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Abstract: Our objective was to understand and describe local spatial and temporal variability in precipitation around Kibale National Park, a tropical forest area of high conservation value. Continental or regional-scale trends are often relied upon to make policy and management decisions, but these analyses are often at too coarse a resolution to capture important variability at a finer scale where management actions operate. Monthly rainfall data derived from ten long-term station records (1941-1975) were used to evaluate local spatiotemporal variability in seasonal and annual rainfall for the area surrounding Kibale National Park. The magnitude, direction and significance of trends in seasonal and annual rainfall within the area surrounding the park were identified using the Mann-Kendall trend test and Sen's slope estimator. The standardized precipitation index was calculated at 3- and 12-month periods to identify areas of relative wetness or dryness. Analysis of annual trends and precipitation indices indicated that patterns in annual time series do not reflect the direction and magnitude of seasonal trends nor the spatial variability in intra-annual rainfall at the local scale. Significant negative trends in the seasonal long rains, following dry season and short rains were identified at stations west of Kibale, while significant positive trends in the seasonal short rains occurred at stations north of the park. Stations along the western park boundary tended to have more years in which the two dry seasons were abnormally dry than those stations located further from the park.

Key words: Albertine Rift, East African rainfall, Kibale National Park, precipitation variability, Uganda climate

INTRODUCTION

Monthly rainfall data derived from ten long-term station records (1941-1975) were used to evaluate local spatiotemporal variability in seasonal and annual rainfall for the area surrounding Kibale National Park. Western Uganda is part of the Albertine Rift region of Africa, one of the world's hotspots for biodiversity (Plumptre *et al.*, 2007; Cordeiro *et al.*, 2007). This area, characterized by small isolated pockets of protected forests and interstitial fragments of forests and wetlands, is surrounded by dense, growing human populations, and intensive agriculture (Brooks *et al.*, 2006; Hartter, 2010). Outside the protected areas of this region, rural livelihoods depend almost exclusively on rain-fed agriculture and locally derived natural resources, both of which are sensitive to variability in the amount and timing of seasonal rainfall. Previous regional- and continental-scale studies suggest that total annual rainfall has increased over much of East Africa since the 1980's (Nicholson, 1993), and the decades-long decline in rainfall characteristic of more arid regions north of Uganda have yet to significantly impact interior, equatorial Uganda (Basalirwa, 1995). However, spatial and temporal patterns in equatorial African rainfall are highly variable (Basalirwa, 1995) and current classifications of regional seasonal and annual rainfall patterns may be too coarse for relevance to local land use and management (Rijks, 1968; Thornton *et al.*, 2009). In addition, the lack of long-term, high-density instrumental climate records in this part of Africa adds to the difficulty in determining local and regional variability (Verschuren *et al.*, 2000).

There is growing interest in the academic community and policy makers to understand the spatio-temporal variability in rainfall within this region of Africa and the

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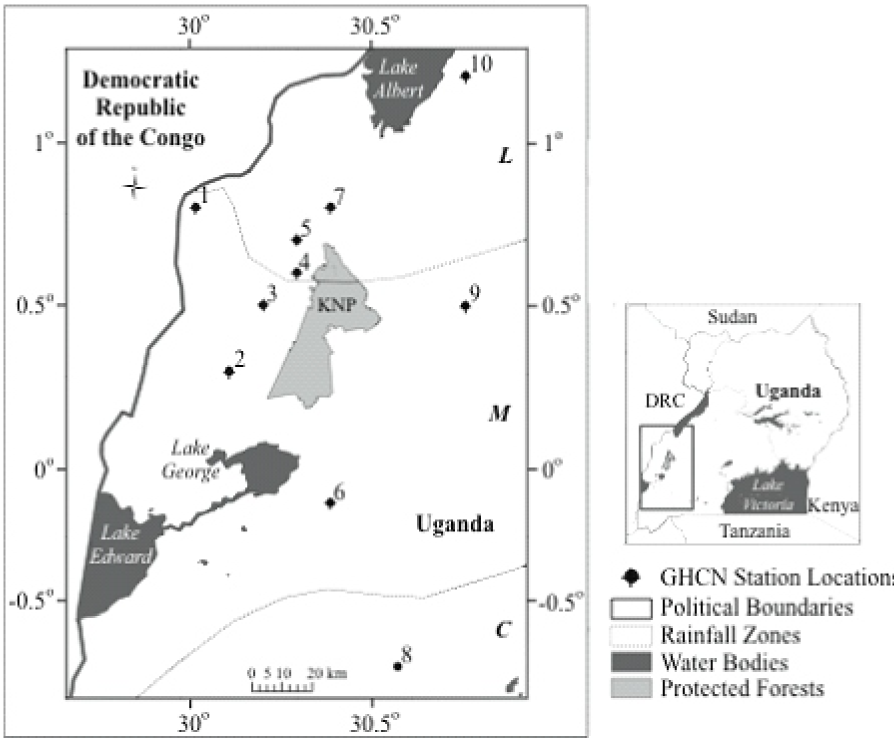

Fig. 1: Map of study region with political boundaries, water bodies, station locations and delineated climatological rainfall zones (*C*, *L* and *M*) from Basalirwa (1995). Station data are from Global Historic Climate Network data for 1941-1975

potential impacts on agro-ecological communities (Hannah *et al*., 2002; Walther *et al*., 2002; van Vliet and Scwhartz, 2002; McClean *et al*., 2005). Agricultural products are the main economic resource in Uganda, where over 80% of the population's livelihoods are based on rain-fed agriculture (Mukiibi, 2001) and understanding local trends in rainfall is very important for planning and management of subsistence and cash crops (Manning, 1956; Huxley, 1965; Hanna, 1971, 1976; Phillips and McIntyre, 2000; Fischer *et al*., 2005). However little attention has been paid to the investigation of local rainfall patterns within East African sub-regions (Phillips and McIntyre, 2000; Thornton *et al*., 2009), which are very complex due to topography, proximity to large inland water bodies, and the existence of large tracts of forest (Myers, 1991; Indeje *et al*., 2000).

Since recent studies have applied a relatively broad-brush approach to characterize East Africa rainfall variability, there is a need for more fine-scale scientific information to assist agro-ecological communities and land use managers (e.g., park managers) in developing effective adaptive management. This study evaluates such fine-scale climatological trends and variability in seasonal and annual precipitation at stations surrounding Kibale National Park (elevation: 1110-1590 m, 795 km^2), a forest park in western Uganda.

Study area: Kibale National Park (Kibale) lies just north of the equator and has an average annual temperature range of 15-23ºC and an average annual rainfall about 1552 mm for the period of record 1903-2007 (Struhsaker, 1997; Chapman, unpublished data). It lies approximately 190 km west of Lake Victoria between Lake Albert to the north and Lakes Edward and George to the south. The stations used in this study are located within natural and anthropogenic landscapes surrounding Kibale (Fig. 1), west of east African savannas near the transition between wet equatorial and moist subtropical precipitation regimes. Elevation across this part of Uganda generally increases from the east (elevation: ~1000 m) to the west toward the Rwenzori Mountains (elevation: >5000 m) along the western border of Uganda and the Democratic Republic of Congo (DRC).

This area represents a diverse landscape of variable topography, disparate and discontinuous land cover types, and seasonally distinct forcings on weather patterns, all of which influence the distribution of rainfall at fine spatial and temporal scales. While the seasonal rainfall varies significantly in response to the north-south migration of the Intertropical Convergence Zone (ITCZ), elevation and proximity to large bodies of water are reported to account for sub-regional and sub-seasonal rainfall variability (Ogallo, 1989; Basalirwa, 1995; Nicholson and Kim, 1997; Indeje *et al*., 2000).

Due to the equatorial location of Kibale, the majority of the total annual rainfall is received during the months corresponding to the biannual migration of the ITCZ across the equator (Fig. 2). This results in a bi-modal rainfall pattern consisting of two rainy seasons separated by two dry seasons. The resulting two wet periods - 'long rains' and 'short rains'- are separated by two dry periods - 'first dry' and 'second dry' - corresponding to the time in which the ITCZ migrates south and north of the region. Given the dominant seasonal mode in intra-annual rainfall variability, annual rainfall can be divided into four distinct seasons of alternating wet and dry climatic conditions (S1-S4) (East African Meteorological Department, 1965).

Other synoptic-scale factors, such as the movements of moist and dry air masses in respond to anticyclonic and monsoonal air flow, explain the majority of intra-annual variability in regional rainfall patterns while reoccurring events, such as El Niño Southern Oscillation (ENSO), explain the majority of extreme rainfall anomalies (Ogallo, 1989; Basalirwa, 1995; Nicholson and Kim, 1997; Indeje *et al.*, 2000). Superimposed upon the seasonal rainfall cycle are localized, high frequency temporal fluctuations in response to topographic forcings on sub-synoptic scale, low-level circulation (Basalirwa, 1995). Several studies have delineated East Africa into homogenous climatological rainfall zones, incorporating influences on east African rainfall at finer scales (Ogalla, 1980, 1989; Basalirwa, 1995). In particular, Basalirwa (1995) identified sub-national zones of homogenous rainfall regimes for all of Uganda accounting for sub-synoptic scale influences on the distribution of seasonal rainfall.

METHODOLOGY

To identify local rainfall variability in western Uganda, this study quantifies trends and variability in total seasonal and annual rainfall derived from the Global Historic Climate Network (GHCN) monthly rainfall observations at ten stations surrounding Kibale National Park for the period of record 1941-1975 inclusive (Fig. 1). The period of record was chosen to be coincident with the period of record used by Basalirwa (1995) to identify Ugandan rainfall sub-regions and represents the most complete record of rainfall observations for this part of Uganda (Table 1). Station records were evaluated for discontinuities by inspection of each time series and station metadata were then tested for homogeneity using the Student's t-test and the Mann-Whitney test (von Storch and Zwiers, 1999) and found to be homogenous.

The magnitude, direction and significance of trends in total seasonal and annual rainfall over the period of record were identified at each station. In many cases, parametric and non-parametric methods of trend identification have been shown to perform similarly. However, small variations from normality within a dataset can reduce the power of parametric statistical methods, such as a linear regression (Helsel and Hirsch, 1992; Longobardi and Villani, 2009). Therefore, trends were identified using the Mann-Kendall test, a non-parametric test for data interdependence over time in which normality is not assumed (Mann, 1945; Kendall, 1975). A threshold confidence interval of 90% was used for significance and significant trends in annual and seasonal rainfall were reported for the 99, 95 and 90% confidence intervals.

The Mann-Kendall test (Mann, 1945; Kendall, 1975) is used here to determine the presence of significant trends in total annual and seasonal rainfall (x) with time (t). Kendall's S statistic is calculated for data pairs (x, t) over the period of record length n years. Kendall's S is used to evaluate the dependence of x on t, such that $S = P - M$ where P is the number of pairs in which x increases with t and M is the number of pairs in which x decreases with t (Helsel and Hirsch, 1992).

The null hypothesis (H_0) that no correlation exists between y and t, or no trend, results in an $S = 0$ and a probability $p\ [x_j > x_i] = 0.5$ as t increases ($t_j > t_i$). A trend exists and H_0 is rejected for time series in which $p\ [x_j > x_i] \neq 0.5$ for $t_j > t_i$ and S is significantly different from zero. In the case where H_0 is rejected in favor of an alternative hypothesis (H_1), a positive trend occurs for P>M and a negative trend is assumed for P<M.

Table 1: Name, location, and rainfall zones for rainfall stations used in this study. Station numbers and rainfall zones correspond to those shown in Fig. 1. Station data are from Global Historic Climate Network data for 1941 – 1975

Common name	Station no.	Longitude (ºE)	Latitude (ºN)	Elevation (m)	Rainfall Zone*
Bundibugyo	1	30.0	0.8	920	*M*
Bunyaruguru	2	30.1	0.3	1219	*M*
Kisomoro	3	30.2	0.5	1585	*M*
Kyenjojo	4	30.3	0.7	1524	*L*
Fort Portal	5	30.3	0.6	1539	*L*
Kitwe	6	30.4	-0.1	1372	*M*
Butiti	7	30.4	0.8	1542	*L*
Mbarara	8	30.6	-0.6	1443	*C*
Matiri	9	30.8	0.5	1341	*M*
Buhuka	10	30.8	1.2	1067	*L*

*: Climatological rainfall zones from Basalirwa (1995)

Table 2: Wet and dry categories based on the standardized precipitation index

SPI	Category
> 2.00	Extremely wet
1.50 to 1.99	Severely wet
1.00 to 1.49	Moderately wet
0.99 to -0.99	Near normal
-1.00 to -1.49	Moderately dry
-1.50 to -1.99	Severely dry
< -2.00	Extremely dry

The probability that S differs significantly from zero for time series size n > 10 is calculated using the normalized, large sample approximation for Z:

$$Z = \begin{cases} \dfrac{s-1}{\sigma_s} & if\ S > 0 \\ 0 & if\ S = 0 \\ \dfrac{S+1}{\sigma_s} & if\ S < 0 \end{cases}$$

where, σ_s is the standard deviation. The significance of Z, and the dependence of x on t, is evaluated against the two-tailed probability of exceedance for α = 0.01, 0.05 and 0.10 in which the null hypothesis is rejected for $|Z| > Z_{\alpha/2}$.

The direction and magnitude of significant trends were then calculated using Sen's slope estimator (Sen, 1968). The slope and magnitude of trends in total annual and seasonal rainfall over the period of record for stations near Kibale, Uganda, are identified following Sen (1968):

$$Q = \frac{x_j - x_i}{t_j - t_i}$$

where, Q' is the slope between x_i and x_j at times t_i and t_j for $i < j$. Sen's slope Q is assigned the median slope for N' number of slopes calculated:

$$Q = \begin{cases} Q_{[(N'+1)/2]} & if\ N' is odd \\ \dfrac{\left(Q_{[N'/2]} + Q'_{[(N'+2)/2]}\right)}{2} & if\ N' is even \end{cases}$$

Lastly, the standardized precipitation index (SPI; Mckee *et al.*, 1993) was calculated for annual (12 month scale) and seasonal (3 month scale) time series at each station to identify the relative tendency toward above or below normal annual and seasonal precipitation (Table 2). Rainfall time series data (x) were fitted to a gamma distribution defined by $\Gamma(\alpha)$ and represented by the following cumulative probability function:

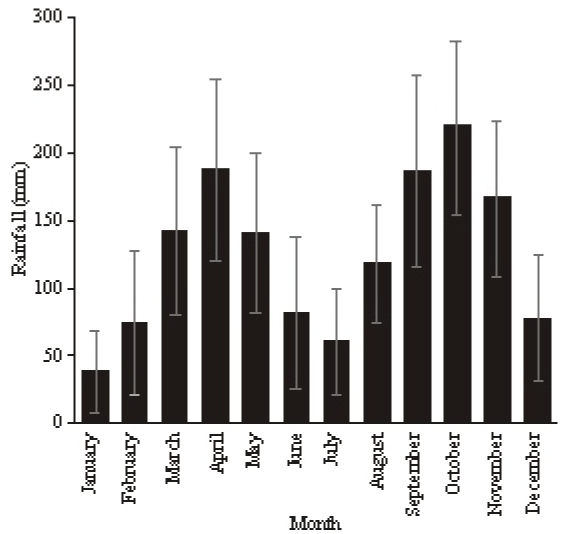

Fig. 2: Average total monthly rainfall and standard deviations (mm) at Fort Portal, Uganda (station 5) for the period of record 1903-1979

$$G(x) = \int_0^x g(x)dx = \left[\beta^\alpha \Gamma(\alpha)\right]^{-1} \int_0^x x^{\alpha-1} e^{-x/\beta} dx$$

where α and β are positive, non-zero parameters that represent the shape of the distribution (Mckee *et al.*, 1993).

Since $G(x)$ is undefined for x = 0, which may occur in rainfall particularly during the dry season, q is the probability of $x_i = 0$ and $G(x)$ becomes:

$$H(x) = q + (1-q)G(x)$$

The SPI values for each time period j = 3 and 12 months are a set of standard normal random variables (Z) with a $Z = 0$ and variance of 1 derived from the transformation of following the algorithm described by McKee *et al.* (1993, 1995).

RESULTS AND DISCUSSION

Although the temporal pattern of intra-annual rainfall is largely driven by synoptic-scale processes, temporal patterns vary spatially in response to sub-synoptic or mesoscale processes. The stations used in this study fall within three of the homogenous rainfall zones identified by Basalirwa (1995) in which the localized effects of topography (C and L) and proximity to inland water bodies (M) were important factors in the distribution of rainfall, particularly during the dry seasons (Fig. 2; Basalirwa, 1995). Although each zone represents a relatively homogenous rainfall regime, results of

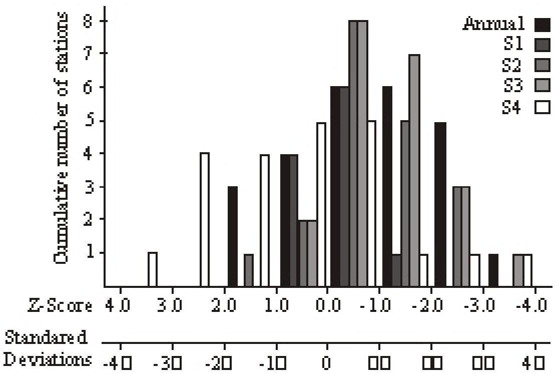

Fig. 3: Cumulative distribution of positive ($Z > 0.00$) and negative ($Z < 0.00$) trends in total annual and seasonal rainfall derived from GHCN station observations for 1941 – 1975 with respect to standard deviation from the mean

statistical analyses indicated that the trends and tendency toward above or below normal seasonal rainfall vary within each zone.

Significant trends in total annual rainfall over the period 1941-1975 were identified at 70% of stations analyzed (Fig. 3). The majority of these trends were negative and located within, or along the border of Basalirwa's (1995) zone *M*. While positive trends in total annual rainfall were identified at stations within zones *L* and *C*, only one was significant (Table 3A). Although the annual trends varied in both direction and magnitude, the probability of wet and dry annual cycles for most stations fell within the range of 'near normal' (-0.99 < SPI < 0.99; Table 4A). This indicates that over the period of record, the likelihood of moderate, severe or extreme wet or dry years was low throughout the study area. This is in contrast to the distribution of above and below normal seasonal rainfall over the period of record (Fig. 4 and 5).

While the annual trends in station data conformed to Basalirwa (1995) rainfall zones, trends in total annual rainfall are a poor indicator of rainfall trends at practical temporal scales. In most cases, the significance of the magnitude of trends in total annual rainfall did not reflect that of the seasonal trends, which for stations 5, 8, 9, and 10 varied, not only in magnitude but also direction (Table 3). Furthermore, the distribution of SPI values indicated no distinction between or within rainfall zones in terms of the occurrence in abnormally wet or dry years (Table 4A).

The first dry season (S1) typically begins during early December and lasts through late February when the ITCZ approaches the area from the south. During this period, rainfall patterns are highly local and tend to be limited to areas in close proximity to large, inland water bodies (Basalirwa, 1995). Over the period of record, no significant trends in S1 rainfall were identified (Fig. 3, Table 3B). Although SPI values for most stations within

Table 3: Annual and seasonal time series and trend statistics at western Uganda GHCN stations over the period of record from 1941- 1975. Time series mean standard deviation (SD), and linear trend statistics given in units of mm. Significant trends at the 90% confidence level in italics

	Station and rainfall zone									
	M					L				C
Statistics	1	2	3	6	9	4	5	7	10	8
(A) Annual:										
$\bar{x}$	1281	1057	1474	1333	1224	1308	1559	1476	1116	935
SD	295	261	324	395	209	227	261	228	169	153
Trend	- 385	- 348	- 667	- 371	- 186	- 308	215	229	41	114
Z-score	- 2.93	- 2.49	- 3.88	- 1.78	- 2.08	- 2.38	1.4	1.78	0.61	1.19
(B) S1:										
$\bar{x}$	203	154	216	214	159	173	203	163	114	187
SD	99	75	105	136	82	69	81	73	62	74
Trend	- 22	- 28	- 44	- 46	52	- 47	38	6	- 27	9
Z-score	- 0.28	- 0.71	- 0.87	- 0.89	0.99	- 1.33	0.72	0.26	- 0.61	0.26
(C) S2:										
$\bar{x}$	365	345	447	418	385	426	494	509	361	312
SD	122	120	160	162	88	107	103	126	99	88
Trend	- 178	- 221	- 204	- 17	- 113	- 100	22	69	- 36	- 27
Z-score	- 2.71	- 2.79	- 2.55	- 0.1	- 1.95	- 1.4	0.422	1.19	- 0.75	- 0.6
(D) S3:										
$\bar{x}$	353	194	260	220	223	238	285	291	231	114
SD	152	90	75	87	82	75	88	95	66	57
Trend	- 244	- 93	- 105	- 79	- 133	- 73	- 14	0	- 60	12
Z-score	- 3.34	- 2	- 2.93	- 1.89	- 2.72	- 1.65	- 0.25	0.03	- 1.76	0.37
(E) S4:										
$\bar{x}$	360	364	553	481	458	475	579	515	410	319
SD	121	106	169	179	146	103	152	137	118	92
Trend	- 25	- 50	- 207	- 60	15	- 47	204	213	133	115
Z-score	- 0.48	- 0.83	- 3.16	- 0.43	0.16	- 0.91	2.27	3.23	2.08	2.37

Table 4: Probability of wet and dry period occurrence (%) for annual and seasonal time series at western Uganda GHCN stations based on SPI-12 and SPI-3 values for the period of record 1941-1975. Categories in which the probability of occurrence for all stations was zero are omitted

	Station and rainfall zone									
	M					L	C			
Category	1	2	3	6	9	4	5	7	10	8
(A) Annual:										
Near normal	97.1	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Moderately dry	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(B) S1:										
Moderately wet	0.0	0.0	0.0	2.9	0.0	0.0	0.0	0.0	0.0	0.0
Near normal	65.7	77.1	74.3	88.6	68.6	57.1	62.95	7.18	5.7	100.0
Moderately dry	22.9	14.3	20.0	5.7	20.0	34.3	20.0	31.4	14.3	0.0
Severely dry	8.6	8.6	5.7	2.9	8.6	8.6	11.4	11.4	0.0	0.0
Extremely dry	2.9	0.0	0.0	0.0	2.9	0.0	5.7	0.0	0.0	0.0
(C) S2:										
Severely wet	0.0	0.0	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Moderately wet	8.6	14.3	11.4	14.3	2.9	11.4	5.7	11.4	5.7	11.4
Near normal	91.4	85.7	82.9	85.7	97.1	88.6	94.3	88.6	94.3	88.6
Moderately dry	0.0	0.0	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(D) S3:										
Moderately wet	11.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Near normal	85.7	85.7	85.7	94.3	91.4	91.4	100.0	100.0	100.0	74.3
Moderately dry	0.0	14.3	14.3	5.7	8.6	8.6	0.0	0.0	0.0	20.0
Severely dry	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.7
(E) S4:										
Severely wet	2.9	2.9	8.6	2.9	2.9	2.9	5.7	5.7	0.0	0.0
Moderately wet	0.0	14.3	25.7	17.1	25.7	11.4	22.9	8.62	0.0	14.3
Near normal	97.1	82.9	65.7	80.0	71.4	85.7	71.48	5.78	0.08	5.7

the area fell within the near-to below-normal rainfall categories, there were inter- and intra-zonal differences in the number of years in which S1 was drier than normal (Table 4B). Within zone *M* (Fig. 4), S1 was drier than normal 35% of the time at stations located to the northwest and east of Kibale compared to an occurrence of <25% at the other stations within zone *M*. Station 6 to the south of Kibale had the fewest years with an abnormally dry S1 with a moderately wet S1 occurring nearly 3 % of the time. Within zone *L* (Fig. 5), station 10, located near Lake Albert, had a lower probability of S1 being dry than stations located along the northern boundary of Kibale, closest to zone *M*. This intra-zonal variability is most likely indicative of the localized influence of nearby water bodies and elevation on dry season rainfall.

The long rainy season (S2) begins in early March as the ITCZ approaches from the south, leading to an increase in the amount and frequency of rainfall. Known as the 'long rains', rainfall occurs in response to the convergence of southeasterly air flow from the Indian Ocean into the approaching ITCZ. The long rainy season lasts until mid-to-late May, when the ITCZ migrates north of the region (Basalirwa, 1995). Negative trends existed for the majority of the stations analyzed (Fig. 3) with significant trends limited to zone *M* (Table 3C). While positive trends in S2 rainfall amounts were identified at stations within zone *L*, none were significant. Although significant negative trends were identified at stations within zone *M*, SPI values indicated consistent normal to moderately wet conditions during S2 (Table 4C).

Season three (S3) is the second dry period within the intra-annual rainfall cycle occurring between the end of the long rains in late May and the onset of the short rains in early September. Rainfall during this period occurs primarily in response to the movement of humid air masses from the west commonly referred to as 'Congo air masses' (Basalirwa, 1995). Trend analyses indicated that most of the significant changes in rainfall were negative including all stations within zone *M* and the northernmost station in zone *L* (Fig. 3, Table 3D). Although the northwest corner of zone *M* had a significantly greater probability of a moderately wet S3 (Table 4D), stations along the western border of Kibale had a greater tendency toward moderately dry conditions during S3 (~14 %) than other stations (<10 %) in zone *M* (Fig. 4).

Beginning in September, the second approach of the ITCZ, this time from the north, ushers in monsoonal air flow from the northeast, resulting in a second wet season through the end of November (S4) known as the 'short rains' (Basalirwa, 1995). The majority of the significant positive trends in seasonal rainfall occurred during S4 (Fig. 3) but were limited to zones *L* and *C* (Table 3E). The characteristic rainfall pattern during S4 ranged from near normal to severely wet over the period of record at all stations (Fig. 4 and 5). However stations that tended to have similar SPI distributions during the other seasons, such as stations 2 and 3 in *M* and 5 and 7 in *L*, differed in the distribution of SPI value between event categories (Table 4E).

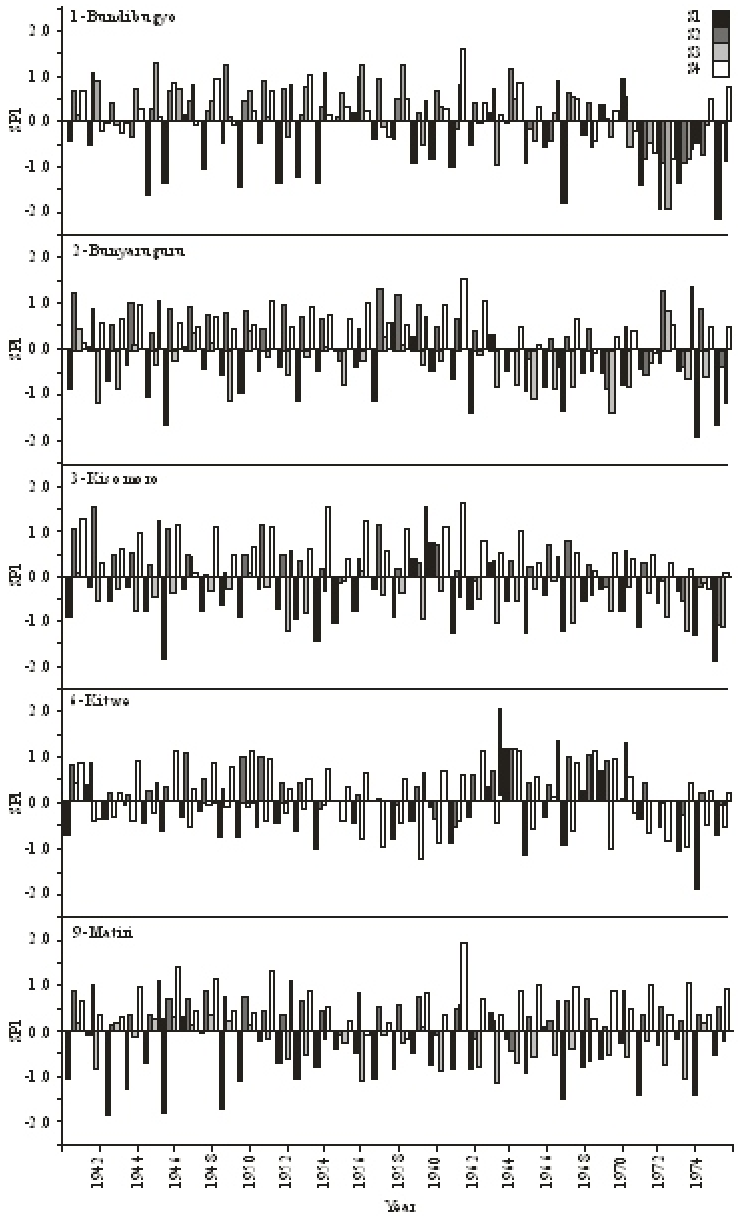

Fig. 4: Time series of SPI-3 (seasonal) for GHCN stations located within Basalirwa (1995) rainfall zone *M* over the period of record 1941- 1975

CONCLUSION

Our results indicate that the amount and distribution of rainfall within western Uganda are far more complex than previous regional analyses indicate. While an emphasis on total annual rainfall may be appropriate at national, regional or continental spatial scales, localized trends and intra-annual variability in seasonal rainfall is of greater concern to local farmers and conservation managers. Given the lack of local-scale rainfall analyses within the vicinity of Kibale, policy and management decisions are based on information derived from continental or regional-scale studies, which may not reflect important variability at a finer scale where management operates.

Although the homogenous rainfall zones identified by Basalirwa (1995) adequately describe rainfall patterns for western Uganda at the annual level of analysis, spatial patterns in seasonal rainfall within western Uganda are not homogenous within such zones. SPI values varied

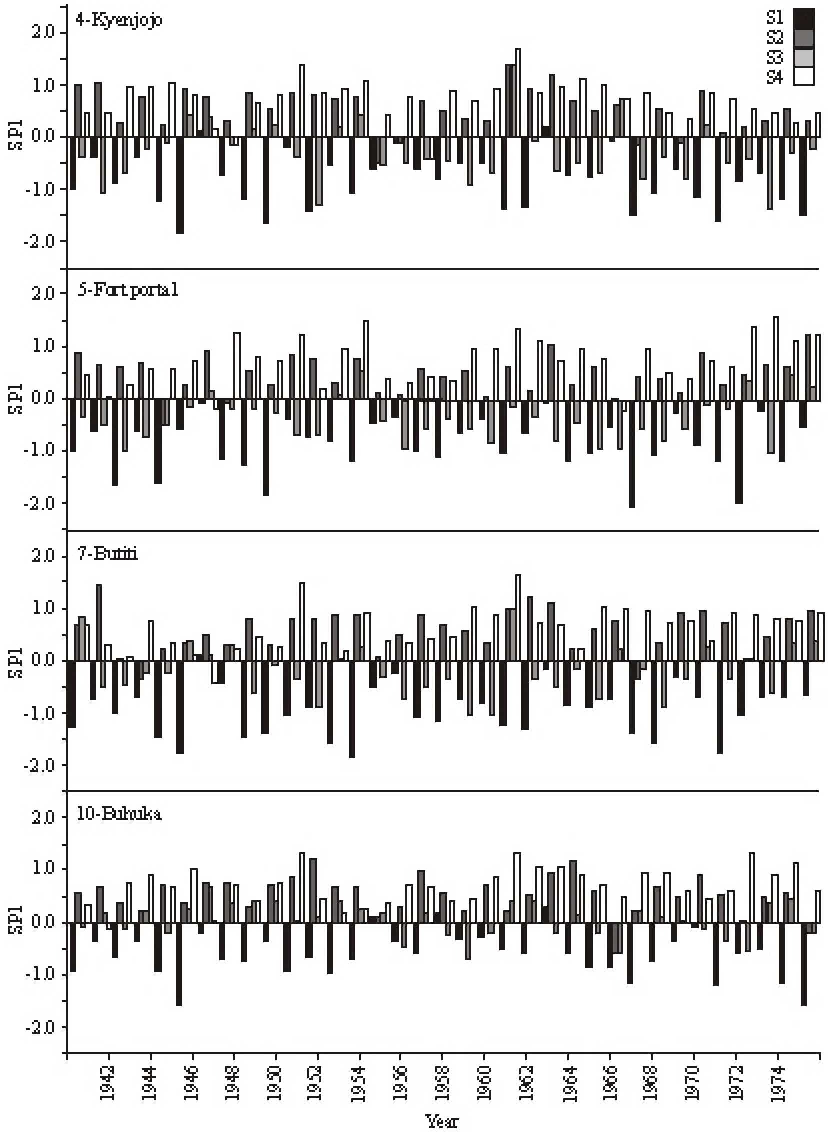

Fig. 5: Time series of SPI-3 (seasonal) for GHCN stations located within Basalirwa (1995) rainfall zone *L* over the period of record 1941-1975

between stations, particularly within zone *M*, and the climatological trends in annual rainfall differed in magnitude and direction from seasonal trends. Therefore, the utility of these designations may be limited for practical applications and may result in inappropriate or untimely land-use decisions.

Given the dependence of rural communities on rain-fed agriculture and the high degree of spatial variability with respect to trends and variability in total seasonal rainfall, identifying intra-annual rainfall patterns at the local level is crucial for use in planning, training, and on-the-ground applications in resource management and conservation. For conservation managers, trends and seasonality of rainfall will affect plants' phenology patterns. This, in turn will affect resource availability of parks, which will influence animal population trends, the intensity of crop raiding activities, possibly leading to illegal extraction of food resources by local communities. Results of local-scale rainfall analyses, disseminated to the community through education and outreach, may be used by local farmers and conservation managers to make more informed decisions regarding land use and management in an already threatened environment.

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