Diagnosis of September - November Drought and the Associated Circulation Anomalies Over Uganda

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Abstract

Extreme weather and climate events such as floods and droughts are common in Uganda. These events have always had devastating impacts on various sectors of the country's economy. In this study we investigate the drought events of September-November (SON) season and the associated circulation anomalies over Uganda for the period 1962-2007. A regional drought index (Z-index) with a scheme of grading severity of drought and flood is used to classify the drought/flood events using station rainfall data. The index successfully classified the drought and flood events, with SON heavy floods (droughts) experienced in the years 1967,1972,1977,1999, 2000 and 2001 (1974 1976,1979,1984,1985 and 1993). Analysis of the drought and flood years with respect to the different variables including wind, velocity potential and divergence/convergence vectors revealed that the drought (flood) years were characterized by divergence (convergence) in the lower troposphere and convergence (divergence) at the upper level, implying sinking (rising) motion, especially over the western Indian Ocean and the study area. The anomaly convergence zone was identified within (outside) the region of study during flood (drought) years.

Key Words: Drought, Flood, Z-index, Anomaly, Uganda.

Introduction

Floods and Droughts are extreme climate events that have always caused substantial damage to the environment, economic losses in various sectors, damage to infrastructure, loss of life and/or livelihood in Uganda. It is therefore of great importance to have a good understanding of previous climate events and their impacts so as to make reliable and accurate forecasts to minimize the impact of these extreme occurrences of climate. In the tropics, where the domain of this study lies, the most important climate element is rainfall (Okoola, 1998), and it is the major determinant of the economies of most tropical countries. Rainfall over Uganda exhibits a large spatial and temporal variability. The spatial variation has been attributed to the existence of large scale systems and local systems such as inland water bodies which includes Lake Victoria, Lake Kyoga, among others and the complex topography. The two main rainfall regimes experienced in Uganda are bimodal and unimodal. The bimodal regime is observed towards/near the equator with the first peak in April, for March-May (MAM) season, locally referred to as 'long rains' in East Africa. The second peak occurs in October, for September-November (SON) season. It is worth noting that both MAM and SON seasons (wet seasons) coincide with the passage of the Inter Tropical Convergence Zone (ITCZ) that lags behind the overhead sun by about a month while the wet seasons are separated by two dry spells from June to August and December to February (Okoola, 1996; Mutemi, 2003). Many researchers, including Ropelewski and Halpert, 1987; Jonawiak, 1988; Ogallo, 1988; Nicholson,1996; Indeje, 2000; Mutemi, 2003, among others have investigated and linked rainfall over East Africa with El Niño Southern Oscillation (ENSO). Mutemi (2003) for example, got a strong relationship between rainfall over East Africa and evolutionary phases of ENSO. The results showed that ENSO plays a significant role in determining the monthly and seasonal rainfall patterns in the East African region. In general, it is argued that floods are likely to occur in the region during El- Niño events and droughts tend to occur during La Nina events. Most of these previous studies covered the entire region of East Africa such that their results were generalized over the whole region. Further they used regional rainfall indices or indices from delineated climatic zones based on the regional rainfall variability. The regional studies may have not captured in detail the localized events of floods/droughts over Uganda. The current study therefore attempts to fill this gap by investigating the SON drought/flood events and their associated circulation anomalies over Uganda. The data and methods used in the study are discussed

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in section 2, while the results are presented in section 3. The summary and conclusions drawn from the study are presented in section 4.

Data and Methodology

Data

The data used in this study include the average monthly and seasonal rainfall records at 12 stations distributed over Uganda (Figure 1(a)) within the period 1962-2007. Reanalysis fields from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) (Kalnay et al., 1996), including zonal and meridional wind and velocity potential, with a horizontal resolution of 2.5^0 X 2.5^0 were also used.

Classification of Floods and Droughts

Many indices and methods for drought and flood assessment, including Palmer Drought Severity Index, used by Dai et al,2004 and Standardized precipitation index (SPI),as in Bordi et al,2001 have been developed over the past years.

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) is used in this study. 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.

The severity of the drought/flood events of each station of the study area was graded using single Z-index, given by;

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

Where C_S and ϕ_i are the skewness coefficient and normalized variables, respectively with the following definitions:

$$c_s = \frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^3}{n\sigma^3}, \quad \phi_i = \frac{x_i - \bar{x}}{\sigma} \qquad \textbf{(2)}$$

The climatic mean $\bar{x}$ and standard variance σ are determined from the expressions;

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \ , \quad \sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2} \qquad \textbf{(3)}$$

where x_i denotes 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;

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

The expression 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 same as p_i 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. 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. They are; extreme, severe, mild and normal for both drought and flood events.

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	5%	$I_F - I_D \geq 1/p_2$
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	15%	$1/p_4 < I_F - I_D < 1/p_3$
4	Normal	-0.5244≤Z≤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<-1.0367	10%	$-1/p_6 < I_F - I_D \leq 1/p_5$
7	ExtremeDrought	Z≤-1.645	5%	$I_F - I_D \leq 1/p_6$

Composite Analysis

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 key conditions for the composite analysis are floods and droughts, where the composites for wet and dry years were separately done, especially for wind and velocity potential/divergence. This is mainly to detect the circulation anomalies associated with wet/dry events. A number of authors, including Okoola (1999) and Ininda (1995) have used composite methods in their analyses over the East African region.

EOF Analysis

Empirical Orthogonal Functions (EOF) is used in this study to show the dominant modes of variability of SON rainfall over the region. The data used is normalized in order to prevent areas and seasons of maximum variance from dominating the eigenvectors (Walsh and Mostek, 1980). The standardized rainfall anomaly z is computed from:

$$z = \frac{X - \overline{X}}{S_d} \qquad \textbf{(5)}$$

where X is the observed mean SON rainfall, $\overline{X}$ is the long term mean SON rainfall and S_d is the SON rainfall standard deviation. The value of z provides immediate information about the significance of a particular deviation from the mean (Kabanda, 1999).

Simple Correlation

Correlation analysis reveals simple relationship between pairs of variables. In this study, correlation analysis is aimed at establishing whether the areal average SON rainfall (SON index) is representative of the different stations used in the study. SON index is correlated with individual station SON rainfall over the study area.

The simple correlation (r_{xy}) between variables X and Y is expressed as:

$$r_{xy} = \frac{\left[\frac{1}{(n-1)}\right]\sum_{i=1}^{n}\left[\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)\right]}{\left\{\left[\frac{1}{(n-1)}\right]\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2\right\}^{1/2}\left\{\left[\frac{1}{(n-1)}\right]\sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2\right\}^{1/2}} \quad \textbf{(6)}$$

The simple correlation has two important properties. First, it is bounded by -1 and 1, i.e., $-1 \leq r \leq 1$. When the value of r_{xy} is +1 or –1, it indicates a perfect positive or negative correlation between the given pairs of variables, respectively. The square of the correlation coefficient, r^2_{xy}, represents the portion of the variability of one of the two variables that is linearly accounted for or explained by the other. The calculated correlation coefficients are tested for statistical significance using the t-test summarized as:

$$t = r_{xy}\sqrt{\frac{N-2}{1-r_{xy}^{\,2}}} \quad (7)$$

The calculated values of *t* are then compared with those of the theoretical *t*-distribution with N-2 degrees of freedom. If the calculated value of $t \geq$ the theoretical value, then the correlation is significant. A significant correlation in two or more variables indicates the predictive potential (Wilks, 2006).

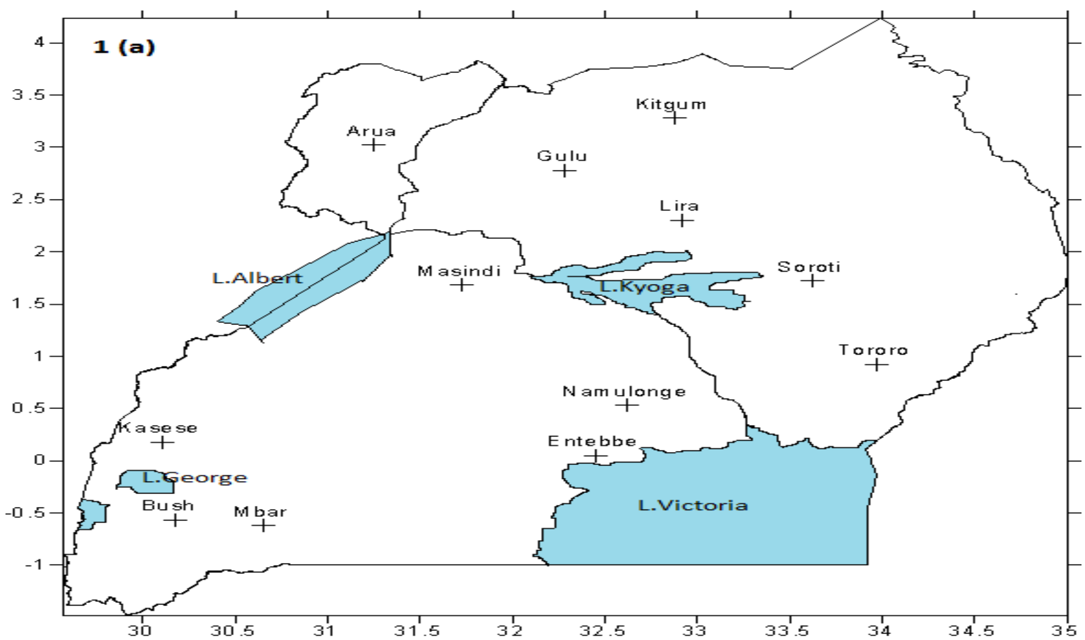
Case Study

The case study is formulated based on the years of severe floods and droughts. The year 1977 is used as a wet year whereas for the dry year, 1984 is considered. The anomaly patterns of wind and velocity potential/divergence are assessed during these years of dry and wet events.

Results and Discussion

In this chapter the results obtained from the various methods that were used to address the objectives of the present study are presented and discussed in their respective sub-sections.

Some Statistical Characteristics of SON Rainfall



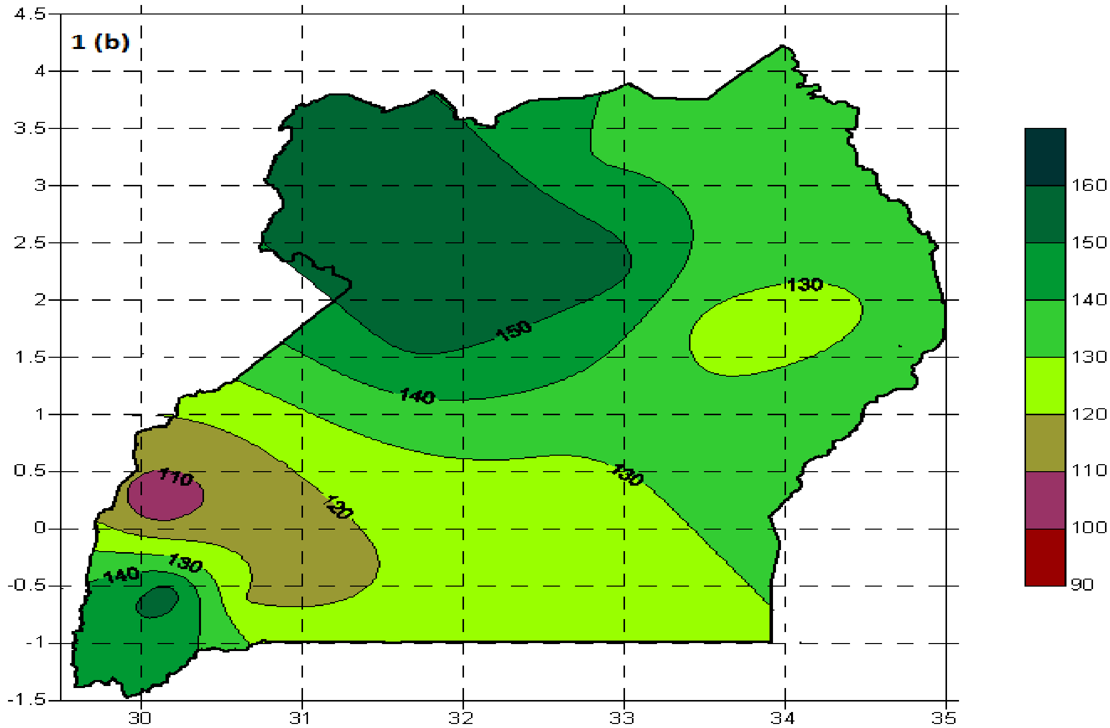


Figure 1:(a)Distribution of the rainfall stations used in the study **(b)** Mean SON seasonal rainfall distribution (SON index) over Uganda (Contours are at 10 mm interval).

The stations used in the study and their locations are shown in Figure 1(a), in which Bushenyi and Mbarara stations are represented by Bush and Mbar, respectively. Correlation coefficients between individual station rainfall and the areal averaged SON rainfall (SON index) for the period 1962-2007 are significant. Gulu station has the highest correlation coefficient of 0.7 followed by Lira, Masindi and Tororo, each having correlation coefficient of 0.6. The rest of the stations had correlation coefficients of between 0.4 and 0.5. Stations with the least correlation coefficients are Arua and Kasese. In general, the distribution of SON rainfall over the region is relatively uniform. Figure 1(b) displays the average SON seasonal rainfall over the study area. From the figure, it can be seen that the north and northwestern regions such as Arua, Gulu, Masindi and Lira, tend to receive more SON rainfall compared to other regions of the country. The standardized anomaly of SON rainfall for the study period is shown in Figure 2.

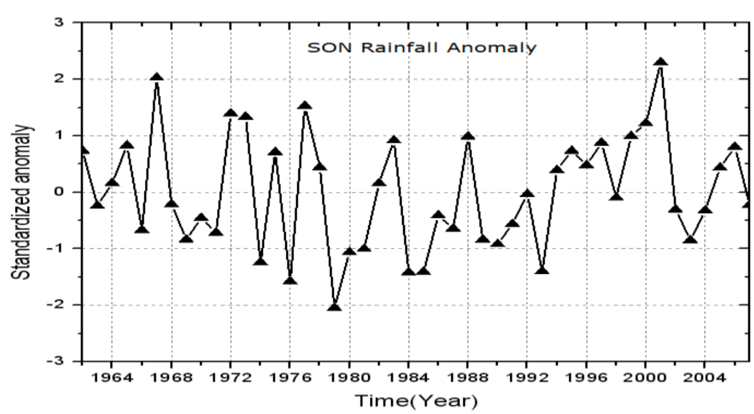


Figure 2: Interannual variability of SON rainfall (standardized anomaly) for the Period 1962-2007

Spatial and Temporal Patterns of SON Rainfall

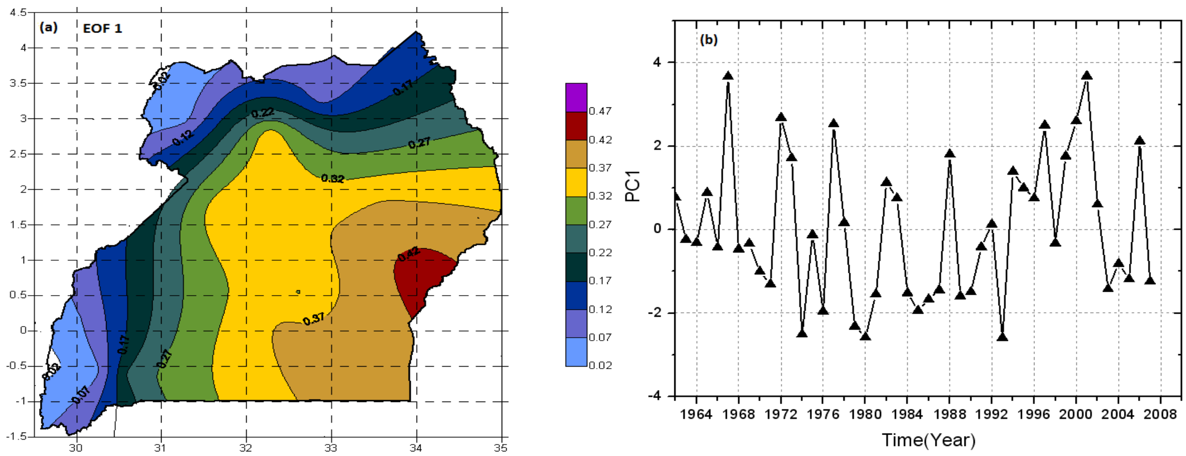


Figure 3: (a) The first EOF spatial mode, EOF1 (explains 24% of the total variance) of SON rainfall **(b)** its corresponding PC (PC1)**.**

The spatial component, Figure 3 (a) displays the pattern of the first eigenvectors (EOF1) of SON seasonal rainfall, showing positive loadings throughout the country, with the strongest loadings concentrated in the eastern parts of the country, which include the basins of Lake Victoria and take Kyoga. According to Asnani (1993), there exists a quasi-permanent trough that occurs over Lake Victoria due to locally induced convection, orographic influence and land-lake thermal contrast which modulates rainfall pattern over the lake and hinterlands. The existence of this quasi-permanent trough over the lake favors convection over the basin throughout the year. The rest of the regions exhibit weak loadings, probably due to weaker effect of local systems in the annual cycle. It is similarly worth noting that, on average, the pattern has east-west orientation, with the weak positive loadings to the south western region of the country.

Figure 3(b) on the other hand shows the first EOF time series (PC1). It captures the pattern of variability shown in Figure 2, i.e., SON rainfall anomalies, with years of maximum values having at least a standard deviation of +1.5 as 1967, 1977, 2001 and those with at least a standard deviation of -1.5 include; 1976, 1979, 1984, 1985, and 1993.

EOF2 and EOF3 on the other hand (Figures omitted) explain 16% and 13% of the total variance of SON rainfall, with varying spatial and temporal patterns.

Diagnosis of Wet/Dry Events

Table 2: Number of years and the corresponding Probability for Grading Flood/Drought**.**

Station	Extreme Fld	Severe Fld	Mild Fld	Normal	Mild Drt	Severe Drt	Extreme Drt
Aru	2	5	9	16	6	6	2
Bus	2	4	8	20	6	2	4
Ent	3	4	5	24	3	4	3
Gul	2	5	6	20	7	3	3
Kas	3	4	8	21	3	5	2
Kit	2	3	8	21	6	3	3
Mas	3	5	6	17	7	7	3
Mba	4	4	3	25	6	1	1
Lir	2	7	8	14	8	5	3
Nam	2	3	10	17	8	4	2
Sor	2	4	10	16	6	6	2
Tor	1	7	8	17	6	5	2
Total	28	55	89	228	72	51	29
Real prob	5.1%	10%	16%	41.3%	13%	9.2%	5.3%

Table 2 provides the probability of grading flood/drought and the number of years under each category for the stations considered in this study based on the z index. A summary of the occurrences of the grades are shown in Figure 4.

The following abbreviations were used to represent the different stations.
Aru: Arua, Bush: Bushenyi, Ent: Entebbe, Gul: Gulu, Kas: Kasese, Kit: Kitgum, Mas: Masindi, Mba: Mbarara, Lir: Lira, Namu: Namulonge, Sor: Soroti, and Tor: Tororo.

Table 2 gives the result of grading/classifying the severity of drought/flood events for individual stations based on the standards displayed in Table 1. The results show that the calculated single station flood/drought frequency distribution is approximately equal to the theoretical values in Table 1, where for example, the normal grade accounted for 41.3%, slightly higher than the theoretical counterpart of 40%, and extreme flood (drought) accounted for 5.2 (5.3)% which are similar to the theoretical value of 5%.

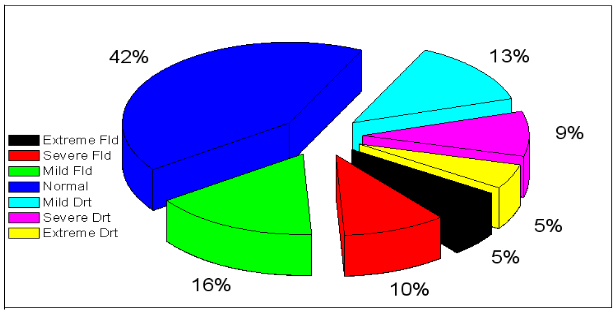


Figure 4: The approximate percentage of occurrence of events per grade

Figure 4 shows the approximate percentage of occurrence of events in the different grades, in which case; Fld: flood and Drt: drought. These results indicate that wet events were more frequent as oppose to dry events. The normal grade however took the highest proportion, implying that there were more normal events of SON rainfall during the study period 1962-2007 compared to flood/drought incidences. The results for the regional flood/drought years identified out of the 46 years of SON rainfall analyzed are shown in Table 3. From the table, the real probability is similar to that of the single theoretical one of each grade. Extreme droughts were experienced in 1976 and 1979 and severe droughts in 1974, 1984, 1985 and 1993, whereas extreme floods were in 1967 and 2001 with severe floods in 1972, 1977, 1999 and 2000, among others. It is similarly visible from the SON rainfall anomaly (Figure 2) and Table 3 that there was a higher frequency of dry events compared to wet events between 1962 -1993, with 7 wet events in the years 1962, 1967, 1972,1973,1977,1983 and 1988, and 11 dry events in the years 1966, 1970, 1974, 1976, 1979, 1980, 1981, 1984,1985,1989,1993. However wet events dominated after 1993, with 5 cases of wet events in the years 1997,1999,2000,2001 and 2006 as oppose to only 1 dry event in the year 2003.

Table 3: SON flood/drought years in the period 1962-2007

S.No	Grades	I_F-I_D	Flood/Drought Years	Tot	Real probability
1	Extreme Fld	≥10	1967,2001	2	4.3%
2	SevereFld	[6.67,10)	1972,1977,1999,2000	4	8.7%
3	Mild Fld	(2.5,6.67)	1962,1973,1983,1988,1997,2006	6	13%
4	Normal	[-2.5,2.5]	1963,1964,1965,1968,1969,1971, 1975, 1978,1982,1986,1987,1990, 1991,1992, 1994,1995,1996,1998, 2002,2004,2005, 2007	22	48%
5	Mild Drt	(-6.67,-2.5)	1966,1970,1980,1981,1989,2003	6	13%
6	Severe Drt	(-10,-6.67]	1974,1984,1985,1993	4	8.7%
7	Extreme Drt	≤-10	1976,1979	2	4.3%

Spatial Rainfall Distribution of Floods/Droughts

Figure 5 displays the composite rainfall percentage anomalies of (a) drought years (b) flood years. In order to show the contrast between the two mean anomalies, the difference between the composite dry and wet years is computed (Figure 5 (c)), where the shaded area is the significant region as a result of statistical *t*-test over 0.05 level of confidence. The composite dry years are; 1974, 1976,1979,1984,1985 and 1993, and the composite wet years used are; 1967, 1972,1977,1999,2000 and 2001.

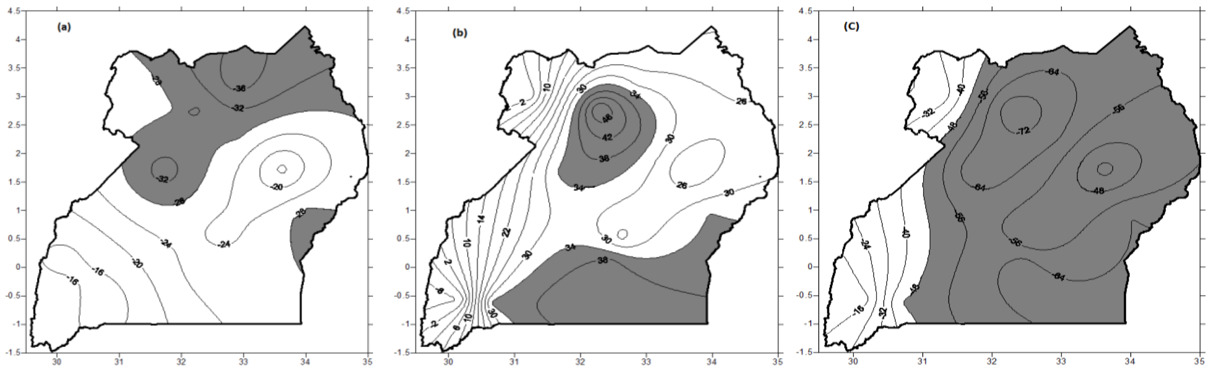
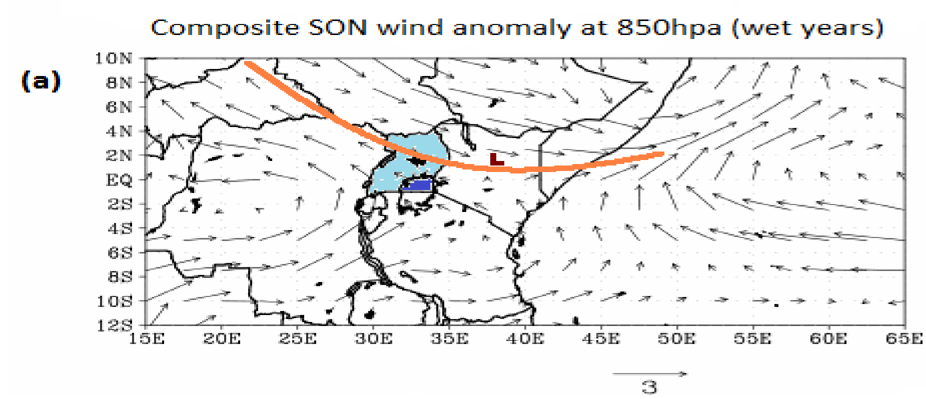


Figure 5: Composite rainfall percentage anomalies **(a)** Drought years **(b)** Flood years, and **(c)** Difference between the dry composite and wet years, where the shaded areas are significant over 0.05 level of confidence. Contours are at 4% interval.

Results suggest that the anomaly rainfall intensity in the floods is stronger than that in the droughts for having larger absolute values. The rainfall anomaly over most parts of Uganda is generally positive, except for Kasese area (southwestern) which is negative during floods (Figure5 (b)). Figure 5 (a) shows that SON drought events are more pronounced in the northern part of the country as opposed to the rest of the country. On the other hand, Figure 5 (b) reveals that the regions which have high flood incidences include; Lake Victoria basin, extending to the eastern parts of Uganda and the regions close to Lake Kyoga, stretching northward. This concurs with the trend of flood events over the region (Gruntfest and Handmer, 2001).

Circulation Anomaly Patterns Associated With Wet and Dry Events of SON

Wind



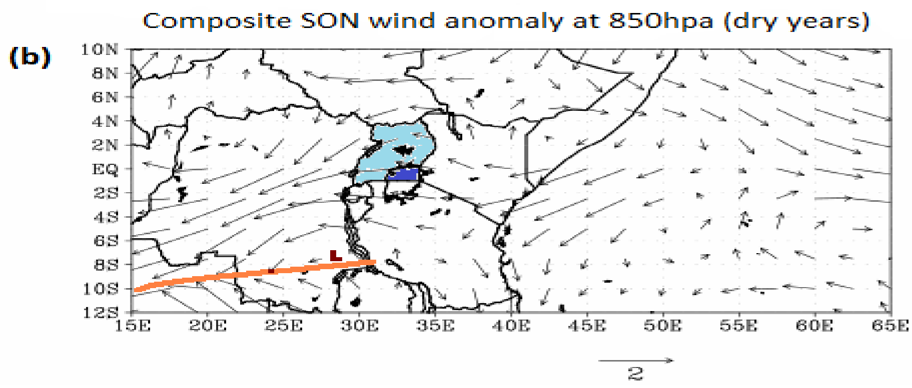


Figure 6: Composite wind anomaly vectors (ms^{-1}) at 850 hpa for **(a)** wet years, showing anomaly convergence, L over the study region **(b)** dry years, with L outside the study region**.**

The composite wind anomaly vectors for the wet and dry years shown in Figure 6 (a) and (b), respectively. During wet years, the circulation anomaly over the study area is characterized by wind convergence (zone marked L) at 850 hpa, whereas in the dry years, the anomaly convergence zone is far away from the study area. At 200hpa, the region is dominated by easterlies during wet years, as oppose to the dry years which are dominated by westerly wind (Figure 7 (a) and (b)).

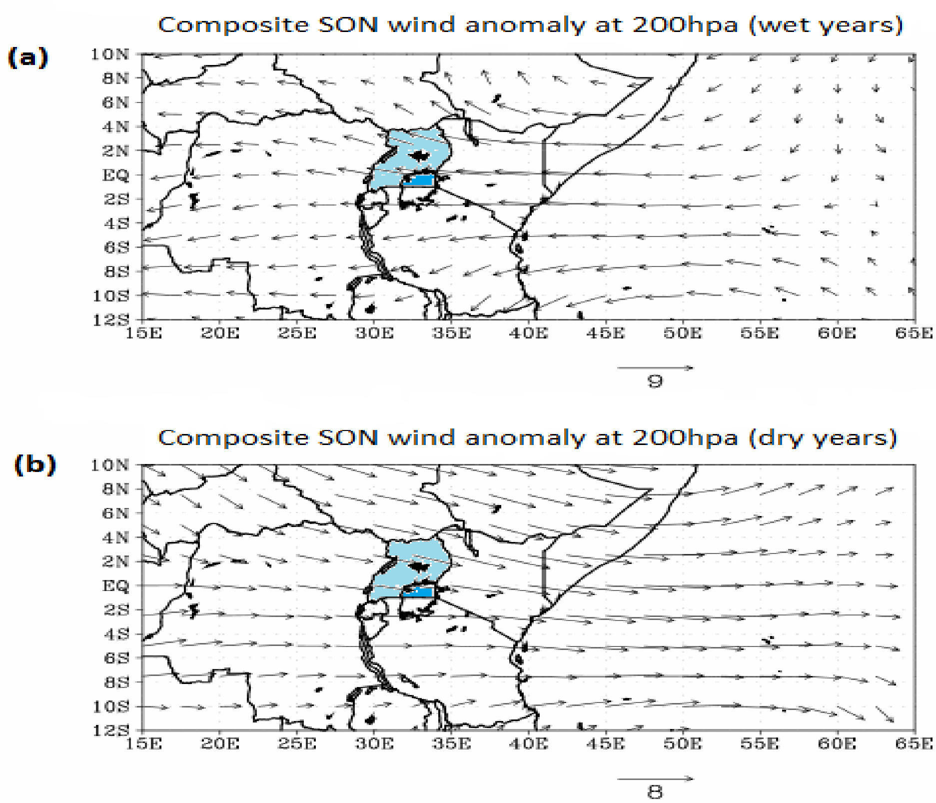
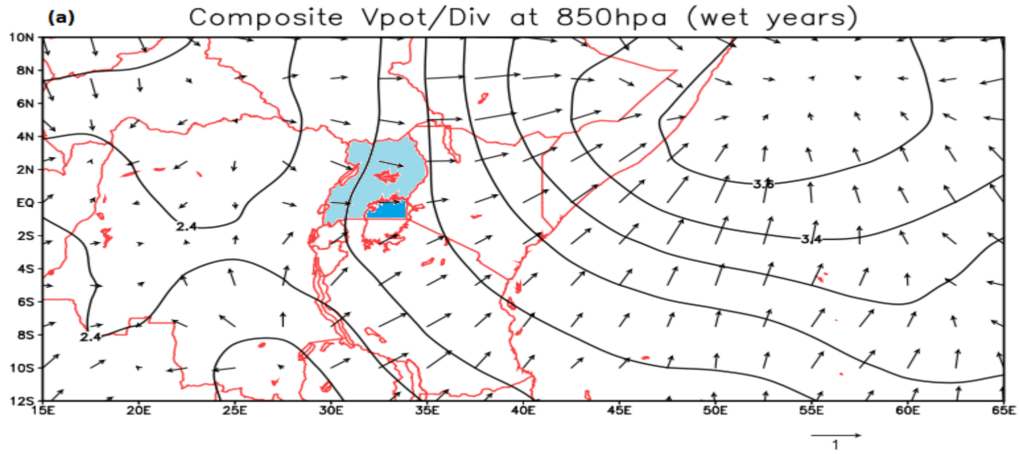


Figure 7: Composite wind anomaly vectors (ms^{-1}) at 200 hpa for **(a)** wet years **(b)** dry years

Velocity Potential/Divergence



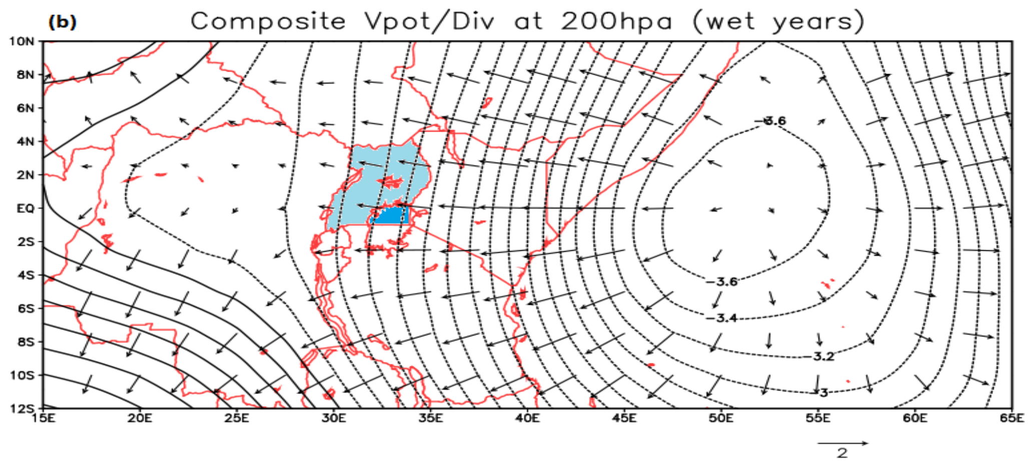
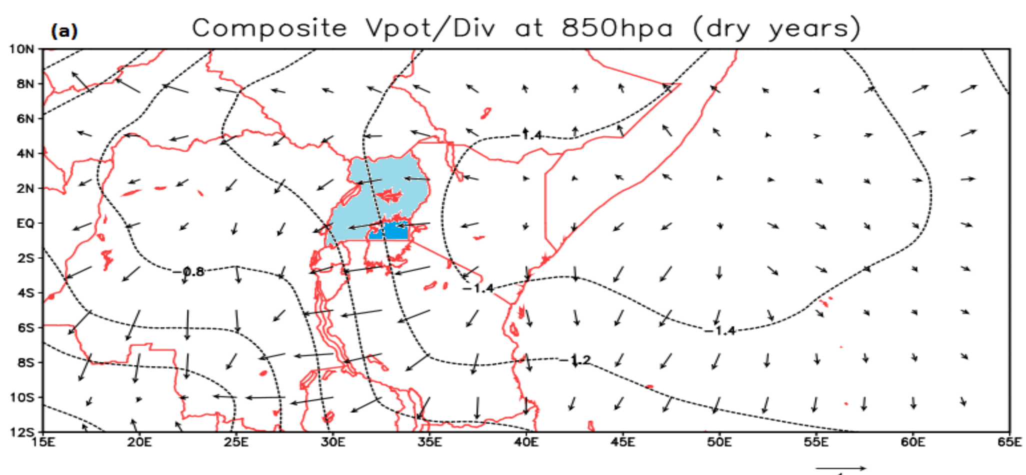


Figure 8: Composite mean anomaly of velocity potential ($x10^6 m^2 s^{-1}$)/ divergent (convergent) wind at **(a)** 850hpa and **(b)** 200hpa, for wet years. (Contours represent velocity potential and are at $0.2x10^6$ $m^2 s^{-1}$ intervals. Vectors show divergence/convergence of wind. Shaded is the study area*)*.

The anomaly fields of velocity potential/divergence (convergence) associated with the composite wet and dry years are analyzed. The wet years show wind convergence at low level (a), and divergence at upper level (b), especially over the western Indian Ocean and the study area, thus the composite wet years are associated with rising motion over the region.



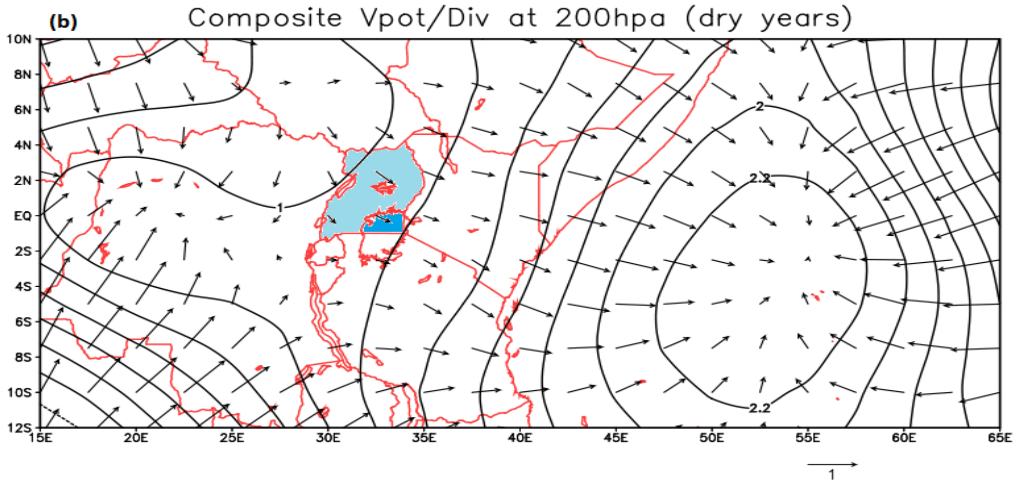


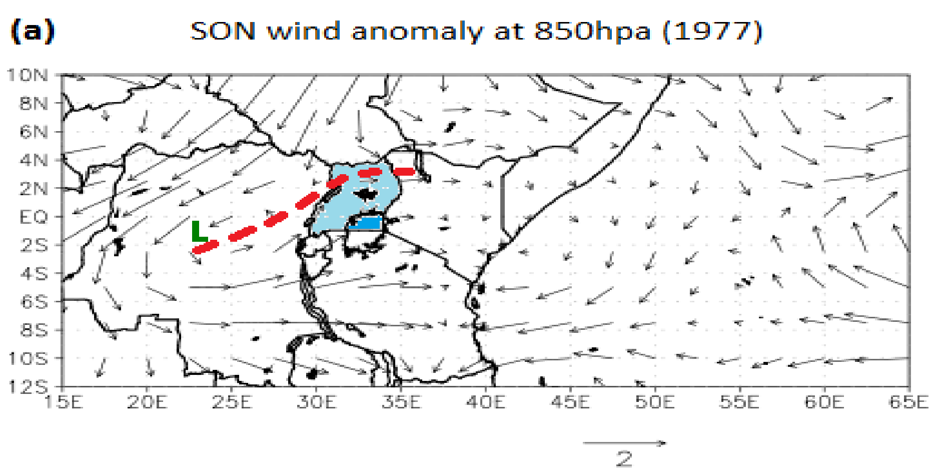
Figure 9: Composite mean anomaly of velocity potential ($x10^6 m^2 s^{-1}$)/ divergent (convergent) wind at **(a)** 850hpa and **(b)** 200hpa, for dry years. (Contours represent velocity potential and are at $0.2x10^6\ m^2 s^{-1}$ intervals. Vectors show wind divergence/convergence. Shaded is the area of study).

The mean anomaly fields of velocity potential/divergence for the dry years show results which are opposite to the wet counterpart, for example at low level (high level), i.e at 850 hpa (200 hpa); it is characterized by divergence (convergence) over the western Indian Ocean and the study area. The composite dry years are therefore associated with sinking motion over the region.

Convergence at low level gives rise to vertical stretching, whereas divergence results in vertical shrinking, which suppresses convection due to subsidence (Barry and Chorley, 2003).

Case Study

Two years were considered for further investigation, one wet year (1977) and a dry year (1984) (severe drought (1984) and severe flood (1977), Table 3) in order to depict the anomalous patterns of wind and velocity potential/divergence associated with the wet year (1977) and the dry year (1984).



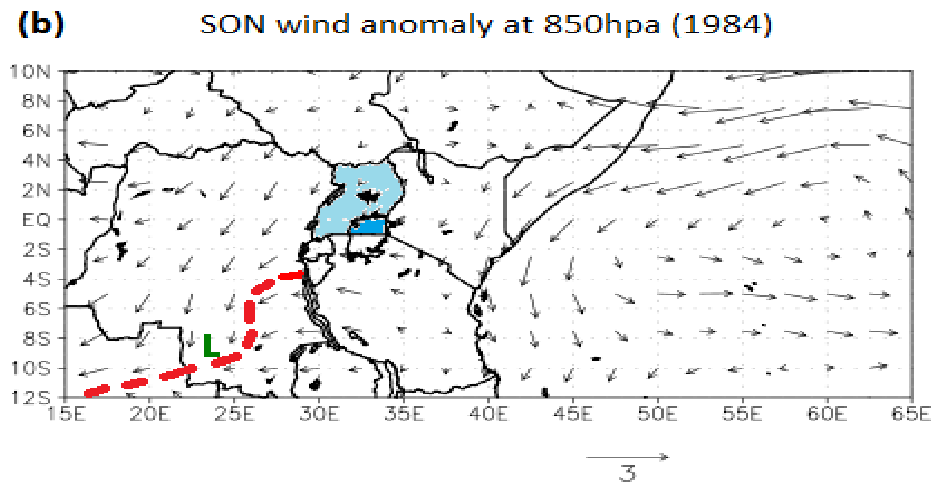


Figure 10: Wind anomaly vectors at 850hpa **(a)** Wet year, 1977 and **(b)** Dry year, 1984. The anomaly convergence zone is marked L (dotted line).

Results reveal that both dry (1984) and wet (1977) anomaly patterns have similar characteristics as those of the composite dry and wet years, where the anomaly convergence zone for 1977(1984) is within (outside) the study region. Velocity potential/divergence for the years 1977 and 1984 (figures omitted) show results with similar characteristics to the corresponding composite years of wet and dry events.

Summary and Conclusion

The Z-index used in the study has been able to capture to a greater extent the actual events of floods and droughts which have been experienced over Uganda. Basing on the grading from the set of indices, the SON heavy flood/drought events in the period 1962-2007 were identified. The six heavy flood years include 1967, 1972, 1977, 1999, 2000 and 2001 and the drought years include 1974, 1976, 1979, 1984, 1985 and 1993. Results further reveal that dry events were dominant before the year 1993.However after this year (1993), there were more cases of wet events as compared to the dry events.

Analysis of the drought and flood years with respect to the different variables including wind, velocity potential and divergence/convergence vectors revealed that the drought (flood) years were characterized by divergence (convergence) in the lower troposphere and convergence (divergence) at the upper level, implying sinking (rising) motion, especially over the western Indian Ocean and the study area. The anomaly convergence zone was identified within (outside) the region of study during flood (drought) years.

The statistical analysis approaches used in the study provided insights into the SON rainfall anomaly associations with respect to floods and droughts. However, further study based on numerical simulations will be done to fully understand the physical mechanisms responsible for the observed events of floods and droughts.

Acknowledgements

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