Scientific Research Publishing

Journal of Geoscience and Environment Protection, 2024, 12, 131-152
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Characteristics of Extreme Rainfall Events over Uganda during September to November Rainfall Season

Donnata Alupot[1,2,3], Guirong Tan[1*], Kokou Romaric Posset[2], Peter Natiko[3]

[1]Key Laboratory of Meteorological Disaster, Ministry of Education (KLME)/Joint International Research Laboratory of Climate and Environment Change (ILCEC)/Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD), Nanjing University of Information Science and Technology, Nanjing, China
[2]Climate Change Department, Pan African University Institute for Water and Energy Sciences (Including Climate Change), C/O Université Abou Bekr Belkaid Tlemcen, Campus Chetouane, Tlemcen, Algeria
[3]Directorate of Weather Forecasting, Uganda National Meteorological Authority, Port Bell Road, Kampala, Uganda
Email: alupodonnata@gmail.com, *tanguirong@nuist.edu.cn, posromaric@gmail.com

How to cite this paper: Alupot, D., Tan, G. R., Posset, K. R., & Natiko, P. (2024). Characteristics of Extreme Rainfall Events over Uganda during September to November Rainfall Season. *Journal of Geoscience and Environment Protection, 12,* 131-152.
https://doi.org/10.4236/gep.2024.123008

Received: February 5, 2024
Accepted: March 24, 2024
Published: March 27, 2024

Abstract

Understanding the characteristics of extreme rainfall is crucial for effective flood management planning, as it enables the incorporation of insights from past extreme rainfall patterns and their spatiotemporal distribution. This work investigated the changes in the frequency and pattern of extreme rainfall over Uganda, using daily datasets sourced from Climate Hazard Group InfraRed Precipitation with Station (CHIRPS-v2) for the period 1981 to 2022. The study utilized the extreme weather Indices provided by the Expert Team on Climate Change Detection and Indices (ETCCDI). Attention was directed towards September to November (SON) rainfall season with precise analysis of four indices (Rx1day, Rx5day, R95p, and R99p). The Sequential Mann-Kendall (SQMK) non-parametric test was applied to identify abrupt changes in SON extreme rainfall trends. Results showed that October consistently recorded the highest count of extreme rainfall days across all four indices. The long-term analysis revealed fluctuations in extreme rainfall events across years, with certain periods exhibiting heightened intensity. The analysis portrayed a shift in the decadal variations and region-specific distribution of extreme rainfall, with Eastern Uganda and areas around Lake Victoria standing out compared to other regions. The findings further revealed an increase in extreme rainfall for all indices in the recent decade (2011-2022) with 2019/2020 standing out as the extreme years of SON for the study period. While trendlines suggested a slight increase in intense daily rainfall events, the SQMK tests revealed statistical significance in the trend of prolonged periods of intense daily rainfall. This study contributes to the understanding of the spatiotemporal variability and trends of extreme rainfall events over Uganda during the SON season, which is crucial for the assessment of climate change impacts and adaptation strategies. It provides valuable information for seasonal extreme rainfall forecasting, development of early warning systems, flood risk management, and disaster preparedness plans.

Keywords

CHIRPS, Variability, Region-Specific, Early Warning, Climate Change

1. Introduction

Extreme weather has garnered considerable attention in scientific research and has become a matter of great societal significance (Ross & Lott, 2004; O'Hara et al., 2009; Mazon et al., 2016). Forecasting extreme rainfall events that can lead to floods and mudslides presents a noteworthy challenge in the field of weather forecasting, particularly in regions with complex topography, where specific features can intensify precipitation (Guastavino et al., 2022). In the case of Uganda, which serves as a case study, the country experiences two primary rainfall seasons: long rains from March to May (MAM) and short rains from September to November (thereafter, SON) (Majaliwa et al., 2015). Additionally, there is a prolonged dry season from December to February (DJF). The third rainfall season, which occurs from June to August (JJA), is associated with moisture influx from the Congo air mass and the influence of the Inter-Tropical Convergence Zone (ITCZ) over Northern Uganda (Ogwang et al., 2016b; Nsubuga & Rautenbach, 2018).

Studies have observed variations in these rainfall patterns across Uganda, with particularly high variability during the SON season (Omondi et al., 2014; Ngoma et al., 2021a). The considerable variability that characterizes the short rains (SON) has been linked to the influence of Sea Surface Temperature (SST) variability, including phenomena such as El Niño Southern Oscillation (ENSO) (Indeje & Semazzi, 2000; Jury, 2018) and Indian Ocean Dipole (IOD) conditions in the Indian and Pacific Oceans. The Indian Ocean plays a crucial role in determining above or below normal rainfall (Khan et al., 2021) during the short rains, primarily due to Sea surface temperature (SST). The IOD creates an anomalous temperature gradient within the Indian Ocean, resulting in positive or negative SST anomalies in the western and eastern parts, respectively, known as the Dipole Mode Index (DMI) (Dubache et al., 2019). These oceanic mechanisms enhance short rains (SON) anomalies often leading to heavy rainfall events, flash floods, rising water levels, and mudslides during the positive phases of both ENSO and IOD modes (Palmer et al., 2023).

According to Ogwang et al. (2016a), the SON season in Uganda, as assessed using Empirical Orthogonal Functions (EOF), constitutes 29% of the country's mean rainfall and demonstrates a notably higher standard deviation of 24.5 mm for the period spanning from 1901 to 2013. This significant interannual variability within the SON season leads to fluctuations in rainfall amounts annually. Ngoma et al. (2021b) revealed similar findings for the interannual variability in SON season between 1981 and 2019, prompting some farmers to transition their main growing season from MAM to SON. The increase in rainfall during SON season in Uganda was documented by (Majaliwa et al., 2015; Ogwang et al., 2016a; Nicholson, 2017). Furthermore, recent projections for Uganda derived from Coupled Model Intercomparison Project Phase 6 (CMIP6) models revealed wetter conditions during SON season under two emission scenarios for both the near and far future (Ngoma et al., 2022). Examining extreme rainfall events in East Africa, Ongoma et al. (2018) observed a general increase in the number of wet days in Uganda, although, statistically insignificant at the 5% significance level. However, the assessment needed to highlight on the seasonal variations and specific characteristics of extreme rainfall. Meanwhile, Nicholson et al. (2022) analysed October and November rainfall extremes across equatorial Africa, noting heavy rainfall during the SON season of 2019 which was attributed to enhanced moisture flux from the Indian Ocean, impacting Eastern Africa, including Uganda.

Previous studies have primarily investigated seasonal or annual rainfall totals by examining changes in rainfall amounts over different seasons or years. However, these studies were limited to analysing the overall pattern and changes in mean rainfall amounts without thoroughly examining extreme rainfall events or other specific characteristics of extreme rainfall intensity and frequency. As a result, there is a lack of knowledge regarding the characteristics of extreme rainfall in Uganda, particularly during the SON season, where future projections indicate an increase in rainfall. Thus, the present study aims to address this knowledge gap by providing climatological information and evidence of extreme rainfall. For instance, this study investigates whether the frequency, intensity and pattern of extreme rainfall events changed in Uganda. For this purpose, the research utilized Extreme weather indices from the Expert Team on Climate Change Detection and Indices (ETCCDI), focusing on four indices (Rx1day, Rx5day, R95p, and R99p). Extreme weather indices from the ETCCDI are useful tools for assessing and quantifying climate change-induced alterations in key climate variables and extreme events (Zhang et al., 2011). These indices capture various characteristics of extreme events, such as magnitude, frequency, duration, and spatial extent (Jeong et al., 2021). The study then employed Mann Kendall trend analysis to assess the significance of the trends of rainfall extremes during the study period, drawing on previous research (Nsubuga et al., 2011; Gocic & Trajkovic, 2013; Chinchorkar et al., 2015). The study's findings have significant implications beyond academia, for example results have direct applications in seasonal extreme rainfall monitoring and prediction particularly for vital sectors in Uganda. Furthermore, the study contributes valuable insights for water resource management, disaster preparedness, and enhanced seasonal forecasting, aiming to fortify Uganda's resilience and promote sustainable development amid changing weather patterns. Section 2 provides a concise overview of the study domain, detailing the data sources and methodologies employed. Section 3 delves into the study's findings and subsequent discussions; finally, the summary of the study and proposed potential recommendations.

2. Study Area, Data and Methods

2.1. Study Area

Uganda is a landlocked country in East Africa (Figure 1), bordered by Tanzania, Rwanda, the Democratic Republic of Congo, South Sudan, and Kenya, covering 241,038 square kilometers (Masum, 2020). The climate characteristics are influenced by a combination of global and regional factors, including sea surface temperatures, wind patterns, and atmospheric circulation (Jury, 2018). Various geographical features including mountains such as Mount Elgon and Mount Rwenzori, as well as water bodies like Lake Albert, Lake George, Lake Edward, Lake Victoria, Lake Kyoga, and the White Nile River, can influence rainfall variation. Studies have observed variations in Uganda's rainfall patterns, with the SON season showing high variability (Omondi et al., 2014; Nicholson, 2017).

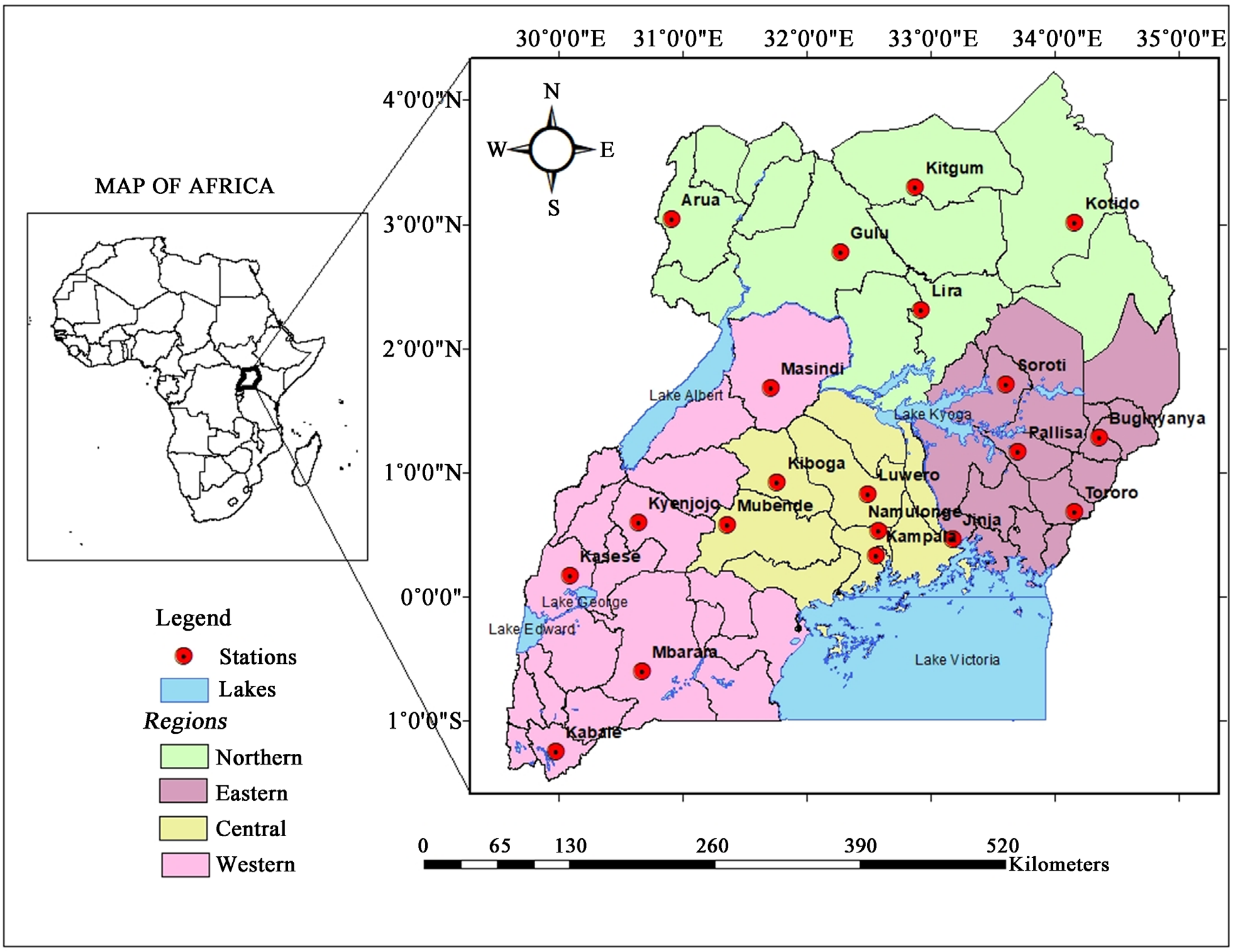

Figure 1. Location of the study area showing the distribution of stations across various regions.

However, irrespective of the rainfall patterns, there is still an ongoing occurrence of extreme rainfall (Nsubuga et al., 2014) with some areas experiencing heavy rainfall and other areas receiving below normal rainfall. The vulnerability of populations to extreme rainfall is influenced by geographic location, social, and economic factors. Extreme rainfall causes riverine and flash floods, with the most affected areas along major rivers and lowlands. According to the World Bank, Uganda experienced 20 floods and five landslides between 1900 and 2018 (World Bank, 2019). In 2022, two rivers burst their banks after heavy rainfall causing severe flooding in Eastern Uganda (Mbale and surrounding districts, some 220 kilometers east of the capital, Kampala), leaving homes, shops, and roads submerged and other infrastructure destroyed and killing at least 26 people (IOM, 2022).

2.2. Data

Satellite derived dataset for daily rainfall data (1981 to 2022) was downloaded from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) at a cell size of 0.05 (~5 km) with a one (1) day temporal resolution. CHIRPS is a 35+ year quasi-global rainfall data set, spanning 50˚S-50˚N (and all longitudes) and ranging from 1981 to near-present (digital Earth Africa). The data source can be accessed on the website https://iridl.ldeo.columbia.edu/SOURCES/.UCSB/.CHIRPS/.v2p0/.daily-improved/.global/.0p05/.prcp. Datasets from a total of twenty (20) weather stations ranging from 1981 to 2022 were used to accomplish the tasks. The station(s) include; Kotido, Lira, Kitgum, Gulu, Arua, Tororo, Jinja, Pallisa Soroti, Bugi-nyanya, Kabale, Kasese, Masindi, Mbarara, Kyenjojo, Kampala, Mubende, Luwero, Namulonge and kiboga. The stations are evenly distributed in the study area as seen in (**Figure 1**). CHIRPs-v2 data displays high temporal agreement and preserved variability compared to gauge observations, indicating its reliability in capturing rainfall variability in the Eastern and South African region (Muthoni et al., 2019). Similarly, when compared to other satellite products (ARC, TAMSAT), CHIRPS products are significantly better with higher skill and low or now bias across East Africa (Dinku et al., 2018). According to Kimani et al. (2017), CHIRPS performed well in accurately estimating rainfall over East Africa, during the rainfall seasons, and was able to capture different rainfall regimes.

2.3. Methods

2.3.1. ETCCDI Indices

Extreme weather indices and definitions were obtained from Expert Team on Climate Change Detection and Indices (thereafter, ETCCDI), (https://etccdi.pacificclimate.org/indices.shtml). The ETCCDI indices primarily focus on a standardized set of climate indices that are widely recognized and used for analyzing climate extremes. From the ETCCDI, the study used four ETCCDI indices (**Table 1**) including; duration indices Rx1day (Max 1-day

Table 1. Extreme Precipitation indices by ETCCDI. Source: (Zhang et al., 2011).

Index	Indicator name	Description	Unit
Rx1day	Max 1-day precipitation	Maximum 1-day precipitation amount	mm/day
Rx5days	Max 5-days precipitation	Maximum 5-day precipitation amount	mm/5day
R95p	Very wet days	Annual total precipitation from days > 95th percentile	mm/year
R99p	Extremely wet days	Annual total precipitation from days > 99th percentile	mm/year

precipitation amount), Rx5day (Max 5-day precipitation amount), and percentile indices R95p (very wet days), and R99p (extremely wet days). Rx1day and Rx5days are defined as maximum accumulation over 1 day and 5 days respectively. These indices were proposed by Alexander et al. (2006) as indices that represent the peak value of the highest rainfall amount reached during a season or year. The maximum accumulation of precipitation over a single day, known as Rx1day, offers ultimate data that can be utilized to draw conclusions regarding alterations in extremes with extended return periods in both observations and model (Min et al., 2011; Kharin et al., 2013). Both the Rx1day and Rx5day represent extremely heavy rainfall; Rx1day causes flash flooding while Rx5day is more likely to cause long-term riverine flooding (Basher et al., 2018). R95p and R99p are percentile indices used to calculate percentile thresholds based on the collection of wet days in the reference period, without taking into account the yearly cycle. These indices offer a straightforward way to monitor trends in the occurrence or intensity of extremes, while not extremely severe, could still potentially impose stress on both humans and the environment (Zhang et al., 2011). The reason for selecting percentile thresholds lies in the fact that the number of days exceeding these percentile thresholds is uniformly distributed across regions and holds significance regardless of the specific location. The extreme rainfall indices were calculated from the mean daily rainfall of the 20 weather stations (Section 2.2) during SON season across Uganda for the period 1981 to 2022.

2.3.2. Generalized Extreme Value (GEV) Distributions

GEV distributions are statistical models that Jenkinson (1955) developed based on the Gumbel, Frechet, and Weibull distributions (Chu et al., 2013). The GEV distribution is designed to capture the characteristics of extreme events, making it a valuable tool for estimating and predicting extreme values (Walshaw, 2014). As a crucial method for analyzing extreme events, GEV distributions serve as a model that constrains the distribution of both maximum and minimum values derived from random observations drawn from the same arbitrary distribution (Abdulali et al., 2022). In this study, the GEV distribution model was employed to estimate extreme rainfall and its parameters. By fitting the GEV distribution to observed extreme rainfall data, the distribution parameters were estimated allowing for the calculation of return periods, which measure the average time between occurrences of extreme events that exceed a specific threshold. Return periods were calculated based on the probability of exceedance and then interpolated according to the fitted distribution. This was done to represent the average recurrence interval of an event with a certain rainfall value. This method has been used in previous studies (Nadarajah, 2005; Chu et al., 2013).

2.3.3. Sequential Mann-Kendall Test

Mann Kendall non parametric test (Mann, 1945; Kendall, 1975) was applied to the extreme rainfall indices to identify trends during the period from 1981 to 2022 for general trend analysis of the data. The Mann Kendall test has been used in studies to understand the trends in the meteorological parameters (Nsubuga et al., 2011; Gocic & Trajkovic, 2013; Chinchorkar et al., 2015). The sequential Mann-Kendall (MK) trend test was used to detect abrupt changes in SON extreme rainfall trends. It graphically illustrates the forward (u(F)) and backward (u(B)) trends of extreme rainfall over Uganda, which signifies increase or decreasing patterns respectively.

3. Results and Discussion

3.1. Statistical Characteristics of Extreme Rainfall Events during SON Season

Figure 2 shows the number of days in the SON season when extreme rainfall

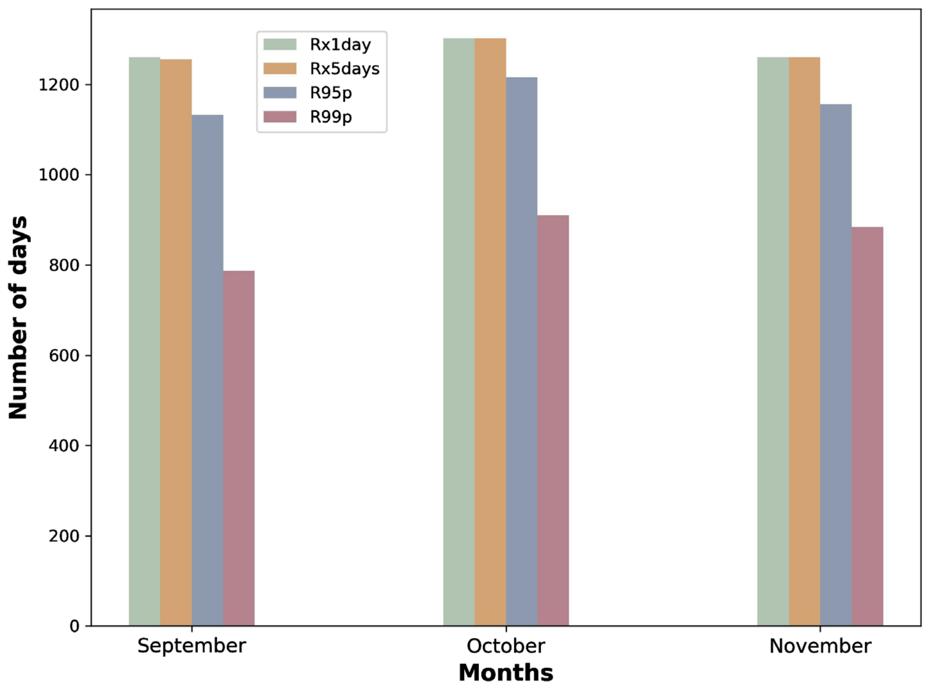

Figure 2. Count of extreme rainfall days for each month in SON in Uganda from 1981 to 2022 based on CHIRPS v2.0 daily rainfall dataset.

occurred for each month, using different extreme rainfall indices as defined by (Zhang et al., 2011). The count of extreme rainfall days in SON season reflects on the variability of extreme rainfall events. Notably, the month of October had the highest count across all four indices compared to September and November. This suggests that October received extended periods of intense and extreme daily rainfall events well beyond the typical $95^{th}/99^{th}$ percentiles compared to other SON months. To get a clear investigation of the extreme rainfall characteristics, the study examined each index (rx1day, rx5days, r95p, r99p) with their frequency distribution and return periods within 1981-2022 SON seasons in Uganda. This was done to understand when certain extreme rainfall events with specific magnitude were likely to occur during SON season. The normal distribution (**Figure 3(a)** and **Figure 3(c)**) suggests that the extreme rainfall values tend to be systematically distributed around the mean.

The distribution of Rx1day during SON season (**Figure 3(a)**) indicates that most maximum daily rainfall was within 0 - 10 mm and the accumulation of daily rainfall for 5 consecutive days was within 0 - 35 mm. The magnitudes of both Rx1/Rx5days were moderate with a frequency probability exceedance of 0.20 (20%)/0.05 (5%) respectively in 42 years. Indicating that there was a 20% chance of intense 1 day rainfall and 5% chance of extended periods of intense rainfall during SON season (1981 to 2022). Rx1day events occurred more frequently

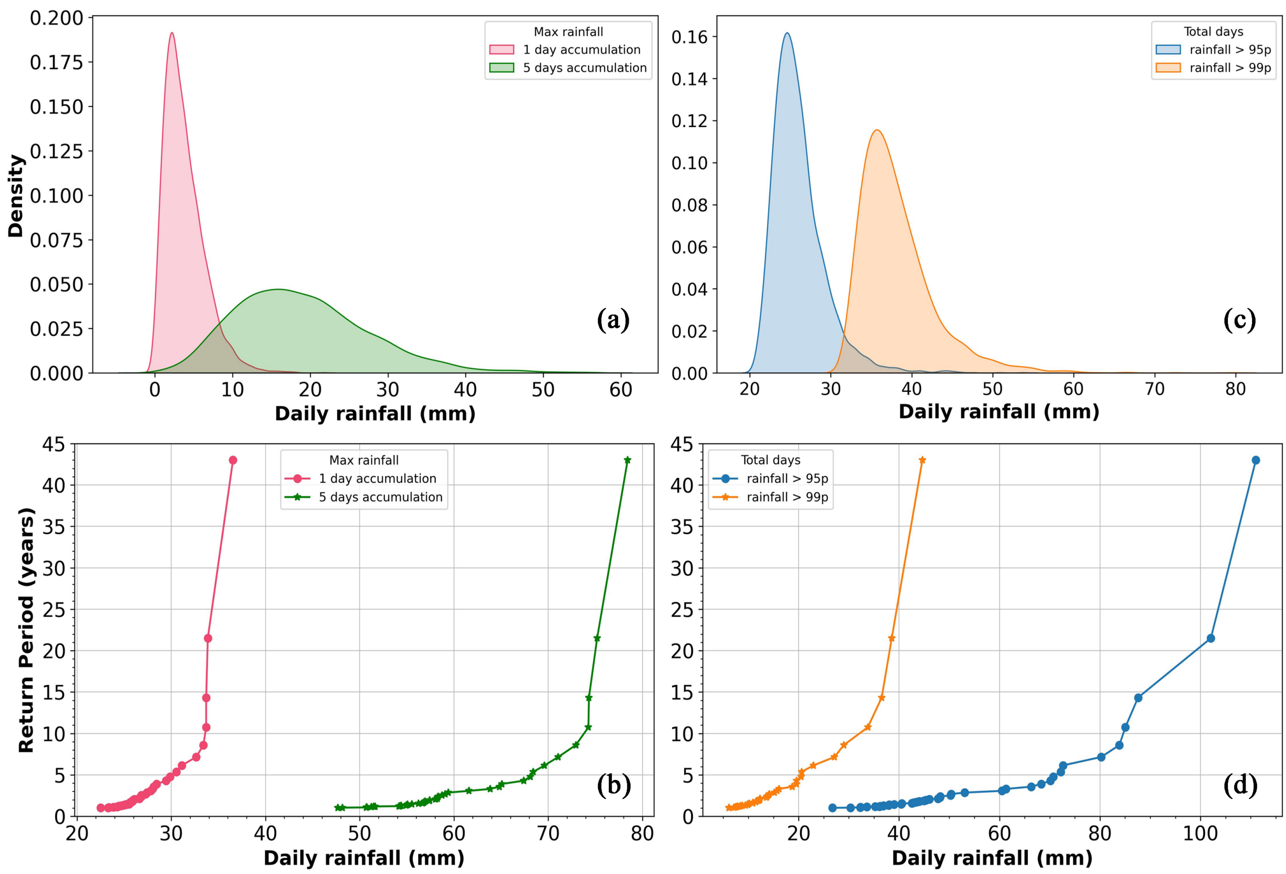

Figure 3. Extreme rainfall occurrences over Uganda during SON season from 1981 to 2022 based on CHIRPS dataset.

but with smaller magnitudes compared to Rx5days events, which occurred less often but with higher magnitudes. The average return period of Rx1/Rx5days was 1.63/3.40 years (**Table 2**) showing that intense 1-day rainfall (Rx1day) and extended periods of intense rainfall (Rx5days) occurred approximately once every 1.63 years and 3.40 years, respectively, from 1981 to 2022. On average, records of prolonged intense daily rainfall events, ranging between 50 - 80 mm, were observed once every 3.40 years. Regarding R95p (total daily rainfall > 95th percentile), the distribution (**Figure 3(c)**) shows values within 20 - 30 mm with frequency probability exceedance of 0.16 (16%) and 0.12 (12%), while R99p (total daily rainfall > 99th percentile) values were within 30 - 45 mm with frequency probability exceedance of 0.16 (16%) and 0.12 (12%), respectively. This shows that there was a 12%/16% chance of receiving extremely intense daily rainfall events well beyond the 95th/99th percentiles respectively. On average, extremely intense daily rainfall occurred approximately once every 1.58/1.47years (**Table 2**) for R95/R99p respectively. Records of extreme daily rainfall events beyond the 95th percentile, ranging between 30 - 112 mm, were observed once every 1.58 years for the period 1981 to 2022. This indicates that such extreme daily rainfall events were relatively common, occurring more frequently than the prolonged intense daily rainfall events.

3.2. Temporal Characteristics of Extreme Rainfall Events during SON Season

The long-term temporal distribution was presented in (**Figure 4**) using standardized anomalies to measure how much extreme rainfall in a given year differs from what is considered normal. Rainfall extremes were categorized as either above or below normal based on these anomalies. If the standardized anomaly value was ≥+1, it meant the extreme rainfall was above normal (higher than the long-term average). Conversely, values ≤ +1 indicated extreme rainfall below the long-term average. The severity of extreme rainfall was determined by the departure of its anomaly from a threshold value of +1. The same criteria was used in previous studies on extreme rainfall analysis (Seleshi & Zanke, 2004; Jury, 2018; Ongoma et al., 2018; Oo et al., 2023). The long-term analysis reveals that the variability in extreme rainfall during the SON season in Uganda changed each year and some years experienced more intense and extreme daily rainfall compared to others. Notable peaks in R95p (**Figure 4(c)**) were observed in 1993, 2005, and 2006. For R99p (**Figure 4(d)**), exceptionally high values of daily rainfall

Table 2. Mean, standard deviation and average return period of extreme rainfall during SON based on CHIRPSv2.0 from 1981 to 2022.

	Rx1day	Rx5days	R95p	R99p
Mean	3.79	18.95	28.14	41.17
St.dev	5.35	15.52	8.52	10.81
Av. Return period (years)	1.63	3.40	1.58	1.47

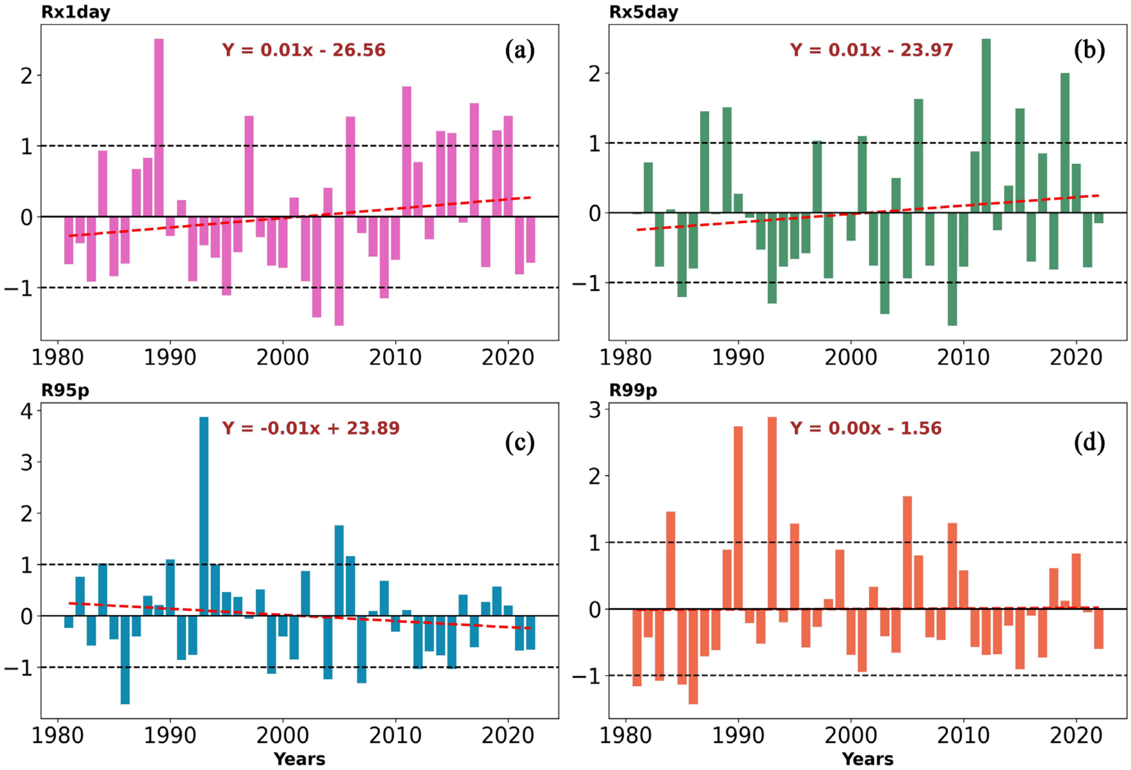

Figure 4. Temporal distribution of extreme rainfall during SON season based on CHIRPS (1981 to 2022). (a) and (b) Rx1day and Rx5days, (c) and (d) R95p and R99p. The corresponding trendlines and equations are displayed on all figures.

exceeding the 99th percentile occurred in 1984, 1990, 1993, 1995, 2005, and 2009, in the past four decades. Regarding Rx1day and Rx5days (Figure 4(a) and Figure 4(b)), the years 1989, 1997, 2006, 2011, 2012, 2017, 2019, and 2020 stood out with extremely high anomaly values (≥1), indicating intense and prolonged daily rainfall during the SON season. Similar results by Ogwang et al. (2016a) on extreme rainfall over Uganda and Kenya that highlighted an increase in the intensity of extreme rainfall events in the recent past, specifically from the late 1980s and early 1990s onwards, particularly those categorized as above normal. Overall Uganda has experienced intense and extreme daily rainfall events in the past years during the SON season.

Trend Analysis

The trendlines in Figure 4 suggested a slight increase in intense daily rainfall events, as indicated by slope magnitude values of 0.01 for Rx1day, Rx5days, and R95p. However, R99p shows no discernible trend with a slope of 0.00. To assess the significance of these trends, a Mann-Kendall test was used and the results (Table 3) indicated that these trends were not statistically significant, as the p-values consistently exceeded 0.05. The Z-statistic and Kendall's tau values revealed weak correlations further supporting the absence of statistically significant trends. Taking a closer look at the Mann Kendall analysis, the sequential Mann-Kendall (thereafter, SQMK) was employed (Figure 5) to graphically display

Table 3. Summary of Mann-Kendall test for SON extreme rainfall events over Uganda during 1981 to 2022.

Mann-Kendall test	Rx1day	Rx5days	R95p	R99p
Trend	No trend	No trend	No trend	No trend
Slope	−0.002	−0.005	0.005	0.018
Z	−0.173	−0.238	0.195	0.737
Kendall's tau	−0.019	−0.027	0.022	0.080
P value	0.862	0.811	0.845	0.461
Alpha	0.05	0.05	0.05	0.05
Significance	NST	NST	NST	NST

NST: No significant trend.

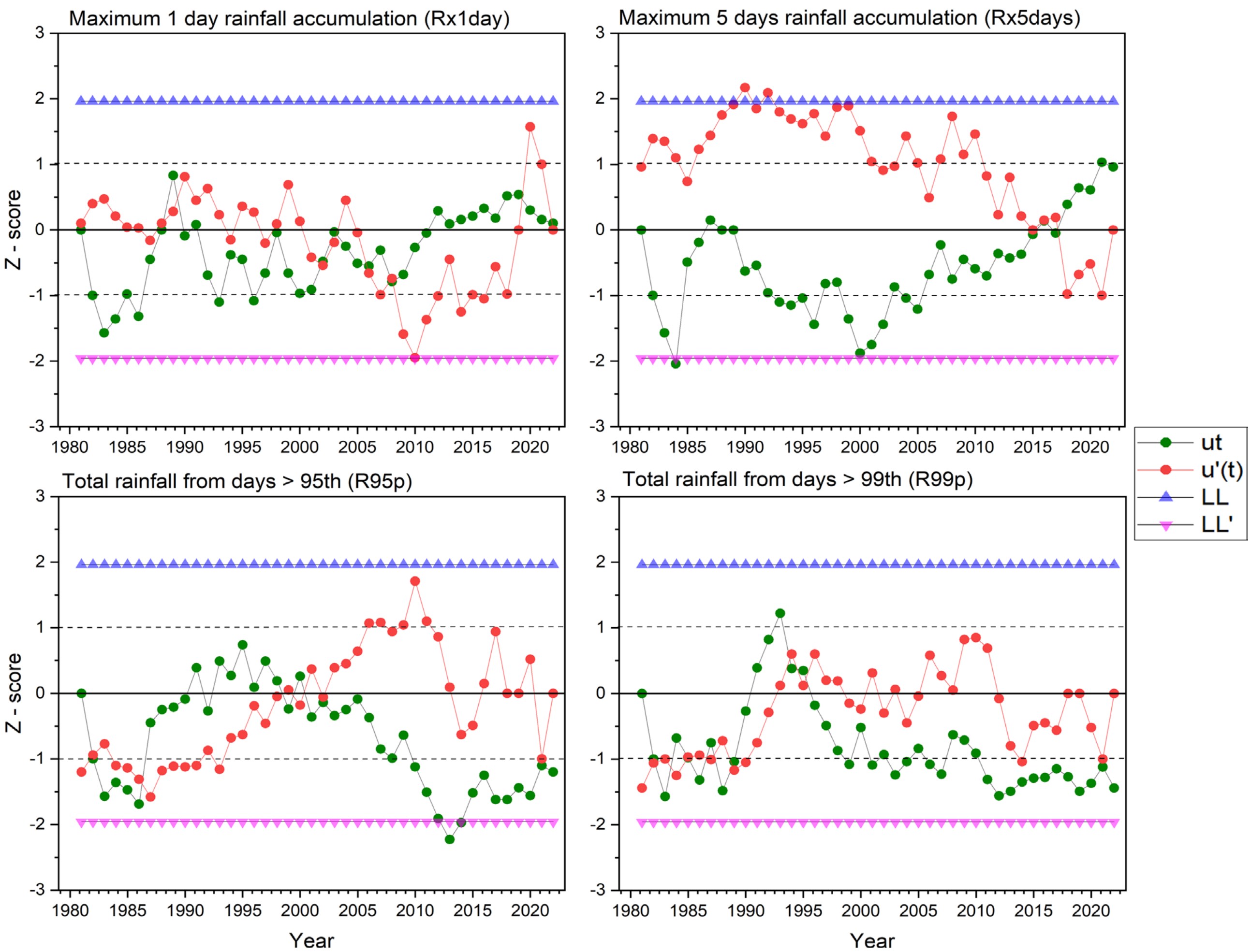

Figure 5. The sequential Mann-Kendall trend test of SON extreme rainfall over Uganda. The ut is forward trend while u'(t) is backward trend based on CHIRPS dataset 1981 to 2022. The upper (LL (+1.96)) and lower (LL' (−1.96)) rugged lines represent the confidence limits of 95%.

the forward (ut) and backward (u'(t)) trends in SON extreme rainfall for 1981 to 2022 climatology. SQMK results showed that most of the values for Rx1day, R95p and R99p were lying within the confidence level except for Rx5day which exhibited significant trends. This suggests that the trend in prolonged intense daily rainfall (Rx5days) was statistically significant at the given confidence level of 95% (corresponding to −1.96 and +1.96) during SON season from 1981 to 2022. Additionally, SQMK revealed the existence of abrupt changes in both (ut) and (u'(t)) values indicating shifts in trend direction over the period of time.

This highlighted the variability in extreme rainfall during SON season ranging from trend shifts to changes in the rate of increase and decrease in extreme rainfall. Specifically examining Rx5day, the forward trend (ut) depicted an increase after 2000s and abrupt changes in 2015 and 2017. Such variability in extreme rainfall impact sectors within the country that rely on rainfall patterns. For instance, the variability has the potential to interrupt optimal growing conditions, leading to crop failures that can have severe consequences for food security, water resources, and overall agricultural productivity (Nsubuga et al., 2014).

3.3. Spatial Characteristics of Extreme Rainfall Events during SON Season

The observed spatial distribution shows that almost all areas in Uganda received extreme rainfall during the SON season for the study period. However, there were notable discrepancies between the extreme rainfall events, represented by all the indices across Uganda, with some parts of the country receiving more extreme rainfall events compared to others during this season. The consistent low values of Rx1day (**Figure 6(a)**) and Rx5days (**Figure 6(b)**) in all decades over northeastern Uganda indicates that on average this region tends to receive few short duration daily rainfall events compared to other regions. The results in **Figure 7** displaying the average of events with extreme rainfall having Z score > +1 show that northeastern Uganda received both intense short duration daily rainfall (**Figure 7(a)** and **Figure 7(b)**) and extreme daily rainfall (**Figure 7(c)** and **Figure 7(d)**) for all the decades compared to other regions. Moreover, the frequency of these events in this region (**Figures 8(a)-(d)**), further reveals that on average, they occurred between 15% - 30% of the study period 1981 to 2022. This implies that the area relatively had low occurrences of short/5-day duration heavy rainfall events, however, these events were very intense and extreme across all decades. Despite this, northeastern Uganda exhibited high values for total rainfall days exceeding the 95^{th} and 99^{th} percentiles. While the northeastern Uganda may not frequently experience intense rainfall over short or extended period of time, when extreme rainfall events occur, they contribute significantly to the total rainfall in the region. The findings align with Egeru et al.'s (2014) study, which identified significant spatial variability shifts leading to increased wetness in northeastern Uganda. The heightened rainfall during the 1997/98 rainy season, particularly in April, November, and December, was noted. The study attributed this shift to the intensification of the dipole rainfall pattern over Eastern Africa and projected further variability with increased wetness in the region from 2010 to 2039. Considering the region's semi-arid climatic conditions

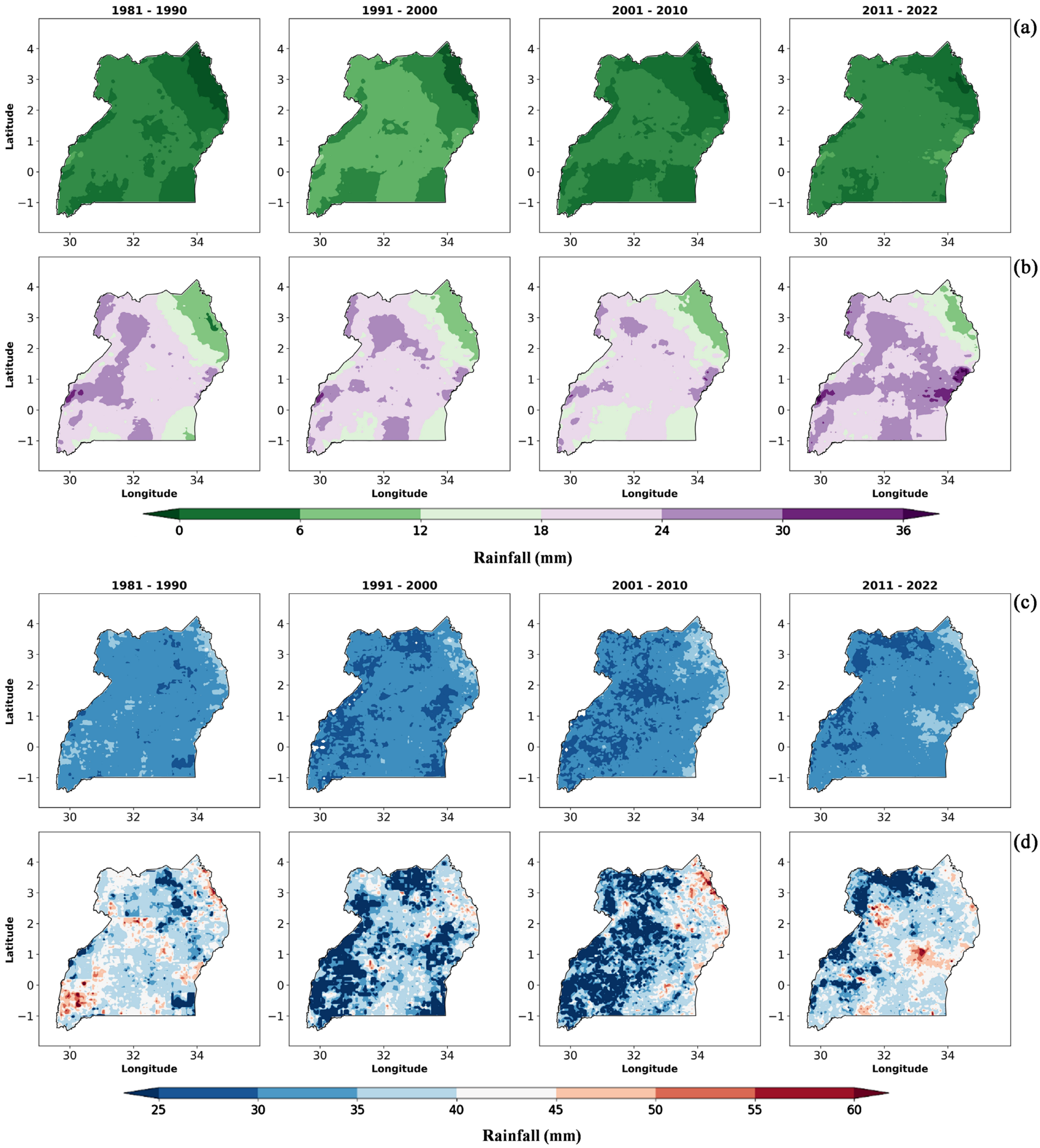

Figure 6. Decadal daily extreme rainfall spatial distribution during SON season over Uganda based on CHIRPS 1981 to 2022. (a) Rx1day, (b) Rx5days, (c) R95p and (b) R99p.

and susceptibility to drought, the observed rise in wetness implies a noteworthy climate shift in this area.

Eastern, Western, and areas around Lake Victoria, exhibited moderate to high values for both short and prolonged intense daily rainfall, (Figure 6(a) and Figure 6(b)) across all four decades, where Eastern Uganda stood out as a region with the highest values of historical extreme rainfall events (Figure 6(c) and Figure 6(d)). Moreover, the observed high values of the R95 and R99p indices (Figure 6(c) and Figure 6(d)) across these regions showed an increase in the amount of daily extreme rainfall ranging from 45 - 60 mm during the recent decade. This indicates a notable surge in daily extreme rainfall events, specifically those surpassing the 95th and 99th percentiles over these regions. Meanwhile, the intensity (Figure 7(a) and Figure 7(b)) and frequency (Figure 8(a) and Figure 8(b)) clearly portrays the occurrence of these events increased up to 40%

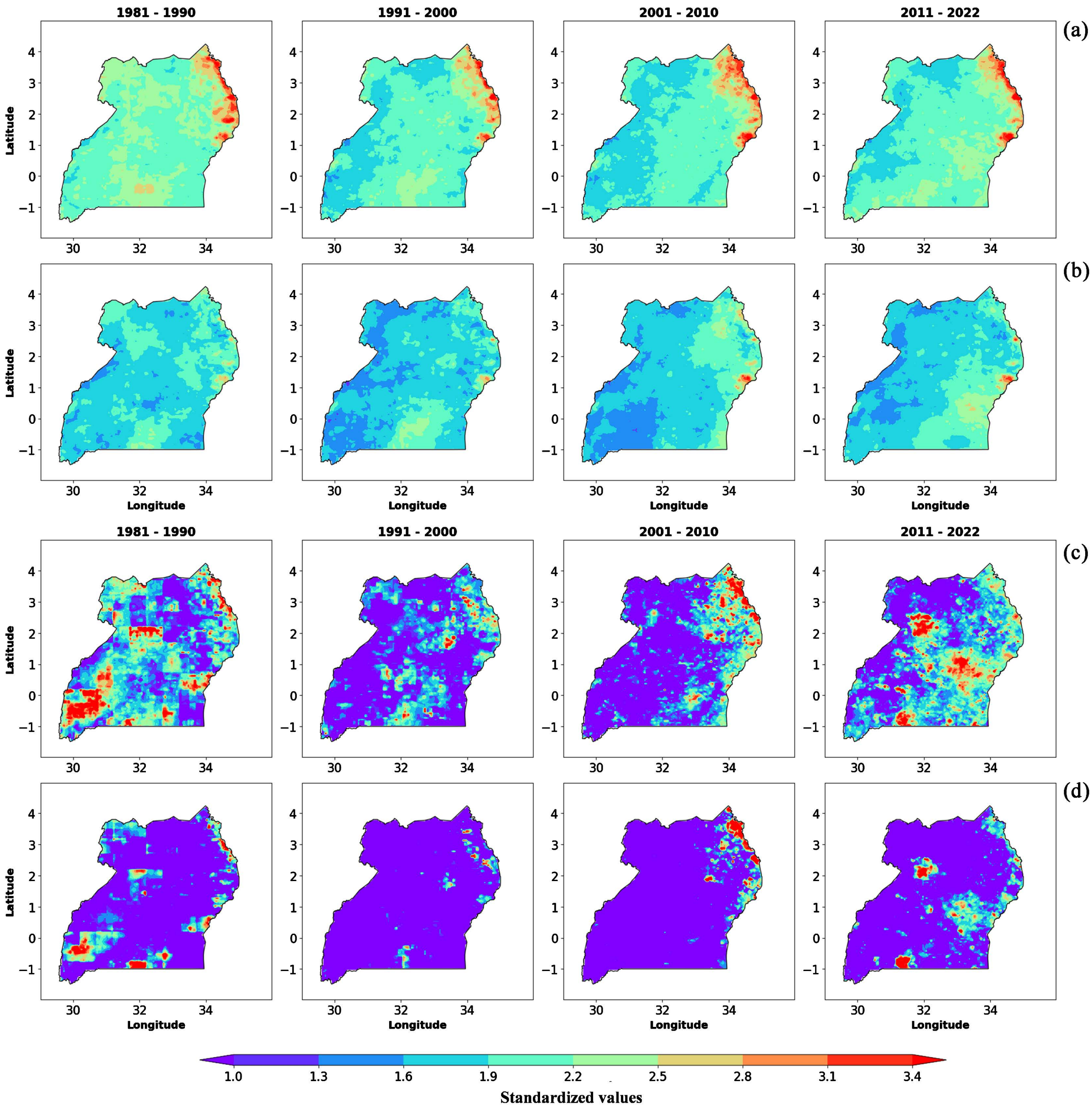

Figure 7. Intensity of extreme rainfall in SON season displayed in decades from 1981 to 2022 expressed as the average of values with Z score > +1. (a) Rx1day, (b) Rx5days, (c) R95p and (b) R99p.

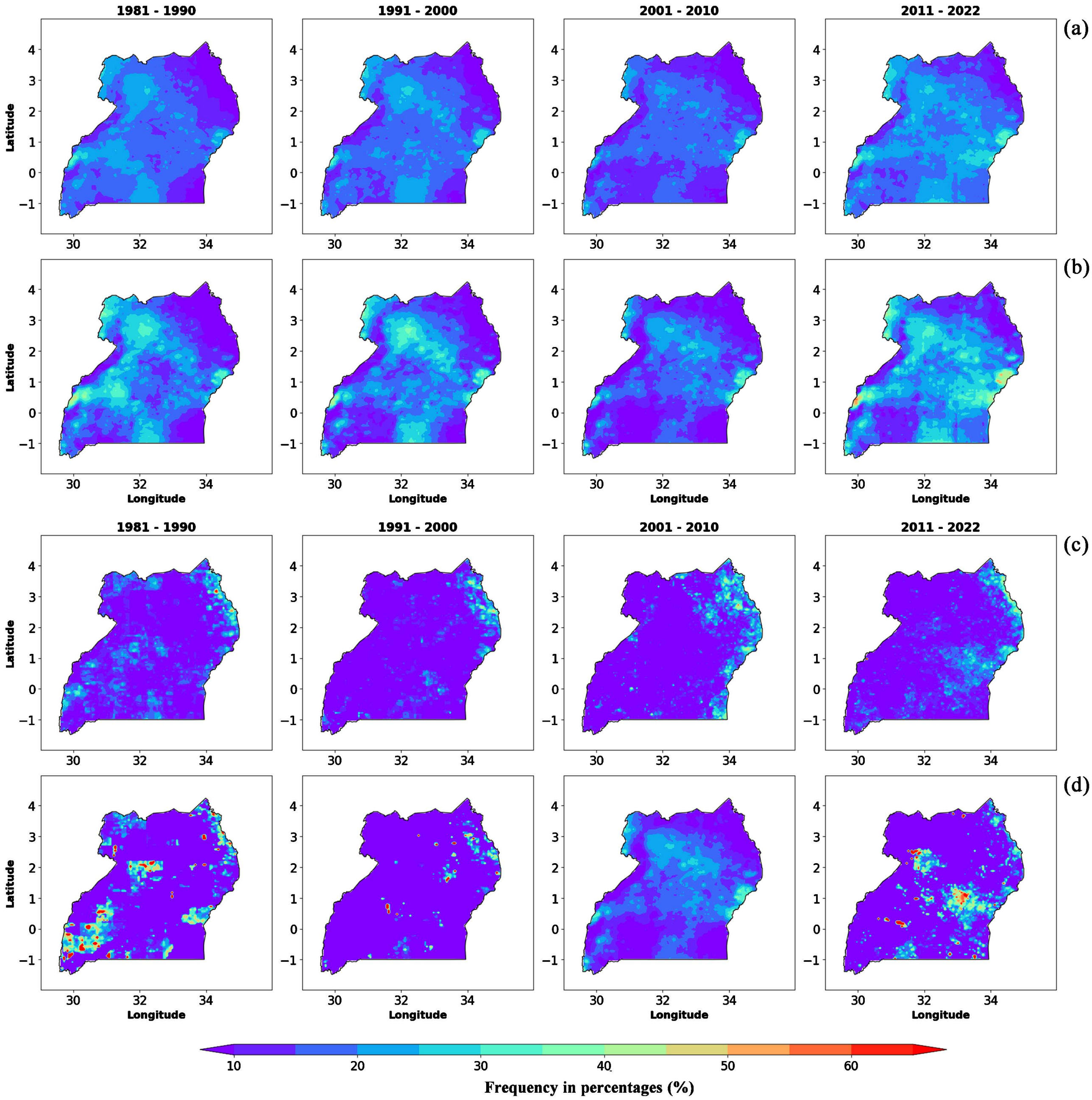

Figure 8. Frequency of extreme rainfall in SON season displayed in decades from 1981 to 2022 expressed as the percentage of values with Z score > +1. (a) Rx1day, (b) Rx5days, (c) R95p and (b) R99p.

during SON in Eastern Uganda compared to other regions. Similarly, areas around Lake Victoria, the findings reveal a surge in the intensity (**Figure 7**) and frequency (**Figure 8**) of extreme rainfall for all indices in the recent decade. The frequency increased from 30% - 60% occurrence in SON season. This aligns with the findings of (Kizza et al., 2009), where positive increase in rainfall was observed at most stations along Lake Victoria. The increase has been attributed to the existence of a quasi-permanent trough that occurs over the Lake and land-lake-thermal contrast which favors convection (Ogwang et al., 2012). The increase in occurrence of extreme events, as illustrated in **Figure 8(c)**, around Lake Victoria can also be attributed to thunderstorms and rainfall displaying a distinct diurnal cycle, with convective activity peaking at night and being suppressed during the daytime (Thiery et al., 2017). The significant rise during the 2011 to 2022 decade suggests an intensification and frequency of short-term and prolonged intense rainfall events in these areas during SON season. The observed increase in both intense rainfall events and extreme rainfall indices aligns with broader patterns associated with climate variability in Uganda as discussed by (Nsubuga & Rautenbach, 2018). This increase gave rise to increased runoff and flooding. The International Monetary Fund Uganda country report mentioned that over the last four decades, spanning from 1985 to 2021, floods have been the predominant natural disasters in Uganda, constituting a significant majority (55%) of such incidents (IMF, 2022). These floods encompassed both flash floods and slow-onset floods and were particularly prevalent in urban areas, low-lying regions, and areas situated along riverbanks and swamplands.

Regarding, southwestern Uganda, a consistent reduction was observed in extreme rainfall for almost all indices (**Figure 6**). The intensity (**Figure 7(c)** and **Figure 7(d)**) and frequency (**Figure 8(c)** and **Figure 8(d)**) of extreme daily rainfall reduced since 1981 over this region. This suggests a potential decline in the recorded extreme rainfall events in the region over the long term. The observed decrease in this region was mentioned by Ogwang et al. (2012) and Ngoma et al. (2021a) in their studies. Despite the overall trend of decreasing extreme rainfall in southwestern Uganda, a noteworthy exception is observed in the most recent decade (2011-2022) where there was a slight increase in the intensity of extreme rainfall, (**Figure 7(c)**). Similar observations by Diem et al. (2019) showed a greater increase in rainfall intensity during the SON season compared to the MAM season in southwestern Uganda. The increase was attributed to changes in the middle-troposphere conditions and lower-troposphere flow, which influence the duration, intensity, and overall characteristics of rainfall over Western Uganda. Such changes may encompass variations in temperature, humidity, and atmospheric pressure.

Overall, there was an observed reduction in extreme rainfall recorded in Uganda during the third decade (2001-2010) when compared to the initial decades (1981 to1990 and 1991 to 2000) suggesting a period of relatively lower observations of extreme rainfall events for SON season during the early 2000s compared to the 1980/1990s. Contrary to the trend observed in the third decade, the recent decade (2011 to 2022) recorded an increase in extreme rainfall across all indices. This indicates that there was a shift in rainfall patterns during the recent years, deviating from the overall decreasing trend seen in previous decades. The above spatial analysis portrayed evident variations in both temporal and spatial distribution of extreme rainfall during SON over Uganda for the period 1981 to 2022.

4. Conclusion

The study analyzed extreme rainfall events from mean rainfall of 20 weather stations across Uganda during the SON season from 1981 to 2022 based on CHIRPS-v2 datasets. The motivation behind this research lies in the growing importance of understanding the historical characteristics of extreme rainfall events in Uganda, particularly in regions vulnerable to such occurrences. The analysis of statistical characteristics showed that intense 1-day rainfall (Rx1day) and extended periods of intense rainfall (Rx5days) occurred approximately once every 1.63 years and 3.40 years, respectively. Similarly, extremely wet days (R95p and R99p) occurred approximately once every 1.58 years and 1.47 years, respectively. October was revealed to be the month with most extreme rainfall events compared to September and November. The temporal analysis indicated variability in extreme rainfall events, with notable peaks in certain years. Despite the observed peaks, the trends were not statistically significant, with weak correlations and p-values consistently exceeding 0.05 significant level. However, the Sequential Mann-Kendall analysis highlighted significant trends in prolonged periods of intense daily rainfall (Rx5days) after the 2000s with abrupt changes in 2015 and 2017, emphasizing the variability in extreme rainfall over the study period. The spatial analysis revealed a complex and region-specific pattern in extreme rainfall events across Uganda. While most areas experienced extreme rainfall during the SON season, there were notable differences in the frequency and intensity of events. Eastern Uganda and areas around Lake Victoria exhibited high values for both short and prolonged intense daily rainfall, with a surge in extreme events during the recent decade. Conversely, southwestern Uganda showed a consistent reduction in extreme rainfall over the years, with a slight increase in the most recent decade, indicating a shift in rainfall patterns. Overall, the results highlight a complex and dynamic situation in Uganda's rainfall patterns particularly in terms of extreme rainfall during SON season. As the extreme rainfall patterns are subject to change, incorporating climate models and projections in future research could provide a comprehensive understanding of the future behavior of extreme rainfall events in Uganda during SON. It is important to consider both the frequency and intensity of events when assessing the overall extreme rainfall regime in a particular area and the socioeconomic impact.

The study's findings have significant applications in seasonal extreme rainfall monitoring and prediction particularly for vital sectors in Uganda. Furthermore, the study contributes valuable insights for water resource management, disaster preparedness, and enhanced seasonal forecasting, aiming to fortify Uganda's resilience and promote sustainable development amid changing weather patterns. The study recommends that more resources should be allocated to increasing public awareness, improving early warning systems and enhancing emergency preparedness to mitigate the impact of extreme rainfall events, especially in regions experiencing increasing intensity.

Acknowledgements

The authors acknowledge Nanjing University of Information Science and Technology (NUIST) for providing a favorable environment and infrastructural needs for conducting the research. The first author is thankful to the Ministry of Commerce, People's Republic of China for providing financial support to conduct this research. Recognition goes to the Uganda National Meteorological Authority and the Pan African University Institute for Water and Energy Science (including Climate change) for providing the skills and knowledge used in conducting the research. Special appreciation to the UC Santa Barbara for availing the CHIRPS datasets that were used in this analysis. The authors appreciate Prof. Tan Guirong for the exceptional support and supervision of the research.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Abdulali, B. A. A., Abu Bakar, M. A., Ibrahim, K., & Mohd Ariff, N. (2022). Extreme Value Distributions: An Overview of Estimation and Simulation. *Journal of Probability and Statistics, 2022,* Article ID: 5449751. https://doi.org/10.1155/2022/5449751

Alexander, L. V, Zhang, X., Peterson, T. C., Caesar, J., Gleason, B., Tank, A. M. G. K., Haylock, M., Collins, D., Trewin, B., Rahimzadeh, F., Tagipour, A., Kumar, K. R., Revadekar, J., Griffiths, G., & Vincent, L. (2006). Global Observed Changes in Daily Climate Extremes of Temperature and Precipitation. *Journal of Geophysical Research: Atmospheres, 111,* D05109. https://doi.org/10.1029/2005JD006290

Basher, M. A., Stiller-Reeve, M. A., Saiful Islam, A. K. M., & Bremer, S. (2018). Assessing Climatic Trends of Extreme Rainfall Indices over Northeast Bangladesh. *Theoretical and Applied Climatology, 134,* 441-452. https://doi.org/10.1007/s00704-017-2285-4

Chinchorkar, S. S., Sayyad, F. G., Vaidya, V. B., & Pandye, V. (2015). Trend Detection in Annual Maximum Temperature and Precipitation Using the Mann Kendall Test—A Case Study to Assess Climate Change on Anand of Central Gujarat. *Mausam, 66,* 1-6. https://doi.org/10.54302/mausam.v66i1.360

Chu, L.-F., McAleer, M., & Wang, S.-H. (2013). Statistical Modelling of Recent Changes in Extreme Rainfall in Taiwan Region. *International Journal of Environmental Science and Development, 4,* 52-55. https://doi.org/10.7763/IJESD.2013.V4.302

Diem, J. E., Sung, H. S., Konecky, B. L., Palace, M. W., Salerno, J., & Hartter, J. (2019). Rainfall Characteristics and Trends—And the Role of Congo Westerlies—In the Western Uganda Transition Zone of Equatorial Africa from 1983 to 2017. *Journal of Geophysical Research: Atmospheres, 124,* 10712-10729. https://doi.org/10.1029/2019JD031243

Dinku, T., Funk, C., Peterson, P., Maidment, R., & Tadesse, T. (2018). Validation of the CHIRPS Satellite Rainfall Estimates over Eastern Africa. *Quarterly Journal of the Royal Meteorological Society, 144,* 292-312. https://doi.org/10.1002/qj.3244

Dubache, G., Ogwang, B. A., Ongoma, V., & Towfiqul Islam, A. R. M. (2019). The Effect of Indian Ocean on Ethiopian Seasonal Rainfall. *Meteorology and Atmospheric Phys-*

ics, 131, 1753-1761. https://doi.org/10.1007/s00703-019-00667-8

Egeru, A., Osaliya, R., MacOpiyo, L., Mburu, J., Wasonga, O., Barasa, B., Said, M., Aleper, D., & Majaliwa Mwanjalolo, G. J. (2014). Assessing the Spatio-Temporal Climate Variability in Semi-Arid Karamoja Sub-Region in North-Eastern Uganda. *International Journal of Environmental Studies, 71,* 490-509. https://doi.org/10.1080/00207233.2014.919729

Gocic, M., & Trajkovic, S. (2013). Analysis of Changes in Meteorological Variables Using Mann-Kendall and Sen's Slope Estimator Statistical Tests in Serbia. *Global and Planetary Change, 100,* 172-182. https://doi.org/10.1016/j.gloplacha.2012.10.014

Guastavino, S., Piana, M., Tizzi, M., Cassola, F., Iengo, A., Sacchetti, D., Solazzo, E., & Benvenuto, F. (2022). Prediction of Severe Thunderstorm Events with Ensemble Deep Learning and Radar Data. *Scientific Reports, 12,* Article No. 20049. https://doi.org/10.1038/s41598-022-23306-6

IMF (2022). *Selected Issues on Uganda: Vol. No.22/78 (Issue 22).*

Indeje, M., & Semazzi, F. H. M. (2000). Enso Signals in East African Rainfall Seasons. *International Journal of Climatology, 20,* 19-46.

IOM. (2022). *Uganda's Perennial Floods Cast the Spotlight on the Region's Climate Change-Related Disasters.* https://reliefweb.int/report/uganda/ugandas-perennial-floods-cast-spotlight-regions-climate-change-related-disasters

Jenkinson, A. F. (1955). The Frequency Distribution of the Annual Maximum (or Minimum) Values of Meteorological Elements. *Quarterly Journal of the Royal Meteorological Society, 81,* 158-171. https://doi.org/10.1002/qj.49708134804

Jeong, J. W., Jeung, S. J., & Kim, B. S. (2021). Future Extreme Climate Analysis of Jeju Using Climate Change Scenario and ETCCDI Index. *Journal of the Korean Society of Hazard Mitigation, 21,* 13-21. https://doi.org/10.9798/KOSHAM.2021.21.4.13

Jury, M. R. (2018). Uganda Rainfall Variability and Prediction. *Theoretical and Applied Climatology (Springer Vienna), 132,* 905-919. https://doi.org/10.1007/s00704-017-2135-4

Kendall, M. G. (1975). *Rank Correlation Methods* (4th ed., p. 8). Charles Griffin. https://archive.org/details/rankcorrelationm0000kend

Kendall, M. G. (1975). *Rank Correlation Methods* (4th Edition). Griffin.

Khan, S., Piao, S., Zheng, G., Khan, I. U., Bradley, D., & Khan, S. (2021). Sea Surface Temperature Variability over the Tropical Indian Ocean during the ENSO and IOD Events in 2016 and 2017. *Atmosphere, 12,* Article 587. https://doi.org/10.3390/atmos12050587

Kharin, V. V., Zwiers, F. W., Zhang, X., & Wehner, M. (2013). Changes in Temperature and Precipitation Extremes in the CMIP5 Ensemble. *Climatic Change, 119,* 345-357. https://doi.org/10.1007/s10584-013-0705-8

Kimani, M. W., Hoedjes, J. C. B., & Su, Z. (2017). An Assessment of Satellite-Derived Rainfall Products Relative to Ground Observations over East Africa. *Remote Sensing, 9,* Article 430. https://doi.org/10.3390/rs9050430

Kizza, M., Rodhe, A., Xu, C. Y., Ntale, H. K., & Halldin, S. (2009). Temporal Rainfall Variability in the Lake Victoria Basin in East Africa during the Twentieth Century. *Theoretical and Applied Climatology, 98,* 119-135. https://doi.org/10.1007/s00704-008-0093-6

Majaliwa, J. G. M., Tenywa, M. M., Bamanya, D., Majugu, W., Isabirye, P., Nandozi, C., Nampijja, J., Musinguzi, P., Nimusiima, A., Luswata, K. C., Rao, K. P. C., Bonabana, J., Bagamba, F., Sebuliba, E., Azanga, E., & Sridher, G. (2015). Characterization of Historical Seasonal and Annual Rainfall and Temperature Trends in Selected Climatological Homogenous Rainfall Zones of Uganda. *Global Journal of Science Frontier Research, 15,* 21-40.

Mann, H. B. (1945). Nonparametric Tests against Trend. *Econometrica, 13,* 245-259. https://doi.org/10.2307/1907187

Masum, A. (2020). UGANDA: A Country Profile. *Journal of International Studies, 8,* 149-161. https://doi.org/10.32890/jis.8.2012.7931

Mazon, J. J., Castro, C. L., Adams, D. K., Chang, H. I., Carrillo, C. M., & Brost, J. J. (2016). Objective Climatological Analysis of Extreme Weather Events in Arizona during the North American Monsoon. *Journal of Applied Meteorology and Climatology, 55,* 2431-2450. https://doi.org/10.1175/JAMC-D-16-0075.1

Min, S. K., Zhang, X., Zwiers, F. W., & Hegerl, G. C. (2011). Human Contribution to More-Intense Precipitation Extremes. *Nature, 470,* 378-381. https://doi.org/10.1038/nature09763

Muthoni, F. K., Odongo, V. O., Ochieng, J., Mugalavai, E. M., Mourice, S. K., Hoesche-Zeledon, I., Mwila, M., & Bekunda, M. (2019). Long-Term Spatial-Temporal Trends and Variability of Rainfall over Eastern and Southern Africa. *Theoretical and Applied Climatology, 137,* 1869-1882. https://doi.org/10.1007/s00704-018-2712-1

Nadarajah, S. (2005). Extremes of Daily Rainfall in West Central Florida. *Climatic Change, 69,* 325-342. https://doi.org/10.1007/s10584-005-1812-y

Ngoma, H., Ayugi, B., Onyutha, C., Babaousmail, H., Lim Kam Sian, K. T. C., Iyakaremye, V., Mumo, R., & Ongoma, V. (2022). Projected Changes in Rainfall over Uganda Based on CMIP6 Models. *Theoretical and Applied Climatology, 149,* 1117-1134. https://doi.org/10.1007/s00704-022-04106-4

Ngoma, H., Wen, W., Ayugi, B., Karim, R., & Makula, E. K. (2021a). Mechanisms Associated with September to November (SON) Rainfall over Uganda during the Recent Decades. *Geographica Pannonica, 25,* 10-23. https://doi.org/10.5937/gp25-29932

Ngoma, H., Wen, W., Ojara, M., & Ayugi, B. (2021b). Assessing Current and Future Spatiotemporal Precipitation Variability and Trends over Uganda, East Africa, Based on CHIRPS and Regional Climate Model Datasets. *Meteorology and Atmospheric Physics, 133,* 823-843. https://doi.org/10.1007/s00703-021-00784-3

Nicholson, S. E. (2017). Climate and Climatic Variability of Rainfall over Eastern Africa. *Reviews of Geophysics, 55,* 590-635. https://doi.org/10.1002/2016RG000544

Nicholson, S. E., Fink, A. H., Funk, C., Klotter, D. A., & Satheesh, A. R. (2022). Meteorological Causes of the Catastrophic Rains of October/November 2019 in Equatorial Africa. *Global and Planetary Change, 208,* 103687. https://doi.org/10.1016/j.gloplacha.2021.103687

Nsubuga, F. N. W., Olwoch, J. M., De Rautenbach, C. J. W., & Botai, O. J. (2014). Analysis of Mid-Twentieth Century Rainfall Trends and Variability over Southwestern Uganda. *Theoretical and Applied Climatology, 115,* 53-71. https://doi.org/10.1007/s00704-013-0864-6

Nsubuga, F. W., & Rautenbach, H. (2018). Climate Change and Variability: A Review of What Is Known and Ought to Be Known for Uganda. *International Journal of Climate Change Strategies and Management, 10,* 752-771. https://doi.org/10.1108/IJCCSM-04-2017-0090

Nsubuga, F. W., Olwoch, J. M., & Rautenbach, C. J. de W. (2011). Climatic Trends at

Namulonge in Uganda: 1947-2009. *Journal of Geography and Geology, 3,* 119-131. https://doi.org/10.5539/jgg.v3n1p119

O'Hara, B. F., Kaplan, M. L., & Underwood, S. J. (2009). Synoptic Climatological Analyses of Extreme Snowfalls in the Sierra Nevada. *Weather and Forecasting, 24,* 1610-1624. https://doi.org/10.1175/2009WAF2222249.1

Ogwang, B. A., Ayesiga, G., Ojara, M., Kalema, A., Nimusiima, A., Tindamanyire, T., Serwanga, M. N., Ssebabi, F., Gugwa, G., Nsubuga, Y., Atim, R., Kibwika, R., Kiwuwa Balikudembe, J., Kikonyogo, H., Ongoma, V., Taire, A., Kiryhabwe, A., Semujju, M., Einyu, F. et al. (2016a). Characteristics and Changes in SON Rainfall over Uganda (1901-2013). *Journal of Environmental and Agricultural Sciences, 8,* 45-53.

Ogwang, B. A., Guirong, T., & Haishan, C. (2012). Diagnosis of September-November Drought and the Associated Circulation Anomalies over Uganda. *Pakistan Journal of Meteorology, 9,* 11-24. http://www.pmd.gov.pk/rnd/rnd_files/vol8_issue17/2.pdf

Ogwang, B. A., Ongoma, V., & Gitau, W. (2016b). Contributions of Atlantic Ocean to June-August Rainfall over Uganda and Western Kenya. *Journal of the Earth and Space Physics, 41,* 131-140.

Omondi, P. A. O., Awange, J. L., Forootan, E., Ogallo, L. A., Barakiza, R., Girmaw, G. B., Fesseha, I., Kululetera, V., Kilembe, C., Mbati, M. M., Kilavi, M., King'uyu, S. M., Omeny, P. A., Njogu, A., Badr, E. M., Musa, T. A., Muchiri, P., Bamanya, D., & Komutunga, E. (2014). Changes in Temperature and Precipitation Extremes over the Greater Horn of Africa Region from 1961 to 2010. *International Journal of Climatology, 34,* 1262-1277. https://doi.org/10.1002/joc.3763

Ongoma, V., Chen, H., & Omony, G. W. (2018). Variability of Extreme Weather Events over the Equatorial East Africa, a Case Study of Rainfall in Kenya and Uganda. *Theoretical and Applied Climatology, 131,* 295-308. https://doi.org/10.1007/s00704-016-1973-9

Oo, K. T., Haishan, C., & Jonah, K. (2023). Climate Change Impact on the Trigger of Natural Disasters over South-Eastern Himalayas Foothill Region of Myanmar: Extreme Rainfall Analysis. *International Journal of Geophysics, 2023,* 1-20. https://doi.org/10.1155/2023/2186857

Palmer, P. I., Wainwright, C. M., Dong, B., Maidment, R. I., Wheeler, K. G., Gedney, N., Hickman, J. E., Madani, N., Folwell, S. S., Abdo, G., Allan, R. P., Black, E. C. L., Feng, L., Gudoshava, M., Haines, K., Huntingford, C., Kilavi, M., Lunt, M. F., Shaaban, A., & Turner, A. G. (2023). Drivers and Impacts of Eastern African Rainfall Variability. *Nature Reviews Earth and Environment, 4,* 254-270. https://doi.org/10.1038/s43017-023-00397-x

Ross, T. F., & Lott, J. N. (2004). A Climatology of Recent Extreme Weather and Climate Events. *Bulletin of the American Meteorological Society,* 5079-5088.

Ross, T., Lott, N., & Center, N. C. D. (2003). *A Climatology of 1980-2003 Extreme Weather and Climate Events.* National Climatic Data Center Technical Report No. 2003-01. https://www.ncdc.noaa.gov/billions/docs/lott-and-ross-2003.pdf

Seleshi, Y., & Zanke, U. (2004). Recent Changes in Rainfall and Rainy Days in Ethiopia. *International Journal of Climatology, 24,* 973-983. https://doi.org/10.1002/joc.1052

Thiery, W., Gudmundsson, L., Bedka, K., Semazzi, F. H. M., Lhermitte, S., Willems, P., Van Lipzig, N. P. M., & Seneviratne, S. I. (2017). Early Warnings of Hazardous Thunderstorms over Lake Victoria. *Environmental Research Letters, 12,* Article 074012. https://doi.org/10.1088/1748-9326/aa7521

Walshaw, D. (2014). Generalized Extreme Value Distribution. In N. Balakrishnan, T. Colton, B. Everitt, W. Piegorsch, F. Ruggeri, & J.L. Teugels (Eds.), *Wiley StatsRef: Sta-*

tistics Reference Online. Wiley. https://doi.org/10.1002/9781118445112.stat07347

Walshaw, D. (2014). *Generalized Extreme Value Distribution.* Wiley StatsRef: Statistics Reference Online. https://doi.org/10.1002/9781118445112.stat07347

World Bank (2019). *Disaster Risk Profile, Uganda*.

Zhang, X., Alexander, L., Hegerl, G. C., Jones, P., Tank, A. K., Peterson, T. C., Trewin, B., & Zwiers, F. W. (2011). Indices for Monitoring Changes in Extremes Based on Daily Temperature and Precipitation Data. *Wiley Interdisciplinary Reviews: Climate Change, 2,* 851-870. https://doi.org/10.1002/wcc.147