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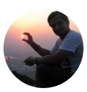

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Rainfall Characteristics over Togo and their related Atmospheric circulation Anomalies

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Abstract: This study attempts to reveal features of rainfall over Togo, in relationship to the prevailing atmospheric circulation. The study employed correlation analysis and composite analysis in the analysis of rainfall, sea surface temperature, wind, and humidity. Empirical orthogonal functions (EOF) analysis was employed in this study. The years: 1989, 1991, 1995, 2003 and 2007 were identified to be anomalously wet years while 1982, 1983, 1990, 1992, 2001 and 2006 fall in the anomalously dry years' category. The dominant mode of variability exhibits a dipole pattern, and explains 36% of the total variance. The rainfall was robustly correlated to Southern Atlantic Ocean Dipole (SAOD). The predominant wind flow over the country is westerly. Wet years were associated with anomalous low pressure area over Togo as opposed to the dry years which exhibited an anomalous high pressure area in the same region at low level. The results from this study provided basic climate information on Togo's rainfall. The SAOD can be further investigated of how it can be factored into seasonal rainfall forecasting over Togo. Accurate and timely rainfall forecasting will help to minimize the devastating impacts associated with anomalous rainfall in the region.

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1. Introduction

Togo is located in West Africa; it lies on the Atlantic coast of the Gulf of Guinea. The country is confined within longitude 0° - 2°E and latitude 6°N - 12°N (Fig. 1). The country stretches 600 km from north to south, and has an area of about 56,600 km^2. The country is bordered by Ghana to the west, to the north by Burkina Faso and Benin is on its east. The country's vegetation is mainly dominated by two savannah regions, divided by rolling southwest-northeast hills. The country's climate varies; it ranges from tropical to savanna. The country is faced with a number of challenges related to population growth, just like many other developing nations in Africa.

Rain-fed agriculture is the backbone of the Togo's economy, contributing approximately 45% of the country's Gross Domestic Product (GDP). The common extreme weather events in the region are droughts and floods (EM-DAT, 2010). The occurrence of droughts and floods is associated with devastating socio-economic impacts. To minimize these negative impacts, there is a need to understand the features of rainfall (RF) in Togo and their relationship with the atmospheric circulation anomalies. Studies (e.g. McSweeney et al., 2010; Adewi et al., 2010), revealed that the climate of Togo is influenced by the West Africa Monsoon (WAM). According to Adewi et al. (2010), northern Togo experiences a single wet season occurring between April and October.

According to IPCC (2007), there is general consensus that there will be an increase frequency or intensity of extreme weather and climate events owing to climate change. The anticipated changes are likely to cause profound impacts on both living things and property. This has led to understanding the changes in rainfall in different regions so as to devise effective adaptation measures. The West Africa region is no exception.

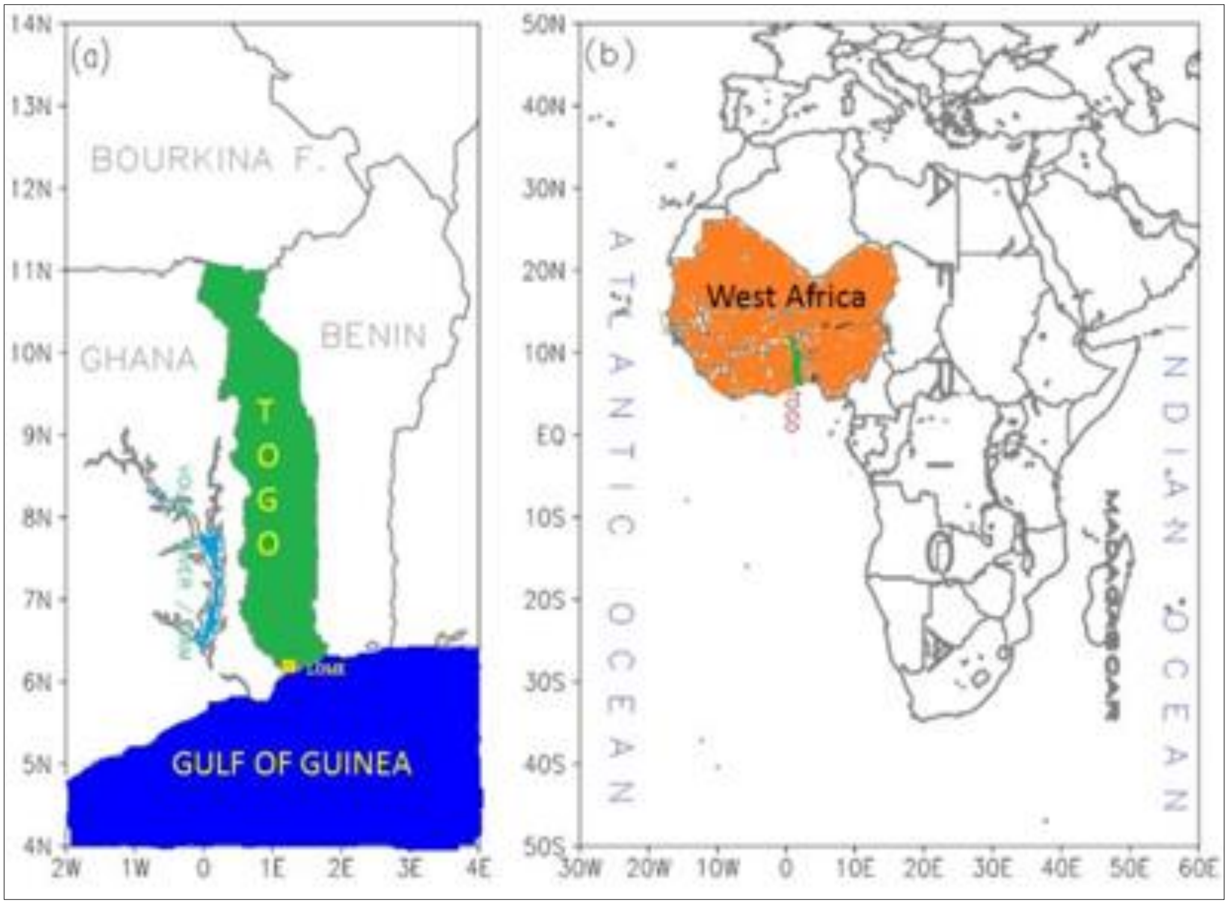

Fig. 1:Area of study; (a) Location map of Togo in West Africa (WA), (b) Location map of WA

Studies (e.g. Dai et al., 1998) have observed that on overall, areas of the world affected either by flood or drought have increased. The region is one of the areas that have recorded significant climate anomalies globally during the last century (IPCC, 2007).

On a regional scale, Togo's climate is influenced by large-scale air mass circulation over WA such as the Inter-tropical Convergence Zone (ITCZ), African Easterly Waves (AEWs), African Easterly Jet (AEJ), West African Westerly Jet (WAWJ) and Tropical Easterly Jet (TEJ) (Ghassan and Maloney, 2014; Berry et al., 2007; Reed et al., 1977; Skinner and Diffenbaugh, 2013, 2014). LeBarbe et al. (2002) and Nicholson and Grist (2003) gave details on the annual cycle of rainfall in West Africa (WA) using long-record surface gauge data from 1950 to 1990. They reported the existence of two rain seasons near the Gulf of Guinea during April-June and one single rainy season regime in the north around 10ºN during JAS. These studies suggest that rainfall dynamics near the Guinean Coast is associated with the continuous development of rain events from February to May.

The process evidently is associated with seasonal cycles in the tropical eastern Atlantic and North Atlantic Oscillation (NAO) which modulates convection and RF in the Gulf of Guinea by means of Sea Surface Temperature (SST) thermal forcing and SST-related meridional gradient. However, the effects of the various SST Anomalies (SSTA) types over WA are not uniform (Fontaine and Janicot, 1996; Nicholson and Webster, 2007). Nnamchi and Li (2010) observed a causal link between the air - sea phenomenon and Southern Atlantic Ocean Dipole (SAOD), and the interannual variability of precipitation over WA during the boreal summer monsoon rainy season. However, the complexity of the coincident SSTs phenomenon calls for continuous attention on how one can understand the way the global system and particular SST phenomenon interact to modulate the rainfall over Togo.

Table 1: Weather stations and their location details

Weather Station	Station ID	Latitude (°N)	Longitude (°E)	Elevation (m)*
Lome	65387	06-10	001-15	20
Tabligbo	65380	06-35	001-30	44
Kara	65357	9-33	1-1	341
Mango	65352	10-22	000-28	145
Dapaong	65351	10-52	000-15	330

*MASL:Meters Above Sea Level

The objective of this study was to investigate the rainfall characteristics; spatiotemporal changes in rainfall extremes over Togo and their related atmospheric circulation anomalies. The study will focus on temperature variations in the oceans, which consequently have effect on the West African monsoon (Xue et al., 2010), the region where Togo lies.

2. Data and Methodology

The study utilized both observed and reanalyzed rainfall data. Observed daily rainfall data was obtained National Meteorological Service Togo for 5 stations (Table 1). The data used in this study spans from 1981-2010. The reanalyzed monthly precipitation data spanning from 1981 to 2010 was obtained from Global Precipitation Climatology Centre (GPCC) gridded at a resolution of 0.5 degrees (Schneider et al., 2014). This is because the GPCC data has a long time series, with regular grid spacing. The rainfall data was only used to validate the reanalyzed data. The GPCC Precipitation data is provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/. The data was successfully used by Ogwang et al. (2015a) to diagnose of East African climate and the circulation mechanisms associated with extreme wet and dry events.

The circulation and moisture transport was computed from monthly ERA-Interim data obtained at European Centre for Medium Range Weather Forecasts (ECMWF) database. The data include zonal wind and meridional wind components, mean sea level pressure (MSLP), relative humidity (RH), Temperature (T) and pressure vertical velocity (omega). ERA-Interim is a reanalysis of the global atmosphere gridded at 0.75 degree resolution (Dee et al., 2011). The data has been used in the West Africa region by Xue et al. (2010) and found to present the rainfall pattern well.

May-October rainfall characteristics during wet and dry years were analyzed through composites calculated over a 30 year period. Composite analysis involves summarizing a meteorological element, where the composite is the mean of the elements averaged over a number of cases sampled out according to a certain similarity.

The study uses Empirical Orthogonal Function (EOF) method to identify the dominant modes of the inter-annual rainfall variability. The variability is analyzed based on seasonal mean data for the May-October seasonal rainfall. The EOF analysis involves computation of the Eigen modes for a correlation matrix based on the normalized rainfall data for each season for all grid points over Togo stacked into a single vector. Grid Assimilation Data Software (GrADS) version 1.8 was used. Lorenz (1956) gives a detailed discussion on EOF technique as well as Preisendorfer and Mobley (1988) and Bartlein (1982). The method has been successfully utilized in similar studies (e.g. Englehart and Douglas, 1985; Widmann and Schar, 1997).

Correlation coefficient was computed based on GPCC dataset and three indices: South Atlantic Dipole Index (SAODI), North Atlantic Oscillation Index (NAOI) and Dipole Mode Index (DMI). A good understanding of the features of rainfall over Togo is of value, particularly in the predicting the seasonal and interannual anomalies over the country and the West Africa region at large.

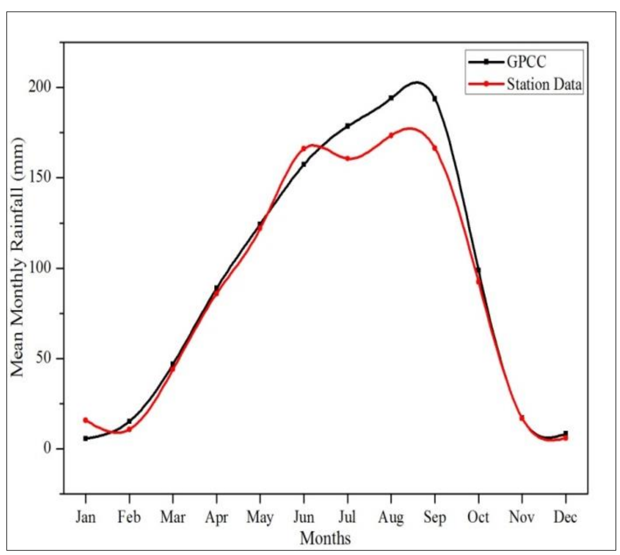

Fig. 2: Mean annual cycles of RF between 1981 and 2010 in Togo based on respectively GPCC and Observed Data.

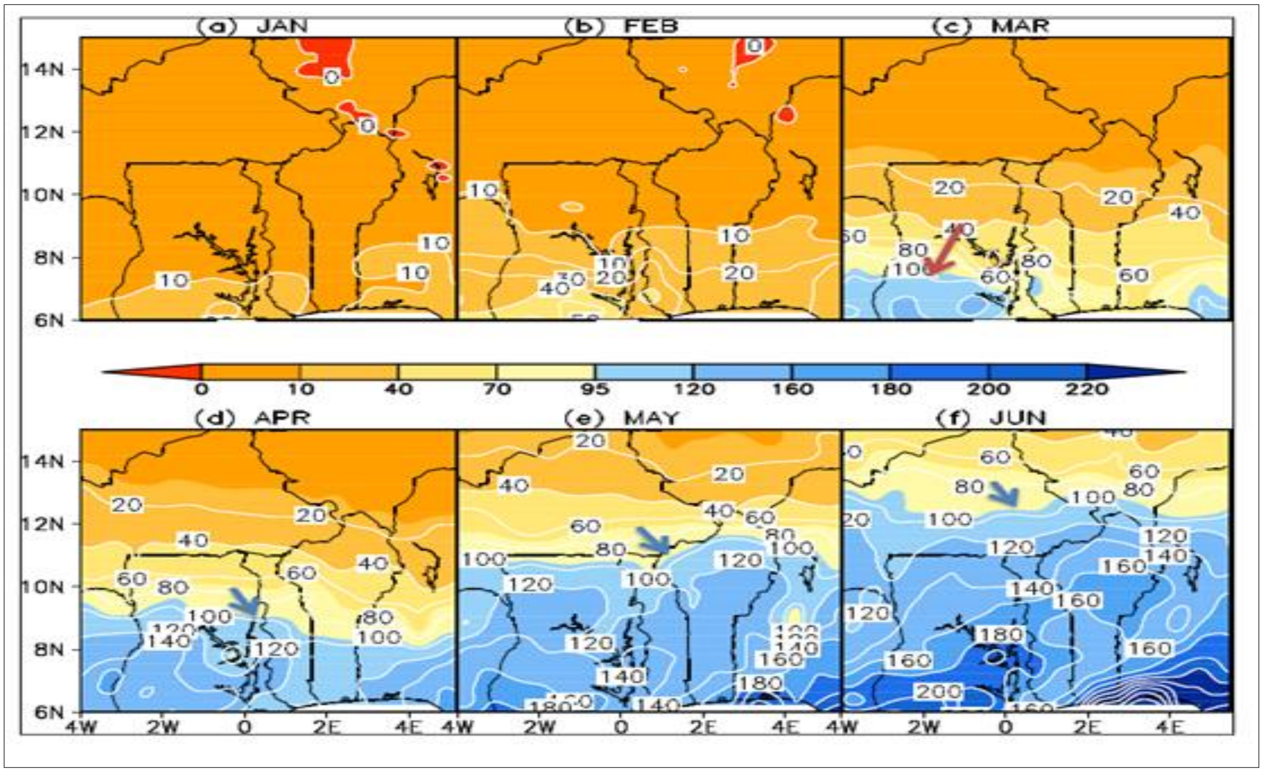

Fig. 3: Spatial Mean annual cycles of RF from January to June between 1981 and 2010 in Togo based on GPCC data; the arrow indicating the RF LTM = 95mm/month.

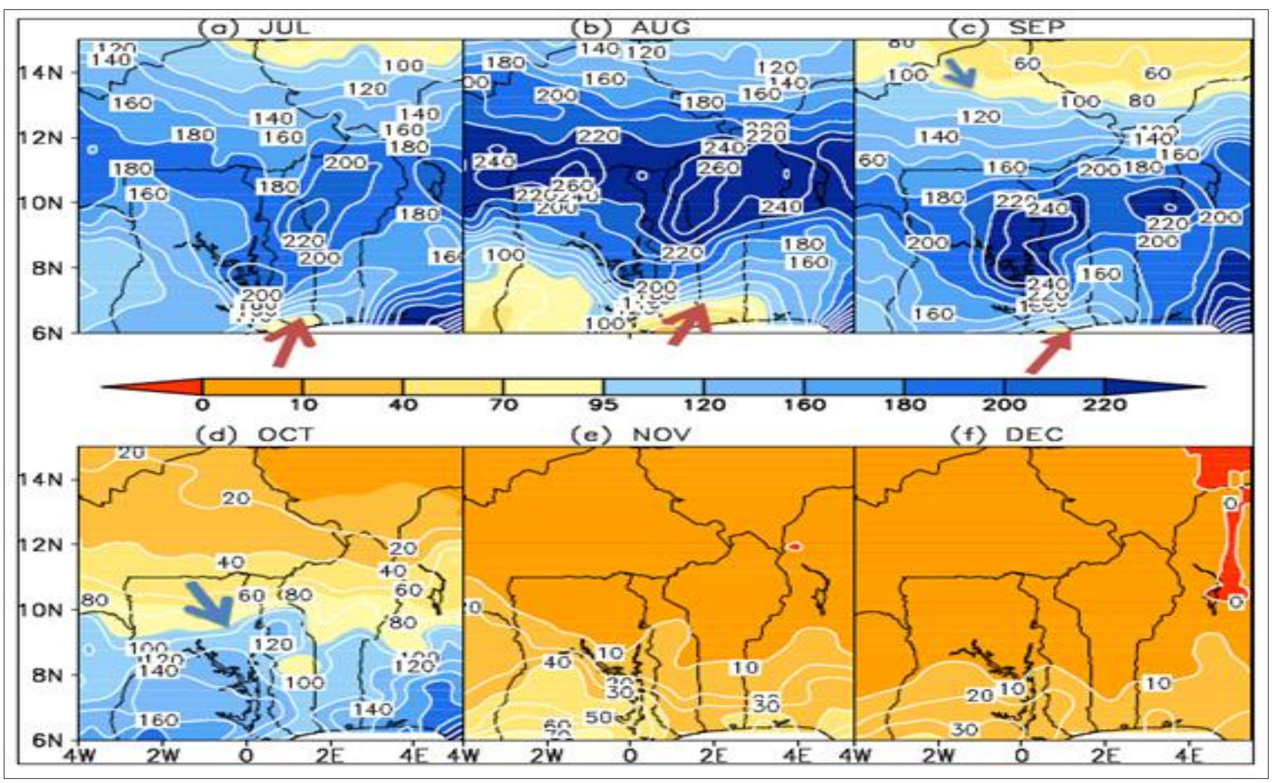

Fig. 4: Spatial Mean annual cycles of RF from July to December between 1981 and 2010 in Togo based on GPCC data; the arrows indicating the RF LTM = 95mm/month.

3. Results and Discussion

Togo receives rainfall during the months of April to October (Fig. 2). The two rainfall datasets: observed (OBS) and reanalyzed (GPCC) exhibit similar RF pattern and thus one dataset can be used in place of the other.

The observed rainfall cycle is linked to the seasonal march of the ITCZ. The ITCZ forms a region the hot and dry tropical easterly winds flowing in from the northeast meet with the air blowing from the Southern Atlantic Ocean. The convergence of the two is always linked to the onset of the monsoon. The same observation was made by (Sultan and Janicot, 2000).

According to the study, the maximum rainfall associated with West Africa monsoon is reported in the northernmost locations in August and then withdraws southwards during September, but continues to October. Xue et al. (2010) describes the months of June, July, August, and September as the major WAM season. On the other hand, LeBarbe et al. (2002) reported the annual rainfall over West Africa, distinguishing the southern and northern parts of the region. According to LeBarbe et al. (2002), there exists a two rain season regime near the Gulf of Guinea during April-June and one single rainy season regime in the north around 10ºN during July-August-September (JAS).

Monthly spatial RF climatology is presented in Fig. 3 and 4.The months of July-August are the wettest, while December-February are the driest. The observed average unimodal rainfall over the area of study can be attributed to the meridional march of the ITCZ.

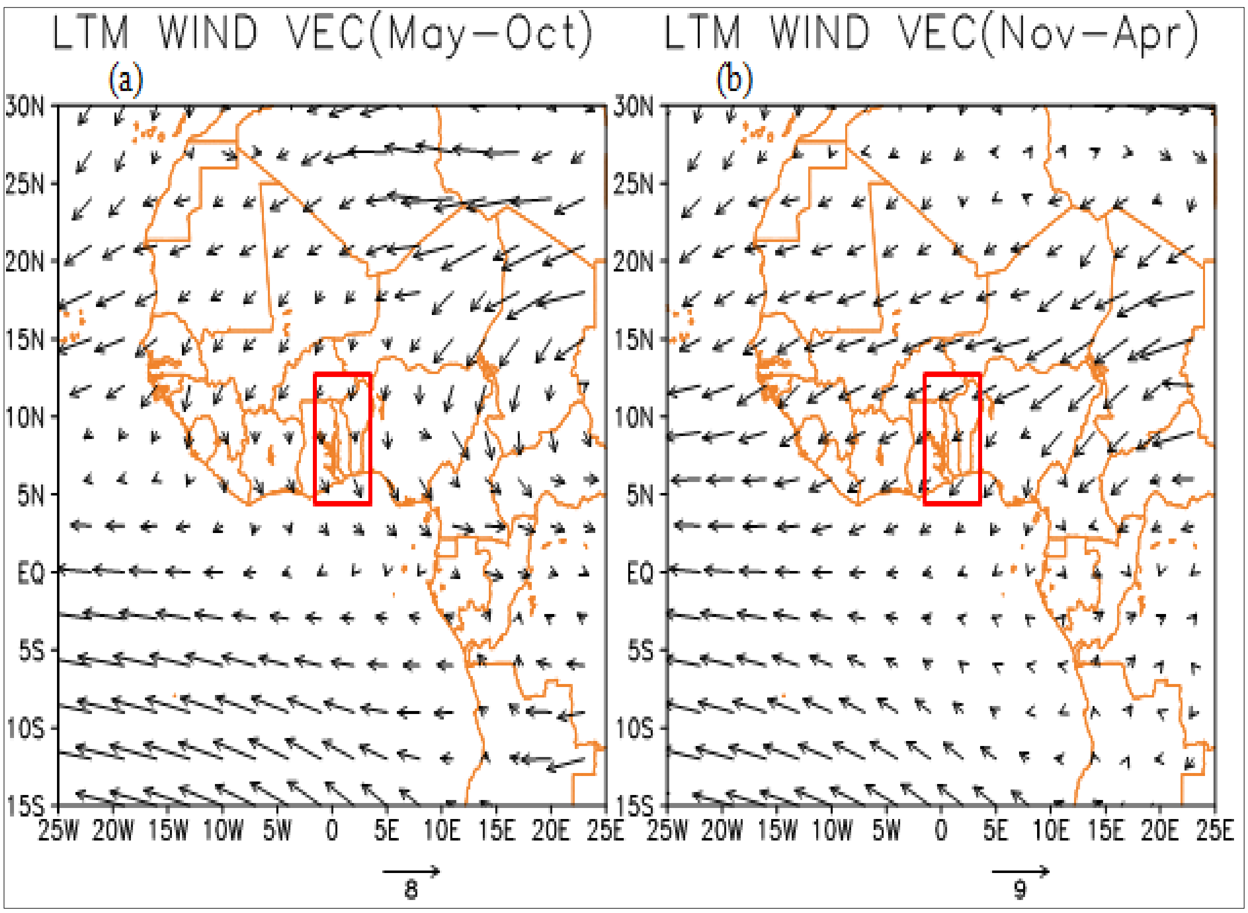

Fig. 5: Mean (May-October) wind vector (ms^{-1}) at 850mb over WA and AO based on ERA interim dataset. The red rectangle shows Togo country's location.

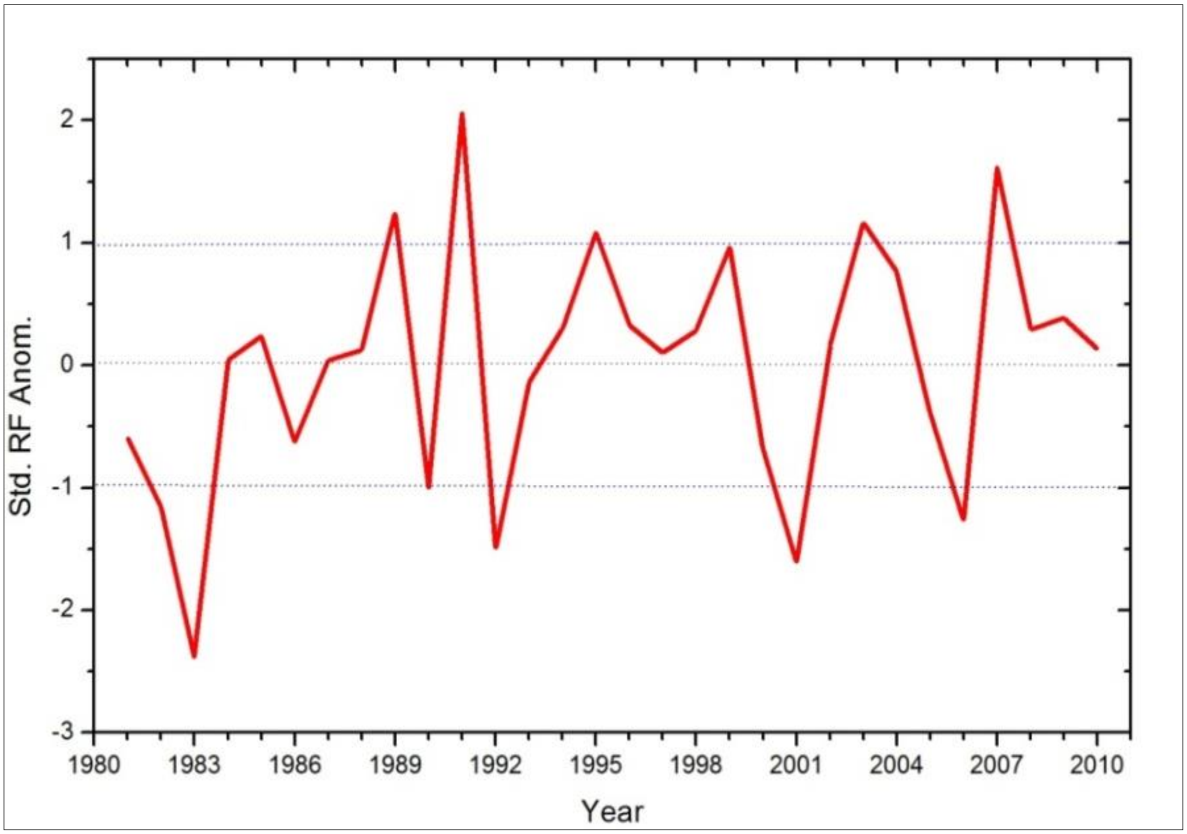

Fig. 6: The inter-annual variability of the standardized May-October RF anomaly over Togo

Wind circulation patterns over Togo presented in Fig. 5. During May-October, north-westerly wind is predominant over the country at low level. The periodic dry season easterly flow from Sahara desert dominates the country during the months of November to April (Fig.5b). The easterly flow is generally dry and dusty, explaining the little rainfall recorded during the period as compared to May - October.

Togo experiences high interannual rainfall variability. The time series of inter-annual variability of RF over Togo is given in Fig. 5. The study classified wet and dry years on the basis of the standardized rainfall anomaly being ≥ 1 and ≤ -1 for wet and dry years respectively. The same approach was successfully used by other authors (e.g. Tan et al., 2014; Ogwang et al., 2015b). The wet years were 1989, 1991, 1995, 2003 and 2007, while 1982, 1983, 1990, 1992, 2001 and 2006 were typical dry years.

The identified wet and dry years were considered as composite years in further analysis so as to understand the circulation anomalies associated with the extreme rainfall events.

The two dominant modes of variability EOF1 and EOF2 are presented in Fig.7. They explain 36% and 21.5% of the total variance of the mean May - October RF respectively. EOF1 (Fig. 7a) exhibits a dipole mode of variability, with positive anomaly over Togo and much strongest in the northern sector. EOF2 (Fig. 7b) similarly exhibits a dipole mode of variability, but with positive anomalies of RF much pronounced in the southern sector. The northern sector exhibits the negative anomalies of RF pattern. This mode has a great influence on the RF due to the fact that its frequency (21.5%) is closer the first mode of variability of RF (36%). Following the Nnamchi and Li (2010) the second mode of variability could be representing the influence of Southern Atlantic Ocean Dipole (SAOD).

The study presents two dominant modes of variability (Fig. 8). Generally, EOF1 exhibits the highest frequency of above normal variability occurrences.

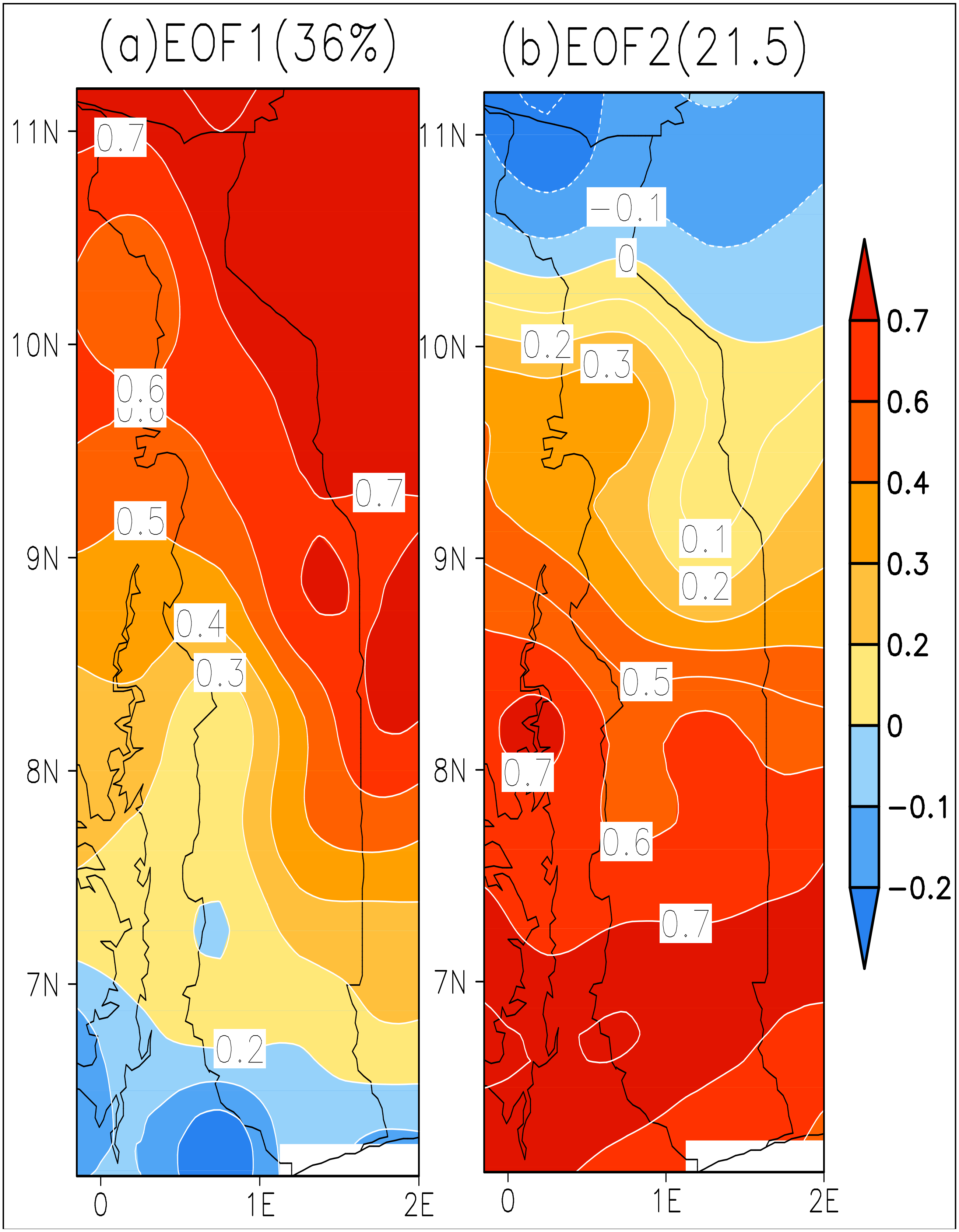

Fig.7. Two dominant EOFs, explaining 36% and 21.5% of the total variance of the mean May - October RF over Togo respectively

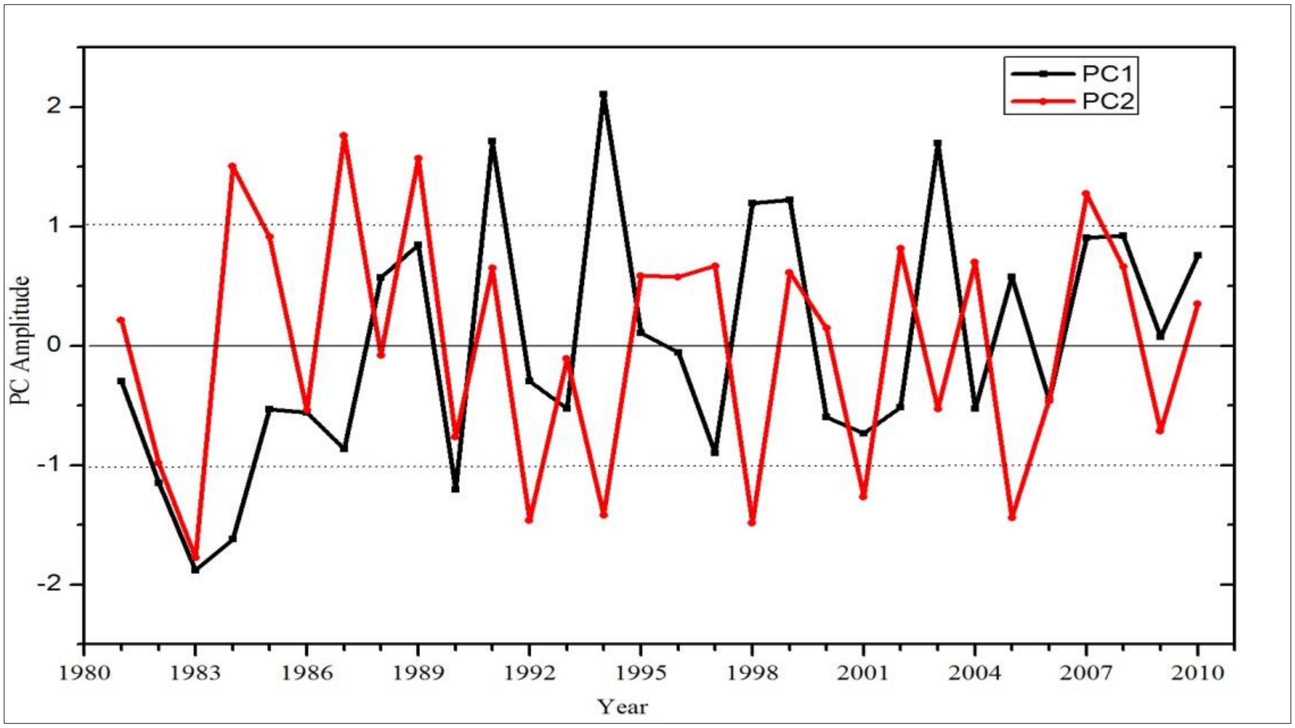

Fig. 8: Time series of the two modes of variability; PC1and PC2

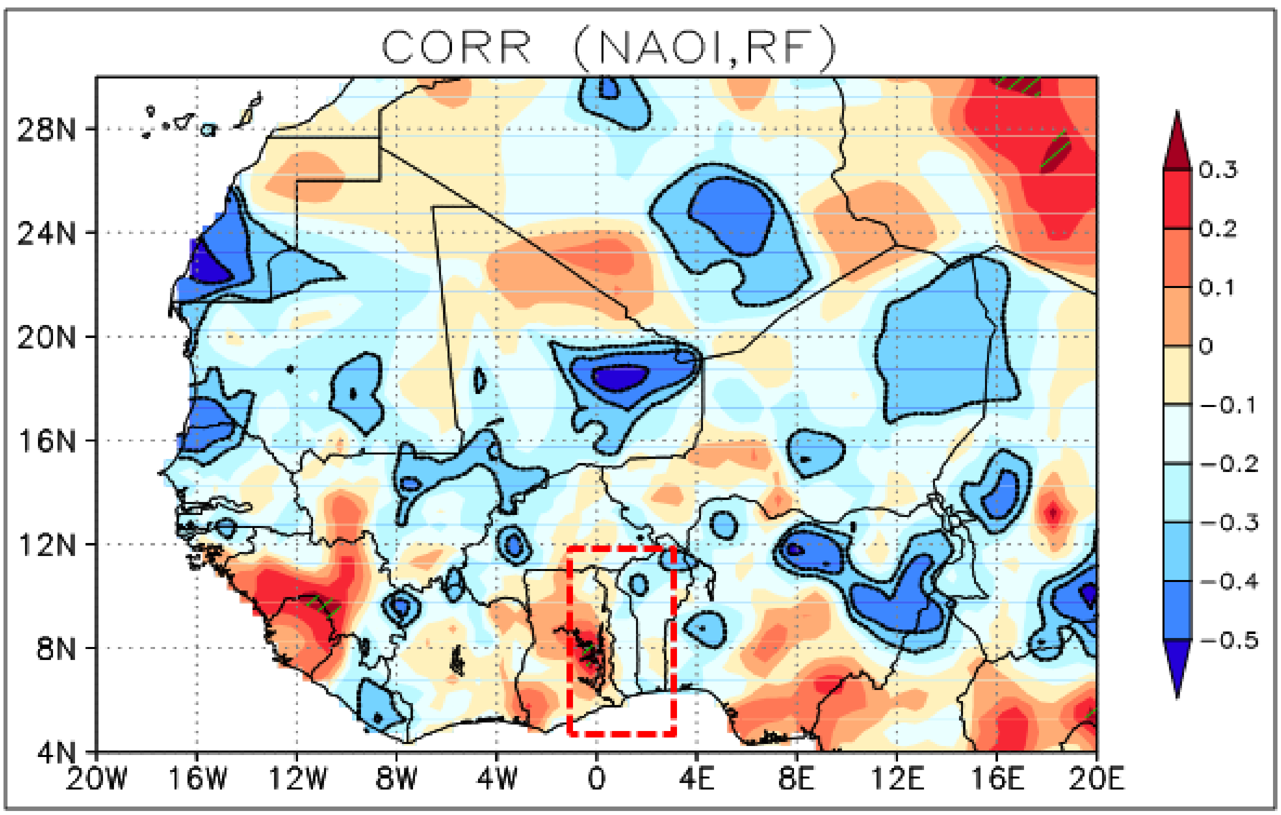

Fig. 9: Correlation map between NAOI and RF over Togo (Red rectangle), at 5% significant level (significance correlation is exhibited from a correlation coefficient equal or more than |0.3| and hatched line indicate positive correlation)

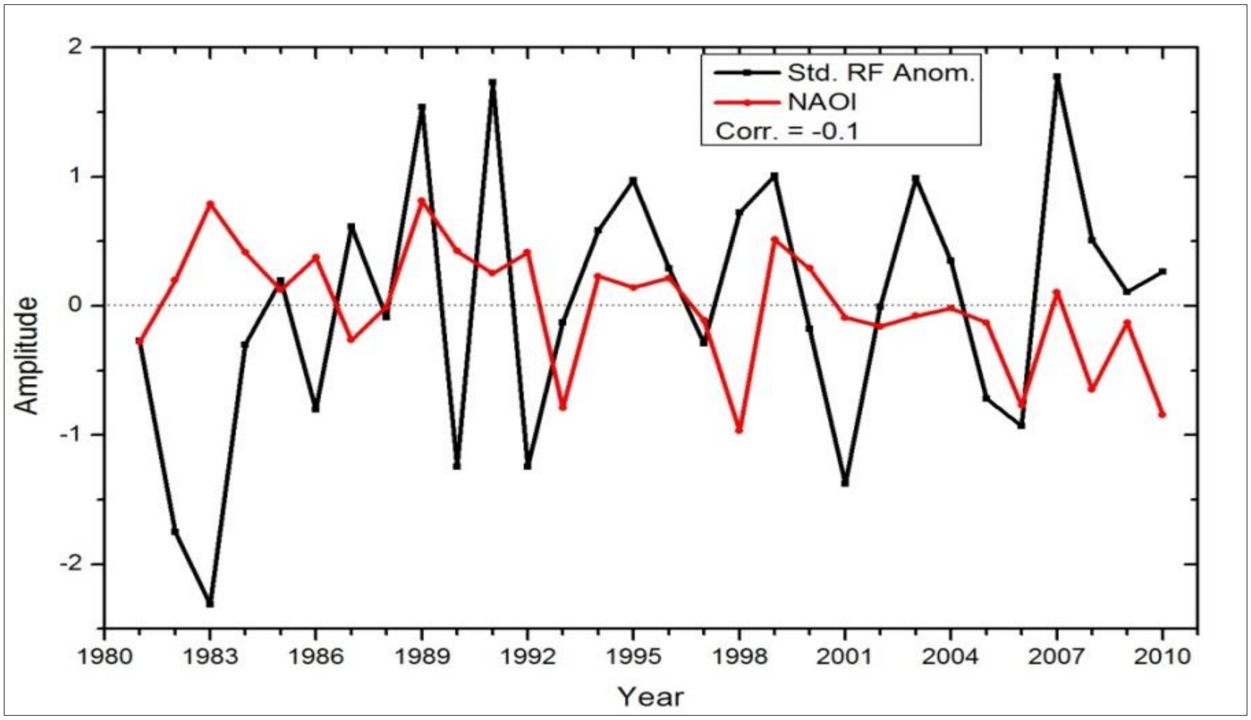

Fig. 10: Inter-annual variability of standardized May-October RF anomaly Togo and NAOI index over the period 1981-2010 (correlation between NAOI and RF is -0.1).

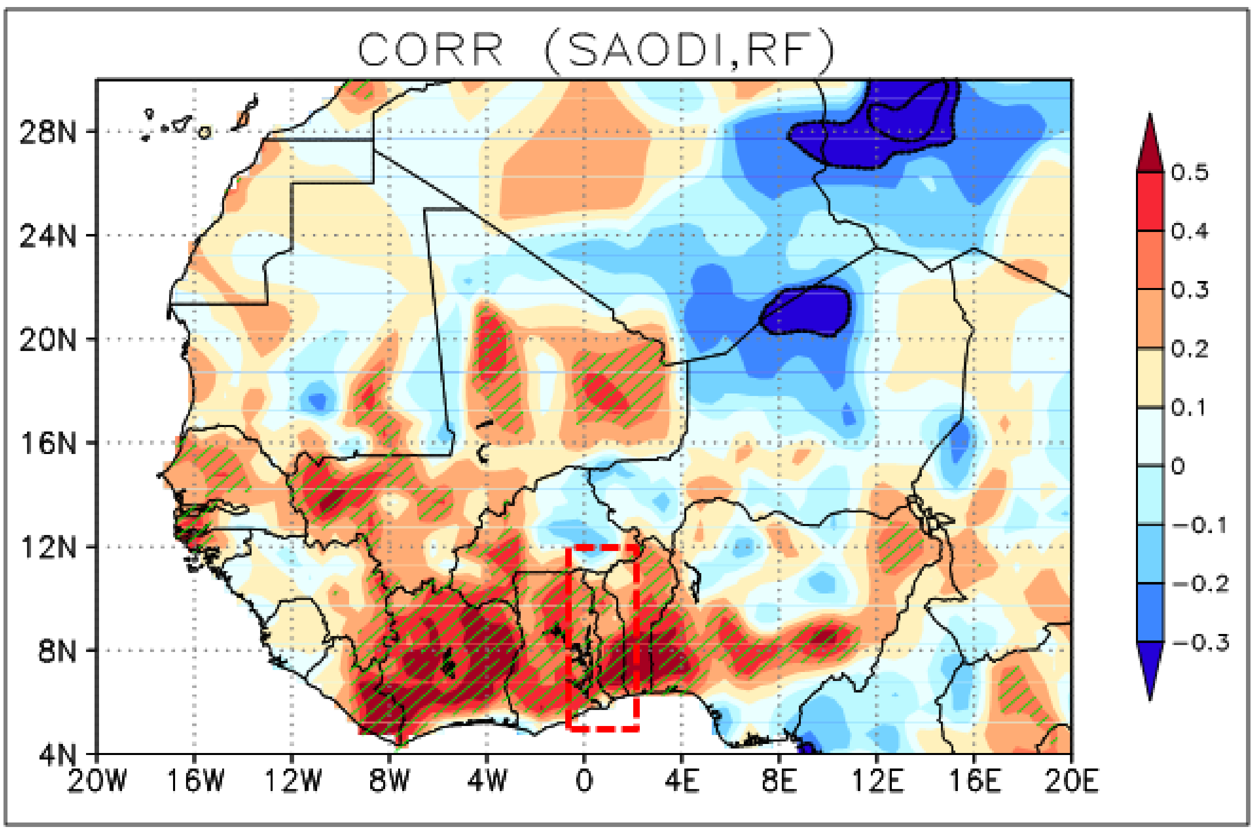

Fig. 11: Correlation map between SAODI and RF over Togo (Red rectangle), at 5% significant level (Significant correlation is exhibited from a correlation coefficient equal or more than |0.3| and hatched line indicate positive significant correlation).

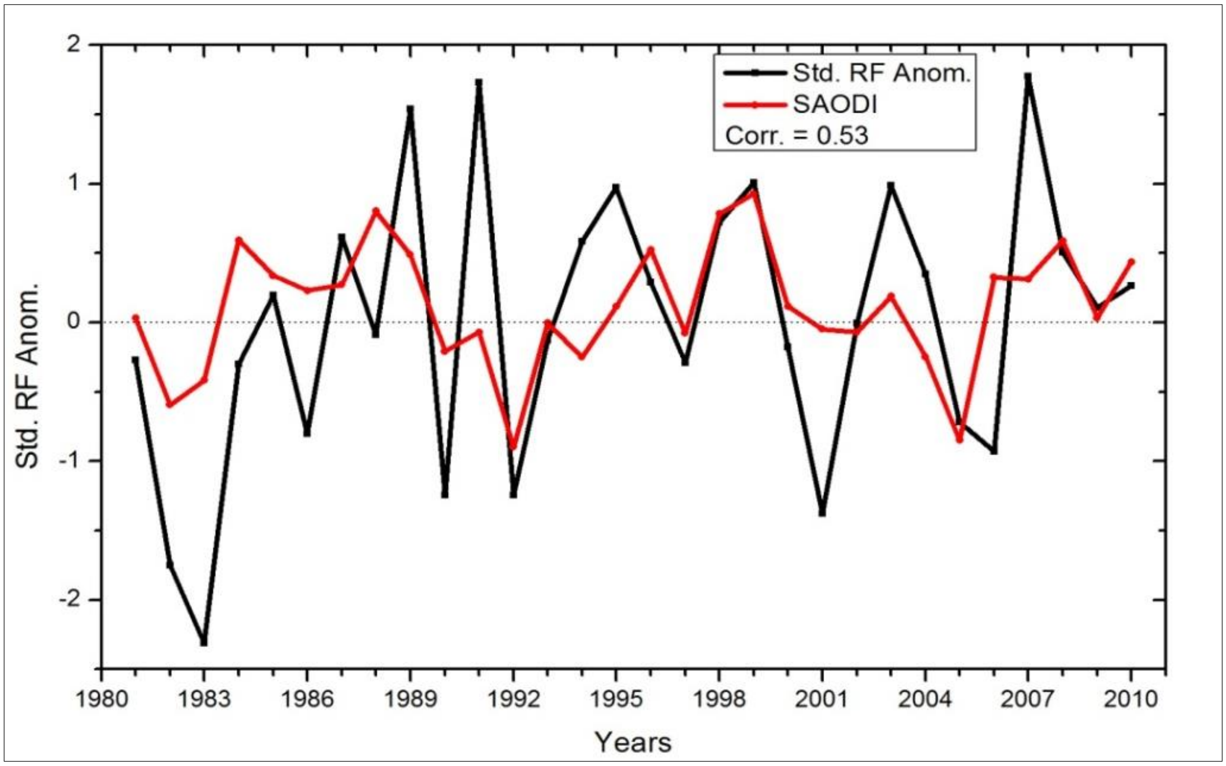

Fig. 12: Interannual variability of May-October standardized RF anomaly over Togo and SAOI over the period 1981-2010. There exists a high correlation of 0.53 between SAOI and area average RF anomaly over Togo.

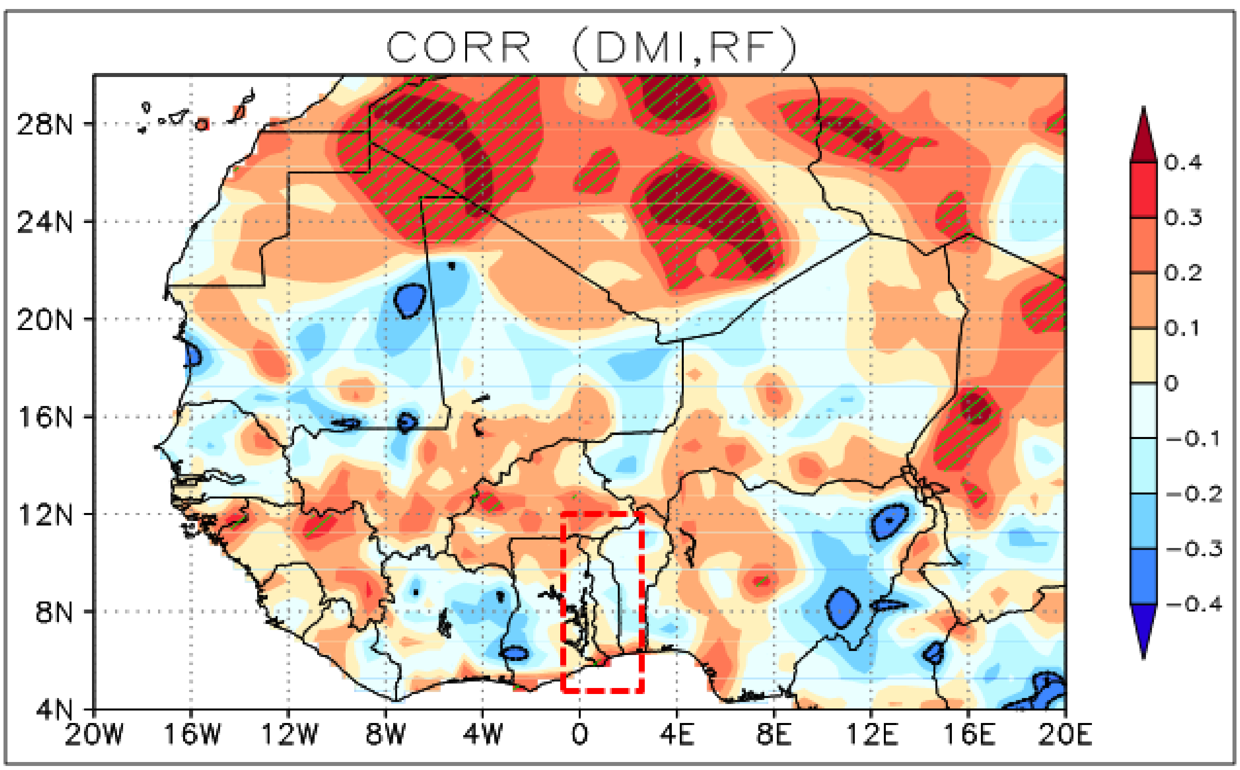

Fig. 13: Correlation map between DMI and RF over Togo (Red rectangle), at 5% significant level (Significant correlation is exhibited from a correlation coefficient equal or more than |0.3| and hatched line indicate positive correlation).

The spatial and temporal correlation map between RF over Togo and Northern Atlantic Oscillation Index (NAOI) respectively are presented in Fig. 9 and 10 respectively. There exist a weak and insignificant negative correlation between NAOI and RF. The correlation map between RF over Togo and Southern Atlantic Ocean Dipole Index (SAODI) is shown in Fig. 11. The correlation between the two is notably positive and significant.

The temporal correlation between SAODI and RF over Togo is given in Fig.12. The correlation between the two is 0.5, the country tends to receive little RF during the negative (-ive) phase of SAOD and enhanced RF during positive (+ive) phase of SAOD. The observation is in support of earlier observation by Nnamchi and Li (2010). According to their study, the relationship between precipitation of Guinea Coast and SAO SST variability is a stable dipole pattern. They further reported that during the positive phase of the SAOD, the imprint of SST gradients gives rise to divergence over the South West Pole (SWP) of the dipole, linked to convergence and vigorous upward motion over the North Eastern Pole (NEP) thereby leading to enhancement of precipitation over the Guinea Coast.

The correlation between RF and IO Dipole Mode Index (DMI) is presented Fig.13 and 14. There exists a weak correlation between the two. Thus during La Niña, Togo as well as most WA countries receive enhanced rainfall. Ashok et al. (2001) noted that negative correlation between Indian summer monsoon RF and El Niño can be deduced by the IOD during some decades. Similarly, Cherchi and Navarra (2013) showed that El Niño and positive IOD tend to co-occur.

The mean (May - October) sea level pressure anomaly (shaded) and the mean (May - October) 10m wind vector (arrow) anomalies over the region for wet and dry periods are given in Fig. 15. Analysis of surface 10m wind vector anomalies reveals that there is a negative pressure anomaly during wet years and the opposite during dry years. Such feature of pressure pattern increased southwesterly flow at the surface in wet years and northeasterly flow at the surface in dry years over Togo. In support of the observation, Nnamchi and Li (2010) showed that in wet years, there is the region of ascent over the GG at about 5°N and 1°E.The location is in the south coast of Togo and consequently, this may have a great influence on the RF in wet years over Togo. In fact with more intense Guinea Coast’s low and strongest high pressure at about 20°E, the pressure gradient over Togo will intensify the West-East jet steam leading to moisture transport over Togo. The increase moisture transport leads to increase RF as well.

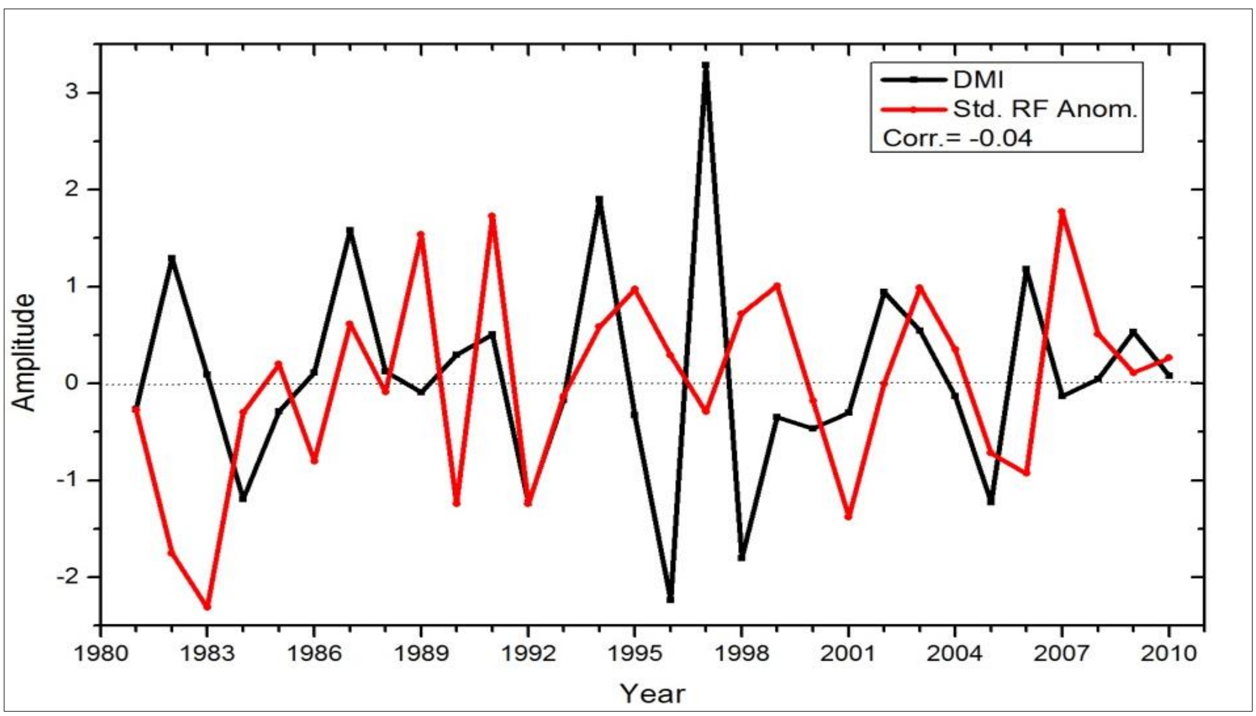

Fig. 14: Inter-annual variability of standardized May-October RF anomaly over Togo and IOD index during the period 1981-2010 (correlation between DMI and RF is -0.04).

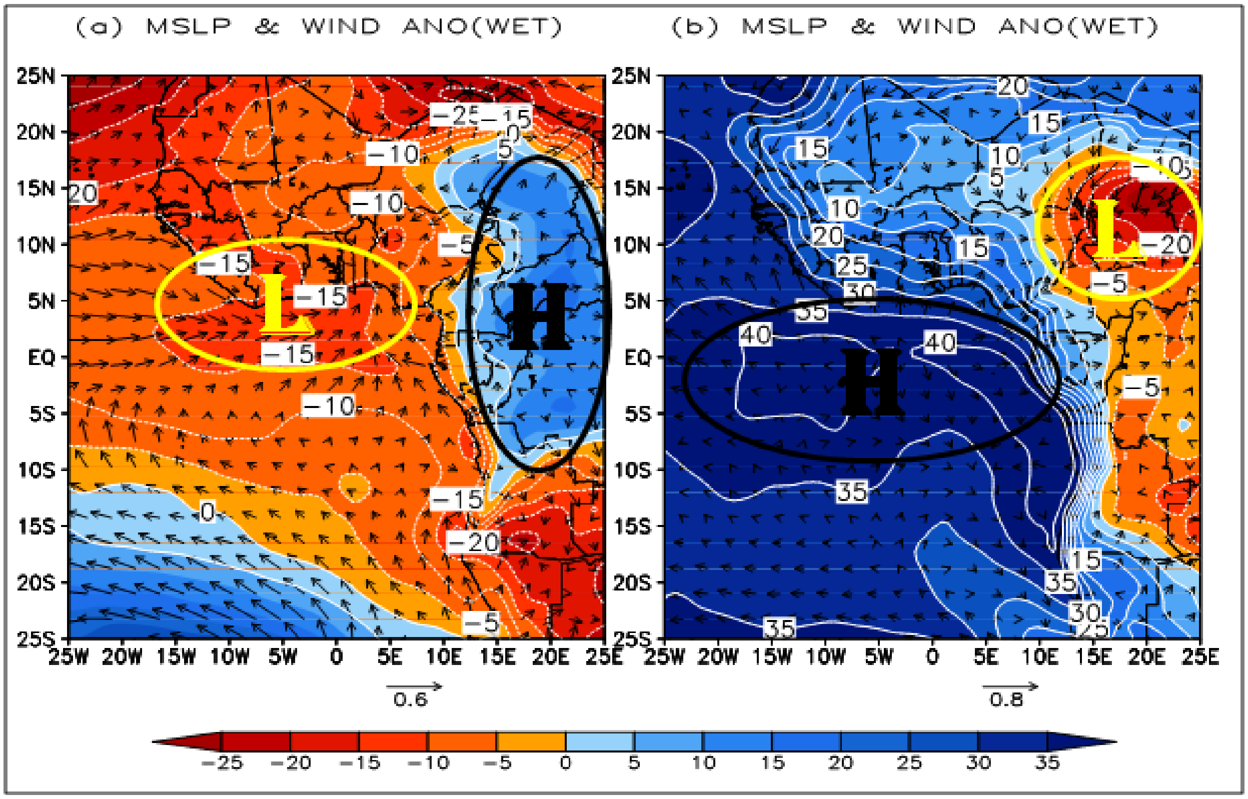

Fig. 15: The mean (May-October) sea level pressure anomalies (shaded) (hPa) and the mean (May-October) 10m wind vector (arrow) anomalies (ms^{-1}) over the Togo region (a) wet years, and (b) dry years; L denote low pressure center and H denote high pressure center.

Further examination of pressure vertical velocity (omega) was made to support the previous aforementioned predictability on the circulation mechanism. The analysis reveals that during the wet years, there was raising air motion south of 10°N over Togo but sinking in north of 10°N over the same area (Fig.16a). The rising motion is associated with convergence at low level and divergence at upper level. During dry years, sinking motion is observed over the area at about 850mb but below that level there was raising air motion which is suppressed by the sinking motion (Fig.16b). The sinking may be associated with convergence at upper level and divergence at low level.

Convergence at low level leads to vertical stretching, whereas divergence at low level results to vertical shrinking which suppresses convection due to subsidence (Barry and Carleton, 2003; Ogwang et al., 2014). For understanding the link between such mechanism and the RF over Togo, the study has already shown in the general characteristics that the maximum average RF during the study period was about 260 mm in the month of August (Fig.4b) and the core of this rain belt lidded over the mountain between 7°N and 10°N. Following the mechanism of atmospheric motion, the RF variability may be associated to anomalous high or low pressure over Togo. The study by Adewi et al. (2010) revealed that north of 10°N receive little RF. Current analysis of atmospheric motions over the area have shown that there is high pressure center over that area in wet years. Such condition explains the dry pattern of RF over north of 10°N in Togo and the neighboring countries of that region.

The moisture transport over Togo and the neighboring countries at 850 mb level is displayed in Fig. 17. The anomalous years of RF was used for quantifying the insight of moisture flux. The study has shown that wet years are dominated by anomalous moisture convergence at low level over the country (Fig.18a). During dry years, an anomalous moisture divergence (negative anomaly) is exhibited in the same region at low level (Fig. 18b). Such convergence in dry years could be explaining by the wind feature already mentioned in this study.

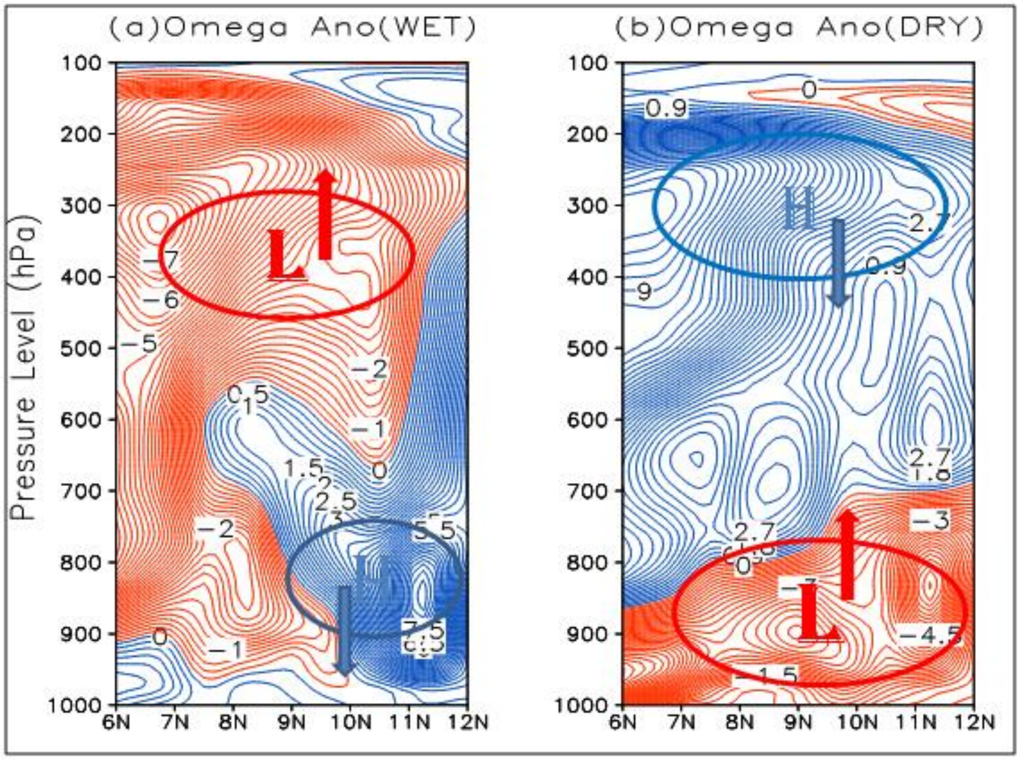

Fig. 16: The mean May-October omega (ω) anomaly ($10^{-3}Pas^{-1}$) over Togo at longitude 1ºE during (a) wet years (1989, 1991, 1995, 2007) and (b) dry years (1982, 1983, 1992, 2001, 2006). Arrows indicate high (blue, H)/Low (red, L) pressure centers and Sinking/Rising air motion.

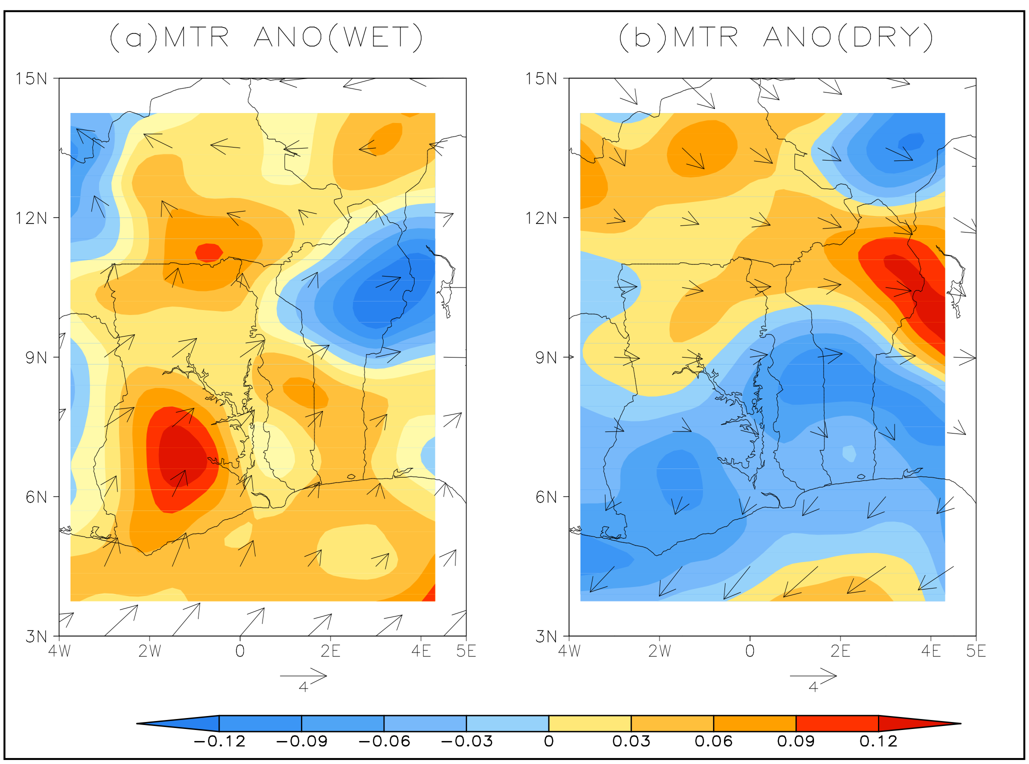

Fig.17: The mean May-October moisture transport (MTR) ($gKg^{-1}ms^{-1}$) at 850 hPa level over Togo during wet years (a) Dry years (b). Vectors show moisture transport, whereas the shaded regions indicate convergence (positive) and divergence (negative) of moisture fluxes.

4. Conclusion and Recommendation

This study examined the features of RF in Togo and their relationship with the atmospheric circulation anomalies. The country experiences unimodal rainfall pattern during the period of May to October. The years 1989, 1991, 1995, 2003 and 2007 were noted to have been wet years, while the years 1982, 1983, 1990, 1992, 2001 and 2006 were dry years. The core of the RF lay between 8-10°N. There was a general decrease in the mean May-October RF between 1981 and 1987. After that period, the RF maintained an increasing trend, with a little contrast explaining the periodical increase and decrease change in climate from 1994 to 2006. The mean May-October seasonal RF over Togo exhibits more or less a dipole mode of variability as noted in the first dominant mode of variability (EOF1), explaining 36% of the total variance.

The RF over Togo is insignificantly negatively correlated to NAOI and DMI. SAOD has a significant positive influence on RF over Togo. DMI and NAO were fairly negatively correlated to the RF. Wet years were associated with anomalous low pressure area over Togo's and the heat low in the north of the country, as opposed to the dry years which exhibited an anomalous high pressure area over Togo at low level. Vertical velocity analysis revealed that the region experiences rising motion during wet years, which is associated with convergence at low level and divergence at upper level. During dry years, sinking motion is exhibited over Togo. Wet years were dominated by anomalous moisture convergence at low level, particularly at 6mb between 8°N and 9°N. During dry years, anomalous moisture divergence is displayed in the same region. The results from this study provide basic climatic information on Togo's RF. The SAOD can be further studied of how it can be adopted as a predictor for seasonal forecasting of Togo's May-October RF to avoid the devastating impacts of extreme weather events in the region.

List of Abbreviations: AEJ - (African Easterly Jet), AEWs - (African Easterly Waves), DMI - (Dipole Mode Index), EOF - (Empirical Orthogonal Function), ECMWF - (European Centre for Medium Range Weather Forecasts), GPCC - (Global Precipitation Climatology Centre), GrADS - (Grid Assimilation Data Software), GDP - (Gross Domestic Product), ITCZ - (Inter-tropical Convergence Zone), JAS - (July-August-September), NAO -(North Atlantic Oscillation), NAOI- (North Atlantic Oscillation Index), SAODI- (South Atlantic Dipole Index), SAOD - (Southern Atlantic Ocean Dipole), SSTA - (SST Anomalies), SST - (Sea Surface Temperature), TEJ - (Tropical Easterly Jet), WA - (West Africa), WAM -(West Africa Monsoon), WAWJ - (West African Westerly Jet).

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Competing Interests: The authors declare that they have no conflict of interest.

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