Temporal/Spatial Distribution of Rainfall and the Associated Circulation Anomalies over West Africa

Koumare, I.[1]

Abstract

The most important climate variable over West Africa is rainfall, where many sectors of the economy depend on water resources. In this study we investigate the temporal/spatial features of rainfall and the associated circulation anomalies over West Africa. The spatial and temporal distribution of Jun-Sept (JJAS or wet) seasonal rainfall over West Africa was analyzed during the period 1960-2009, inclusive. Empirical Orthogonal Functions (EOF) was used and the associated large scale circulation patterns analysed. The result from EOF analysis shows that the spatial distribution of rainfall during wet season is relatively uniform (EOF1), showing positive loadings in most parts of the study region, except southeastern part. The wet (dry) years of PC1 were identified as; 1961, 1962, 1964, 1965, 1967, 1988, 1994, 1999, and 2003 (1972, 1973, 1982, 1983, 1984, 1987, 1990, and 2002). Analysis of the wet and dry years with respect to the different variables including wind, velocity potential/divergence (convergence) shows that the wet (dry) years were associated with convergence (divergence) in the lower troposphere, (at 850hpa) and divergence (convergence) at the upper level (200hpa). This suggests rising (sinking) motion, especially over the study area. The study region is dominated by westerly and southwesterly wind anomalies vectors, especially during wet years at 850hpa and northeasterlies during dry years at 850hpa.

Key Words: Rainfall, circulation anomalies, West Africa.

Introduction

In West Africa, precipitation is characterized by seasonal movement of the Intertropical Convergence Zone (ITCZ). During boreal summer ITCZ moves northward and reaching near 20ºN, whereas in winter time, it is located along the Gulf of Guinea Coast. The ITCZ marks the convergence zone of moist monsoon air masses in West Africa originating from St.Helena anticyclone system and dry northeastern trade wind originating from the North African subtropical high, called Intertropical Discontinuity (ITD), (Nicholson 2008, 2009). The northward movement of the monsoon trough is often very variable, causing monsoon breaks with dry condition. During the northern summer time, the surface airflow is peaked by two (2) easterly jets, the tropical easterly jet (TEJ) and the African easterly jet (AEJ). The precipitation patterns over West Africa are experienced in the location of the monsoon Trough, (Nicholson 2008, 2009). The main factors that influence the precipitation distribution in West Africa are associated with sea surface temperatures (SST) in the Atlantic and the El Nino-Southern Oscillation (ENSO). In this framework El Nino events significantly correlate with dry events in the Sahel region (Camberlin et al.2001, Ward 1998). Hirst and Hastenrath (1983) showed that warmer SSTs in the south Atlantic corresponds to strong rainfall in the Gulf of Guinea and the coast, resulting in lower precipitation in the Sahel region from July until September, but no relation between Sahel precipitation and ENSO events, especially at a low-frequency scale. It is a clear response to SST variations in the Atlantic (Janicot et al .2001). Janicot et al.(2001) concluded that a complex influence of SSTs is responsible for rainfall patterns and trends in the Sahel at different frequency scales , including SSTs- ENSO in the Indian Ocean (Bader and Latif 2003) and the Mediterranean Sea (Rowell 2003). Furthermore, land – surface – moisture feedbacks play an important role (Paeth and Thamm 2007). The region of Sahel represents a transition zone between the wet climate of tropical Africa and the Saharan desert. The West African Monsoon (WAM) system is the dominant feature of the climate of this region, which is a recurrent low latitude large-scale circulation pattern ascending from the meridional boundary layer gradient of dry and moist

[1] koumareismahila@yahoo.fr
College of International Education, Nanjing University of Information Science & Technology, China.

static energy between the tropical Atlantic Ocean and warm sub-Saharan continent. The WAM system develops from April to October bringing the ITCZ, and associated rainfall maxima to their northernmost location in August. The analysis of daily rain gauge data performed by Sultan and Janicot (2000) and Le Barbe et al (2002) reveal that the intraseasonal migration of rainfall maxima is discontinuous and nonlinear process with three main phases:

i. The preonset or arrival of the Inter-tropical Front (ITF) at 15 ºN in May, bringing enough moisture for isolated convective system to develop over the Sahel;
ii. The onset which occurs at the end of June and corresponds to abrupt latitudinal at 5 ºN in May-June to another quasi-stationary location at 10 ºN in July-August, and
iii. The retreat of the ITCZ towards the equatorial Atlantic Ocean, which occurs in September – October.

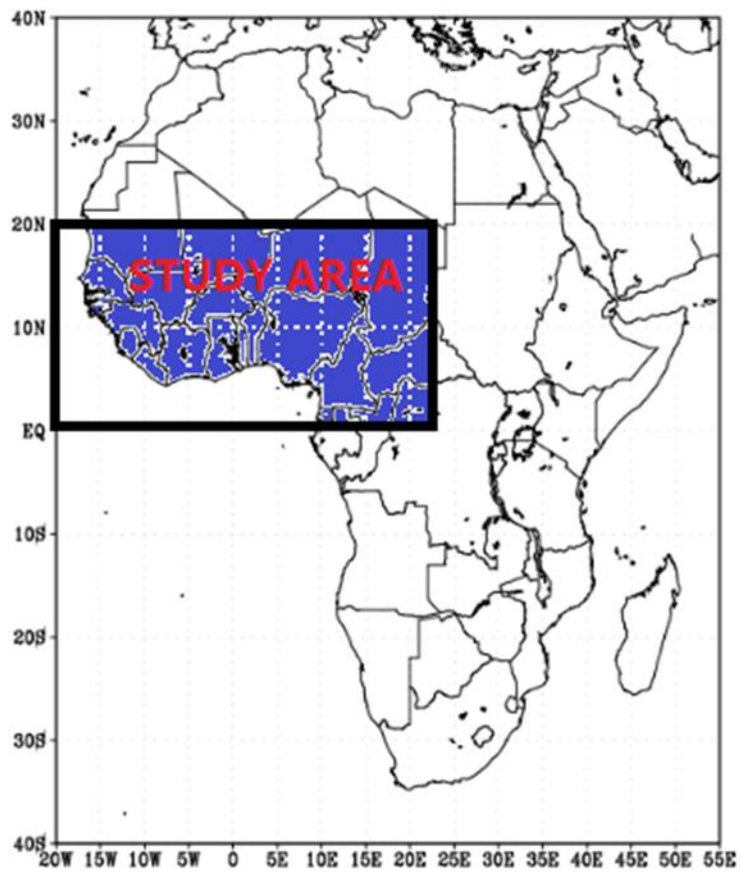

Figure 1: Map of the study area.

The study was carried out over West Africa between (0-20 ºN and 20 ºW-20 ºE). The study area can be identifying with blue color.

In this study we investigate the spatial and temporal features of the West African rainfall and the associated circulation anomalies. The next section provides the data and methodology used, section 3 gives the results and discussion, and summary and conclusion is provided in section 4.

Data and Methodology

Data

The data used in the study include; seasonal rainfall, Zonal and meridional wind, and the velocity potential.

Rainfall Data

Rainfall data used in this study were obtained from Global Precipitation Climatology Center (GPCC), version 5 (V.5), with a horizontal resolution of 2.5º *2.5º, with global grids 144*72. The dataset in this study is from 1960-2009 at monthly total precipitation. Datasets (U. Schneider and B. Rudolf 2008) of National Oceanic and Atmospheric Administration (NOAA), GPCC supports global and regional climate monitoring and research and is a German contribution to the World Climate Research Program (WCRP) and to the Global Climate Observation System (GCOS); its precipitation data are available for download free of charge from the NOAA's web site at http://www.esrl.noaa.gov/psd/ or from GPCC web portal at http://gpcc.dwd.de/.

NCEP/NCAR Reanalysis Data

The NCEP/NCAR project is a combined project between the National Centre for Environmental Prediction (NCEP) and the National Centre for Atmospheric Research (NCAR), (Kalnayet al.1996).The joint effort has produced atmospheric re-analyses using historical data from 1948 onward. This effort involves the recovery of land surface, ship, rawinsonde, aircraft, satellite, and other data sources. Quality control and assimilation of these data is the responsibility of NCEP/NCAR. These data are gridded to a horizontal resolution of 2.5º X 2.5º. The NCEP/NCAR reanalysis data used include the zonal and meridional wind components, and the velocity potential.

Empirical Orthogonal Function Analysis (EOF)

The Empirical Orthogonal Function (EOF) is used in the study to show the dominant modes of variability of June-Sept (JJAS) rainfall over West Africa. The data used is normalized in order to prevent areas and seasons of maximum variance from dominance of eigenvectors (Walsh and Mostek. 1980).The Eigenvector with the highest Eigen value is the first principal component of the dataset. The first eigenvector (EOF) points to the direction in which the data vectors jointly exhibit the most variability. The second structure is the pattern that describes the second largest amount of variance, calculated the same way as the first structure. Only the EOF was used in the study. A very important property of the second structure is that it is completely uncorrelated with the first structure, as well as all other following structures. The second eigenvector is perpendicular to the first eigenvector, which is perpendicular to the third eigenvector and so on.

This property is what led Lorenz 1956 to call the technique empirical orthogonal function analysis. The principal component analysis is quite possibly the most widely-used multivariate statistical technique used in the atmospheric sciences or in meteorology. Gregory et al. (1991) used the principal component analysis to divide the United Kingdom (UK) into nine regions of spatially coherent precipitation variability. The technique allows us to explain the variance-covariance of the data through a few modes of variability. The modes that account for the largest percent of the original variability are considered significant. These modes can be represented by orthogonal spatial patterns (Eigenvectors) and corresponding time series (principal components). Two modes are spatially and temporally uncorrelated due to the orthogonal nature of the EOF.

The orthogonal function of EOF is defined as follows:

$$z(x, y, t) = \sum_{k=1}^{N} PC(t) \times EOF(x, y) \tag{1}$$

Where $z(x, y, t)$ denotes the function of space (x, y) and time (t), therefore, EOF(x, y) represents the spatial structure in relation to temporal variation of Z.

Composite Analysis

The composite analysis involves identifying and averaging one or more categories of 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 typical years wet and dry of EOF1 PC time series (PC1) was used to investigate the composite analysis for different variable. The typical wet and (dry) years has been identifying like years of maximum values exceeding standard deviation of +1 include; 1961, 1962, 1964, 1965, 1967, 1988, 1994, 1999, and 2003,and (years exceeding standard deviation of -1 include; 1972, 1973, 1982, 1983, 1984, 1987, 1990, and 2002), respectively. The key conditions for the composite analysis are wet and dry, where the composites for wet and dry years were separately done, especially for rainfall, wind and velocity potential/divergence.

This is mainly to detect the circulation anomalies associated with wet and dry events, especially for wind and velocity potential. A number of authors, including Okoola (1999) and Ininda (1995) have used composite methods in their analyses.

Mann Kendall Method

For a series T_i, $i=1, 2, 3 \ldots n$, a rank-one statistic is constructed as in

$$S_k = \sum_{j=1}^{k} \sum_{i=1}^{j} R_{ij} \tag{2}$$

Where

$$R_{ij} = \begin{cases} 1 & T_i > T_j \\ 0 & T_i \leq T_j \end{cases} \tag{3}$$

with the assumption that S_k observes the identical distribution at any time, the statistic can be defined as

$$U_k = [S_k - E(S_k)] - sqrt(Var)(S_k) \tag{4}$$

Where $E(S_k) = \frac{k(k+1)}{4}$ i.e.$Var(S_k) = k(k-1)(2k+5) - 72$

Run computation for the statistic U_{2k} following the temporal sequence of T_{2i} and the result is denoted as *UF*. Then, rerun the computation following the sequence of $i=n,n-1,\ldots 1$ and denote the result as *UB*. *UF* intersects *UB* between lines of confidence before the *UF* line surpasses it. The intersected point is considered where the abrupt change has taken place. In addition, phases of rainfall rise and fall can be divided according to the meaning of U_k itself. During the rising phase of *UF*, $T_i > T_j$ when the event of $T_i > Tj$ goes mainly and the *UF* line goes outside of the confidence line, it is implying that such dominance has grown to a level that would never have reached with random settings. Phases like this can be taken to be flood. Drought phases can also be determined in same way. Liang Jian Yin and Wu Shang-sen (2000) used this method for analysed of monthly minimum temperature in Guangdong.

Student's t-test (Difference of Means)

Student's t-test is a method used in statistics to determine the probability (P) between two samples variables. So student's t-test is one of the most commonly used techniques for testing a hypothesis on the basis of difference between sample means. The calculated mean and standard deviation may deviate from the "actual" mean and standard deviation only by chance. For example, it is likely that the true mean of the observed precipitation at station A is "close" to the mean calculated from a sample of N randomly collected rainfall observations at a particular station. The null hypothesis for all tests is that 'the selected composite means (for certain conditions – i.e. based on climatic events and circulation types) are not significantly different from the long-term means (of the entire data)'. The null rejected hypothesis will be if P (probability that the mean difference is a result of chance) is "small" (Dambul, 2005).

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\left(\frac{n_1 S_1^2 + n_2 S_2^2}{n_1 + n_{2-2}}\right)\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \quad (5)$$

Where $\bar{X}_1$ and $\bar{X}_2$ are the means of samples *1* and *2*, n_1 and n_2 are the corresponding sample sizes of samples *1* and *2*, S_1 and S_2 are the standard deviations of samples *1* and *2*, respectively. (Beri, 2005).

Results and Discussion

In this section the results obtained from different methods that are presented and discussed.

Empirical Orthogonal Function (EOF) Analysis

Spatial and Temporal Patterns of JJAS rainfall over West Africa from 1960-2009 inclusive

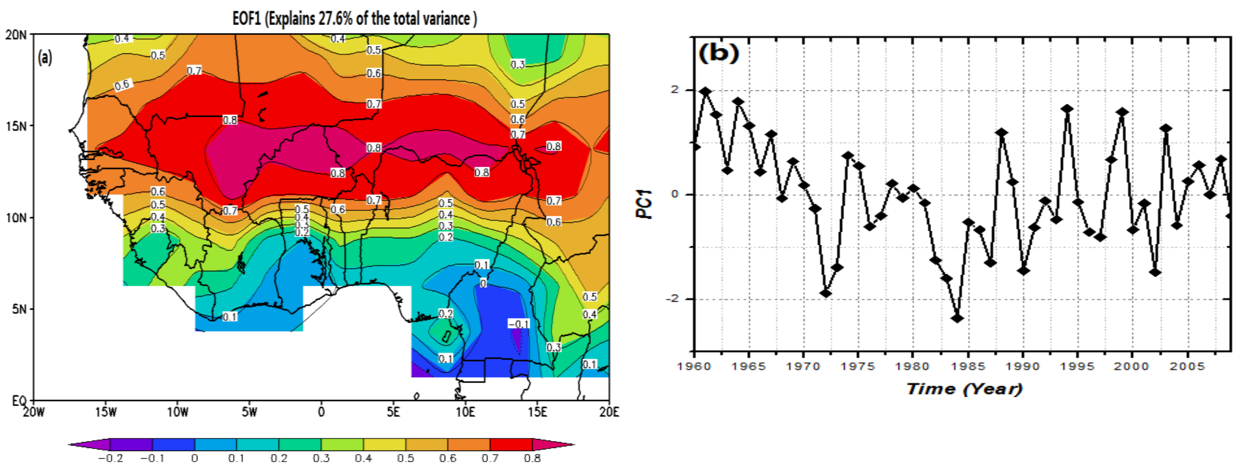

Figure 2: (a) First EOF spatial mode, EOF-1 (explains 27.6% of the total variance) of JJAS rainfall **(b)** its corresponding PC (PC1).

The spatial component, Figure.2(a) shows the pattern of the first eigenvectors (EOF-1) of JJAS seasonal rainfall, showing positive loadings throughout the study area, except a small portion of the southern part, which displays negative loadings between (3 ºN, 4 ºN and 14 ºE, 15 ºE), with the highest loadings concentrated over Sahel region of the study region, maybe due to influence of the West Africa Summer Monsoon (WASM), according to (NNAMCHI and Li, 2011), the mainly interannual variability of rainfall in the Sahel region is WASM. They found that correlation between precipitation anomalies and WASMI over West Africa, were significant in the Sahel region. Figure 2(b) on the other hand shows the EOF-1 time series (PC1). Years of maximum values exceeding standard deviation of +1 include; 1961, 1962, 1964, 1965, 1967, 1988, 1994, 1999, and 2003, which correspond to wet years and those years exceeding standard deviation of -1 include; 1972, 1973, 1982, 1983, 1984, 1987, 1990, and 2002, which, they are considered dry years.

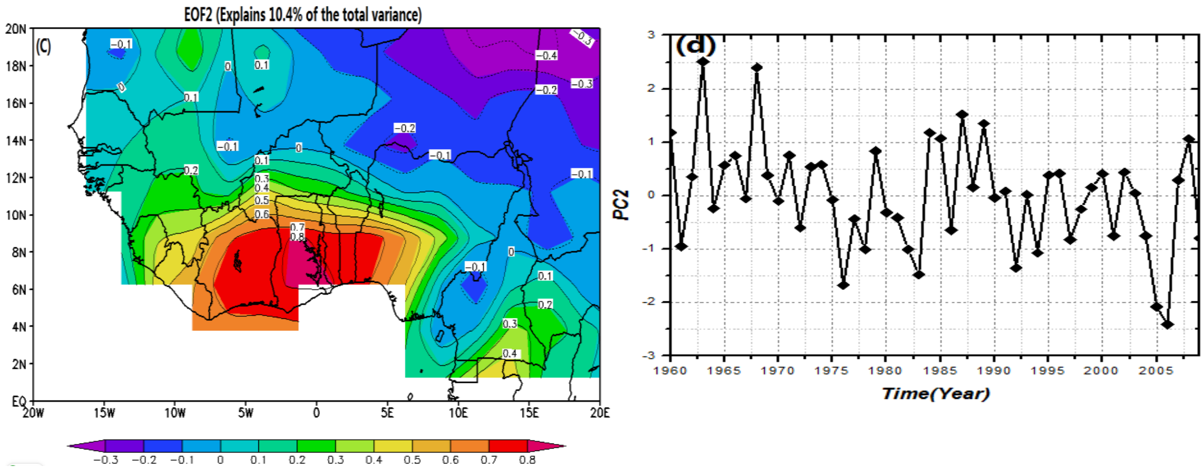

Figure 3: (c) Second EOF spatial mode, EOF-2 (explains 10.4% of the total variance) of JJAS rainfall **(d)** its corresponding PC (PC2).

The second mode (EOF-2), which carries 10.4% of the total variance, is characterized by significant eigenvector loadings over Guinea Coast, with strongest positive loadings over Guinea Coast, probably due to variability of South Atlantic Ocean Dipole (SAOD). According to a study by (NNAMCHI and Li, 2011), it is found that correlation between precipitation anomalies and

SAODI over West Africa, and were significant over Guinea Coast. The northeastern region exhibit highest negative loadings. Figure 3(d) on the other hand displays the EOF-2 time series (PC2). Years of maximum values having a least standard deviation of +1 as 1960, 1963, 1968,

1984, 1985, 1987, 1989, 2008 and those with a least standard deviation of -1 include; 1976, 1978, 1982, 1983, 1992, 1994, 2005, and 2006.

EOF-3 on the other hand (Figure omitted) explains 7% of the total variance of seasonal JJAS rainfall, with varying spatial and temporal patterns.

Mann-Kendall Analysis

The results obtained from Mann-Kendall trend test of PC1, the UF line remains above zero until1962 and keeps falling until exceeding the line of critical values in 1970 (Figure 4(a)).It is implying that such the precipitation has been decreasing since 1963's. Additionally, the UF line intersects UB line in 1966. It is concluded that the EOF-1 time series of PC1 over West Africa since 1967 has started dry event and sudden change took place in 1966.

In PC2 (Figure 4(b)), the UF line remains above zero from 1963 to 1971 and keeps crossing until above the line of critical values in 1983. Further, the UF line intersects UB line over 1975~1979, 1984~1991, and 1993~2001. It's evident that the time series of EOF-2 (PC2) over the region since 1963 until 1971 have been were considered flood years over the study area, and intersects years are taken to be abrupt changes points.

Spatial Rainfall Distribution of Wet and Dry Events

Figure 5 shows the composite rainfall anomalies of (a) wet years (b) dry years. In order to display the contrast between the two mean anomalies, the difference between the composite wet and dry years is computed (Figure 5(c)), where the shaded region is the significant region as a result of statistical t-test over 95% level of confidence. The composite wet years are; 1961, 1962, 1964,1965, 1967, 1988, 1994, 1999, and 2003, and the composite dry years used are; 1972, 1973, 1982, 1983, 1984, 1987, 1990, and 2002.

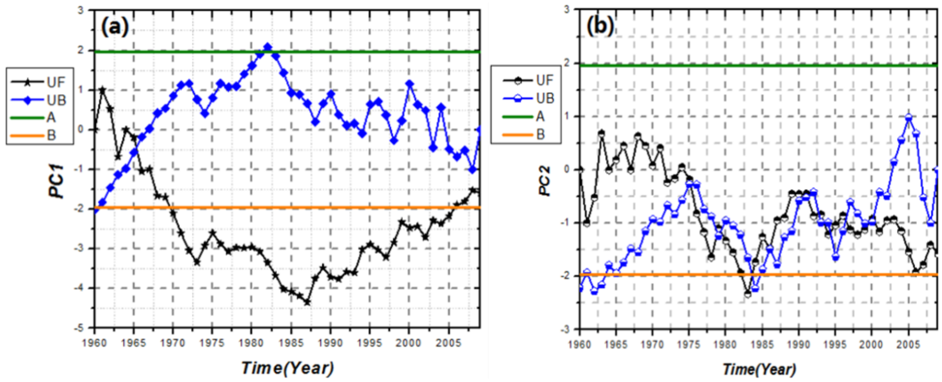

Figure 4: Testing curves of Mann-Kendall for the average JJAS rainfall of wet season over West Africa. **(a)** PC1. **(b)** PC2. (UF is original series, UB is counter series, A and B are lines of critical values).

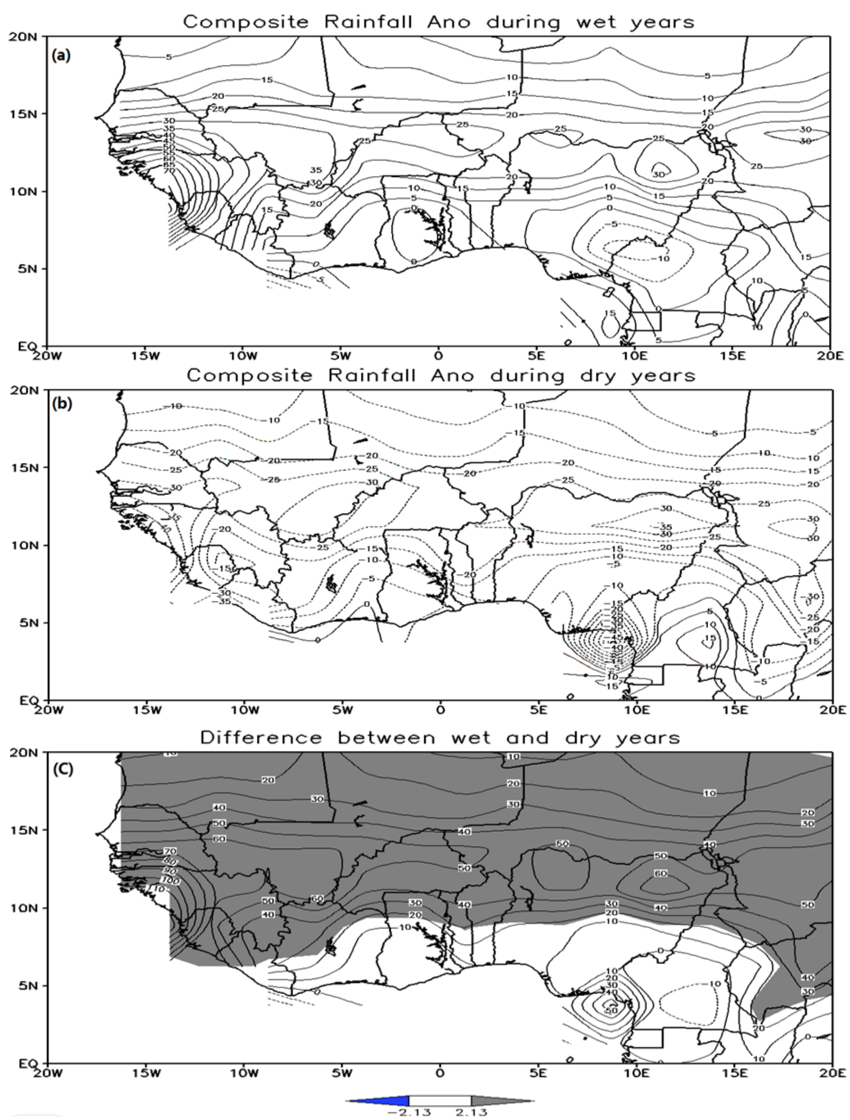

Figure 5: Composite rainfall anomalies; **(a)** wet years, **(b)** dry years, and **(c)** difference between wet and dry years, where the shaded areas are the significant regions as a result of statistical t-test over 95% level of confidence.

Results imply that the anomaly rainfall intensity in the wet is highest than that in the dry for having larger absolute values. The precipitation anomaly over most parts of region is generally positive, except a small portion of southeastern part, which is negative during wet event (Figure 5 (a)). Figure 5(b) displays that dry years, the rainfall anomaly in the study area is generally negative, except a small portion of southeastern part, which shows positive rainfall anomaly.

Circulation Anomaly Patterns Associated Wet and Dry Events of JJAS

Wind

The composite wind anomaly vectors during the wet and dry years shown in Figure 6(a) and (c), respectively. During wet years (at 850hpa), the circulation anomaly over the study region is associated by cyclone circulation (zone marked L), whereas in the dry years, the circulation anomalies, over the region is characterized by anticyclone circulation. At 200hpa, the region is dominated by northeasterly and easterly wind anomaly vectors during wet years, opposite to the dry years which are dominated by westerly wind anomaly (Figure 6(b) and (d)).

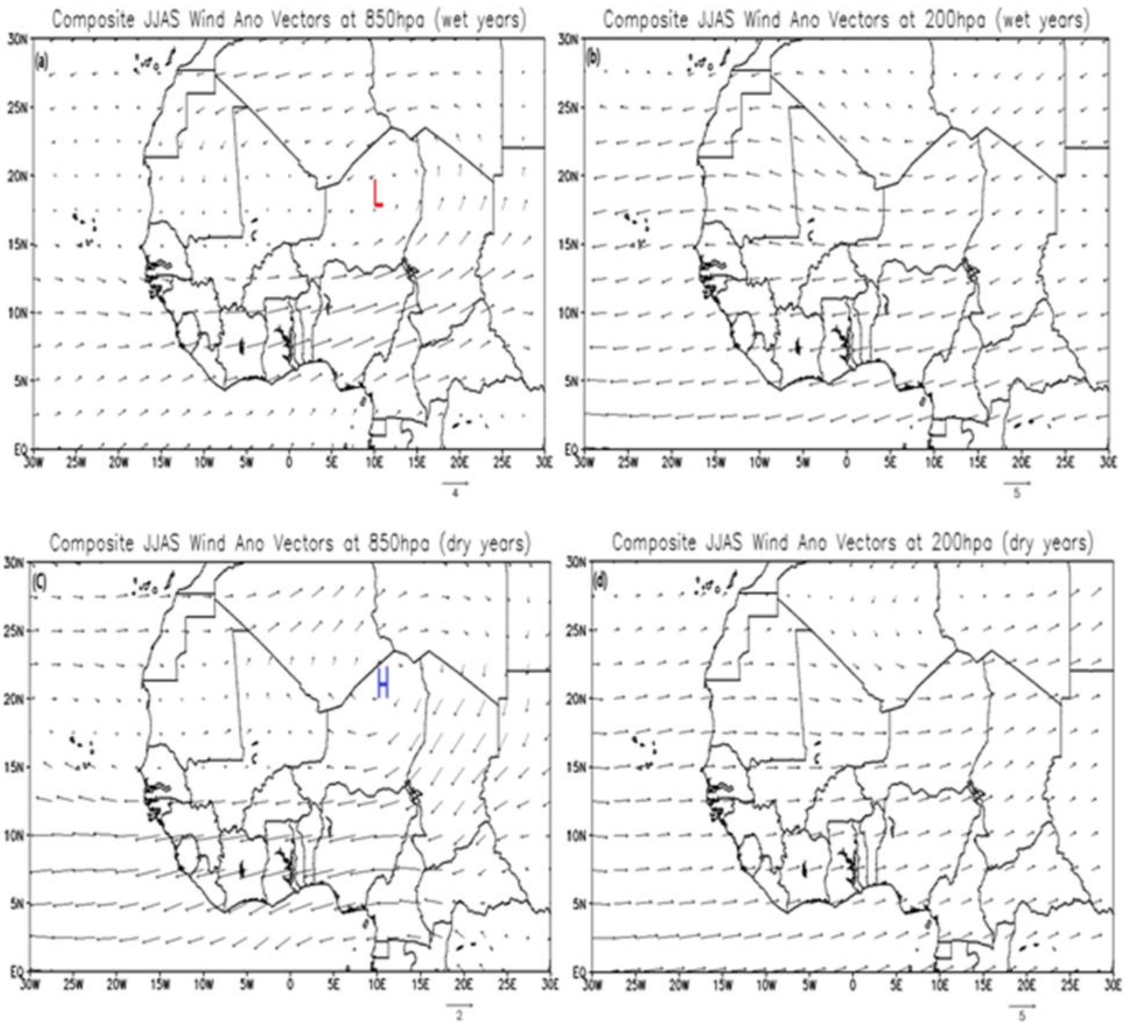

Figure 6: Composite wind anomaly vectors (m/s); **(a)** wet years at 850hpa, **(b)** wet years at 200hpa, **(c)** dry years at 850hpa, and **(d)** dry years at 200hpa.
The Low centers (L, red color) and High centers (H, blue color). (Ano=Anomalies)

Velocity Potential/ Divergence

The anomaly field of velocity potential/divergence (convergence) associated with the composite wet and dry years are analyzed. The wet events is characterized by convergence (divergence) at low level (upper level), respectively (Figure 7(a) and (b)). Especially over the study area, thus the composite velocity potential during wet years is associated with rising/upward motion over the region, especially at 850hpa in the (Figure 7(a)). The dry years show results which are opposite to the wet years, for example at 850hpa (200hpa), it is associated by divergence (convergence) over the study region (Figure 7(c) and (d)), respectively. The composite dry years are therefore characterized with sinking/downward motion over the study region; see Figure 7(c).

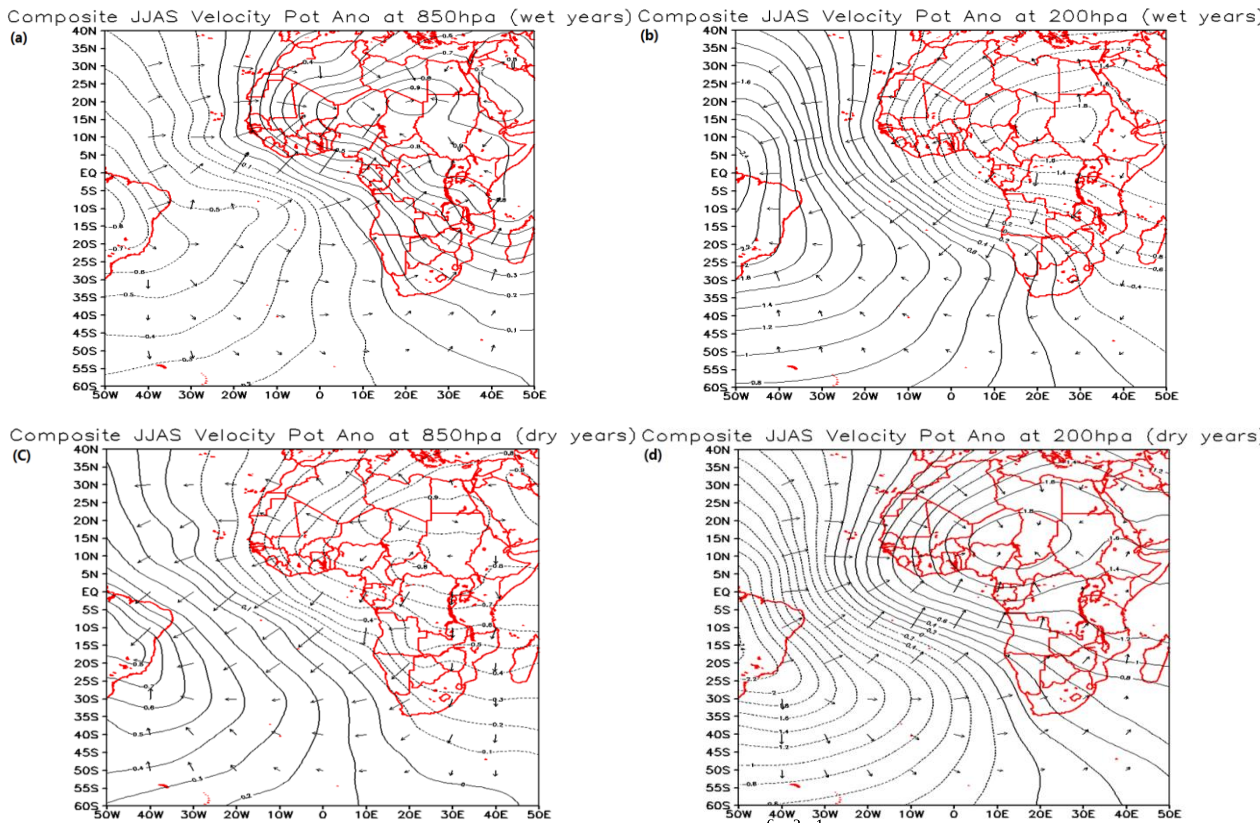

Figure 7: Composite average anomaly of velocity potential ($x10^6 m^2 s^{-1}$)/ divergence (convergence) at **(a)** 850hpa and **(b)** 200hpa, for the wet years. **(c)**at 850hpa and **(d)** at 200hpa, for the dry events (Contours represent velocity potential and are at 0.1 ($0.2x10^6 m^2 s^{-1}$, interval) at 850 (200hpa), respectively. Vectors show divergence/convergence.

Summary and Conclusion

This study investigates temporal/spatial distribution of rainfall and the associated circulation anomalies over West Africa. The spatial and temporal distribution of Jun-Sept (JJAS or wet) seasonal rainfall over West Africa was analyzed during the period 1960-2009, inclusive using Empirical Orthogonal Function (EOF) and the associated large scale circulation patterns. The result obtained from first mode-EOF, the spatial distribution of rainfall have shown that during wet season, it relatively uniform (EOF1), showing positive eigenvectors loadings over most part of study region, except southeastern part. The temporal explained wet (dry) years were identified as; 1961, 1962,1964, 1965, 1967, 1988, 1994, 1999, and 2003 (1972, 1973, 1982, 1983, 1984, 1987, 1990, and 2002).

The composite analysis of the wet and dry years with respect to the different variables including wind, velocity potential/divergence (convergence) reveals that the wet (dry) years were associated with convergence (divergence) in the lower troposphere, i.e. at 850hpa and divergence (convergence) at the upper level (200hpa), implying rising (sinking) motion, especially over the study area. The study region is dominated by westerly and southwesterly wind anomalies vectors, especially at 850hpa (wet years), whereas it is characterized with northeasterly and easterly wind during the dry years, especially at 850hpa.

The statistical analysis approaches used in the study provided insights into the Jun-Sept (JJAS) rainfall anomaly associations with the large scale systems. However, further work based on numerical simulations is required to fully understand the physical mechanisms responsible for the observed linkage, and also to assess the relative contribution of each individual system.

References

Beri, G. C., Business statistics. Second edition: Tata McGraw-Hill publisher, 2005, 312-340

Camberlin, P./S. Janicot/I. Poccard, 2001: seasonality and atmospheric dynamics of the teleconnection between African rainfall and tropical sea-surface temperature: Atlantic vs. ENSO. International Journal of climatology, 21: 973-1005.

Dambul, R., 2005: The Relationships between Large-scale Atmospheric Circulation andSurface Climate. A PhD thesis, University of East Anglia, England.

Folland, C. K., 1983: Regional-Scale Interannual variability of climate. A north-west EuropeanPerspective.Meteorological. 12: 167-187.

Hirst, A.C. /S. Hastenrath, 1983: Atmosphere-ocean mechanisms of climate anomalies in the Angola-tropical Atlantic Sector. Journal of physical oceanography, 13: 1146-1157.

Ininda, J.M., 1995: Numerical simulation of the influence of sea surface temperature anomalies Of the East African seasonal rainfall. PhD. Thesis.Department of Meteorology.University of Nairobi. Kenya.

Janicot, S./S. Trazaska, S. /I. Poccard, 2001: Summer Sahel ENSO teleconnection and decadal time scale SST variations. Climate Dynamics, 18: 303-320.

Janicot, S., and B. Sultan, 2001: Intraseasonal modulation of convection in the West AfricanMonsoon. Geophys.Res.Lett. 28, 523-526.

Jian-Yin, L. and W. Shang-Sen, 2000: Guangzhou Institute of tropical and oceanic Meteorology, Guangzhou 510080 China ID: 1006-8775 (2000)

Nicholson, S.E., 2009: A revised picture of the structure of the ‘’ monsoon’’ and land ITCZ over West Africa. Climate Dynamics, 32(7-8): 1155-1171.

Nicholson, S.E., 2008: The intensity, location and structure of the tropical rain belt overWest Africa as factors in Interannual variability. International Journal of climatology, 28 (13): 1775-1785.

Okoola, R.E., 1999: A diagnostic study of the East African monsoon circulation during the Northern hemisphere spring season. International Journal of Climatology. 19, 143-168.

Paeth, H., H.P. Thamm, 2007: Regional modelling of future African climate north of 150 S including greenhouse warming and land degradation. Climatic change, 83: 401-427.

Rowell, D.P., 2003: The impact of Mediterranean SSTs on the Sahelian rainfall season. Journal of climate, 16(5): 849-862.

Schneider,U., T. Fuchs, A. Meyer-Christoffer and B. Rudolf, 2008: Global Precipitation Analysis Products of the GPCC. Global Precipitation Climatology Centre (GPCC), DWD, Internet Publication, 1-1

Ward, M.N., 1998: Diagnosis and short-lead time prediction of summer rainfall in tropicalNorth Africa at interannual and multidecadal time scales. Journal of climate, 11(12): 3167- 3191.

Walsh, J. E. and A. Mostek, 1980: A Quantitative Analysis of Meteorological Anomaly patterns over the United States. 1900-1977. Mon Weather Rev, 108.615-630.

Acknowledgments

This work has been completed Allah grace, Who always gave me power to finish this research. I thank Him for everything. I am sincerely grateful goes to Staff and Workers of the ASECNA, Agency National Meteorological in Mali (Mali-Meteo), Delegation pour la Gestion Des ActivitesAeronautiquesNationales du Mali and the Ministry of the transport in Mali.

Special thank goes to World Meteorology Organization (WMO), and the Chinese Scholarship Council (CSC). My profoundly appreciation goes to Staff of the Station Synoptic Meteorology in Kita, AdamaDaou, Mohamed LamineSacko, SafisatouKante and SayonCoulibaly for their continuous advice and encouragement me.