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Evaluation of Past and Future Extreme Rainfall Characteristics over Eastern Uganda

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Abstract: Weather and climate are very important to everyday life because they affect almost every sector of the economy. Climate change associated with increased weather and climate extremes and its associated impacts has become equally important. These weather extremes can be characterized in terms of indices involving precipitation intensity, duration and frequency. This study examined the past and future characteristics of extreme rainfall over Eastern Uganda with 1981-2010 taken as baseline period and 2021-2050 representing a future period. Annual trends in four precipitation indices were analyzed: number of days with precipitation ≥20mm and 50 mm, very wet day precipitation quantity and simple daily intensity index. Linear trends were calculated by using the least squares fit and significance of the trends were identified using the Student t-test. The results showed an overall decreasing trend of all rainfall indices during the period of 1981-2010. Projected trends indicated positive trends in all the indices except the Simple daily intensity index which was projected to have negative trends under RCP4.5. Projected shifts in the mean values also indicated significant increments in all indices. These results indicate that rainfall extremes will continue in the future and therefore it calls for decision-makers to design appropriate preparedness and mitigation strategies in Eastern Uganda.

Keywords: Climate change, climatic extreme; extreme rainfall; future climate projection.

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1. Introduction

Weather and climate are very important as they influence various aspects of daily life including water resources, food security, transport, tourism and health (Below et al., 2015; Diem et al., 2014; Majaliwa et al., 2015; Rehmani et al., 2014), Like other agrarian countries, the economy of Uganda is heavily regulated by weather and climatic conditions. Therefore, a better understanding of climate variability and anomalies will help stakeholders to devise strategies and policies for sustainable and climate resilient economy (Amin et al., 2018; Darand et al., 2017; Letta et al., 2019; Tajbar et al., 2018).

Consequently, there is an increasing concern regarding anthropogenic-induced increasing frequency, intensity and duration of weather extremes (Cutter, 2018; Devkota et al., 2018; Hao et al., 2018; McPhillips et al., 2018). These anomalies affecting the climate which may increase the potential to trigger disasters especially in vulnerable regions (IPCC, 2013; Sagero et al., 2018). In Uganda, the frequent incidences of extreme rainfall events have led to widespread damage to livelihoods. For instance, the 1961/62, 97/98 and 2007 floods resulted in infrastructure damage, displacement and destruction of livelihood assets. Similarly, in September 2010, floods hit the Teso sub-region in eastern Uganda, leading to rotting cassava, sweet potato tubers and groundnuts worth UGX8 billion which consequently led to food insecurity (KCCA, 2015). Information on the characteristics of extreme climatic events is therefore vital for effective disaster preparedness and mitigation planning.

Africa is one of the most vulnerable continents to climate change and climate variability (Nangombe, et al., 2018; Nikulin et al., 2012; Tumushabe, 2018). According to (Omondi et al., 2013), extreme precipitation changes over eastern Africa such as droughts and heavy rainfall have been experienced more frequently in the last 30-60 years. However, rainfall trends in eastern Africa vary greatly over time

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and space. Some assessments suggest that wet seasons will be more intense and droughts less severe over eastern Africa by the end of the century, which indicates a reversal of the observed increase in droughts and heavy rainfall during the past 30 to 60 years (Gitau et al., 2018; Omondi et al., 2013; Ongoma et al., 2018).

In Uganda, climate change and increased climate variability has been observed and it is manifested in the increasing the frequency and intensity of weather extremes including high temperatures and precipitation leading to prolonged drought and erratic rainfall patterns (Egeru et al., 2019; Gitau et al., 2018; Jury, 2018; Nsubuga and Rautenbach, 2018). Moreover, the frequency and intensity of extreme climatic events have generally been on the increase in the last century and are predicted to increase in future (Bamweyana and Kayondo. 2018; Kaggwa et al., 2009). Agricultural products are the major economic resource in Uganda where over 80% of the population's livelihoods are based on rain-fed agriculture (Stampone et al., 2011) and therefore the heavy reliance of the rural and agriculturally dependent population may severely harm them because of its high sensitivity to impacts of adverse effects of climate change.

Previous studies on rainfall variability and trends over Uganda and the region (Mugume et al., 2016; Stampone et al., 2011; Ongoma et al., 2018; Muthoni et al., 2019; Kisembe et al., 2018) mainly focused on seasonal or annual totals and also the assessments of climate change that have been done are often limited to mean rainfall. It's on this basis that detailed studies on rainfall extremes are carried out especially over Eastern Uganda that has frequently experienced extreme events (such as floods). Nevertheless, there's a need to understand how these extremes are changing because of their profound effects especially on agriculture which is the backbone of the economy. This study therefore aimed at assessing the trends and variability of the observed and future rainfall extremes in Eastern Uganda.

2. Methodology

2.1. Study Area

The study was carried out in Eastern Uganda; one of the four regions in the country with a total area of 39,478.8 km2 (Fig. 1). The region has around 6.301 million population, which is 25.5% of the total population of Uganda (UBOS, 2016). The region receives moderate rainfall with annual rainfall averages of about 1100-1200mm, which is distributed between two seasons of March to July and September to November. However, late November to late February or early March is traditionally termed as the long dry season, and mid-June to late July is the short one; but this has become variable with frequent drought spells causing famine. The region has also experienced severe flooding in 1976, 1996 and 2007 and 2010. Incidents of strong winds and storms occur frequently in the region (NEMA, 2007). The soils are of sandy sediments and sandy loams, well drained and highly friable with alluvium deposits in the bottomland (Nabikolo et al., 2012).

2.1. Meteorological Data

The study utilized both observed and modelled daily rainfall data. The observed station gauged data for Soroti weather station (1.72ºN, 33.62ºE, see Fig. 1) was obtained from the Uganda National Meteorological Authority (UNMA) for the period 1981–2016. We analysed downscaled daily rainfall from the Rossby Center Swedish Meteorological and Hydrological Institute (SMHI) regional climate model (RCA4) within the Coordinated Downscaling Experiments (CORDEX) framework that was used to downscale a set of GCMs from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) global climate projections. All simulations were performed at a grid resolution of 0.44°×0.44°.

The GCMs projections are forced by the Representative Concentration Pathways (RCPs, Moss et al. 2010). The RCPs are prescribed greenhouse-gas concentration pathways throughout the 21st century, corresponding to different radiative forcing stabilization levels by the year 2100. RCP 4.5 and 8.5 were chosen as they represent the intermediate and upper range respectively and are considered more realistic with comparison to RCP2.6. RCP4.5 represents a mitigation scenario, which stabilizes radiative forcing at 4.5 W m^{-2} in 2100.while RCP8.5 represents a rising scenario with very high greenhouse gas emissions and radiative forcing of 8.5 W m^{-2} in 2100.

The future daily precipitation time series were collected from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) Global Circulation Model (GCM); Norwegian Earth System Model 1- medium resolution (NorESM1-M), under two Intergovernmental Panel on Climate Change (IPCC) RCP 4.5 and 8.5 for the period of 2021-2050 which was downscaled by Regional Climate Model (RCM) SMHI-RCA4 of the Swedish Meteorological and Hydrological Institute (SMHI) under CORDEX Africa downscaling initiative.

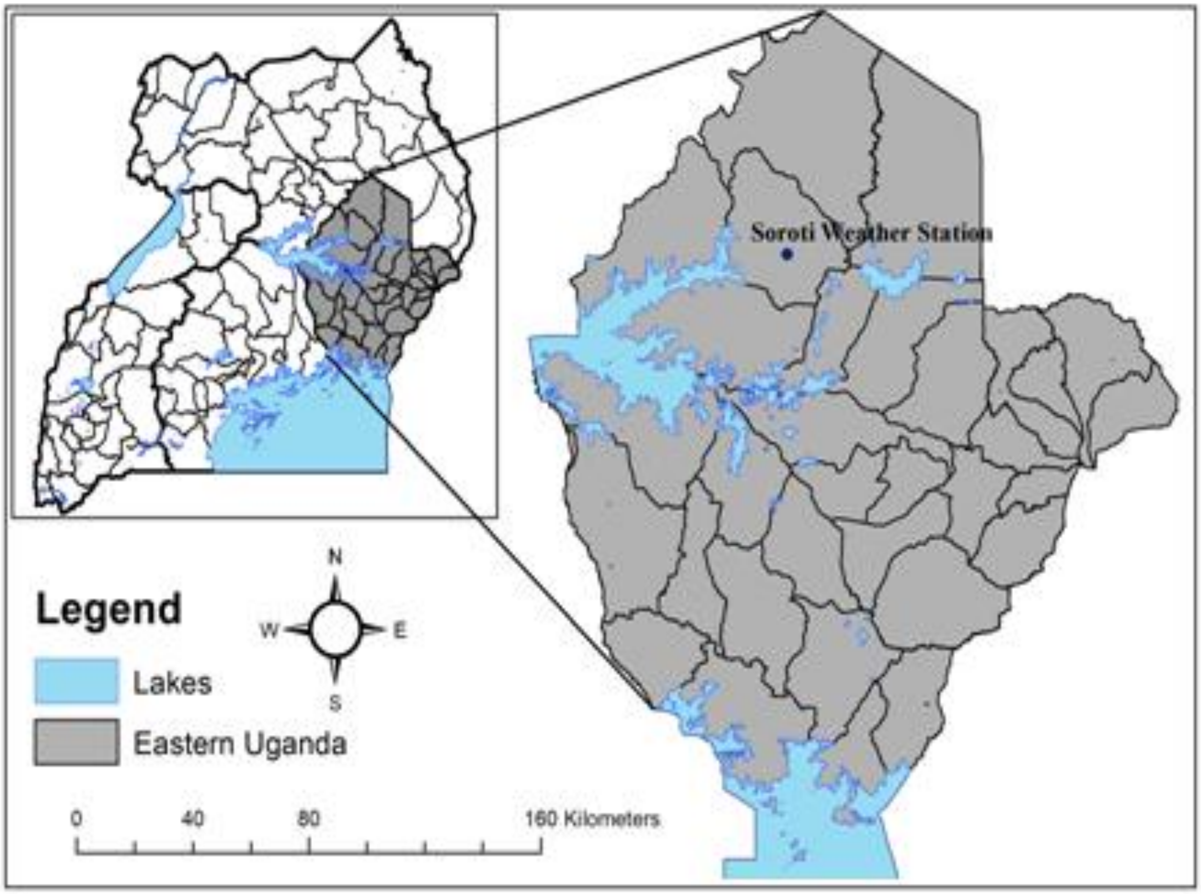

Fig. 1. Location of the study area showing the different districts and Soroti weather station

2.2. Quality Control and Homogenization of Meteorologial Data

Both datasets were quality controlled using the RClimdex software package (Zhang and Yang, 2004) which was downloaded from the ETCCDMI website http://cccma.seos.uvic.ca/ETCCDI/. Quality control of historical and projected daily rainfall data was performed using RClimDex using the following steps: i) the software replaces all missing values into an internal format which can be recognized by the software (-99.9) ii) It also replaces all unreasonable values say negative daily precipitation amounts into NA (not available) iii) It examines the potential outliers such as precipitation values above 200 mm in the data sequence so that the researchers make a test, calibration and delete according to the actual data and iv) It generates data plots for visual inspections to reveal more outliers in a subdirectory plot located in the folder log.

Temporal homogeneity was assessed using RHtests_dlyPrcP software following the methodologies of (Wang et al., 2010;Wang, 2008a and Wang, 2008b). Homogeneity testing was therefore performed to identify sudden change points in the precipitation data and ensure that time fluctuations in the data are only due to the vagaries of weather. No change points were however found in the data series.

Table 1. Selected indices for the analysis of rainfall extremes

Index	Indicator name	Definition	Units
R20	Days with very heavy precipitation	Annual count of days when precipitation ≥ 20mm	Days
R50	Days with severe precipitation	Annual count of days when precipitation ≥ 50mm	Days
R95p	Very wet days	Annual total precipitation from daily rainfall>95th percentile	mm
SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days in the year	mm/day

Table 2. Past Annual linear trends of extreme precipitation indices for the study area

Indices	Linear trend	p-value
SDII	-0.042	0.227
R20mm	-0.085	0.455
R50mm	-0.045	0.346
R95p	-2.633	0.507

2.3. Extreme Precipitation Indices

This study used four indices from the Expert Team on Climate Change Detection and Indices (ETCCDI) that are based on daily precipitation and have also been widely used in climate extreme studies (Shonge et al., 2011; Sun et al., 2016 and Trawblay et al., 2013). The details of the indices are shown in Table 1, and a full descriptive list of the indices can be found on the ETCCDI website http://etccdi.pacificclimate.org/list_27_indices.shtml.

2.4. Data Analysis

RClimDex 1.0, an open source software developed by Zhang and Yang (2004) was used to obtain the extreme precipitation indices and these were calculated on an annual basis for both the historical and future periods by following the methodologies of Zhang et al. (2005) and Haylock et al. (2006). Annual time series were computed from which trends of both historical and future periods were obtained. The statistical significances of the trends were assessed using the student t-test at 95.0% confidence level.

3. Results

3.1. Historical Extreme Precipitation Observations

The annual linear trends of the extreme precipitation indices for eastern Uganda over the period 1981-2010 are presented in Table 2. The results show that at 5.0% significance level, no statistically significant trends were detected over the study period for all the indices. Though generally, there was a decreasing trend for all the indices. The highest values of the indices were in 1981 for all the indices. Two indices (R20 and SDII) had their lowest values in 2004 while R50 and R95p had their lowest values in 1984.

All indices revealed much of similar trend lines indicating decreasing trends for all the indices during the entire baseline period. The annual count of days with precipitation = 20mm (R20) and 50mm (R50) decreased at rates of -0.085 days year^{-1} and -0.045 days year^{-1} [Fig. 2 (a) and 2(b)] respectively. The R20 index fluctuated between 38 days and 12 days whereas R50 had a range of 0 to 11 days. The annual total precipitation on very wet days (days with rainfall>95th percentile; R95p) decreased at a rate of -2.633mm year^{-1} (Fig. 2c) and fluctuated between 46.8mm and 883.4mm. The simple daily intensity index (SDII defined as daily precipitation amount on wet days, when (RR = 1mm)) also decreased at a rate of -0.042mm day^{-1} year^{-1} (Fig. 3d) with fluctuations between 9.6- 17.6 mm day^{-1}.

3.2. Future Projections of extreme Precipitation Events

The downscaled projections of extreme precipitation events under RCP4.5 (Fig. 3) and RCP8.5 (Fig. 4) are presented. This section presents annual trends of the four extreme precipitation indices computed from the RCM simulated dataset to investigate future changes in extreme precipitation in Eastern Uganda. Both scenarios projected increasing trends for all the indices except for the simple daily intensity index which is projected to decrease under RCP4.5. However, the ranges of the maximum values are greater (R20, R95p and SDII) or equal (R50) in RCP8.5 than RCP4.5 (Fig.3, Fig. 4).

3.2.1. Projected future trends for the indices under RCP4.5

The annual linear trends of the extreme precipitation indices for eastern Uganda for the future period (2021-2050) under RCP4.5 are presented in Table 3. The results show that, at 5% significance level, no statistically significant trends at the annual time scale were detected over the study period for all the indices.

RCP4.5 projected a slight increasing trend (0.003mm year^{-1}) in the annual count of days with precipitation = 20mm (R20) (Fig. 3a) and a consistent trend in number of days with precipitation= 50mm (R50) meaning no decrease or increase in R50 from 2021-2050 (Fig. 3b). The R20 index will fluctuate between 13days and 41days (Fig. 3a) whereas R50 will be in the range of 0 to 9 days (Fig. 3b).

Table 3. Future annual linear trends of extreme precipitation indices under RCP4.5

Indices	Linear trend	P-value
SDII	-0.007	0.768
R20mm	0.003	0.982
R50mm	0	0.993
R95p	0.836	0.843

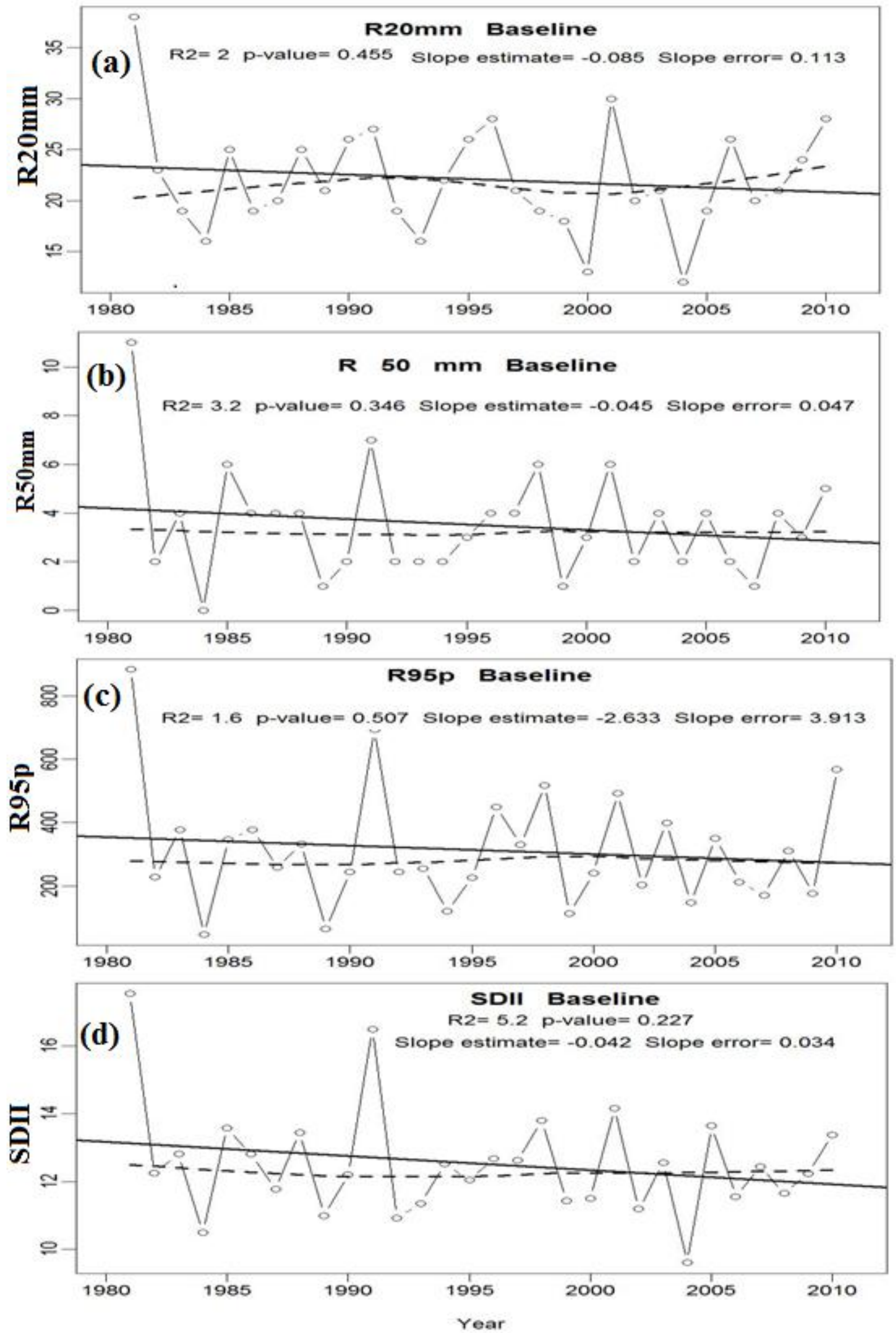

Fig. 2. Time series of (a) R20, (b) R50, (c) R95p and (d) SDII for the period 1981-2010. The solid line is the ordinary least squares fit.

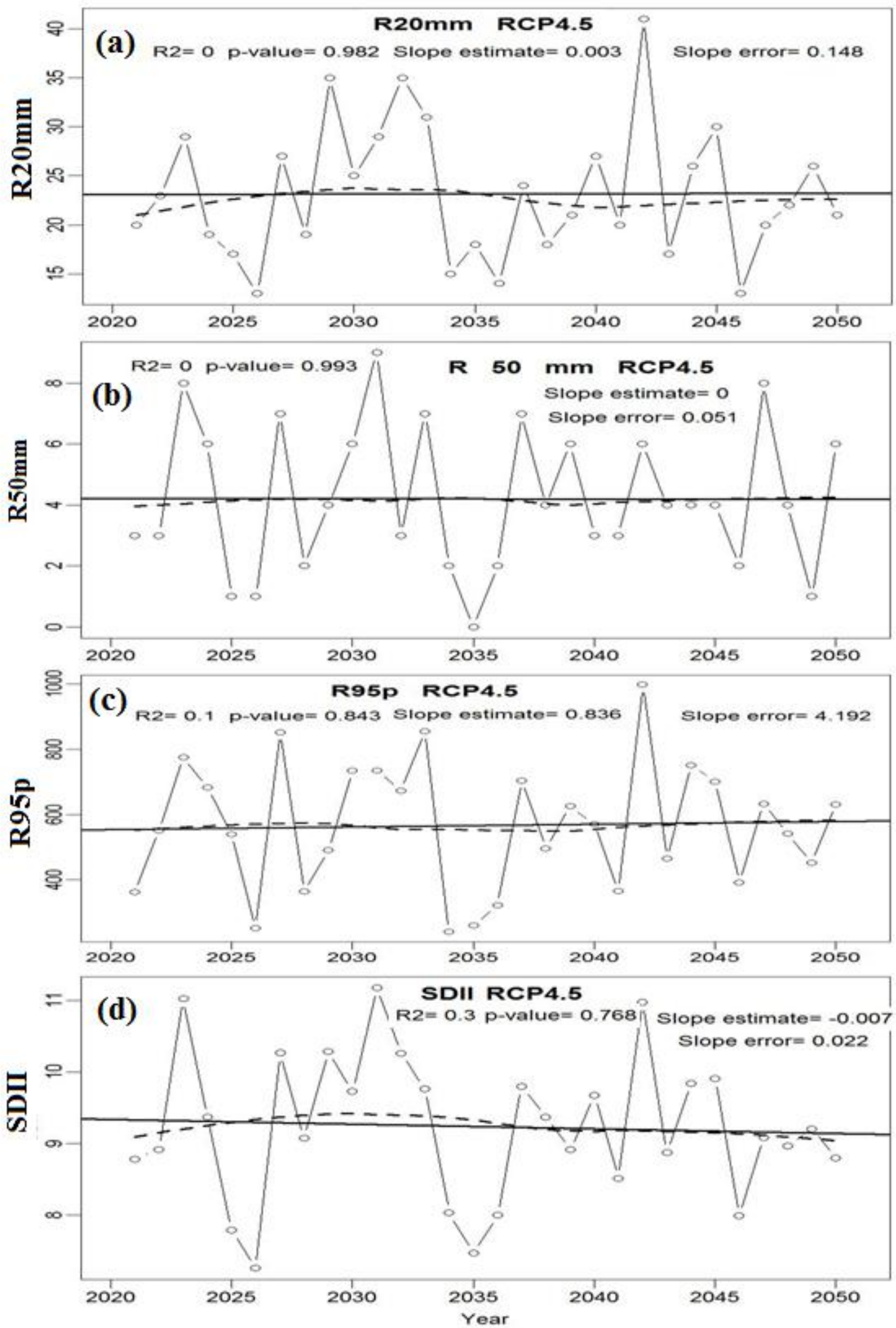

Fig. 3. Time series of (a) R20, (b) R50, (c) R95p and (d) SDII for the future period (2021-2050) under RCP4.5. The solid line is the ordinary least squares fit.

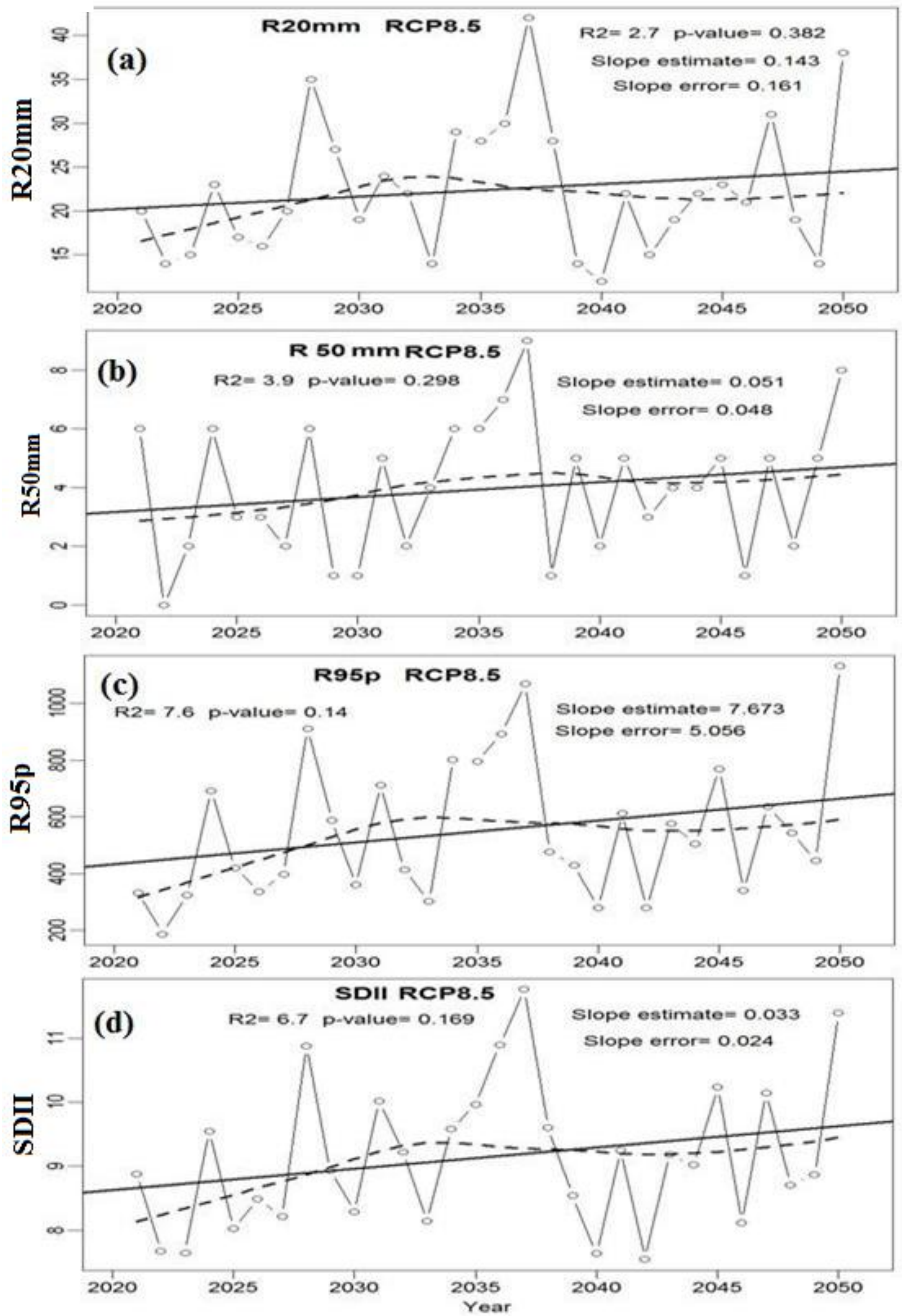

Fig. 4. Time series of (a) R20, (b) R50, (c) R95p and (d) SDII for the future period (2021-2050) under RCP8.5. The solid line is the ordinary least squares fit.

Table 4. Future annual linear trends of extreme precipitation indices under RCP8.5

Indices	Linear trend under RCP8.5	P_ value
SDII	0.033	0.169
R20mm	0.143	0.382
R50mm	0.051	0.298
R95p	7.673	0.14

The annual total precipitation on very wet days (days with rainfall >95th percentile; R95p) was projected to increase at a rate of 0.836mm $year^{-1}$ as shown in Fig. 4c. The very wet day precipitation is expected to fluctuate between 240.2mm and 997.4 mm. The simple daily intensity index (SDII) was also projected to decrease slightly at a rate of -0.007mm day^{-1} $year^{-1}$ with fluctuations between 7.3mm day^{-1} and 11.2mm day^{-1} (Fig. 3d).

3.3. Projected future trends for the indices under RCP8.5

The annual linear trends of the extreme precipitation indices for eastern Uganda for the future period (2021-2050) under RCP8.5 are presented inTable 4. The results show that, at 5% significance level, no statistically significant trends at annual time scale are detected over the study period for all the indices, however all indices exhibited positive trends.

The number of days when precipitation is greater than 20mm (R20) was projected to have an increasing trend (0.143days year-1) with a positive trend between 2021 and 2033 and afterwards a negative trend between 2033 and 2050 (Fig. 4a). This similar pattern is exhibited by indices R95p and SDII which increased at rates 7.673mm $year^{-1}$ and 0.033mm day^{-1} year-1, respectively (Fig. 4c and d respectively). Very heavy precipitation days were projected to fluctuate between 12days and 42days. Very wet day precipitation (R95p) was also projected to be in the range of 1131.9-186.7mm and this is slightly higher than the range projected by the RCP4.5 scenario.

R50 index which was projected to increase at a rate of 0.051days year-1 had an increasing trend between 2021 and 2035 and then a decreasing trend between 2035 and 2050 as shown in Fig. 5. Severe precipitation days were projected to be between 0 and 9 days similar to those projected under RCP4.5.

3.4. Future changes in rainfall extremes

In this section, the future changes are defined by the difference between the future period average (2021-2050) and the historical base period average (1981-2010). A student's t-test is employed for the significance test. The mean values for the two periods and the P-values are summarized in Table 5.

Of the four extreme precipitation indices calculated, two indices (R50, R20) showed significant shifts in the mean and the other two (R95p and SDII) showed insignificant shifts in their mean values in both RCP4.5 and RCP8.5 as shown in Table 5 above. RCP 4.5 projected greater changes in the mean values than RCP4.5 for all indices except for SDII.

3.5. Mean shift in the frequency indices

Both precipitation frequency indices (R20 & R50) considered for this study are projected to increase insignificantly (Fig. 5). A slight insignificant increase from 22 days to 23 days (4.98%) is projected for R20 under RCP4.5 whereas no shift is expected in R20 under RCP8.5. Almost no shift is expected in the number of days with precipitation = 50 mm (R50) for both RCP4.5 and RCP8.5.

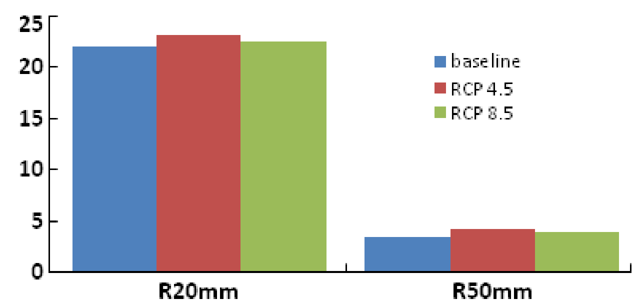

Fig. 5. Mean values for frequency indices (R20 and R50) for the baseline period (blue) and future period under RCP4.5 (red) and RCP8.5 (Green).

Table 5. Average precipitation indices for the two periods, 1981-2010 and 2021-2050.

Index	Baseline	Mean RCP4.5	Mean RCP8.5	P-value RCP4.5	P-value RCP8.5
R20mm	22.07	23.17	22.43	0.55	0.81
R50mm	3.50	4.20	3.97	0.27	0.37
R95p	312.61	566.68	552.42	**0.00**	**0.00**
SDII	12.52	9.25	9.14	**0.00**	**0.00**

P-value is shift in mean with bold figures representing significant shifts at 95% level.

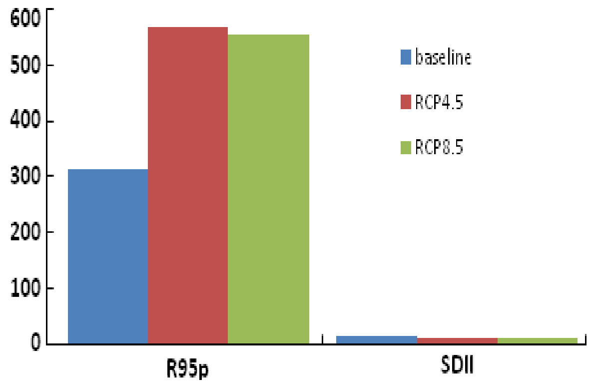

Fig. 6. Mean values for intensity indices (R95p and SDII) for the baseline period (blue) and future period under RCP4.5 (red) and RCP8.5 (Green).

Both the very wet precipitation (R95p) and the simple daily intensity index (SDII) were projected to have significant shifts in their mean values. Precipitation from very wet days is expected to increase significantly from 312.61mm in the baseline to 566.68mm (81.27%) under RCP4.5 and 552.42mm (76.71%) under RCP8.5 (Fig. 6). Simple Daily Intensity Index is expected to decrease for both scenarios that are to say, from 12.52mm day^{-1} to 9.25mm day^{-1} (-26.12%) for RCP4.5 and 9.14mm day^{-1} (-27%) for RCP8.5.

4. Discussion

The annual indices of precipitation extremes that were used to characterize extreme wet and intense precipitation events in Eastern Uganda revealed no statistically significant trends at the 5 % level for both the historical base (1981-2010) and the future (2021-2050) periods for both scenarios. All indices indicated negative trends over the entire historical period: the number of days with rainfall more than 20 and 50mm (R20 and R50), the simple daily intensity index (SDII) and Precipitation from very wet days (R95p) from 1981-2010 and summarized a reduction of rainfall in Eastern Uganda.

These results even without statistical significance present agreement with those found by (Borges et al., 2018; Santos, 2014), which found similar trends while analyzing extreme precipitation indices in an ecological reserve in Brazil. Similarly, (Ongoma et al., 2018) indicated decreasing trends of R20, R50 and SDII over Kenya and Uganda. Moreover, decrease in R95p reported over the Greater Horn of Africa for the period 1961-2010 (Omondi et al., 2013).

Both RCP scenarios projected non-significant positive trends for all indices except the simple daily intensity (SDI) index which has a negative trend for RCP4.5. Increments in mean values of all indices with exceptions for SDII were also projected. These projected changes were significant at 5% level for only the very wet day precipitation amount and the simple daily intensity index as shown in Table 5. This means that more frequent and intense precipitation is expected over the region. These results are consistent with the results by (Shongwe et al., 2011) that there is more likelihood of an increase in the intensity of rainfall events in East Africa.

The projected increase in these indices indicates that Eastern Uganda which is prone to floods and landslides will experience more extremes in precipitation which will put a lot of property at risk to destruction, as well as the lives of the people in the region.

5. Conclusion

The rainfall extremes over Eastern Uganda were investigated through four rainfall indices calculation for both the past (1981-2010) and future (2021-2050) periods using RClimDex. The results revealed that for all the indices both for the past and future periods revealed no significant trends. However, the mean shifts in the indices showed significant changes in two out of the four indices. Baseline findings indicated decreasing trends in all the indices showing a reduction of extreme rainfall in Eastern Uganda. Future projections however showed increasing trends for all the indices for both scenarios except the SDII which is projected to decrease under RCP4.5. All indices are projected to have a positive shift in future except the precipitation per day (SDII) which will continue to decrease slightly. These results indicate that rainfall extremes will continue in the future and are likely to impact natural ecosystems as well as agricultural and societal infrastructure. It therefore calls for decision makers to design appropriate preparedness and mitigation strategies in Eastern Uganda.

List of Abbreviations: AR4, IPCC Fourth Assessment Report; CCI, Commission for Climatology; CLIVAR, Climate Variability and Predictability; CMIP5, Coupled Model Intercomparison Project Phase 5; CORDEX, Coordinated Regional Climate Downscaling Experiment; ETCCDMI, Expert Team on Climate Change Detection, Monitoring and Indices; GCM, Global Climate Model; GDP, Gross Domestic Product; ICPAC, IGAD Climate prediction and Application Centre; IPCC, Intergovernmental Panel on Climate Change; KCCA, Kampala Capital City

Authority; NCC, Norwegian Climate Centre; NEMA, National Environment Management Authority; NorESM1-M, Norwegian Earth System Model 1-Medium resolution; RCM, Regional Climate Model; RCP, Representative Concentration Pathways; RMSC, Regional Specialized Meteorological Centre; SMHI, Swedish Meteorological and Hydrological Institute; UBOS, Uganda Bureau of Statistics; UNMA, Uganda National Meteorological Authority; UBOS, Uganda Bureau of Statistics; USAID, United States Agency for International Development; WMO, World Meteorological Organization ;WRCP, World Climate Research Programme.

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Author's Contribution: A.N. was involved in the conception, design of the study and manuscript writing. N.N. and J.K. were involved in the conception and provided the plots used in the manuscript. All authors proof read and approved final draft of manuscript..

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