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Investigation of the atmospheric circulation anomalies associated with extreme rainfall events over the Coastal West Africa

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Abstract

This study investigates the atmospheric circulation associated with extreme rainfall events over the coastal West Africa. The rainfall data of this study were obtained from the Global Precipitation Climatology Centre (GPCC), spanning from 1981 to 2010. The atmospheric datasets were also obtained from the ERA-Interim reanalysis. The study employed the Z-Index to categorize dry and wet years into seven distinct grades. The analyses focused on the summer monsoon rainfall season experienced in July to September (JAS). The extreme drought years were identified to be 1982 and 1983, while extreme wet years were pointed out to be 1999 and 2007. The area of study was dominated by anomalous westerly moisture transport, characterized by convergence at low level during wet years. The major source of moisture over the study area is Atlantic Ocean. Dry and wet years are characterized by positive and negative low-level geopotential height anomalies, respectively. Although the results of this study do not give a diagnosis of the reported rainfall variability, the information herein can be useful in the monitoring and update of seasonal forecasts. Accurate and reliable seasonal forecasting is beneficial in that it helps us minimize loss of lives and destruction of property.

Keywords: Drought, Rainfall, West Africa, Variability.

1. Introduction

West African Guinea Coast Countries (WAGCCs) located between latitude 5-15°N and longitude 9°W-9°E (Fig. 1) are strongly influenced by the West African Monsoon (WAM). The WAM is the seasonal reversal of wind between land and ocean that has strong rain effect at 10°N (Leonard and Matthew, 2014). The climate is tropical wet and dry, and this pattern defines the economy, agriculture and other sectors over the region (Gadgil and Rao, 2000; Sultan et al., 2005). However, despite the region's over-dependence on rainfall to sustain its economy, some of their aspects such as the inhomogeneity of seasons is difficult to understand. In particular, the diagnosis and prediction of flood and drought events over the region has not been well understood. This has left the socio-economic well-being of the region very vulnerable to the effects of extreme weather events: drought and floods.

Many studies have been conducted over the region on the rainfall dynamics (e.g., Nicholson and Webster, 2007; LeBarbe et al., 2002). According to the studies, the dominant wind direction in the regions on southern areas of 10°N is southwesterly; it is generally moist blowing from the Atlantic into the continent. On the other hand, in the northern areas of 10°N, the prevailing winds come from northeast, transporting hot and dusty air from the Sahara Desert, the two flows converge in the Inter-Tropical Convergence Zone (ITCZ) (McSweeney et al., 2010; Nicholson, 2008, 2009). The low-level easterly African jet-stream is considered to play a crucial role in the southwest monsoon of WAGCCs and forms the tropical waves which march across the tropical Atlantic and eastern Pacific oceans during the warm season.

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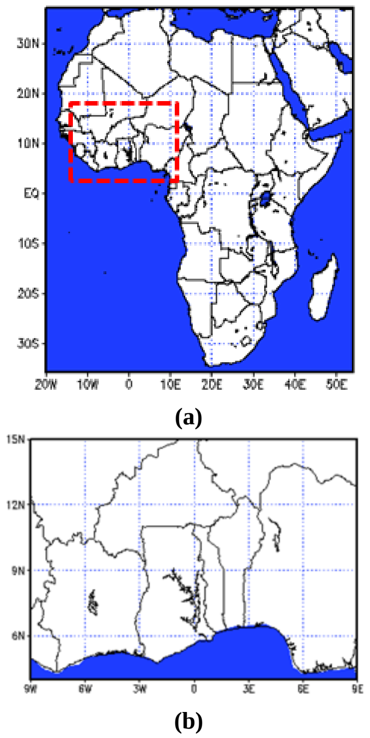


Fig. 1. (a) Map of Africa showing the location of the study area (red dotted rectangle), (b) the coastal West Africa.

The oceanic forcing plays a relevant role to determine WAGCCs rainfall variability on inter-annual and inter-decadal timescales (Folland et al., 1986; Cook, 2008; Rodriguez-Fonseca et al., 2010). The sea surface temperature (SST) anomalies in the Atlantic Ocean, namely Atlantic Niño and Benguela Niño events, explain the observed inhomogeneity in seasonal rainfall in the WAGCCs (Xie and Carton, 2004; Barreiro et al., 2004; Rouault et al., 2009; Polo et al., 2008; Keenlyside and Latif, 2007). A study by Hirst and Hastenrath (1983) showed that warmer SST in the south Atlantic is associated with enhanced rainfall over the Gulf of Guinea and the coast of West Africa. The earliest case study by Nnamchi and Li (2010) showed that Southern Atlantic Ocean Dipole (SAOD) mode remarkably controls the wet and dry spell in the region. McSweeney et al. (2010) attributed El-Niño Southern Oscillation (ENSO) to the observed climate variably in the study area. Other studies (e.g. Camberlin et al., 2001; Ward, 1998) studied El Nino events with dry events over the Sahel region. There is, however, a gap between the causes and atmospheric circulation patterns associated with extreme rainfall events over the West African region.

Koumare (2014) studied the spatial and temporal distribution of June-September seasonal rainfall over West Africa (0-20°N and 20°W-20°E), during 1960-2009. The study used Empirical Orthogonal Functions (EOF) to investigate the dominant modes of variability in rainfall. The study area was reported to be dominated by westerly and southwesterly wind anomalies at 850hpa level, especially during wet years and north easterlies during dry years. This research, however, recommended for further work based on numerical simulations to understand the physical mechanisms responsible for the observed results, assessing the relative contribution of each system.

A study by Rufus et al. (2013) that dwelt on troposphere circulation features during wet and dry years over West Africa called for further understanding of atmospheric circulation features. This was conducted by more upper-air data in the broad context of the full seasonal cycle of the region of West Africa. The study mainly used the NCEP reanalysis dataset (Kalnay et al., 1996).

This study aims at enhancing the understanding of atmospheric circulation anomalies associated with the observed climate variability over WAGCC, focusing on July-September (JAS) rainfall. The knowledge, especially on atmospheric circulations, will greatly help us improve the accuracy and timeliness of long range weather forecasting. The improved quality of weather forecasting can save lives and minimize destruction of property.

2. Data and Methodology

2. 1. Data

Reanalysis of monthly mean rainfall data were obtained Global Precipitation Climatology Centre (GPCC) for the period of 1981-2010. In the meridian and zonal winds, the temperature and relative humidity statistics used to determine moisture transport are used from the ERA-Interim data, gridded at 0.75° resolution (Dee et al., 2011). ERA-Interim data were obtained from European Centre for Medium Range Weather Forecasts (ECMWF) database. The ERA- Monthly averages of daily means are prepared for analyses (the average of the four main synoptic monthly means at 00, 06, 12, and 18 UTC). The instantaneous forecast data were used from the average of the four synoptic means at forecast steps of 6 and 12 hours from the forecasts initiated at 00 and 12 UTC.

2. 2. Methodology

2. 2. 1. Classification of floods and droughts

There are many indices and methods for drought and flood assessment that have been developed over the past years. The indices include Palmer Drought Severity Index (PDSI), used by Dai et al. (2004), and Standardized Precipitation Index (SPI), used by Bordi et al. (2001).

The Z-index has a set of regional flood/drought indices and a scheme for grading their severity as proposed by Tan et al. (2003). This Z-index is used in this study. This is mainly because of the numerous advantages including easy computation and large sensitivity. The indices not only clarify the different influences of varied grades but also recognize the effect of the normal grade on the regional severity. Furthermore, the numerically determined criteria are associated with the theoretical probability of the single stations, and so, the indices have less limitation to terrain properties.

The severity of the drought/flood events of each station of the study area was graded using single Z-index, given by Equation (1):

$$Z_i = \frac{6}{C_s}\left(\frac{C_s}{2}\phi_i + 1\right)^{1/3} - \frac{6}{C_s} + \frac{C_s}{6} \tag{1}$$

where C_S and ϕ_i are the skewness coefficients and normalized variables, where C_S is given by Equation (2):

$$C_S = \frac{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2}{n\sigma^3}, \quad \varphi_i = \frac{X_i - \overline{X}}{\sigma} \tag{2}$$

The climatic mean $\overline{X}$ and σ standard variance are determined from the expression (3):

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i, \sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2} \tag{3}$$

where X_i denotes the unprocessed variable. On the other hand, the wet/dry severity of the whole division/area of study was assessed in the context of the regional indices, given by Equation (4):

$$I_F = \frac{\left(\sum_{i=1}^{3} n_i/p_i + n_4^+/p_4\right)}{n}, I_D = \frac{\left(\sum_{i=5}^{7} n_i/p_i + n_4^-/p_4\right)}{n} \tag{4}$$

The Equation (4) gives the flood index, I_F, and the drought index, I_D, where p_i denotes the probability of grade *i*, p_4 is the probability of grade 4, n_i is the total station number of grade *i*, n_4^- is n_i but for grade 4 (normal grade) with negative anomaly, and n_4^+ is similarly for grade 4 but with positive anomaly. The contribution of a single station to the flood/drought severity of the whole area under study is in direct proportion to its statistical probability. Thus, the individual stations with smaller statistical probability have a great contribution to the regional disasters. This is the basis on which the indices are established (Tan et al., 2003). The severity grades and the corresponding standards are shown in Table 1.

2. 2. 2. Moisture transport and composite analysis

Composite analysis involves identification and averaging of one or more categories of the fields of a variable selected according to their association with key conditions. Results of the composites are then used to generate hypotheses for patterns which may be associated with the individual scenarios (Folland, 1983). In this study, the key conditions for the composite analysis are floods and droughts, where the composites for wet and dry years were separately conducted, especially for wind and velocity potential/ divergence. This is to detect the circulation anomalies associated with wet/dry events. A number of authors, including Tan et al. (2003), Okoola (1999), Ogwang et al. (2012) and Ininda (1995) have used composite methods in their analyses over the East African region.

3. Results and Discussions

The rainfall over WAGCC is characterized by a unimodal pattern; during the months May to October (Fig. 2). This is in agreement with previous studies such as Hamilton and Archbold (1945). According to Koumare (2014), monsoon onset in Sub-Saharan Africa occurs at the end of June and retreats southwards in September- October, following the movement of ITCZ towards the equatorial Atlantic Ocean. The location of the

ITCZ can increases precipitation; it forms a region of convergence in the northeasterly Harmattan winds of eastern equatorial in Atlantic Ocean. The winds from the ocean are mainly moist and thus can cause rainfall formation. However, LeBarbe et al. (2002) found the existence of two rainy season regimes near the Gulf of Guinea during April-June and one single rainy season regime in the north, around 10ºN during July-August-September. In the study, they reported that near the Guinean Coast, the rainfall dynamics is associated with the continuous development of rain events from February to May. However, the summer monsoon rain season is experienced in July-September (JAS).

Table 2 presents classification of years according to drought and flood severity using Z Index. The years 1982 and 1983 were identified as extreme drought years while 1999 and 2007 were in the extreme flood years. Further analysis of dry and wet years, however, considered both extreme and severe years of drought and flood, respectively. The identified years experienced extreme rainfall events (Janowiak, 1988; Rufus et al., 2013). Janowiak (1988) used standardized rainfall anomaly to identify extreme rainfall events, considering May - October rainfall over West Africa.

Analysis of the mean moisture transport over WAGCC shows that the region is dominated globally by a strong moisture convergence (positive anomaly) at low level (850 hPa; Fig. 3). However, some regions such as coastal areas, northern areas of Togo, West Niger and central Nigeria exhibit moisture divergence (negative anomaly). The predominant moisture transport is eastward and turning northward in the western side.

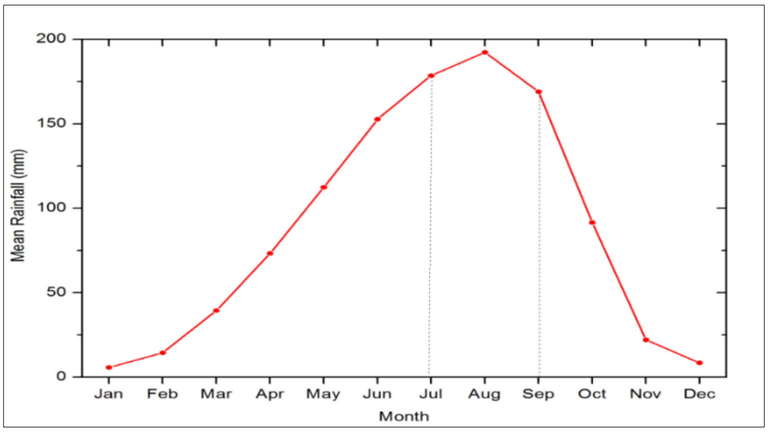


Fig. 2. The mean annual cycle of rainfall based on GPCC datasets, averaged over longitudes 9°W - 9ºE and latitudes 4- 15ºN for the period 1981-2010

Table 1. Standard for grading flood and drought based on single Z-index and the regional index

Sr. No.	Grades	Single Z-Index	Theoretical probability	Regional index
1	Extreme Flood	Z≥1.645	6.7%	$I_F - I_D \geq 1/p_2$
2	Severe Flood	1.0367 ≤ Z <1.645	10%	$1/p_3 \leq I_F - I_D < 1/p_2$
3	Mild Flood	0.5244<Z<1.0367	16.7%	$1/p_4 < I_F - I_D < 1/p_3$
4	Normal	-0.5244≤Z≤0.5244	33.3%	$-1/p_4 \leq I_F - I_D \leq 1/p_4$
5	Mild Drought	-1.0367<Z<-0.5244	16.7%	$-1/p_5 \leq I_F - I_D < 1/p_4$
6	Severe Drought	-1.645<Z<-1.0367	10%	$-1/p_6 < I_F - I_D \leq 1/p_5$
7	ExtremeDrought	Z≤-1.645	6.7%	$I_F - I_D \leq 1/p_6$

Table 2. Severe and Extreme Drought and Flood years

	Drought Years	Flood Years
	2009	1994
Severe	2001	1989
	1997	2008
Extreme	1982	1999
	1983	2007

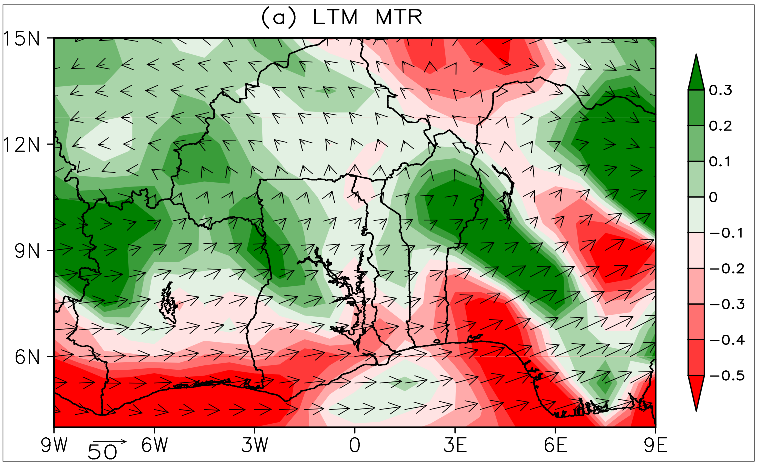


Fig. 3. The mean JAS moisture transport (MTR) at 850hPa in g $kg^{-1}ms^{-1}$ over West African Guinea Coast Countries (WAGCCs) is based on ERA interim dataset for the 30-year period. Vectors show moisture transport, whereas the shaded regions indicate convergence (positive) and divergence (negative) of moisture fluxes.

The analysis of moisture transport during wet and dry years is presented in Figures 4 and 5, respectively. Figure 4 reveals that during wet years the region is dominated by anomalous westerly moisture transport as mainly convergent movements and it exhibited by positive anomalies at low level (850 hPa). This is particularly predominant over 8°N. During dry years (Fig. 5), anomalous easterly moisture transport, weakly divergent at low levels, is exhibited in the study area. This is in agreement with the study carried out by McSweeney et al. (2010).

The observed westerly moisture transport during wet years and easterly transport during dry years suggest the source of moisture that lead to the observed rainfall. The westerly moisture transport is originated from Atlantic Ocean; it is generally warm and moist during JAS, causing the observed rainfall. The air flow from the east of the study area is mainly dry and dusty and, thus, associated with the dry years.

The wind flow over the study area is mainly westerly in the wet years, the opposite is observed during dry years. The observed wind flow is the major transport system for the observed moisture in Figures 4 and 5.

In support of the observations, Nicholson and Grist (2001) observed that well-developed equatorial westerlies is the key factor controlling the occurrence of the 'wet Sahel' mode versus the 'dry' mode. The study area lies partly in the Sahel region.

The mean JAS geopotential height anomalies at 850 hPa level for dry and wet years is displayed in Figure 7. The region experiences negative and positive geopotential height anomaly in low levels during wet and dry years, respectively.

The observed negative and positive geopotential high anomalies are associated with divergence and convergence at low levels, respectively. This can support the occurrence of dry and wet activities. This consequently results in the observed dry and wet years.

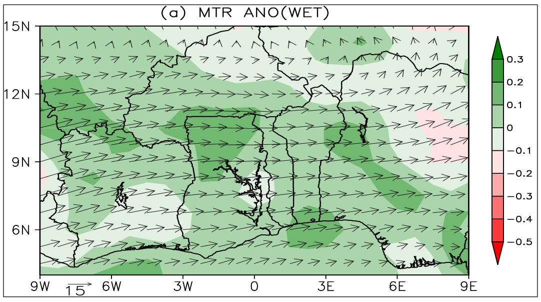


Fig. 4. The mean JAS moisture transport (MTR) at 850hPa in g $kg^{-1}ms^{-1}$over West African Guinea Coast Countries (WAGCCs) during wet years is based on ERA interim dataset. Vectors show moisture transport, whereas the shaded regions indicate convergence (positive) and divergence (negative).

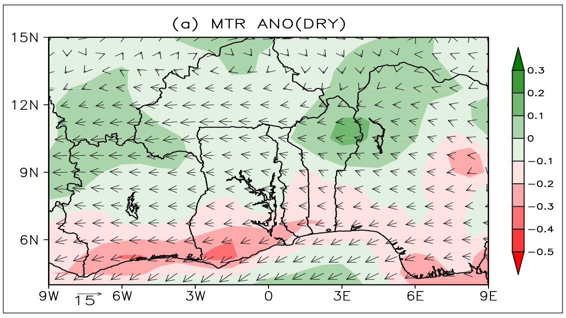
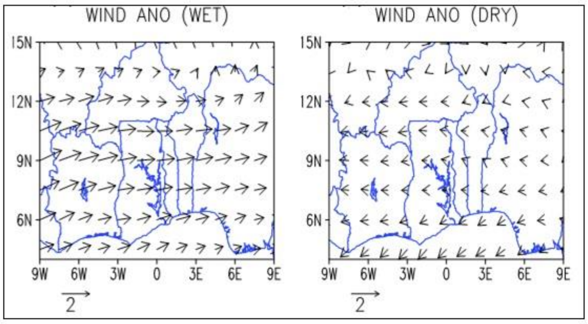


Fig. 5. The mean JAS moisture transport (MTR) at 850hPa in g $kg^{-1}ms^{-1}$ over West African Guinea Coast Countries (WAGCCs) during dry years is based on ERA interim dataset. Vectors show moisture transport, whereas the shaded regions indicate convergence (positive) and divergence (negative).



(a) **(b)**

Fig. 6. The mean JAS wind vector (ms^{-1}) anomaly at 850hPa level, for (a) wet and (b) dry years during 1981-2010

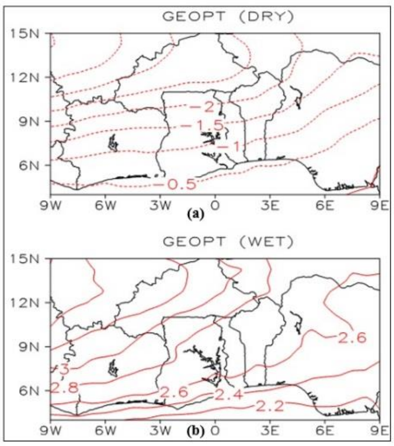


Fig. 7. The mean JAS geopotential height (m^2s^{-2}) anomaly at 850hPa level, for a) Dry years, b) Wet years during 1981-2010

4. Conclusions

This study has identified the atmospheric anomalies associated with rainfall variability over WAGCC. This focuses on the summer monsoon rainfall season experienced during July to September. The study identified the years 1982 and 1983 as extreme drought years and 1999 and 2007 were graded as extreme flood years. The area of study is dominated by mainly convergent anomalous westerly moisture transport at low levels. The major source of moisture leads to wet events is originated from the Atlantic Ocean. Dry and wet years are characterized, respectively, by positive and negative geopotential height anomalies at 850 hPa. Although the results of this study do not give a diagnosis of the observed extreme rainfall events, the information can be of great benefit if it is used to monitor the seasonal forecasts. This can greatly help us minimize the huge socio-economic losses associated with extreme weather events, especially in developing countries in the study area.

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