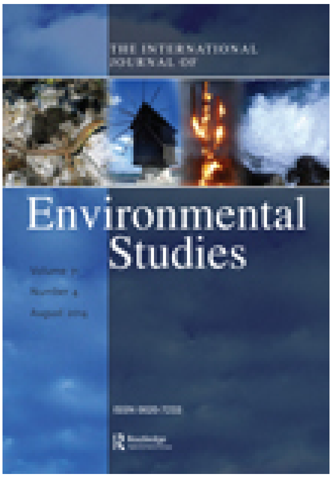

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Assessing the spatio-temporal climate variability in semi-arid Karamoja sub-region in north-eastern Uganda

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Semi-arid areas show climatic variability on a spatio-temporal scale. There are few studies on the long-term trends and intensity of this variability from East Africa. We used National Ocean and Atmospheric Administration re-analysis climate data (1979–2009) in this study. Rainfall exhibited a non-significant long-term trend. The climate of the area is variable (coefficient of variation-CV >35.0%) with spatio-temporal oddities in rainfall and temperature. A rise in minimum (0.9 °C), maximum (1.6 °C) and mean (1.3 °C) temperature occurred between 1979 and 2009. There were more months with climate variability indices below the threshold (<1.0) from 1979 to 1994 than between 1995 and 2009, with wetness intensity increasingly common after 2000, leading to the observed reduction in the recurrence of multi-year drought events. More extreme wet events (rainfall variability index >2.6) were experienced between 2004 and 2009 than between 1984 and 2003. We consider that the use of spatio-temporal climatic information for timely adjustment to extreme climate variability events is essential in semi-arid areas.

Keywords: Climate variability; Forage; Variability index; Karamoja

1. Introduction

During the last two decades, concern has been rife over the debilitating effects of climate variability, particularly in Sub-Saharan Africa where production systems are heavily rain fed. Although current global efforts are more focused on climate change, climate variability remains a formidable challenge in semi-arid regions. At the same time, scientific research into climate variability and change has increased tremendously [1]. Climate variability has had and will have wide ranging impacts on ecosystems, economies and societies' well-being [2]. These impacts include: disease [3]; food insecurity [4]; a surge in displaced populations associated with extreme events such as floods and drought [5]; insecurity [6]; and natural resource conflicts [7]. Developing countries whose resilience has already been eroded by entrenched poverty, degraded and/or threatened environments, and a host of other problems will be most affected [8]. In Uganda, the two regions that are

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considered to be at highest risk are the highland (>1500 m above sea level) and the semi-arid regions. Of the semi-arid regions, the more adverse impacts will be most felt in the Karamoja sub-region where over 80% of the population lives in abject poverty [9]. Thus, increased climate variability is an additional burden on these people. Several scientific studies indicate that the frequency and intensity of extreme weather events will increase in the future [10]. Frequency and intensity of these events will heavily burden developing countries [11], especially in Sub-Saharan Africa [12].

The African climate system is characterised by variability and it is particularly potent in the drylands [13]. Over the years, significant patterns of variability in rainfall and temperatures have been observed; for example, in the Sahel, rainfall has declined by 20–40% [15], while temperature has risen by 1.3 °C [14] since the 1960s. A similar pattern in much of West Africa [16] has been observed. For example, a significant increase in rainfall variability and seasonality, and intensification of aridity conditions during the start and end of the wet seasons has been reported in Eastern Sudan [17]. These shifts have had wide ranging impacts including: decline in vegetation cover [18], changes in land use and degradation of grazing areas [17]. Meanwhile, an intensifying dipole rainfall pattern on a decadal time-scale has been recorded in Eastern Africa [16]. This pattern is attributed to a dipole influencing increased rainfall in the northern sector and declining amounts in the southern sector [19]. Projections over East Africa are presented with mixed uncertainty regarding the scope, timing and magnitude of climate variability and change [20]. Yet, there is some agreement that there will be an increase in rainfall by as much as 10–20% [21]. Similarly, a progression in temperature rise is anticipated with an increase in the margin of 0.7 and 1.5 °C in the short term (2020–2029) and between 1.5 and 4.3 °C by the 2080s. It is also anticipated that the severity and frequency of extreme events will change [22].

Climate variability influences ecosystem functioning in dryland environments [23] by influencing vegetation patterns and water patterns [24] on both spatial and temporal scales [25]. This in turn influences the forms and patterns of use adopted by the pastoral and agro-pastoral communities that inhabit these locations such as those that occur in Uganda. This has resulted in a complex production system – pastoralism – whose functioning relies on stochastic events. Pastoralism is an adaptation to climate variability as well as a rational use of dryland environments [26]. The increased variability is, however, putting the sustainability of this production system under scrutiny. This is because variability has far reaching effects in affecting a range of strategies, e.g. judicious mobility of livestock [27], maintenance of access to key resource areas [28] and use of culturally designated grazing locations [29] often deployed by pastoralists and agro-pastoralists to circumvent constraints in their production system. Tackling the challenges that climate variability poses on pastoral and agro-pastoral communities, therefore, requires a better understanding of the frequency and intensity of variation in climate, so as to facilitate planned and strategic adaptation at local level.

In Uganda, the National Adaptation Programme of Action (NAPA) has recognised the need for strategic planning in adapting to climate variability. NAPA recognises that a failure in rains affects pasture and livestock in most pastoral areas of the country. A decrease in rainfall and shortening of the rainy season has detrimental effects on pasture and crop production [30]. Frequent droughts decrease the resilience of pastoralists and agro-pastoralists [31]. When there are excessive rains, pastures and crops are equally affected [32]. There is a dearth of knowledge with regard to the frequency and intensity of climate variability at the local level in Uganda, yet effective adaptation planning at the local level depends on access to climate information [33]. This calls for an understanding of the changes in temperature and rainfall. In particular, there is a need to establish the frequency and intensity of variability in climate at the local level. Accordingly, this study was designed to provide site-specific evidence of climate variability in Karamoja as a basis for semi-arid resource use planning and management interventions that are responsive to the inherent variability in the sub-region.

2. Materials and methods

2.1. Description of the study area

Karamoja is located in north-eastern Uganda between 1°30′–4°N and 33°30′–35°E (figure 1). The Kidepo Valley is in the north, the Kadam Range to the south and the mountains of Labwor to the west. The Moroto range is about midway between the northernmost and the southernmost features but marks the eastern boundary. Karamoja is generally known as the driest sub-region in Uganda. For many months of the year, the area dries easily and is brown. In most areas, rainfall does not exceed 800 mm per annum [34]. Temperatures in Karamoja are generally high, averaging 28–33 °C (average maximum) and 15–18 °C (average minimum). The temperatures tend to be higher during the dry season, especially from December to February. The drainage is dominated by deeply incised, sand filled, ephemeral channels flowing from east to west in the direction of the general land surface slope. Livestock forms the heart of the economics, social identity and culture in the area. Karamoja alone accounts for 19.8% of the national cattle population with about 2.3 million cattle [35]. The land is largely a dryland plateau sloping westwards to the sub-regions of Teso and Lango. The area is higher in the east where Mount Moroto imposes itself at the border with Kenya, while in the extreme northeast, Mount Zulia drops to the Eastern Rift Valley on the Kenya side and the Morungole Hills (2600 m) slightly inside the Karamoja area.

2.2. Climate data

East African climate data since the post-independence era of the 1970s suffer from many spatial and temporal discontinuities [19]. The situation is worse in areas, such as the current study region, that have long experienced civil unrest. To overcome this data problem, the research team used National Ocean and Atmospheric Administration (NOAA) (1979–2009) Global climate data provided by the National Centers for Environmental Prediction (NCEP). The NCEP are part of NOAA re-analysis programmes, which model the interaction between the earth's oceans, land and atmosphere to eliminate fictitious trends caused by model and data assimilation changes in real time [36]. Thus, the re-analysis provides multi-year global state-of-the-art gridded representations of atmospheric states, generated by a constant model and a constant data assimilation system [37]. The re-analysis climate data were generated under the Climate Forecast System Reanalysis (CFSR) project, which conducts six simultaneous streams of analyses covering a 31-year period. Quality control has been maintained by using both historical and operational archived data, as well as satellite bias correction spin-up [37]. CFSR data have been shown to be reliable weather input in watershed modelling studies [39]. Therefore, based on data consistency, open availability, spatial resolution within the 30-km range and a long-term temporal resolution, the CFSR data were preferred for this study that was conducted in a remote location of Uganda where data gaps, high inconsistency in climate data and limited spatial coverage

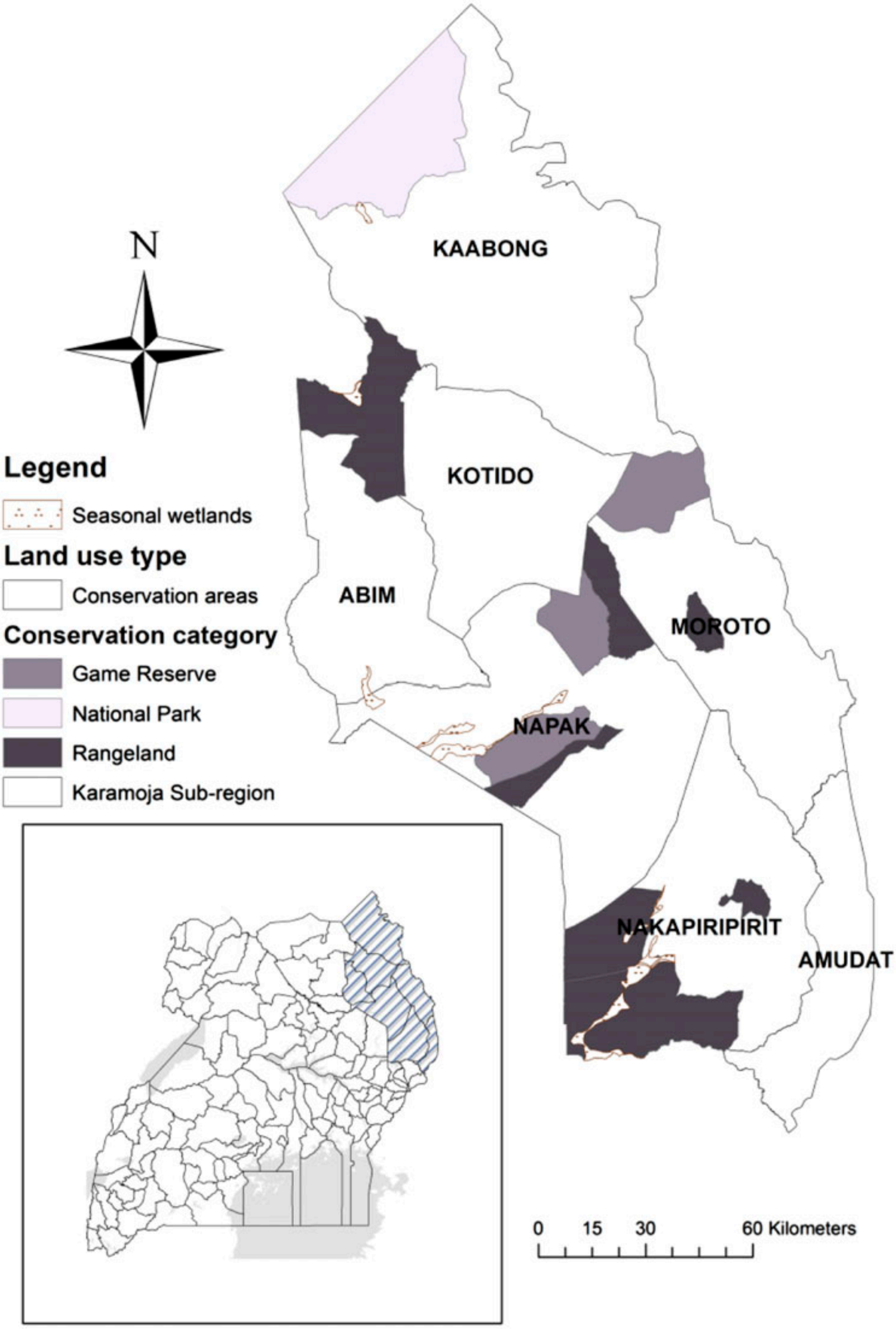


Figure 1. Location of Karamoja sub-region.
(Source: Author, 2014).

of weather stations prevail. The CFSR data-set consists of hourly weather forecasts generated by the National Weather Service's NCEP Global Forecast System. In this system, forecast models are reinitialised every six hours using information from the global weather station network and satellite-derived products. At each level of analysis hour, the CFSR includes both the forecast data, predicted from the previous analysis hour, and the data from the analysis utilised to reinitialise the forecast models [39]. The NCEP CFSR data provided a spatial coverage of 16 stations in Karamoja. The CFSR provides climate data for precipitation, wind, relative humidity and solar radiation for each location. This study used precipitation and temperature data for the analysis of spatio-temporal climate variability in semi-arid Karamoja. Climate data were subjected to quality control: firstly, we conducted outlier detection using the Turkey fence approach for trimming outlier climate values as described in Ngongondo et al. [40]. Secondly, we conducted a homogeneity test using the cumulative deviation approach as described in the work of Hadgu et al. [41] and, thirdly, as observed by Ngongondo et al. [40], climate data for trend analysis ought to be non-persistent. We, therefore, subsequently conducted a test of randomness and persistence as described in Hadgu et al. [41].

2.3. Determination of climate variability

Climate variability (C_v) was determined using the coefficient of variation (CV) computed as:

$$C_v = \left[\frac{\mathrm{Std}_{ij}}{\mathrm{mean}_{ij}}\right] \times 100 \tag{1}$$

where C_v represents the coefficient of variation; Std_{ij} is the standard deviation of a station for the period of analysis (1979–2009) and mean_{ij} is the mean rainfall for period of analysis at a given station. A coefficient of variation is the ratio of the standard deviation to the mean of the rainfall at any given station. The coefficient of variation has previously been applied by Ellis and Swift [42] in assessing rangeland dynamics. Since the coefficient of variation is inadequate for revealing the intensity of variation, there is a risk that a misleading agglomeration of landscapes may occur [43]. Therefore, besides determining the CVs, we have computed the intensity of variability.

2.4. Determination of climate variability intensity

Owing to the limitation of the coefficient of variation to disaggregate the intensity of variability, we compute climate variability intensity for rainfall (rainfall variability index [RVI]; equation (2)) and temperature (temperature variability index [TVI]; equation (3)). We have adopted a computation protocol developed by Balint et al. [44] with a slight modification. The computation protocol is represented by the following equations:

$$\mathrm{RVI}_{i,m} = \frac{\frac{1}{IP}\sum_{j=0}^{IP-1} P^{*}_{i,(m-j)}}{\frac{1}{(n\times IP)}\sum_{k=1}^{n}\left[\sum_{j=0}^{IP-1} P^{*}_{(m-j),k}\right]} \times \sqrt{\left[\frac{RL_{m,i}^{(P^{*})}}{\frac{1}{n}\sum_{k=1}^{n} RL_{m,k}^{(P^{*})}}\right]} \tag{2}$$

$$\mathrm{TVI}_{i,m} = \frac{\frac{1}{IP}\sum_{j=0}^{IP-1} T^{*}_{i,(m-j)}}{\frac{1}{(n\times IP)}\sum_{k=1}^{n}\left[\sum_{j=0}^{IP-1} T^{*}_{(m-j),k}\right]} \times \sqrt{\left[\frac{RL^{(T^{*})}_{m,i}}{\frac{1}{n}\sum_{k=1}^{n} RL^{(T^{*})}_{m,k}}\right]} \tag{3}$$

where P^* is the monthly precipitation; T^* is the modified monthly temperature; IP is the interest period (months); RL (P) represents the run length (1979–2009), that is, the maximum number of months below long-term average rainfall in the interest period; RL (T) is the maximum number of months above the long-term average temperature; n is the number of years with relevant data; j is the summation running parameter covering the IP, and k is the summation parameter covering the years where relevant data are available, in this case 1979–2009. In computing for RVI and TVI, the combined variability index (CVI) is simultaneously computed. The CVI (equation (4)) is computed as the weighted average of rainfall and temperature variability indices. This was computed following the modified equation:

$$\mathrm{CVI}_{i,m} = w_{\mathrm{RVI}} \times \mathrm{RVI}_{i,m} + w_{\mathrm{TVI}} \times \mathrm{TVI}_{i,m} \tag{4}$$

where w is the weight of the individual variability index. Balint et al. [44] recommended a weight of 50% for rainfall and 25% weight for both temperature and vegetation. Where either temperature or vegetation data are missing, the precipitation index is assigned a weight of 67% while the other is assigned 33%. We subsequently implemented the latter specification in this study because vegetation data were not used as they did not serve the interest of this study. Climate variability intensity for Karamoja sub-region and respective stations was computed to discern underlying spatial oddities. The Balint et al. [44] approach, as presented above, was initially developed for drought monitoring. Thus, it only considers the lower end point indices that show a graduating level of dryness in a location. Since Karamoja is known to experience two extreme events including dryness and wetness, we included indices that take care of wetness margins (see tables 1(a) and 1(b)). The indices range from 0 to 1 for dryness margin and 1.01–2.6 (may exceed 2.6 depending on the extreme occurrence of the wet event) for the wetness margin intensity. In inferring the intensity levels, we hold that the smaller the index, the more intense the dryness variability, thus indicating a potential drought in a location. On the other hand, the smaller the wetness index, the less intense the variability, indicating modest rains. As the index value increases, the variability intensity margin rises. We use these indices to disaggregate variability intensity margins for the Karamoja sub-region. The analysis was performed in the combined drought index calculator.

Table 1a. Climate variability intensity indices.

Index	**Description**	
0-0.49	Extreme dryness	↑
0.5-0.69	Severe dryness	
0.7-0.89	Moderate dryness	
0.9-1.0	Mild dryness	Graduating level of intensity
1.01-1.59	Normal wetness	
1.6-2.09	Moderate wetness	
2.1-2.59	Severe wetness	
2.6+	Extreme wetness	↓

Table 1b. Variability indices.

Index	Description
0-0.49	Extreme dry
0.5-0.69	Severe dry
0.7-0.89	Moderate dry
0.9-1.0	Mild dry
1.01-1.59	Normal rains
1.6-2.09	Moderate rains
2.1-2.59	Severe rains
2.6+	Extreme rains

Graduating level of intensity

3. Results

3.1. Temperature trends in the Karamoja

Results showed that there was a significant and progressive rise in temperature. At sub-regional level, long-term minimum temperature rose by 0.9 °C ($R^2 = 0.66$), mean temperature by 1.3 °C ($R^2 = 0.54$) and maximum temperature by 1.6 °C ($R^2 = 0.35$) (see figure 2(a)–(c)). This pattern was observed across all the 16 stations that were analysed in the sub-region. A consistent rise in minimum temperatures across all stations in the sub-region was observed. The coefficients of determination for minimum temperature were observed to be above 50% in most locations in the sub-region. Areas of Dopeth and Matheniko had the highest significant and positive increase in minimum temperature at 71.3%. A phenomenal rise in temperatures was observed in 1998 that affected the entire sub-region (figure 2(a)–(c)). We observed three phases of long-term mean temperature rise in the sub-region. The first phase was indicated by a crest emerging from the 1970s and breaks around 1985 (first trough, figure 3(c)). This was followed by a gradual rise that peaks around 1991–1993 with a break point between 1996 and 1997 (second trough). The third and sharper rise of relatively higher temperature was observed from 1998 cresting around 2000–2002 followed by a break around 2007 (third trough). The 2007 break was not as pronounced as the previous variation in temperature, but the temperature generally stayed high for the remainder to the study period (figure 2(c)).

3.2. Rainfall trend and variation in Karamoja

The times series analysis (1979–2009) showed a positive but non-significant trend ($R^2 = 17.1\%$; figure 3(a)) in total annual rainfall over the sub-region. The trend reflected a fluctuating pattern characterised by increases and decreases above and/or below the sub-regional average. The decreases reflected periods of significantly low rainfall totals with a return period of between three and seven years. This corresponds with the La Niña events observed in Uganda at large. The first major and general decrease in rainfall totals during the period of analysis was observed in 1984 (table 2). This was followed by a sporadic rise that peaked in 1988 (figure 3(a)). Thereafter, rainfall declined to nearly a uniform average total followed by another significant decrease, which reached a low in 1993. This was, however, interrupted by an abrupt increase in 1994 and sudden decrease in 1995. During this period, nine out of the 16 stations analysed (Matheniko, Namalu, Pian-Upe, Lolachat, Okere, Kokeris, Panayangara, Abim and Kidepo) received rainfall below 300 mm for the year.

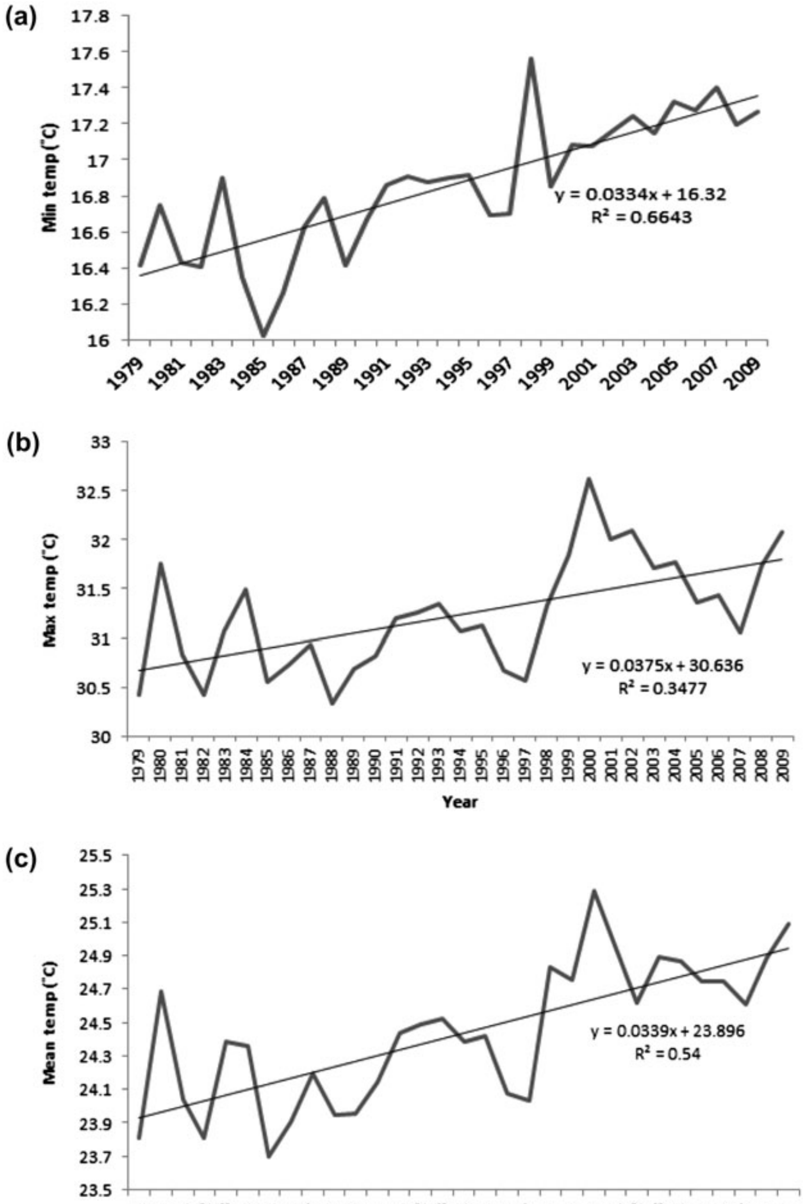


Figure 2. (a) Long term trend in minimum temperature. (b) Long term trend in maximum temperature. (c) Long term trend in mean temperature.

But, this was followed by three years of progressively high rains with peak levels occurring between 1997 and 1998. Despite rainfall peaking for all stations then, there was marked variability. Stations of Namalu, Pian-Upe, Lolachat all in southern Karamoja recorded lower total rainfall compared with areas of Dopeth, Komuria and Nga-Moru in

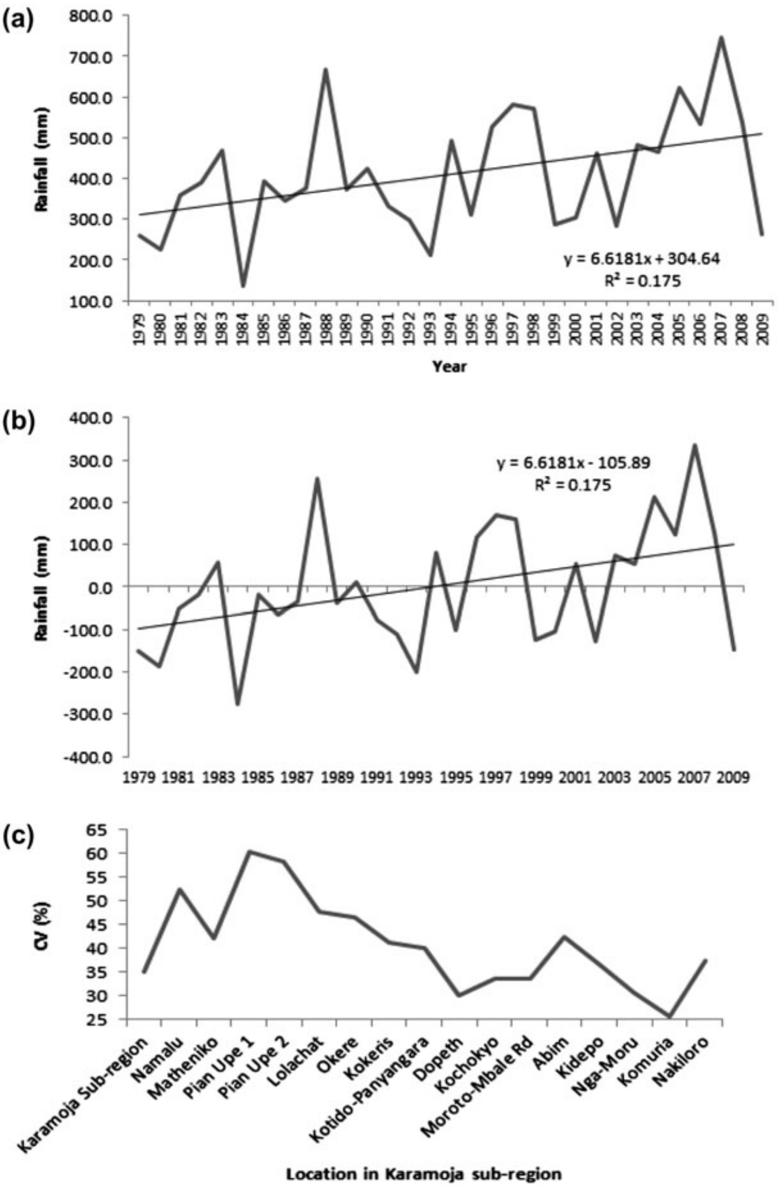


Figure 3. (a) Long term annual rainfall total for Karamoja. (b) Total annual rainfall deviation from the long term annual rainfall mean. (c) Coefficients of variation at sub-regional and location level.

northern Karamoja. In 2009, the sub-region experienced a general decline in rainfall after six years of relatively stable total rainfall.

Results of variability analysis showed that the sub-region's rainfall was variable (table 2) with observable deviations from the total annual rainfall long-term mean (figure 3(b)). This variation led to a pronounced coefficient of variation at 35.0%. The coefficients of variation showed spatial variation (figure 3(c)), such that areas such as Nga-Moru,

Table 2. Variation in annual total rainfall received by station (1979–2009).

Station area	Lowest total annual rainfall (mm) received	year	Highest total annual rainfall (mm) received	year	Long term average (1979–2009)
Abim	141.1	1984	808.9	2007	373.8 ± 158.9
Dopeth	271.8	1984	1002.8	1998	647.7 ± 195.5
Kidepo	183.3	1984	783.6	2007	426.9 ± 156.3
Kochokyo	149.2	1984	813.9	1988	468.7 ± 157.6
Kokeris	109.1	1984	826.3	2007	399.0 ± 164.3
Komuria	411.6	1984	1413.9	1988	922.7 ± 238.4
Kotido-Panyangara	117.5	1984	687.7	2007	352.7 ± 141.9
Lolachat	33.9	1984	449.8	2007	194.9 ± 93.2
Matheniko	74.1	1984	572.5	1998	302.3 ± 127.5
Moroto	130.8	1984	814.1	2007	507.2 ± 170.4
Nakiloro	87.3	1984	697.5	1998	404.7 ± 151.9
Namalu	39.4	1984	590.7	2007	212.6 ± 111.7
Nga-Moru	239.1	1984	932.6	1988	568.0 ± 174.3
Okere	116.3	1984	890.3	2007	391.3 ± 181.8
Pian Upe 1	27.4	1984	624.9	2007	208.4 ± 126.1
Pian Upe 2	33.9	1984	543.3	2007	187.6 ± 109.1

Dopeth and Komuria posted relatively lower coefficients of variation of 30.68, 30.2 and 25.8% respectively. On the other hand, Pian Upe 1 (60.5%), Pian Upe 2 (58.2%), Namalu (52.5%) and Lolachat (47.8%) areas recorded the highest coefficients of variation. Further, the areas of Kotido-Panyagara (40.2%), Kokeris (41.2%), Matheniko (42.2%), Okere river area (46.5%), Abim (42.5%), Kidepo (36.6%) and Nakiloro (37.5%) were observed with high coefficients of variation (figure 2(c)).

3.3. Rainfall and temperature variability intensity in Karamoja

Results of the analysis showed the existence of both extreme dryness and wetness intensity in the sub-region (figure 4). The rainfall variability intensity results revealed that, from 1979 to 1995, there was a predominance of extreme dryness intensity (table 3). This indicated the occurrence of multi-year droughts with a lack of smooth transition between the extreme events. A transition to pronounced wetness intensity was observed to have started around March 1996 with extreme wetness intensity experienced in 1997 and 1998 (table 3). It was also observed that, from around 2000, there has been a break in the occurrence of multi-year extreme dryness intensity. This indicates a reduction in the recurrence of multi-year drought events. In terms of the temporal evolution of variability intensity, the results showed that severe-to-extreme RVI was pronounced during early (January–April) and late (September–December) months of the year. Variability indices (RVI = 0.04–0.43) showed that much of 1984 to early (March) 1985 had the most severe-to-extreme dryness intensity patterns. From December 1983 to March 1985, there were 16 months of severe-to-extreme dryness intensity. The frequency in severe-to-extreme dryness intensity continued for most of the 1980s to early 1990s. From 1995, dryness intensity started easing and by 1997, it switched from pronounced dryness to pronounced wetness intensity. During the 1997/1998 rains, the months of April (RVI = 3.4), November and December (RVI = 4)

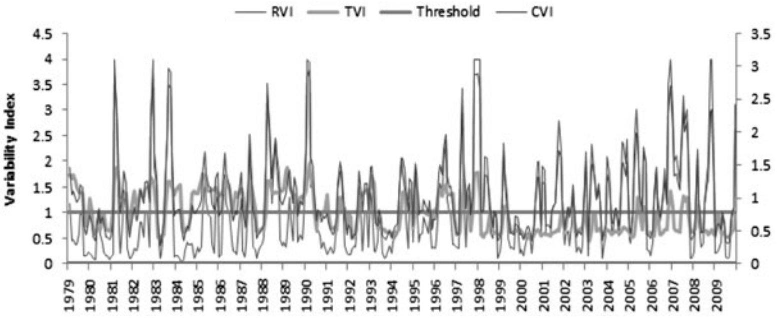
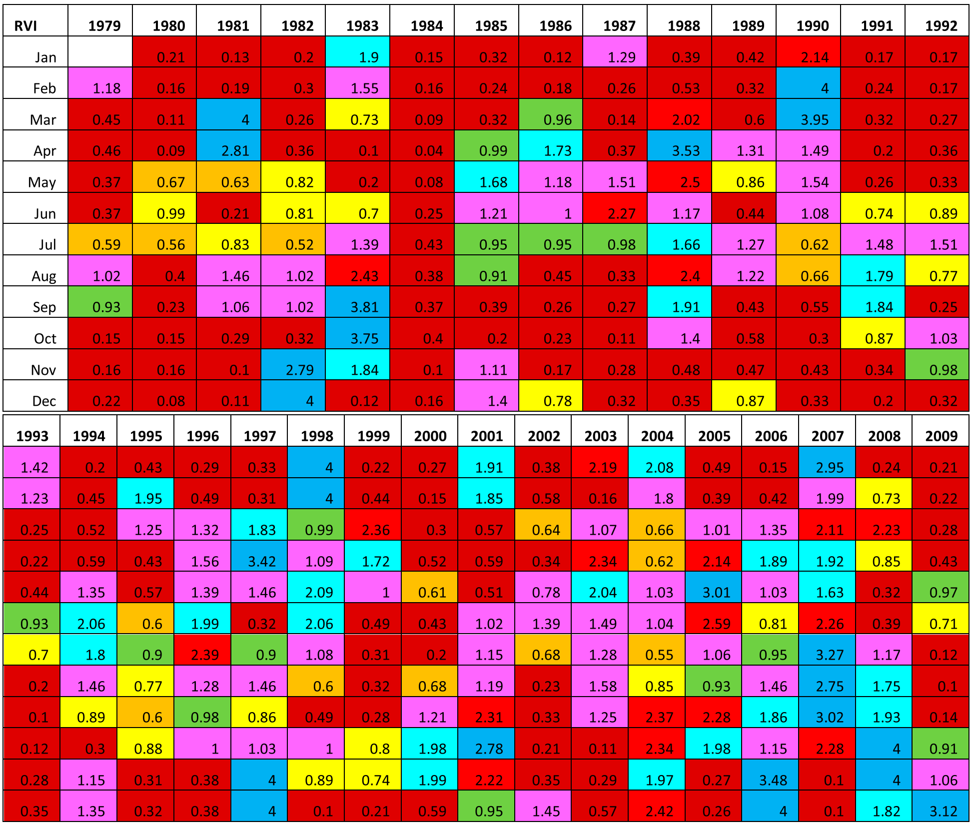


Figure 4. Combined temperature and rainfall variability intensity index.

Table 3. Karamoja long term (1979–2009) RVI indices.



RVI	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
Jan		0.21	0.13	0.2	1.9	0.15	0.32	0.12	1.29	0.39	0.42	2.14	0.17	0.17
Feb	1.18	0.16	0.19	0.3	1.55	0.16	0.24	0.18	0.26	0.53	0.32	4	0.24	0.17
Mar	0.45	0.11	4	0.26	0.73	0.09	0.32	0.96	0.14	2.02	0.6	3.95	0.32	0.27
Apr	0.46	0.09	2.81	0.36	0.1	0.04	0.99	1.73	0.37	3.53	1.31	1.49	0.2	0.36
May	0.37	0.67	0.63	0.82	0.2	0.08	1.68	1.18	1.51	2.5	0.86	1.54	0.26	0.33
Jun	0.37	0.99	0.21	0.81	0.7	0.25	1.21	1	2.27	1.17	0.44	1.08	0.74	0.89
Jul	0.59	0.56	0.83	0.52	1.39	0.43	0.95	0.95	0.98	1.66	1.27	0.62	1.48	1.51
Aug	1.02	0.4	1.46	1.02	2.43	0.38	0.91	0.45	0.33	2.4	1.22	0.66	1.79	0.77
Sep	0.93	0.23	1.06	1.02	3.81	0.37	0.39	0.26	0.27	1.91	0.43	0.55	1.84	0.25
Oct	0.15	0.15	0.29	0.32	3.75	0.4	0.2	0.23	0.11	1.4	0.58	0.3	0.87	1.03
Nov	0.16	0.16	0.1	2.79	1.84	0.1	1.11	0.17	0.28	0.48	0.47	0.43	0.34	0.98
Dec	0.22	0.08	0.11	4	0.12	0.16	1.4	0.78	0.32	0.35	0.87	0.33	0.2	0.32

1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
1.42	0.2	0.43	0.29	0.33	4	0.22	0.27	1.91	0.38	2.19	2.08	0.49	0.15	2.95	0.24	0.21
1.23	0.45	1.95	0.49	0.31	4	0.44	0.15	1.85	0.58	0.16	1.8	0.39	0.42	1.99	0.73	0.22
0.25	0.52	1.25	1.32	1.83	0.99	2.36	0.3	0.57	0.64	1.07	0.66	1.01	1.35	2.11	2.23	0.28
0.22	0.59	0.43	1.56	3.42	1.09	1.72	0.52	0.59	0.34	2.34	0.62	2.14	1.89	1.92	0.85	0.43
0.44	1.35	0.57	1.39	1.46	2.09	1	0.61	0.51	0.78	2.04	1.03	3.01	1.03	1.63	0.32	0.97
0.93	2.06	0.6	1.99	0.32	2.06	0.49	0.43	1.02	1.39	1.49	1.04	2.59	0.81	2.26	0.39	0.71
0.7	1.8	0.9	2.39	0.9	1.08	0.31	0.2	1.15	0.68	1.28	0.55	1.06	0.95	3.27	1.17	0.12
0.2	1.46	0.77	1.28	1.46	0.6	0.32	0.68	1.19	0.23	1.58	0.85	0.93	1.46	2.75	1.75	0.1
0.1	0.89	0.6	0.98	0.86	0.49	0.28	1.21	2.31	0.33	1.25	2.37	2.28	1.86	3.02	1.93	0.14
0.12	0.3	0.88	1	1.03	1	0.8	1.98	2.78	0.21	0.11	2.34	1.98	1.15	2.28	4	0.91
0.28	1.15	0.31	0.38	4	0.89	0.74	1.99	2.22	0.35	0.29	1.97	0.27	3.48	0.1	4	1.06
0.35	1.35	0.32	0.38	4	0.1	0.21	0.59	0.95	1.45	0.57	2.42	0.26	4	0.1	1.82	3.12

and January and February (RVI = 4) of 1998 experienced extreme wetness intensity. A unique trend started around 2003 that reflected a general increase in the prevalence of wetness intensity (figure 4) with a conspicuous intensification of wetness from 2006 to 2008 (table 4). Although most of 2009 was dry (0.1–0.97 index), rainfall intensity rose rapidly up to extreme levels in December (RVI = 3.12).

Table 4. Karamoja long term (1979–2009) TVI indices.

TVI	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Jan		1.29	0.68	1.32	1.46	1.43	1.37	1.33	1.48	0.68	1.48	1.42	1.34	1.01	1.5	0.58	0.7	1.06	0.58	1.79	0.58	0.65	0.56	0.65	0.95	0.67	0.62	0.61	1.1	0.65	0.57
Feb	1.73	1.04	1.09	1.43	1.02	1.5	1.48	1.37	1.41	0.66	1.81	1.66	1.04	0.9	1.72	0.52	1.06	1.06	0.58	1.31	0.6	0.56	0.59	0.71	0.49	0.65	0.54	0.57	0.69	0.69	0.97
Mar	1.67	0.69	1.74	1.06	0.53	1.54	1.64	1.41	1.11	1.02	1.89	1.95	0.7	0.49	1.56	0.62	1.48	1.44	0.64	0.56	1.02	0.53	0.56	1.09	0.45	0.56	0.52	0.55	0.64	1.12	0.96
April	1.75	0.58	1.9	1.12	0.46	1.05	1.77	1.63	0.72	1.61	1.54	1.72	0.7	0.52	0.99	0.65	1.05	1.45	1.36	0.51	1.12	0.58	0.58	1.06	0.66	0.59	0.55	1.02	0.64	1.11	0.59
May	1.62	0.64	1.57	1.44	0.54	0.61	1.72	1.62	1.2	1.62	1.44	1.44	0.71	0.56	0.69	0.67	1.02	1.33	1.68	0.6	1.04	0.54	0.54	1.03	1.02	0.64	0.97	0.98	0.61	0.65	0.61
Jun	1.49	0.69	1.31	1.32	0.57	0.64	1.52	1.5	1.65	1.43	1.37	1.03	0.67	0.94	0.71	1.07	1.02	1.49	1.35	0.62	0.94	0.48	0.59	1.01	0.98	0.63	1.31	0.58	1	0.59	0.57
Jul	1.41	0.67	1.31	1.32	0.95	0.7	1.43	1.45	1.48	1.37	1.36	0.67	0.98	1.31	0.68	1.41	1.03	1.55	1.28	0.94	0.62	0.5	0.62	0.61	0.65	0.61	0.99	0.57	1.33	0.64	0.52
Aug	1.39	0.99	1.35	1.45	1.48	0.67	1.43	1.07	1.32	1.41	1.06	1	1.3	1.33	0.66	1.39	0.99	1.37	1	0.95	0.62	0.56	0.62	0.59	0.66	0.6	0.66	0.63	1.24	0.64	0.51
Sep	1.38	1.01	1.38	1.49	1.62	1	1.45	1.06	1.05	1.39	1.02	1	1.05	1.35	0.67	1.31	0.95	1.35	0.64	0.63	0.62	0.61	0.67	0.67	0.68	0.67	1.1	0.67	1.3	0.58	0.51
Oct	1.04	0.66	1.09	1.53	1.59	1.38	1.46	1.39	0.64	1.38	1.31	0.97	1.09	1.43	0.62	1.29	1.03	1.36	1.05	0.62	0.65	0.66	0.65	0.69	0.58	0.71	1.11	0.66	1.02	0.62	0.61
Nov	0.73	0.66	0.7	1.69	1.5	1.42	1.49	1.31	0.63	1.46	1.32	1.03	1.09	1.45	0.63	1.44	0.71	1.37	1.76	0.6	0.65	0.65	1.01	0.7	0.58	0.7	0.6	1.07	0.65	0.67	0.66
Dec	1.03	0.65	0.98	1.62	1.34	1.37	1.38	1.4	0.66	1.43	1.31	1.04	0.7	1.34	0.65	1.12	1.03	0.98	1.76	0.57	0.66	0.54	0.95	1.01	0.65	0.66	0.59	1.42	0.63	0.56	0.95

Results further showed variation in variability intensity within the sub-region. For example, in Abim, the years 1979 (RVI = 0.1–0.56), 1980 (RVI = 0.11–0.56), 1984 (RVI = 0.11–0.57), 1991 (RVI = 0.17–0.67), 1993 (RVI = 0.08–0.98) and 1995 (RVI = 0.18–0.92) all reflected severe-to-extreme dryness intensity. There were, however, some episodic wetness reflections in the 1980s observed in 1981 during the months of March (RVI = 4) and April (RVI = 3.9), and in 1983 during the months of September (RI = 3.31) and October (RVI = 3.9). All other months remained within the moderately dry and extremely dry segment. Between 2004 and 2008, the area experienced a rise in the number of severe-to-extreme wetness periods. Consequently, in total, 18 months could be classified in this category with nine out of the 18 occurring in 2007 alone.

At Dopeth, the period between December 1983 and April 1985 had 17 months (RVI = 0.03–0.6) in the severe-to-extreme dryness intensity category. Of the first 72 months (1979–1984), 54 months could be classified into severe to extremely dry (RVI = 0.07–0.65) months. In this station, 1983 and 1988 were the only years that could be classified as relatively good years with rainfall variability intensity being within the normal (RVI = 1.01–1.59) to moderate (RVI = 1.6–2.09) range. Like Abim, Dopeth had 18 months of extreme wetness intensity. But, in the period 1994–2009, Dopeth had 37 months in the severe-to-extreme wetness intensity category compared to Abim's 25 months. Meanwhile, in Lolachat, out of 168 months (1979–1992), there were 107 months in the severe-to-extreme dryness category (RVI = 0.04–0.6). In the same period, the area received sporadic intense rains; 18 months could be classified as severe-to-extreme wet months. There were only 33 months in the mild range (RVI = 0.9–1.0) category. This shows that this area experienced multiple drought years between 1979 and 1992 periods. When the remaining 17 years (204 months) are considered (1993–2009), 119 months experienced (RVI = 0.06–0.69) severe-to-extreme dryness conditions. In the same period, we found 37 months with severe-to-extreme wetness (RVI = 2.01–4) conditions. Only 26 months could be observed within the mild (RVI = 1.01–1.59) intensity category. This indicates scarcity in good months/years despite indications of relative increase in rainfall total.

The Kokeris area was one with a high number of months that received severe-to-extreme dry conditions between 1979 and 1992. Out of 168 months, there were 109 months that experienced severe-to-extreme dryness intensity conditions. In the same period, 13 months experienced severe-to-extreme wet conditions. From 1993 to 2009, 96 months could be classified as severe-to-extreme dry intensity, while 39 months fell into the severe-to-extreme wet intensity category. Four stations in southern (Lolachat), central (Kokeris) and northern (Abim and Dopeth) areas of the region demonstrate the spatial variability intensity across the region. The remaining 12 stations oscillate within these ranges. There was one exception, Pian-Upe. This site had increased wetness intensity extremes in 1983, 2006 and 2007.

Results of temperature variability intensity (TVI) analysis showed two phases of TVI pattern in the region. The first phase (1979–1996) was generally characterised by TVI in the normal intensity range (table 4). The second phase (1997–2009) was marked by a shift in TVI from moderate to severe category (table 4). TVI findings also showed that there was a synchronicity between temperature and rainfall in the sub-region (figure 4). When TVI intensity decreases, RVI follows suit. Thus, depression points in temperature are analogous to depression points in rainfall (figure 4). The CVI takes a similar trend (figure 4). These patterns have been observed in all other individual stations where similar analysis was performed.

It was also observable that when temperatures rose above the threshold, the rainfall index also increased. Four years (1983, 1992, 2000 and 2003) recorded months with extreme temperature intensity during April 1983 (TVI = 0.46), March 1992 (TVI = 0.49), June 2000 (TVI = 0.48), February 2003 (TVI = 0.49) and March (TVI = 0.45) (table 4). Further, it was evident that between 1979 and 1992, there was a dominance of mild TVI (104 months) with severe intensity observed in 24 months, and moderate intensity in 22 months. But, between 1993 and 2009, TVI shifted to severe intensity with 116 months most pronounced (table 4). As with RVI, we observed spatial oddities in TVI in the sub-region.

4. Discussion

In Karamoja, between 1979 and 2009, the first major decline in rainfall occurred between 1983 and 1984 and it affected the entire sub-region. Several other researchers have identified this period in East Africa [45] and in Uganda [46] as the period of the early 1980s great drought. Rainfall totals display episodic variability that has been identified as an inherent characteristic of dryland environments [47]. Episodic variability, as well as a shift in rainfall patterns, has been observed in the semi-arid Tigray region of Northern Ethiopia over a similar period (1980–2009) of analysis [48] and in most of semi-arid Ethiopia [49]. In the Tigray region, a non-significant declining trend in total annual rainfall was observed, contrary to the non-significant increase observed in this study. But, some stations in Tigray experienced an increasing trend in total annual rainfall similar to that observed in this study. Further, in the Sahel [15], most of West Africa [16] and in Eastern Sudan [17] significant patterns of variability occurred with a decline in annual rainfall. This was contrary to the relative, although non-significant, increase in total annual rainfall observed in this study. In spite of the decline in rainfall for Sahel, an increase in rainfall has also been observed within the Sahel in recent decades. This increase is said to have helped abate the drought that afflicted the region from the 1960s to the 1980s [50,51]. Further, the increase observed in the Sahel emerges slightly after the 1980s [52,53] and shows a recovery from the drought years that prevailed in the Sahel as well as in East Africa [15]. These patterns are consistent with the findings of this study. The pattern reported in this study could be attributed to the intensifying dipole rainfall pattern over Eastern Africa that has been held to be the cause of increased rainfall over the region [19]. These data support the climate projections for East Africa that show that the area will have an increase in rainfall [21]. This increase will be non-uniform as some areas will be experiencing a downward trend while others will have an upward trend [53]. The Karamoja sub-region appears to fall in the latter category.

The inherent climatic variability in semi-arid regions makes them non-equilibrium ecosystems [40,54,55]. We observed relatively high coefficients of variation characteristic of semi-arid regions. Overall, the sub-regional coefficient of variation (CV = 35.01%) is above the 33% threshold margin identified by Ellis and Swift [42] and Ellis and Galvin [54] as the lower limit above which a location is described as a non-equilibrium ecosystem. But, there is spatial variation between locations in the sub-region. In the areas of Nga-Moru, Dopeth and Komuria, coefficients of variation were below the 33% threshold (figure 3(b)). In line with the classification of equilibrium and non-equilibrium ecosystems of Ellis and Swift [42] and Ellis and Galvin [54], these areas would be considered equilibrium ecosystems. We have reservations in accepting this suggestion since the location's rains varied greatly during the period of analysis (1979–2009). Firstly, Komuria's annual total rainfall ranged from 411.16 mm to 1800.8 mm with an annual average of 950.2 mm, Dopeth 271.8–1363.5 mm (670.1 mm) and Nga-Moru 239.1–1190 mm (568 mm). Secondly, relatively stable rainfall only occurs after rainfall increases, but it does not eliminate the intra-annual and inter-annual variability. Thirdly, there is not agreement on the standard cut-off point to be used as a decision rule to declare locations as either equilibrium or non-equilibrium ecosystems. Ellis and Galvin [54] used a 33% CV threshold and Shepherd and Caughley [55] used a 30% CV cut-off. Conversely, Briske et al. [56] used < 300 mm, while Coppock [57] indicated < 400 mm as a threshold indicative of non-equilibrium systems. Treating Nga-Moru, Dopeth, and Komuria as equilibrium ecosystems based on a single parameter would, therefore, not suffice and the 33% threshold cut-off level was arguably a rule of thumb. An investigation of a range of other ecosystem parameters such as *ecohydrological feedbacks* will be necessary for proper classification of the Karamoja ecosystem and other semi-arid areas in general. In the meantime, this study suggests that a dynamic state description for the Karamoja ecosystem is preferable.

With regard to the trend in temperature, three issues emerge: firstly, temperatures are rising; secondly, the rise displays a spatial and temporal character; and thirdly, all the long-term temperature changes are above 0.5 °C. Earlier studies of 1950–2008 temperatures had also indicated that temperatures in Africa are warmer than they were 100 years ago. The warming over the twentieth century has been at a rate of 0.5 °C [58]. In Uganda, temperatures have also been generally rising by as much as 1.5 °C in most areas [31]. The results of this study are within comparable margins of between 1.2 and 1.4 °C for mean, 0.5 and 1.1 °C for minimum and 1.4 and 2.2 °C for maximum temperature. A shift to warmer climate has the potential of amplifying the effect of periodic droughts with a further likelihood of reducing crop harvests and pasture availability [30,31].

Earlier, we stated that rainfall in the region has shown a positive but non-significant trend. Given the observed positive trend in temperatures, this could imply that the rainfall patterns may not be able to offset the potential impacts of progressively rising temperatures. But, Neely et al. [59] have observed that temperature increases of up to 3.0–3.5 °C could increase the productivity of crops, fodders and pastures. In south-eastern Australia (Barraba and Mutdapilly areas), Cullen et al. [60] have shown that given minimal change in annual rainfall, a temperature increase of up to 4.4 °C will lead to increased pasture production. As shown in the results, the sub-region experienced slight but consistent rise in total annual rainfall from around 2000 to 2008 (figure 3(a)). This may have resulted in an improvement in forage availability. The growth could be sufficiently rapid that some of the grazing landscapes could be converted into bushland. Secondly, the slight progressive improvement in rainfall after 2000 could have altered pasture patterns as well as grazing regimes. This may be due to the influence of increasing biomass growth that, in turn, influences available fuel load. Thirdly, the likelihood of attracting many pastoral people (in particular those that have lost their livestock through livestock raids) to transition into cultivated agriculture thereby increasing cultivable land becomes higher. If cultivators invade grazing lands with cropping, this will inevitably create conflict. Fourthly, increased cropping by some could reduce opportunities for others for accessing pasture lands and thus create a new kind of conflict in the sub-region.

On the other hand, Thornton and colleagues [61] have suggested that the potential increase in pasture production arising from increase in temperature is only feasible where the ratio of evaporation to potential evapotranspiration and nutrient availability do not significantly limit plant growth [61]. This is a potential production constraint in the current study area because it has been shown that there is no month when rainfall exceeds potential evaporation [62]. Further, the sub-region's annual evapotranspiration is generally estimated to be around 2000 mm [63,64]. The observed increase in temperature is thus likely to lead to further moisture deficits and these could reduce the availability of pasture in the region. The potential negative impact of temperature increase on pasture production has been discussed by others. Sivakumar et al. [65] reported that natural vegetation in desert zones will be negatively affected by increases in temperature. Modelled results averaged across Australia have shown that an increase in temperature of up to 3 °C would lead to a slight decrease in pasture growth. Further, in south eastern Australia, Ludwig and Marsden [66] show that predicted temperature increases could significantly alter pasture species composition in the grasslands and shrublands, and affect forage quality by reducing digestibility of grasses [67]. There is apparent disagreement on the likely effects that increased temperature will have on pasture production and availability. The effect will certainly vary regionally, depending on the combination of changes to rainfall, temperature, plant responses to elevated atmospheric CO_2 concentrations, pasture systems and soil nutrients [60]. To understand better, these relations will require long-term trend (past to present) analysis on biomass performance in the sub-region. Using rainfall data coupled with remote sensing technologies, in particular low-resolution imagery with a high temporal resolution such as the Advanced Very High Resolution Radiometer, could help identify trends in biomass performance.

The evolution, as well as the spatial dimension of extreme climatic events, such as a drought, is important if superficially drawn conclusions are to be avoided [44]. Rainfall variability intensity and TVI results were able to identify spatio-temporal variability characteristics of rainfall and temperature. The variability indices in particular, rainfall variability, showed the spatio-temporal evolution of extreme events including drought and potential flood events in the sub-region. Intensity of extreme climatic events has hitherto been observed in Southern Africa with the occurrence of droughts and devastating floods [68]. But, the coefficients of variation in semi-arid locations can only reveal the existence of variability without revealing the distinctive spatio-temporal pattern of such variability. In their work, Balint et al. [44] showed that combined drought indices were relevant in monitoring the evolution of drought and spatial distribution of such droughts in the affected areas. The results of this study underline this. The pattern of variability in the sub-region suggests a lack of smooth transition between events, and this has also been observed in semi-arid areas of Ethiopia [48]. Additionally, the results of this study have shown a reduction in multi-year droughts in the recent past (from around 1997 to 2008) compared to the period between 1979 and 1996. This corresponds to the La Niña events that have been observed in semi-arid areas of Uganda and Uganda in general [69]. These patterns hold implications for pastoralists and their livestock, by influencing forage [70], water (as has been observed in the Transjordon plateau) [71] and disease patterns (as has been observed among East African pastoralists when there are disease epidemics and livestock starvation associated with recurrent drought events) [72]. Further, these patterns could lead to the existence of multiple states. In particular, the spatial oddities allow for reinforcements and sustenance of livestock from other locations through opportunistic management. Opportunistic livestock management has been noted as a key management and coping strategy used in semi-arid regions [73–75]. This is because plant-cover in arid and semi-arid environments shifts across dynamic thresholds between different ecological states in response to disturbance such as grazing, drought and fire [76]. In the event of floods, the presence of good pastures for several months has been observed [77]. Nevertheless, flood events tend to affect poorer herders, and those with small herds much more than those with more resources [28].

5. Concluding remarks

Semi-arid areas are typified by climatic variability with episodic occurrence of high wetness intensity and drought events. This study has revealed these patterns of variability on a spatio-temporal scale, and shown the evolution of climatic extreme events in this semi-arid region. We believe that this kind of information is essential for timely adjustment to extreme climatic events, especially intermittent droughts and floods that often plague the semi-arid regions. The understanding of variability intensity allows for target specific interventions that will avoid the waste of time and effort represented by hasty and ill-informed action in semi-arid regions. In addition, this study offers a picture of the intrinsic heterogeneity associated with patchy rainfall in the semi-arid areas. The return period of extreme events in this study region has been shown to be variable. For example, in the recent past (1997–2008), multi-year drought recurrence has generally reduced, yet at the same time, there has been an increased occurrence of extreme wet events in the same period compared to the period between 1979 and 1996. This situation prevails in most of the semi-arid areas of Eastern Africa. It is therefore imperative that climate variability assessments in semi-arid areas provide detailed characteristics of such climatic variability; in particular, its intensity. Further, the use of climate information in planning interventions, and especially livestock management in semi-arid regions, ought to be increased to take advantage of the heterogeneity at landscape to regional scale.

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