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Application of Z-Index in analysis of recent March-May Drought over Rwanda

Jean Paul Ngarukiyimana[1],GuirongTan[1], Victor Ongoma[1, 2,*], Bob Alex Ogwang[1,3], Floribert Vuguziga[1,4]

(1) Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD)/Key Laboratory of Meteorological Disaster, Ministry of Education (KLME), Nanjing University of Information Science and Technology, Nanjing, P.R. China
(2) South Eastern Kenya University, Department of Meteorology, Kitui, Kenya
(3) Uganda National Meteorological Authority, Kampala, Uganda
(4) Rwanda Meteorology Agency, Kigali, Rwanda.
*) E-mail: victor.ongoma@gmail.com

Abstract. This study analyzed recent extreme weather events in Rwanda with emphasis on drought during March-May (MAM) season using Z-index. Composite analysis identified the years 2009 and 2010 as the most recent dry and wet years respectively. Analysis of the interanual variability over the period of 1981-2010 shows thatapproximately 30% and 27% of the observed rainfall events were drought and flood cases, respectively. The mean MAM rainfall ranges from 90 to 180 mm in the wet year (2009), whereas during the dry year (2010), rainfall was poorly distributed both in space and time.The dry year experienced generally dry easterly winds, with almost uniformly increasing positive wind speed variation with height.The diagnosis of the evolution of Mascarene High (MH) ridge shows that during the dry year,the ridge is anomalously displaced to the westof its normal position, leading to rainfall deficit over the entire eastern Africa. The dry year exhibited a wide spread moisture divergence anomaly at low level. The noted circulation anomalies associated with the dry event are important in future monitoring of occurrence of drought.

Keywords: Drought, Rainfall, Z-index, Circulation Anomalies, Rwanda.

1. INTRODUCTION

Rainfall and temperature changes adversely affect crop production in the tropics (Ongoma 2013). Studies by Muthama et al. (2012) and Okoola (1999a) identified rainfall to be the most important weather element in the tropics where this study lies. The importance of rainfall is tied to its impact on agriculture and its consequent contribution to the economies of most developing countries.

Rwanda is located in eastern Africa, confined within latitude 3°S-1°N and longitude 28.6°E-31°E (Figure 1). The country experiences two "wet" seasons: the "long rains" season March to May (MAM) and the "short rains" season in September to December (SOND). The two are separated by two dry spells from June to August (JJA) and the short dry season from January to February (JF). Although precipitation in eastern Africa shows a high degree of temporal and spatial variability dominated by a variety of physical processes (Rosell and Holmer 2007; Hession and Moore 2011; Indeje et al. 2001), the rainfall variability over Rwanda is low (Megan and Robert 2011). The observed spatial variability has been attributed to the complex topography and the existence of large water bodies (Ntwali 2013). The rainfall patterns are associated with the north-south oscillatory migration of the Inter-Tropical Convergence Zone (ITCZ) (Asnani 1993; Mukabana and Pielke 1996; Okoola 1996, 1999b; Mutai et al. 1998; Ogwang et al. 2014). The subtopic highs, especially the Mascarene High greatly influences the rainfall variability. Studies (e.g., Manatsa et al. 2014; Mutai et al. 2012; Hastenrath et al. 2010; Ogwang et al. 2015a) observed that droughts in east Africa are associated zonal shift of the Mascarene High. According to Manatsa et al. (2014), the westward migration of the Mascarene High eastern ridge from its normal position enhances the relatively cool and dry south easterly trade winds leading to rainfall deficits over eastern Africa.

Drought can build up without warning and persist for months to years (Sheffield and Wood 2011). Although it is a complex phenomenon that can be defined from several perspectives (Wilhite and Glantz 1985), researchers (e.g. Palmer 1965; Beran and Rodier 1985) have argued that the primary characteristic of drought is a reduction in precipitation. There exist a number of definitions ranging from agricultural to economic drought (Agnew 1989). This study is limited to meteorological drought; resulting from a shortage of precipitation.

Droughts have repeatedly caused devastating socio-economic losses especially in the eastern and southeastern regions of Rwanda (Twagiramungu 2006). Agricultural sector which is the country's economy backbone are sensitive to climatic variations (Boko et al. 2007; IPCC 2014); in particular, cash crops such as coffee and tea which are grown in the highland regions of east Africa (IPCC 1998). It is thus very important to have a proper understanding of the occurrence of extreme weather events to help improve the prediction of climate variability or change at local level. Studies (e.g. Williams and Funk 2011; Funk et al. 2008) indicated that over the last three decades rainfall has generally decreased over eastern Africa between March and May/June. The observation has been attributed to the rapid warming of Indian Ocean (IO), which causes an increase in convection and precipitation over the tropical Indian Ocean, contributing to increased subsidence over eastern Africa and a decrease in rainfall during March to May/June. Similarly, Lyon and DeWitt (2012) showed a decline in the March-May seasonal rainfall over eastern Africa. However, precipitation projections are more uncertain as compared to temperature projections (Rowell 2012).

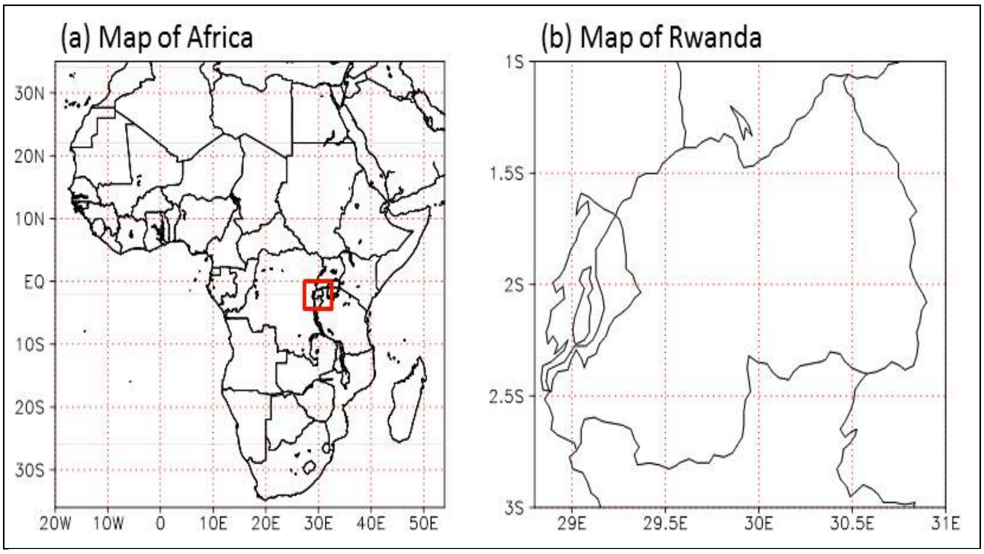


Figure 1. (a) Map of African showing the area of study (red rectangle) (b) Map of Rwanda (study area)

IPCC (2014) has projected significant increase of the amount of precipitation for the sub-Sahara region where Rwanda is located. The observation affirms the results of an earlier study by Seneviratne et al. (2013). The study reported that CMIP5 models project likelihood of increase in mean annual precipitation over areas of central and eastern Africa beginning the mid-21stcentury for RCP8.5. In support, an assessment of 12 CMIP-3 GCMs over eastern Africa suggest that by the end of the 21st century, there will be a wetter climate with more intense wet seasons and less severe droughts during October-November-December (OND) and MAM (Moise and Hudson 2008; Shongwe et al. 2011).

Most studies (e.g., Ogallo 1989; Ogwang 2011; Nicholson 1996; Indeje 2000; Mutemi 2003) have investigated and linked the variability in rainfall over East Africa with El Niño Southern Oscillation (ENSO). In general, it is noted that droughts occur during La Nina event. Most of these studies focused on the entire region of eastern Africa giving generalized results that may fail to capture the mesoscale contribution to the observed extreme weather events over Rwanda in detail.

A study by Shongwe et al. (2011) observed that the recent escalation of drought incidences in the recent decade is not being adequately addressed in seasonal weather forecasts. This study is aimed at filling this gap by investigating the droughts events over Rwanda to improve their forecasting and consequently minimize for socio-economic losses associated with them. The accurate and timely understanding of the occurrence of extreme weather can improve the effectiveness of humanitarian responses (Ververs 2012).

2. DATA AND METHODOLOGY

2.1. Data

The precipitation (rainfall) dataset used in this study is the Global Precipitation Climatology Centre (GPCC) monthly precipitation dataset provided from 1901 to present. It is calculated from the global station data (Schneider et al. 2013). 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. (2015b) to diagnose of East African climate and the circulation mechanisms associated with extreme wet and dry events. According to the study, there exists a significant correlation between simulated rainfall using Regional Climate Model; RegCM4 and the datasets; ERA interim reanalysis, GPCC, and Climatic Research Unit (CRU) of coefficients 0.95, 0.96, and 0.96, respectively, at 99% confidence level over the region. The study further established that the correlation between GPCC and CRU datasets is 0.96.The ERA-Interim reanalysis is adequately discussed by Dee et al. (2011).

The moisture transport was computed from relative humidity, temperature, zonal and meridional wind components, and geopotential height. The datasets have a horizontal resolution of 2.5° X 2.5°. The data was sourced from the National Center for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) Reanalysis 1 datasets, adequately described by Kalnay et al. (1996).

2.2. Methodology

2.2.1. Composite Analysis

Composite analysis can be used to investigate linkages that are not temporally symmetrical. According to Folland (1983) the method entails identification and averaging one or more categories of fields of a variable selected according to their association with key conditions. Researchers such as Okoola (1999a), Ogwang (2011), Ogwang et al. (2012) and Ininda (1995) have used composite methods in their studies over the East African region. The same technique was adopted in the present study to detect the circulation anomalies associated with dry events and generate hypotheses for patterns which may be associated with the scenarios (Folland, 1983). In this study the composite analysis method used specifically for analyzing the wet and dry events that captured by using Z-index method.

2.2.2 Z-index

Many indices including Palmer Drought Severity Index used by Dai et al. (2004) and Standardized Precipitation Index (SPI) as in Bordi et al. (2001) have been in use for drought analysis over the past years. This study adopts Z-index which has a set of regional flood/drought indices and a scheme for grading their severity as proposed by Tan et al. (2003) (Table 1). The index has been used widely, especially in China (e.g., Zou et al. 2005; Wang and Zhai 2003). This is mainly because of the numerous advantages including easy computation, large sensitivity, where the indices not only stand out the different influences of varied grades but also recognize the effect of the normal grade on the regional severity, and the numerically determined criteria values are associated with the theoretical probability of the single stations, and so, the indices have less limitation to terrain.

Although the Z-index has not been used widely in East Africa region, it was successfully used by Ogwang (2012) to diagnose the September-November drought and the associated circulation anomalies over Uganda.

The severity of the drought/flood events of each station of the study area is graded using single Z- index. The general formula for Z-index is computed using Equation 1:

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

where C_S and ϕ_i is the skewness coefficient and normalized variables, respectively with the definitions given by Equations 2 and 3:

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

$$\phi_i = \frac{X_i - \overline{X}}{\sigma} \tag{3}$$

The climatic mean $\overline{X}$ and standard variance σ are determined from the expressions presented by Equations 4 and 5 respectively:

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (4)$$

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2} \qquad (5)$$

where X_i denotes unprocessed variable. On the other hand, the wet/dry severity of the whole area of study was assessed in the context of regional indices, as given in Equation 6:

$$I_F = \frac{\left(\sum_{i=1}^{3}\frac{n_i}{p_i} + \frac{n_4^+}{p_4}\right)}{n} \text{ and } I_D = \frac{\left(\sum_{i=5}^{7}\frac{n_i}{p_i} + \frac{n_4^-}{p_4}\right)}{n} \qquad (6)$$

Equation 6 gives the flood index(I_F)and the drought index (I_D), where P_i denotes the probability of grade *i*, P4is the same as *Pi* but for grade 4, n_i is the total station number of grade i, n_4^- is the same as n_i but for grade 4 (normal grade)with negative anomaly, 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, so the individual stations with smaller statistical probability have a great contribution to the regional disasters.

Table 1. Standard for grading flood and drought based on single Z-index and regional index. (Source: Tan et al. 2003)

No	Grades	Single Z-index	Probability	Regional index
1	Extreme Flood	$Z \geq 1.645$	5%	$I_F - I_D \geq 1/P_2$
2	Severe Flood	$1.0367 \leq Z < 1.645$	10%	$1/P_3 \leq I_F - I_D < 1/P_2$
3	Mild Flood	$0.5244 < Z < 1.0367$	15%	$1/P_4 < I_F - I_D < 1/P_3$
4	Normal	$-0.5244 \leq Z \leq 0.5244$	40%	$-1/P_4 \leq I_F - I_D \leq 1/P_4$
5	Mild Drought	$-1.0367 < Z < -0.5244$	15%	$-1/P_5 \leq I_F - I_D < 1/P_4$
6	Severe Drought	$-1.645 < Z \leq -1.0367$	10%	$-1/P_6 < I_F - I_D \leq 1/P_5$
7	Extreme Drought	$Z \leq -1.645$	5%	$I_F - I_D \leq 1/P_6$

The country was gridded into ten grids over which the rainfall of the country was averaged. Figure 2 displays the ten grids over Rwanda.

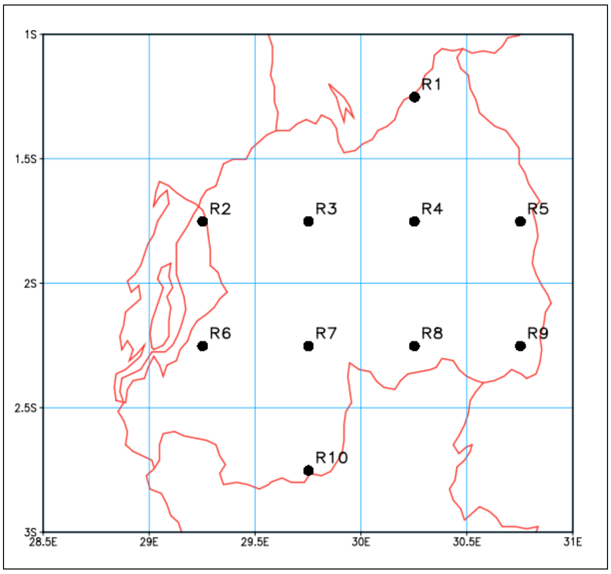


Figure 2. Center locations (marked with dots) of the 0.5° x 0.5° grids over which the gridded rainfall is averaged, as used by Owiti and Zhu (2012). R1 to R10 represent the respective regions.

3. RESULTS AND DISCUSSION

3.1. Characteristics of MAM Rainfall

The time evolution of the normalized area average rainfall anomaly during the MAM season over Rwanda is presented in Figure 3.

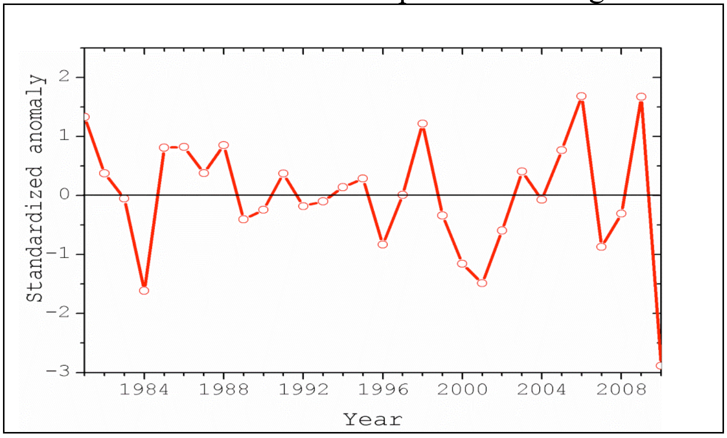


Figure 3. Interannual variability of the area average MAM rainfall over Rwanda.

The years 1984, 2001 and 2010 recorded below normal rainfall; dry years while 1981, 1998, 2006, and 2009 experienced above normal rainfall; wet year. The remaining years in between 1981 and 2010 received normal rainfall.

A case study of the composite years chosen on the basis of the recent occurrences of drought and floods was done, whereone recent drought year (2010) and a recent flood year (2009) were chosen to understand the relative increase and reduction in rainfall over the region during flood and drought years. These years were also examined to understand the prevailing circulation patterns during drought and flood events. Results in Table 4 show that MAM rainfall increased by 28% during the wet year, whereas in the dry year, there was a decrease of 46%.

3.2. Diagnosis of Drought and Flood Events

Table 2 presents the number of years and the corresponding real probability for grading flood/drought over different region over Rwanda. Approximately, 44% of the rainfall events recorded are normal, 30 % are drought cases while flood cases constitute 27% of the events.

Table 2. Number of years and the corresponding real Probability (Real P*) for Grading Flood/Drought per region (R).

Stations	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	Total	Real Prob
Extreme Flood	3	2	2	2	1	2	2	1	2	1	18	6%
Severe Flood	1	3	2	2	2	3	2	4	3	6	28	9.3%
Mild Flood	3	4	5	4	4	4	4	3	4	1	36	12%
Normal	12	12	13	13	16	13	13	14	11	15	132	44%
Mild Drougt	7	4	3	5	4	3	5	4	6	3	44	14.7%
Severe Drougt	3	3	4	3	2	3	2	2	2	2	26	8.7%
Extreme Drougt	1	2	1	1	1	2	2	2	2	2	16	5.3%

Table 3 gives the MAM flood/drought years during the period of study 1981 to 2010 and the respective real probability of occurrence. The probability of occurrence of normal events is 33.3%, with drought and flood having equal chances of occurrence.

Table 3. MAM flood/drought years in the period 1981-2010, and the respective real probability (Real Prb) of occurrence over Rwanda

Nr.	Grades	I_F-I_D	Flood/Drought Years	Total	Real Prob
1	Extreme Flood	≥10	2006, 2009	2	6.7 %
2	Severe Flood	[6.67,10)	1981, 1998, 1988	3	10 %
3	Mild Flood	(2.5,6.67)	1986, 1985, 2005, 2003, 1987	5	16.7 %
4	Normal	[-2.5,2.5]	1982,1991,1995,1994,1997, 1983,2004,1993,1992,1990	10	33.3 %
5	Mild Drougt	(-6.67,-2.5)	2008,1999,1989,2002, 1996	5	16.7 %
6	Severe Drougt	(-10,-6.67]	2007, 2000, 2001	3	10 %
7	Extreme Drougt	≤ -10	1984, 2010	2	6.7 %

The long term mean (LTM) seasonal cycle of rainfall (RF), observed rainfall in a wet year and a dry year over Rwanda are presented in Figure 4.

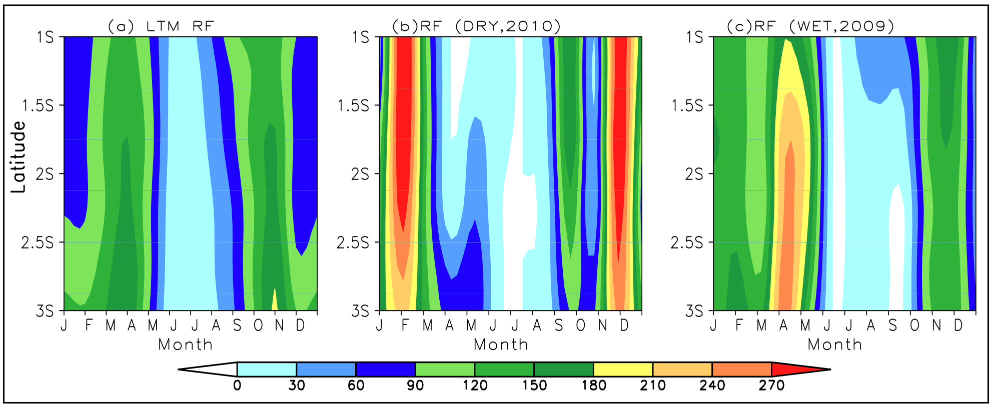


Figure4: (a) The long term mean (LTM) seasonal cycle of rainfall (RF) over the period 1981-2010, at longitude 30 °E, (b) The observed rainfall during the wet year (2009), and (c) The observed rainfall during the dry year (2010).

Table 4: The mean MAM rainfall (RF*) and percentage change (P*). LTM, WET and DRY denote long term mean, wet year (2009) and dry year (2010), respectively.

	RF* (mm)	**P*** (%)
LTM	138	
Wet	176	28 (Increase)
Dry	74	46 (Decrease)

The climatology of the seasonal cycle of rainfall over Rwanda (Figure 4a) shows the distribution of rainfall from January to December, where the two rain seasons: MAM and SONDare clearly evident with MAM rainfall ranging between 90-180 mm while SOND has 60-180 mm. However, during the dry year, rainfall was observed to be as low as 0-30 mm in most areas, increasing gradually to a high of 150 mm in few areas (Figure 4b). High rainfall amounts were experienced in a flood/wet year ranging from 150-280 mm in MAM (Figure 4c).

The climatology of the mean MAM rainfall (mm) (Figure 5a) shows that the western sector of Rwanda receives more rainfall, which is observed to reduce with distance to other parts of country (Fig. 5a). The dry year and the wet year recorded below and above normal rainfall respectively (Figure 5b) and (5c). During the dry year, the highest rainfall deficit was observed to the northern and eastern parts of the country as compared to the western and southern regions (Figure 5b). The central and north western parts of the country experienced the wettest conditions exhibited by the higher rainfall as compared to the other parts of the country (Figure 5c). Generally, the north eastern parts of the country receive the least amount of rainfall as compared to other parts of the country.

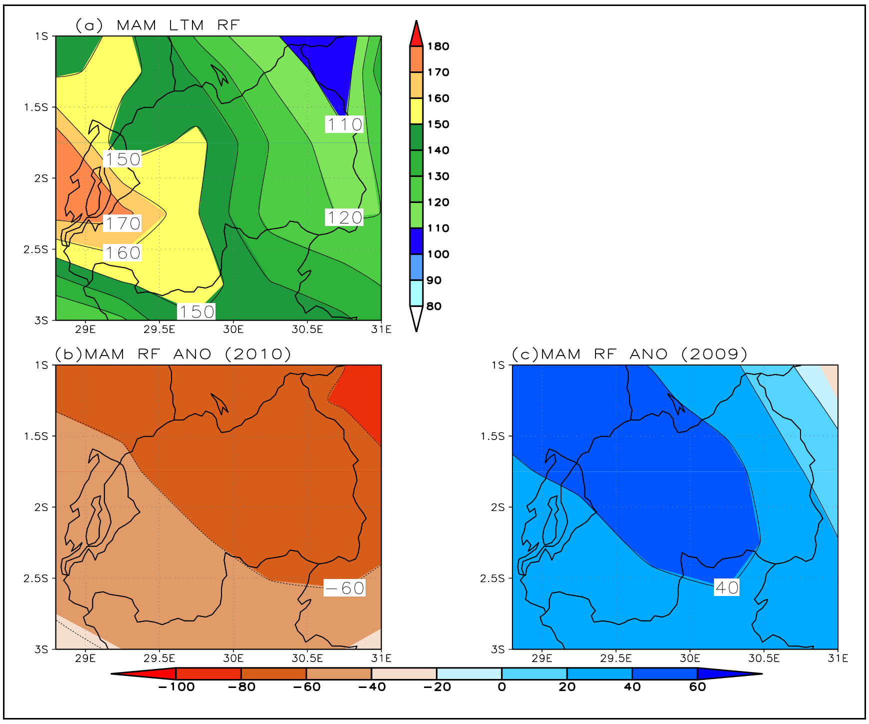


Figure 5. (a) The climatology of the mean MAM rainfall (mm), (b) The mean MAM rainfall anomaly (mm) during the dry year (2010), (c) The mean MAM rainfall anomaly (mm) during the wet year (2009).

3.3. Atmospheric Circulation Characteristics

The circulation characteristics are important in depicting the circulation associated with the observed weather events for future weather monitoring. Figure 6 displays the mean MAM wind anomaly during a wet and dry year.

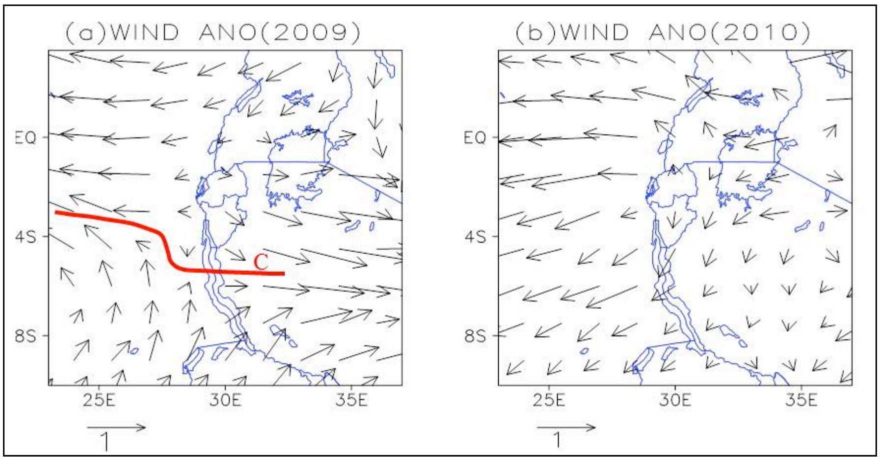


Figure 6: The mean MAM wind anomaly (vector in ms^{-1}) for (a) wet year, with convergence zone (red line) labeled C (b) dry year.

The north westerly winds are observed further to the northern of Rwanda flowing from southern parts of Uganda, and south westerly winds blow from the Democratic Republic of Congo (DRC) towards the Rwanda (Figure 6a). The two wind flows converged in the southern Burundi, the neighboring country to Rwanda. The winds blowing from Congo forest in DRC are generally warm and moist, thus they are likely to have contributed to the observed above normal rainfall over Rwanda. Figure 6b displays wind flow during a dry year, the flow is generally observed to be easterly without convergence; limiting precipitation formation and hence it can be attributed to the observed condition.

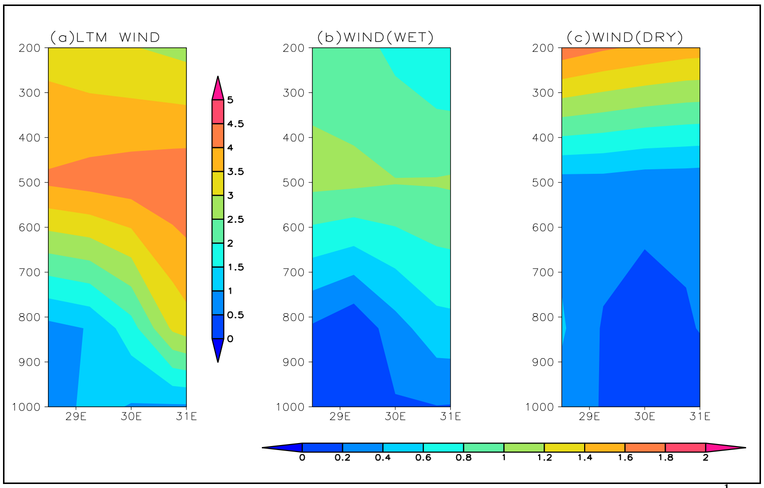
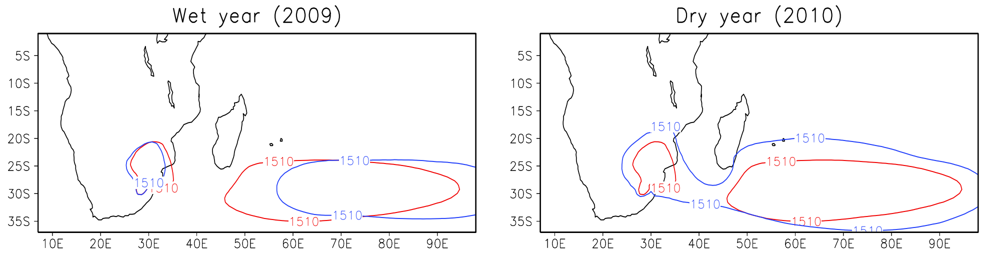


Figure 7: The vertical cross section of the mean MAM wind magnitude (ms^{-1})for (a) long term mean (LTM) over the period 1981-2010, (b) wind anomaly during wet year (2009), (c) wind anomaly during dry year (2010).

The climatology (LTM) of the vertical cross section for MAM wind speed is generally weak in the lower levels (1000 - 700 mb), stronger in the middle level and moderately weak in the upper levels (Figure 7a). During the wet year (Figure 7b), positive wind anomalies dominate but maintain the same vertical profile as in the LTM. In the dry year, the wind anomalies at low to middle levels (1000 - 400 mb) are weaker than in the wet year (Figure 7c). However, in the upper levels (400 - 200 mb), the anomalous winds are stronger during the dry year compared to the wet year. The observed weak anomalous winds at low level (1000 – 800mb) in the wet year generally favor low level convergence that increases chances of cloud formation and consequently enhances rainfall.

Further analysis of the mean moisture transport (Figure 9) shows that during the wet year, the region was dominated by anomalous moisture convergence (positive anomalies) at low level (850 hpa). In the dry year, anomalous moisture divergence (negative anomalies) is dominant in the region. The mean MAM moisture anomaly (Figure 10) similarly shows that there was moisture convergence (divergence) in wet (dry) year, as exhibited by positive (negative) anomalies over the period 1981 - 2010.

Analysis of the geopotential height at 850 hpa to depict the Mascarene High zonal displacement is presented in Figure 8. In the analysis, 1510 gpm contour is chosen and its behavior examined during wet and dry years. Results show that during wet year, Mascarene High ridge shifts to the east but during the dry year, it shifts to the west (Figure 8). The migration of the Mascarene High ridge to the west (east) of its normal position strengthens (weakens) the south east trade winds over the South Indian Ocean. This leads to enhancement (reduction) of the relatively cool and dry south east trade winds and induces cold (warm) sea surface temperature anomaly in the Ocean. Consequently, convection over the western equatorial of the South Indian Ocean is suppressed (enhanced) leading to rainfall deficits (excess) over the larger eastern Africa. The results are in agreement in a recent study carried out by Manatsa et al. (2014).



(a) (b)

Figure 8. Composite mean geopotential height at 850 hpa depicting the high pressure system (Mascarene High) over Indian Ocean during (a) wet year (b) dry year. The climatology of 1510 gpm (red contours) for the period 1981 - 2010 and its behavior during wet and dry years are shown (blue contours).

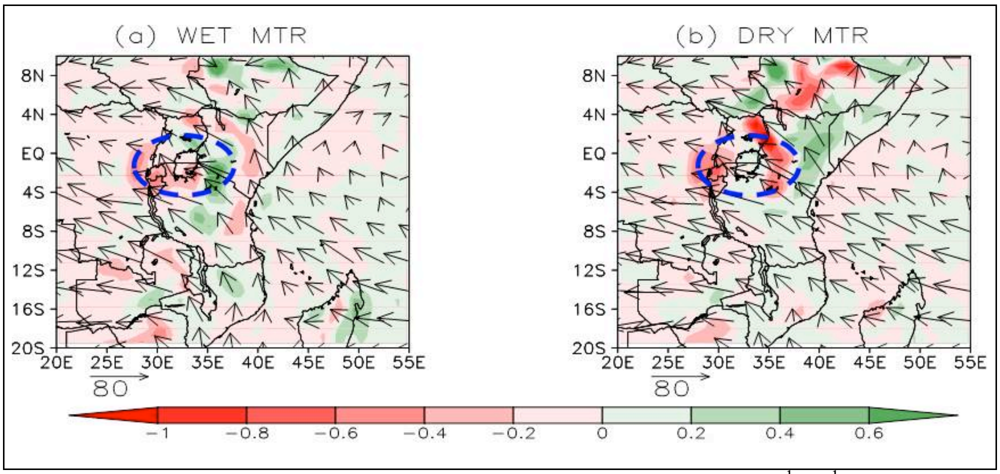


Figure 9. The mean MAM moisture transport (MTR) at 850hpa in g kg^{-1}ms^{-1}over the east African region (a) Wet year (2009), (b) Dry year (2010), based on ERA interim dataset (Vectors show moisture transport, whereas the shaded regions indicate anomalous moisture convergence (positive) and divergence (negative)).The region of concern is shown with the blue dash line.

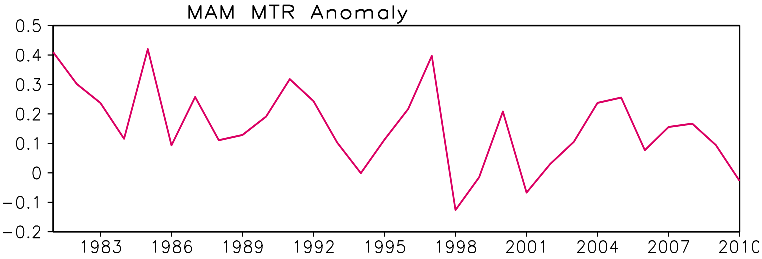


Figure 10. The mean MAM moisture (MTR) anomaly, averaged over 28.8°E-31°E and 3°S-1°S (Negative values show divergence and positive values indicate convergence).

4. CONCLUSIONS AND RECOMMENDATIONS

The study has analyzed extreme weather events in Rwanda with emphasis on drought. A case study of the composite years chosen on the basis of the recent occurrences of drought and floods was performed, recent drought year (2010) and a recent flood year (2009) were identified and considered as representative respective years in further analysis. Interanual variability analysisover the period; 1981-2010 shows that 44% of the mean MAM rainfall events recorded were normal, 30% were drought cases, while flood cases constituted 27% of the events.

The MAM rainfall climatology shows that rainfall range from 90 - 180 mm, however, during the dry year, rainfall was observed to be as low as 0 - 30 mm in most areas, increasing gradually to a high of 150 mm in few areas. During the very year, the highest rainfall deficit was observed to the northern and eastern parts of the country as compared to the western and southern regions. The central and north western parts of the country on the other hand experienced the wettest conditions exhibited by the higher rainfall as compared to the other parts of the country.

The recorded low level convergence of north easterly wind and south westerly wind flow from Congo forest favoured rainfall enhancement in the wet year as compared to the dry year, where the observed wind was generally easterly without any convergence.The observed almost uniformly increasing positive wind speed variation of the easterlies with height in the dry year generally did not favour convergence at low level, reducing chances of cloud formation and concequently, below normal rainfall was recorded.

The westward movement of the Mascaren High ridge from its normal position strengthens the south east trade winds over the south Indian Ocean. This enhances the relatively cool and dry south east trade winds and induces cold sea surface temperature anomaly in the Ocean. As a result, convection over the western sector of the South Indian Ocean is suppressed, leading to rainfall deficits over the larger section of eastern Africa. The region was dominated by anomalous moisture convergence at 850 hpa during the wet year, which enhanced rainfall in the region. On the other hand, the dry year exhibited a wide spread moisture divergence anomaly in the region.

The observed circulation associations with wet and dry events are very important in future monitoring of occurrence of extreme weather events; it will help in timely relay of the anticipated weather for planning purposes, reducing loss of lives and destruction of property.

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