular Mode (SAM) also influences the ‘Short Rains’ of eastern African countries (Manatsa et al., 2016). As emphasized by Morioka et al. (2015), one possible mechanism how SAM influences that region originates via the storm tracks (the westerly jet) and their northward shift that regulate the strengths of the Mascarene high (MH) in its southern part. The MH, also known as the Indian Ocean subtropical high, located near the Mascarene Islands in the Southern Indian Ocean is a high-pressure area situated between 20°S–40°S and 45°E–100°E. The anticyclonic circulation in the MH and its associated cross-equatorial winds in the western Indian Ocean, modulates moisture transport from ocean towards land, establishing a relationship between the MH and the monsoon trough. Hence MH also plays an important role for rainfall patterns over the east African landmass (Miyasaka and Nakamura, 2019). Whether IOD is impacted by other drivers or IOD-ENSO relationship is influenced remotely from midlatitude or polar regions are interesting areas to explore to strengthen our knowledge relating to ENSO, IOD and east African monsoon rain. Studies indeed discussed the influence of SAM on IOD (Zhang et al., 2020 among others) whereas, remote influence from the north Atlantic on IOD-ENSO connection is also detected (Xue et al., 2022). Other drivers of east African monsoon e.g., Madden-Julian Oscillation (MJO) has also been identified though found to have a much stronger influence in the long rains than in the short rains (Berhane and Zaïtchik, 2014). Studies suggested that the effect of MJO can also be modulated in the southern hemisphere by the Quasi-Biennial Oscillation (QBO) (Sena et al., 2022). Moreover, significantly high correlations (with peak values of +0.8) are noted between rainfall over parts of eastern Africa and QBO in some months, which are more prominent while using lag correlation than in the simultaneous correlations (Indeje and Semazzi, 2000). All those analyses indicate the importance of considering other large-scale drivers too alongside IOD and ENSO to further improve east African monsoon rain prediction. Moreover, those also indicate IOD and ENSO may have some connections with other large scale drivers, which needs investigating further to improve our understanding on IOD, ENSO and monsoon rain; however, those are beyond the scope of this analysis.

In this study, the focus is on the combined effect of the two major drivers IOD and ENSO on total accumulated rainfall around eastern Africa in OND season. We also explore the combined strong influence from one season ahead and discuss how such knowledge can be translated for delivering more realistic future outlook even a season early. Here lies the novelty of our analyses. Such prior knowledge, which is key for preparedness, risk mitigation and taking advantage of favourable weather situations, can have enormous impact to the livelihood of millions of east African.

The structure of this work is as follows: in Section 2 we cover the data and analyses part; whereas, major findings are presented in the results section, Section 3, and conclusions are discussed in Section 4. In the results section, we first apply various statistical relationships: correlation, regression and compositing. Then we discuss the time progression of rainfall signals month by month. The discussion on possible mechanisms follows. At the end of result section, we present an outlook for 2022 monsoon (OND) and its validation.

2. Data and methodology

In this study, data of the two climate drivers, ENSO and IOD, are analysed, alongside precipitation. For ENSO, the Niño3.4 temperature index (this is an average over the area 5 N–SS 170 W–120 W in the Pacific Ocean) is used. The Sea Surface Temperature data come from HadISST data (Rayner et al., 2003) and anomalies are computed with respect to the 1981–2010 mean. The IOD represents the SST anomaly of
the 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). This gradient is named as Dipole Mode Index (DMI) (Saji and Yamagata, 2003). Both the data of Niño3.4 and IOD are available from 1870 to present (in this study, data accessed on 30/09/2022). For precipitation, three datasets are used; Global Precipitation Climatology Project (GPCP) data (Huffman et al., 2009), Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data (Funk et al., 2015) and ECMWF Reanalyses Version 5 (ERA5) data (Hersbach et al., 2020). Results from three independent data sources are presented here, as limitations of one particular dataset (in terms of spatial resolution, temporal and spatial coverage, etc.) can be compensated, if all data indicate similarly ensuring robustness of results. For example, CHIRPS data only spans 50°S-50°N and ranges from 1981; while GPCP data covers the whole globe and have a slightly longer record starting from 1979. On the other hand, the resolution of CHIRPS is much finer (0.25°x0.25° or 0.05°x0.05° available, we used the first one) compared to GPCP (2.5°x2.5°). CHIRPS uses a blend of satellite and station data; while for GPCP, rain gauge stations, satellites, and sounding observations are merged together. However, both CHIRPS and GPCP provide only precipitation data and hence if large scale teleconnection patterns and global scale wind patterns are also of interest, ERA5 data could be another choice that have both precipitation as well as wind, alongside other meteorological parameters. Moreover, ERA5 precipitation is available for a longer time period (starting from 1948) with fine resolution (0.25°x0.25°), though it is a reanalyses product. Considering all these factors, results using these three data sources are presented instead of focusing only on a particular one. Most of the analyses cover the recent 30 years period that started from 1993. However, some analyses also cover earlier period based on the availability of data. For example, some results based on GPCP data are presented from 1979 and some analyses, using ERA5 precipitation also cover from 1948.

Various commonly used statistical methods/relationships are applied to identify robust signatures of large-scale drivers of east African OND monsoon. These methods are: correlation, regression and compositing. For significance testing in correlation, the student’s t-test is applied. To identify significant region in compositing, the method of mean difference is applied and then t-test is used. To explore intradecadal, decadal and multi-decadal signal in OND precipitation, a box region is identified from east Africa and the centered moving average method is applied. Finally, a methodology via representation in the form of a box plot is presented and discussed for the outlook preparation and delivering possible estimation of rain.

3. Results

Results with the three methods e.g., correlation, regression and compositing have been applied to the three mentioned precipitation datasets (GPCP, CHIRPS and ERA5). As results using the different data are very similar, a subset from each of these three individual datasets are presented. We further discuss time progression of signals month by month and explore possible mechanisms for variability of OND precipitation, that involved Walker circulation. Based on our detailed analyses of nearly thirty years record (1993–2021), it was possible to derive an outlook for 2022 monsoon (OND). Hence a validation of the 2022 OND monsoon rain is also presented.

3.1. Various statistical relationships applied

First, we discuss results using commonly used statistical methods/relationships, i.e. correlation, regression and compositing.

3.1.1. Signals in correlation analyses

The main results presented here for correlation studies are for ERA5 using a longer record (1948–2021). Knowing that two climate drivers ENSO and IOD separately influence east African monsoon in OND, we further elaborate the analyses to check how far back the influence is noticed and what regions of east Africa are affected. Here we will discuss how those two drivers separately can influence OND monsoon rain in east Africa, considering various lags. The correlation coefficient (c.c.) between Niño3.4 and DMI in OND is 0.67 in the recent thirty years period (1993–2021), compared to 0.55 when considering the last 150 years.

3.1.1.1. Precipitation and Niño 3.4 correlation. A strong positive correlation is identified in the east African sector between Niño 3.4 and OND precipitation (without any lag). It is consistent with earlier studies that detected connections between ENSO and east African rainfall in OND (Lenssen et al., 2020; Dezfuli and Nicholson, 2013 among others). The regions of strong correlation are identified and seen as statistically significant at a 95% level and not only present in simultaneous months of OND (Fig. 1a), but also present by taking Niño3.4 one season ahead, July–August–Sept (JAS) (Fig. 1b). Even when Niño3.4 in June–July–August (JJA) is correlated with precipitation of OND, a similar signal in that region is again noticed (Fig. 1c). Noting that ENSO usually changes phase around June–July and generally continues with similar phase for the rest of the year- that knowledge may explain such strong lag connection.

3.1.1.2. Precipitation and IOD correlation. Similar signals like Fig. 1 are noticed around east Africa when IOD is used in place of Niño 3.4 (Fig. 2a, b and c, respectively). Thus, for IOD too, a strong positive correlation exists with OND rain around east Africa not only based on simultaneous relation (Fig. 2a), but a significant correlation also exists a season ahead (Fig. 2b) and even when the lead time of JJA is considered for IOD (Fig. 2c). Earlier, studies detected a connection between IOD and east African monsoon rainfall in OND when simultaneous months or zero lag situations are considered (Nicholson, 2015; Blau and Ha, 2020) and Fig. 2a is consistent with such observation.

Here results using ERA5 precipitation data are presented for a longer period (1948–2021). However, results are similar in the east African sector if the period 1979–2021 or 1993–2021 are considered instead (not shown here). The same plots using CHIRPS data for the period (1981–2021) is also presented in the Supplementary Section (Figs. S1 and S2 respectively) and results are again similar.

3.1.1.3. Earlier vs. recent period. The 1979–2021 period is split into two (1979–1999) and (2000–2021) for the GPCP data to assess possible temporal changes in the connection between precipitation (OND) and the two drivers, Niño3.4 (Fig. 3A) and IOD (Fig. 3B). Even though longer-term decadal influence might affect results (Nicholson, 2015), the detected signal around east African region is found similar in the earlier as well as later period due to each individual drivers in JAS. To eliminate effects, if any, due to longer time linear climate change signal, the data was detrended beforehand, but it did not make much difference. Results of correlation after detrending the data is presented in Fig. 3.

3.1.2. Regression analysis

Similar results are noticed when the regression analysis, instead of correlation, is applied between precipitation (OND) with Niño 3.4 (JAS) and IOD (JAS) (Fig. 4). A significant deficit or excess in rain is noticed around regions of east Africa in OND, based on the independent phase of both Niño 3.4 and IOD in JAS. The signal is, however, stronger for IOD (Fig. 4, bottom) than Niño 3.4 (Fig. 4, top).

---

Fig. 1. Precipitation (OND) and Niño 3.4 correlation with various lead time of Niño 3.4: a) without any lead i.e., simultaneous relation, b) lead of one season (JAS is used for Niño 3.4), and c) lead of one season and one month (June–July–August, JJA is used for Niño3.4). Results for ERA5 precipitation are presented for 1948-2021. Correlation Coefficient (c.c.) >0.23 are significant at 95 % level.
Fig. 2. Same as Fig. 1a, b and c respectively, but IOD is used instead of Niño 3.4. Like Niño3.4, a similar signal for IOD is also noticed around east Africa.
3.1.3. Signals in the method of compositing

Independent influence of ENSO and IOD though identified on the rainfall (OND) around east Africa one season ahead, but to use that knowledge for early outlook or prediction becomes difficult as those drivers could be in opposite phases too around the same time of the year, making it difficult to identify any signal for some years. To segregate years affected by confounding influences of ENSO and IOD when those are in the opposite phase, and to identify strong signals by separating out years when those are in the same phase, the method of compositing is applied. Table 1, shows how years are stratified when ENSO and IOD are of similar or opposite signs starting in JAS. It shows the importance of segregating years when IOD and ENSO have the same phase (either both negative or both positive) to that from when they are of opposite sign. A significant variation in OND rain (deficit or excess respectively) around east Africa is noticed and discussed in Figs. 5 and 6. Such segregation based on various cases as shown in Table 1 can enable us to detect robust
signals, that can be very beneficial for early preparedness, even one season ahead.

Signals using CHIRPS data are presented in Fig. 5, while that using GPCP data are shown in Fig. 6. An opposite signed anomaly of precipitation is noted in east African sector when ENSO and IOD both switch from a negative phase to positive phase. A deficit (excess) of >100 mm of rain from normal is noticed in east African countries when IOD and ENSO both are negative (positive) in JAS. In Fig. 6, a box region, where strong signal is present in a and b is marked by a green box (‘A’) that covers a boundary of 18° S -12° N to 25° E - 52° E. That region will be used for further analyses and will be discussed later. On the other hand, no signal is detected when IOD and ENSO are in the opposite phase at JAS (Case 5). Moreover, south of that box region, opposite signature is noticed in both cases: it is excess rain for Case 1, while deficient for Case 3. Such prior knowledge about seasonal total rainfall, one season in advance, can play a very useful part for various sectors, especially agriculture related decision making and planning beforehand.

### 3.2. Time progression of signals month-wise

Earlier studies noticed that the time series of interannual variability of rainfall for the months of October and November are strongly correlated around eastern Africa, though mutually uncorrelated for the months of March, April and May (Nicholson, 2017). These contrasts were found to be largely related to the impact of ENSO, which is of the same sign throughout the OND season but weak and inconsistent during the long rains (Camberlin and Wairoto, 1997; Indeje and Semazzi, 2000). Based on our current analyses, that included both IOD and ENSO, it is interesting to check whether signals of precipitation anomaly in OND are consistent over individual months too and whether it is possible to detect any time progression of that signal month by month.

Our analyses suggest that the signals of precipitation anomaly have similar sign in each individual months of October, November and December too, which is negative (deficit in rain) for Case 1 (Fig. 7); though positive (excess rain) for Case 3 (Fig. 8). Hence it is in agreement with earlier works (Nicholson, 2017; Camberlin and Wairoto, 1997; Indeje and Semazzi, 2000). Moreover, we observe that signals of strong precipitation anomaly move from the northern part of east Africa to the southern part as time progresses from October to December. Such time progressions are likely to be associated with the movement of ITCZ. Fig. 7 (a, b and c) show that more deficits of rain are likely in the northern part of Tanzania and Kenya in October followed by November; while the southern part of Tanzania is affected most in the month of December in terms of total anomaly. In terms of percentage change of anomaly with respect to mean, it can even be 60% deficit or excess rain in one month. A similar observation, depicting excess rain, is noticed for Case 3 and shown in Fig. 8 (a, b and c respectively). The result of Case 1 is very similar to Case 2, while Case 3 is similar to Case 4. The strongest signal in the southern part of Africa is noticed during December, which is a reverse signal to that from the box region A (Fig. 6 for Case 1 and 3). Such knowledge of the time progression of signals month by month is very useful for regional planning purposes.

### 3.3. Possible mechanisms for influence on OND rain

The east-west Walker circulation has major roles in monsoon circulation by changing the direction and location of zonal winds. The location of updraft of wind indicates regions with more rain; whereas

---

**Table 1**

Various cases based on IOD and ENSO phase, starting from JAS. Signal in OND rain around east Africa is present when both the drivers are of same phase.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Criteria</th>
<th>Years</th>
<th>Rain (OND) in east Africa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 6</td>
<td>All years together</td>
<td>1993–2021</td>
<td>Normal range</td>
</tr>
</tbody>
</table>

---

Fig. 4. Connection of precipitation (OND) with Niño 3.4 (JAS) [top] and IOD (JAS) [bottom] using the regression analysis. A strong significant signal is identified in east Africa. Results for GPCP data are presented.
the same with downdraft of winds indicate less precipitation. Those east-west wind circulation patterns around tropics with locations of precipitation are nicely portrayed by NOAA and presented in Fig. 9a (top). That figure is shown for neutral years when the Walker circulation is not modulated by the phase of ENSO. For the La Niña phase, that pattern of wind and rain strengthens, while for El Niño the wind pattern reverses/alters and the location of rain changes. The direction of zonal wind at lower level is likely to reverse in the upper level of troposphere (say 250 mb level) and such expected feature is clearly depicted in Fig. 9a (bottom). Fig. 9a (bottom) is longitude-height plot of zonal wind in the form of climatology and hence those are not influenced by a particular phase of ENSO. As expected, the top and bottom plot of Fig. 9a suggests consistent patterns. However, when the focus is on Case 1 (top plot) or Case 3 (bottom plot) situation, the anomaly patterns suggest a reverse behaviour (Fig. 9b) in most places. Such observation indicates that the Walker circulation is playing a key part in regulating OND monsoon precipitation. The variation of the wind direction around the east African sector is very distinct.

The Walker circulation is playing an important role in modulating the precipitation in east Africa during OND. This statement is further tested by analysing the precipitation anomaly (Fig. 10a) and the zonal wind anomaly at 200 mb level (Fig. 10b). When IOD and ENSO are in the same phase (either both positive or negative in JAS and OND), two opposite signed signals are located in the east African sector (Fig. 10). Here Case 1 and Case 3 situations are shown, when IOD and ENSO were either both negative (Case 1) or both positive (Case 3) in JAS and OND, respectively. A deficit in rain (OND) around east Africa is clearly distinct when the signs for both are negative, while excess rain when those are...
positive (Fig. 10a). Signals are similar when using Case 2 instead of Case 1, or Case 4 instead of Case 3. Locations of updrafts and downdrafts for the east west travelling Walker circulation around the east Africa are easily identified - which are opposite in Case 1 to that from Case 3; zonal winds are also reversed at 200 mb level. Zonal wind anomaly at lower tropospheric level is also compared (not shown here). Precipitation anomalies, zonal wind variation at upper tropospheric level and lower levels - all suggest a consistent variation. The importance of including circulation fields and the Walker circulation for improving east African rainfall is discussed in many studies (Hastenrath et al., 2011; Mutai et al., 2012; Ibebuchi, 2021). It also agrees with the work of Pohl and Camberlin (2011), which discussed that the zonal winds at lower tropospheric level around the east Africa are more variable in OND than at any other time of year.

3.4. Outlook for 2022 monsoon (OND) and validation

Validation always plays a crucial part in testifying any prediction or
future outlook. Based on the near thirty years results (1993 upto 2021), an attempt was made to provide an outlook of the monsoon rain, OND for the most recent year of 2022. Such an outlook, purely based on observational analyses, was attempted one season ahead. As the data of OND 2022 is now available at the beginning of 2023, some validation is also done to testify the usefulness of our observation.

In 2022, we were in the Case 1 situation, where IOD and ENSO were both negative in JAS and that continued to OND. In 2022, ENSO and IOD both were strongly negative since JAS and did not change phase till December. Also, major dynamical seasonal prediction models, as for instance analysed routinely by the Australian Bureau of Meteorology

\[3 \text{ http://www.bom.gov.au/climate/enso/#tabs=Pacific-Ocean.} \]
\[4 \text{ http://www.bom.gov.au/climate/enso/#tabs=Indian-Ocean.} \]

Fig. 7. Precipitation anomaly (in mm/day) by month in GPCP data for Case 1: a) October, b) November, and c) December. More deficit in rain in the northern part of Tanzania and Kenya in October followed by November. The southern part of Tanzania is most affected in December.
using the listed models – BoM, CanSIPS, ECMWF, JMA, METEO, NOAA, UKMO – also predicted since July a negative phase of ENSO\textsuperscript{1} and IOD\textsuperscript{2} till December 2022.

Based on our analyses, we derived a future outlook of precipitation for OND in 2022, beforehand during JAS. This is purely based on past records of near thirty years (1993–2021), as presented in Table 1. Case 2 situation does not even require checking phases of IOD and ENSO for OND. As it is not based on any model results, model uncertainty in predicting the phase of IOD and ENSO for OND does not make differences to our results and future outlook. Fig. 11 shows the validation of our result for precipitation in recent months of OND, 2022 based only on phases of IOD and ENSO in JAS, e.g. comparing Case 2 situation (Fig. 11, left). Case 2 situation is very similar like Case 1 as shown in Fig. 6a. That knowledge can be useful for prediction purposes. Fig. 11 (right) shows an anomaly plot of total rain for the 2022 season (OND), which indeed indicated a deficit around the SE African sector. Hence based on our observational analyses, it was possible to give an outlook for OND rain 2022, even in the season of JAS without analysing any

Fig. 8. Same as Fig. 7 respectively, but for Case 3. Similar observation is noticed with excess precipitation that progresses from the northern region to southern region of east Africa as month progresses from October (a) to December (c). The southern part of Tanzania is mostly affected in December.
model results.

Following these analyses, it is also possible to deliver an outlook of total seasonal precipitation in specific locations around east Africa, based on the ENSO and IOD phase during JAS season (Fig. 12). An arbitrarily chosen station Mtera, Tanzania (longitude: 35.971° E, latitude: 7.113° S) is discussed here, and it also has available station data. As CHIRPS data is strongly correlated with station data (Roy et al., 2023b) and it has a longer record of data compared to available station data, analyses with CHIRPS are presented. Exploring past historical records, it is possible to indicate the median value of total rain with most likely ranges of spread in various cases (Case 1–6). Different quartile ranges and the overall spread can also be identified. An excess (deficit) of rain occurs in Mtera when both drivers are in a positive (negative) phase during JAS (Fig. 12). Using such box plots, it is also possible to exclude...
the influence of outlier years from the overall sample, that could affect the distribution of results (one outlier year was identified and excluded for Mtera in Fig. 12). Instead of presenting results in a form of box plot, another approach could be showing mean values and standard deviation in various situations for Case 1 to 6 (Roy et al., 2023b). However, the omission of outliers in the method of box plot not only reduces the uncertainty ranges, but such an approach also has advantages over the presentation in the form of mean values, where few outliers can wrongly shift the overall mean and standard deviation of specific cases (Case 1 to 6). In Fig. 12, the uncertainty range of cumulative rain is reduced the most, when ENSO and IOD both are in negative phase starting from JAS (shown by pink).

Though results for a location Mtera, Tanzania, for which station data are available, are presented for this more in-depth analysis, following similar method of presenting data in the form of box plots and by using the CHIRPS dataset, it is possible to compute accurate estimations of total rain for many other locations of east Africa or average over a certain region. For sub-seasonal prediction, the time window starts from July, though rains during JAS in those east African countries are practically minimal. Considering the matter of sub-seasonal prediction in mind, Fig. 12 covers the month from July to December; however, results are similar if only cumulative rain of OND is considered.

Fig. 9. (continued).
3.5. Compositing in longer record and further classifications based on drivers

In 2023 JAS, both drivers ENSO and IOD turned same sign and positive ($>0.4$) (http://www.bom.gov.au/climate/enso/#tabs=Indian-Ocean, accessed 17/11/23). The upcoming OND precipitation 2023, based on phases of drivers in JAS (Case 4) hence requires attention. Further analyses on Case 4 are focused using longer record (1940–2021) in Figs. 13 and 14. Fig. 13 explores whether the main findings of Case 4 situations are still valid for longer records; whereas,
Fig. 10. (continued).
Fig. 14 does further classifications based on the IOD and ENSO phase, when either of the drivers is small, but positive. There are some years when IOD form without the strong influence of ENSO and vice versa. Moreover, if IOD is playing stronger role or ENSO in such classifications - those deserve attention too and Fig. 14 discusses those areas.

In Fig. 13 (top), a strong positive anomaly of rain is noted in the box region ‘A’ [18°S-12°N, 25°E-52°E], suggesting results of compositing are consistent for longer records too. A deficit of rain is also noticed further south of that box region. Mechanisms involving Walker circulation also indicate consistent anomalies in the longer records (Fig. 13, bottom). As IOD neutral range 4 is usually defined between (+/-) 0.4, we considered that threshold for both ENSO and IOD, to do further classification (Fig. 14). Fig. 14a suggests when ENSO is positive, and IOD is greater than +0.4, the box region experiences heavy rain (left); whereas, if IOD is between 0 to +0.4, the same region does not show much variation in the eastern part (right). The same observation is also true if IOD is kept positive, while ENSO is varied above and below the threshold of +0.4 (Fig. 14b). Excess rain is noticed in region A, in the left plot; while plot on the right does not show much variation in the eastern part of region ‘A’ covering land region. However, anomaly in Fig. 14b (right) is weaker than Fig. 14a (right), that somehow suggest stronger role of IOD than ENSO and those need further exploration. If ENSO and IOD both are varied based on threshold, it shows the signal practically disappears in that region A, when both the drivers are weak and between 0 to +0.4 (Fig. 14c, right). In fact, even though it is in Case 4 situation, if both the drivers are positive but <0.4 in JAS, there is a nominal signal in most part of region A during OND. The signal in region A is the weakest for Fig. 14c (right) among all cases of Fig. 14. One point worth mentioning is that we are focusing only on the Case 4 situation here, which is based on drivers of the JAS season. Though in most cases, sign of drivers remains the same in JAS as well as OND, there are a few cases too when those changes. The changes of phase (positive to negative) between drivers from JAS to OND are more likely when the magnitude of drivers in JAS is low (e.g., less than 0.4) and that might give an explanation for the reduction of signals in OND rain. All these information, based on further classification of two drivers, has major implications for future planning, one season in advance. In all six plots of Fig. 14, signals beyond region A around the southern part, however, seems not much affected and experience a deficit of rain, shown by yellow.
Various studies attended the diversity of ENSO, segregating Canonical (C), Modoki (M) and Canonical Modoki Combined (CM) situations (Roy et al., 2017 among others). Whether the diversity of ENSO influences our findings, we analysed those specific years, as those years are available using HADISST data (Roy et al., 2017, their Supplementary Table S1). The results are similar for El Niño and La Niña, irrespective of specific ENSO phases (C, M or CM). This could be due to the fact that our current study focused Niño3.4 region as the measure of ENSO. In calculating specific C, M and CM years, sea surface temperature of the central tropical Pacific is considered as one parameter and hence the agreement.

### 3.6. Analyses on intra-decadal, decadal and multi-decadal signal

Apart from atmospheric circulation, oceanic circulation and associated heat transport also play parts on rainfall variability around south east African sector. The connection between intra-decadal variability of Meridional Heat Transport (MHT) associated with Indian Ocean Shallow Meridional Overturning Circulation and southern African rainfall has been established very recently (Pai et al., 2023). Intra-decadal (5–7 years) variability significant at 95 % confidence level was identified that suggests oceanic and atmospheric conditions during strong and weak phases of intra-decadal MHT variability act in a reverse manner and all are coupled. A chain of opposite mechanisms is at play to deliver deficit or excess rain. That study indicated enhanced predictability of intra-decadal southern African rainfall in December–February. Fig. 15 showed precipitation anomaly during DJF in Case 4 situation. Signals in the eastern side of region A practically disappeared. A deficit of rain, further south of region A, is still noticed in DJF even though JAS phase of both drivers is considered. Earlier results also suggested a deficit in rain around that region of south east Africa during OND in Case 3 and Case 4 situations (Figs. 6, 13 and 14). Such analyses indicate similar linked ocean-atmosphere coupled mechanisms are likely at work for the east African monsoon around region A, during OND and need to be investigated.

Analyses were carried further to examine rainfall (OND) intra-decadal variability around the box region A [18° S-12° N, 25° E-52° E] using ERA5 data (1940–2021) (Fig. 16). The moving average method of 5-year is applied to detect that signal. The bottom plot in Fig. 16 shows year-wise variability, while plots showing intra-decadal, decadal and multi-decadal signals are placed on top in respective order. The centered moving average method of 5-year, 11-year and 21-year is applied (centered around that year and hence chosen odd number) respectively to identify relevant signals. A linear trend line is shown in each plot and the equation with R squared value is included at the top right corner of each plot. A decreasing trend for OND rain is noticed in all plots; whereas, R squared values are increased from the bottom plot to top plots respectively. In the study period (1940–2021), there are a total of 37 years for Case 2, which are more than double than Case 4 situation (a total of 17 years only) and whether that reduced number has any bearing on the decreasing trend or not needs further testing. The year-to-year variability of OND precipitation is high as is noted from R square value (0.0621) of Fig. 16 (bottom). In that plot, highest rain occurred in 1997 (that year falls in the Case 4 situation), while the lowest was in 1943 (Case 2 situation). For intra-decadal signal, identified using 5 year running method, the highest peaks are noted in years 1951, 1963 and 1984; while major troughs are located around 1942, 1956, 1975 and 1994. In terms of decadal signal, the highest peaks are around 1955, 1981 and 2001, while major troughs around 1970 and 1990. For multi-decadal signature, a point of inflection is noticed at around year 1958, where the trend is reversed from increasing to decreasing. That year is discussed in many studies as one climate shift period when many atmospheric and oceanic features alongside coupling processes suffered deviation (Roy, 2014, 2018, 2020).

### 3.7. Discussion

Various studies discussed the skill of operationally coupled ocean atmosphere long-range ensemble forecasting systems to predict seasonal precipitation around east Africa (Diro et al., 2014; Bahaga et al., 2015, 2016; Young and Klingaman, 2020; Ehsan et al., 2021). Dynamical forecast systems from ECMWF, SEASS (European Centre for Medium-Range Weather Forecasts, fifth generation seasonal forecast system)
Fig. 14. Anomaly of OND precipitation in terms of 1991–2020 climatology for Case 4 situation, using ERA5 data (1940–2021). a) ENSO positive, but IOD has threshold: IOD $> +0.4$ (left), IOD between 0 to +0.4 (right); b) IOD positive, but ENSO has threshold: ENSO $> +0.4$ (left), ENSO between 0 to +0.4 (right) and c) ENSO and IOD both have threshold: both $> +0.4$ (left), both between 0 to +0.4 (right).
demonstrate significant improvement of skill in predicting seasonal rainfall amount around regions of east Africa, specifically during the season of OND (Mwangi et al., 2014; MacLeod, 2019). Incorporating teleconnection features among large scale drivers were found the major scientific basis for such improved dynamical seasonal forecasting (Berhane and Zaitchik, 2014; Ummenhofer et al., 2009; Bahaga et al., 2015; Bahaga et al., 2019). Moreover, multi-model ensembles (MMEs) for seasonal forecasts suggested improved probabilistic skill compared to single model ensemble in regions of Africa, those included east African sector too (Batté and D’equêé, 2011; Bahaga et al., 2016). It is worth mentioning that the statistical methodology presented here constitutes a valuable complement to the methods applied in the dynamic forecasting of the monsoon circulation which are currently still not very reliable for the simultaneous season, let alone a season ahead.

4. Conclusions

Two major drivers for monsoon rain (OND) in east Africa have been identified and affected countries and regions are located. Very strong significant positive correlation is detected for both the individual drivers, ENSO and IOD, in regions of east Africa covering Tanzania and Malawi.

A significant positive correlation is noted even one season ahead e.g., IOD and ENSO in JAS are strongly correlated with the precipitation of OND. Signals are also present from June. This has been tested using various data sources and also splitting the period in an earlier period or later (more recent) period. To eliminate signals of climate change, data was detrended beforehand, but that does not make much difference. Similar signals in the same region are detected using regression analyses too.

To further strengthen results, a compositing technique is applied that can separate out strong signals when IOD and ENSO both are of same phase. It enables us to segregate out years from those when signals are likely to be smudged by confounding influence from two drivers of

---

Fig. 14. (continued).

---

**Fig. 15.** Anomaly of DJF precipitation in terms of 1991–2020 climatology for Case 4 situation, using ERA5 data (1940–2021).
opposite phase. Significant precipitation anomaly (OND), for compositing is noticed, in east Africa, when IOD and ENSO both are of the same sign in JAS. A significant deficit in rainfall is observed when both drivers are negative and vice versa when both are positive. The Walker circulation seems to play a major part in this regard. Analyses of precipitation and zonal wind field at 200 mb level, especially around locations of east African region, suggested a consistent pattern for deficit or excess of rain. A coherent form of zonal wind anomaly is noted when longitude height plots in the troposphere are combined.

In the last near thirty years period (1993–2021), a total of 9 years had both the drivers negative in JAS and suggested a deficit in rainfall (OND). More recently, that criteria occurred also in 2022 (JAS) and OND season was again associated with a deficit in rain. Following this analysis, it is also possible to deliver an estimation of cumulative precipitation in terms of median value, range and distribution of rainfall, one season in advance, at a point location or average over a region. This knowledge can be very useful for future prediction and preparedness/planning purposes, one season ahead.

Analyses on rainfall (OND) variability at intra-decadal, decadal and multi-decadal scales are studied applying the centered moving average method of 5-year, 11-year and 21-year respectively. ERA5 data for a longer period of 1940–2021 is averaged around a chosen box region [region A: 18° S-12° N, 25° E-52° E] to carry the analyses. A decreasing trend is noted in all situations and major peak and trough years are identified. For multi-decadal analyses, a shift at around 1958 is identified when the trend of OND rain is reversed and switched from increasing to decreasing.

The compositing technique is applied for a longer records (1940–2021) too and further classification of drivers, based on a threshold value (+0.4) is tested. As recent year 2023, JAS fell into the Case 4 situation, more analyses in such case are presented. For the Case 4 situation, we note if either of the drivers is weak positive and lies in the range 0 to +0.04, the signal in region A weakens substantially on the eastern side of the box. The strongest weakening happens when both the drivers are of low magnitude in JAS (i.e., between 0 to +0.4). These analyses, applying further classifications based on drivers in JAS, indicate directions of reducing uncertainty in prediction/outlook to a larger degree, and have enormous implications for future planning. The livelihood of millions of Africans can be improved and impacted.

CRediT authorship contribution statement

Indrani Roy: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. Alberto Troccoli: Formal analysis, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

This work was funded by the EU H2020 FOCUS-Africa project GA869575 (https://focus-africaproject.eu/). Some plots are generated using the web site of NOAA/ESRL, Physical Sciences Laboratory, Boulder Colorado at http://psl.noaa.gov/. The authors are thankful to two reviewers for their constructive comments that helped improve the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.169615.


