



Spatiotemporal variation of rainfall and occurrence of extreme events over Burundi during 1960 to 2010

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Abstract

The occurrence of extreme rainfall events, associated mass movements, and flash floods especially during recent years motivated the study on the spatiotemporal rainfall variability over Burundi. This study used data from distinct sources: surface observation (1981–2010), Climatic Research Unit (CRU), Global Precipitation Climate Centre (GPCC) for the period 1960–2010, and European Centre for Medium-Range Weather Forecasts (ECMWF) for the period 2001–2017. This study analyzed the main features of rainfall over the study domain and demonstrated that extreme rainfall contributed to mass movements and flash flood hazard that characterize some sections of the study domain. Analysis revealed a decrease of rainfall and number of rainy days, supported by a generally decreasing trend for annual and seasonal rainfall. The short rains that occur during September–December experienced significant variability than long rains that occur during March–May, especially from 1990s. The study further identified the west, east, and north-east parts of Burundi to be more sensitive to extreme events than other sections of the study domain. The analysis carried out the existence of high variability of rainfall which starts from 1985 with significant decrease of rainfall from 1990. The occurrence of extreme rainfall during short rains has been attributed to wind circulation anomaly due to influx of air mass from Congo basin, local topography, and local wind patterns. This study contributes to understand the spatiotemporal rainfall variability, the relationship between extreme rainfall events, and its possible impact on territory management and will help in forecasting and monitoring future extreme events over Burundi.

Keywords Extreme rainfall · Rainfall · Mass movements: flash flood · Burundi

Introduction

Climate extremes and extreme weather have been observed since 1950 (Field et al. 2012) and have affected socioeconomic activities of many countries including Burundi. In the study

conducted under World Meteorological Organization (WMO) projects, Lanza et al. (2005) reported that events with extremely high precipitation intensities affect all types of daily life needs such as transportation, destruction of crops, and vegetation in many countries. Extreme rainfall events impact directly both social, economic activities and territory management (Mouri et al. 2011; Wu et al. 2015; Jena et al. 2014; Wu and Huang (2015). Burundi is prone to frequent wet and dry conditions and is highly vulnerable to those extreme weather events since its economy relies on rain-fed agriculture (Ngetich et al. 2014; Ongoma et al. 2015). Although change in heavy or extreme rainfall has been documented by many scientists (Lyon 2014; Meehl et al. 2000; Goswami et al. 2006; Iwashima and Yamamoto 1993; Ozer and Mahamoud 2013; Hastenrath et al. 2007), only few studies have been carried out in Burundi. In East Africa, most of extreme rainfall events are linked to El Nino-South Oscillation (ENSO) (Ogallo 1988; Indeje et al. 2000). Owor et al. (2009) found out that change of the intensity of precipitation is expected to be especially pronounced in tropical regions as a result of the global

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warming. Precipitation is considered to be crucial hydrometeorological indicator in Burundi with a large spatiotemporal variability. During recent years, floods, mass movements, and drought have become the most frequent disastrous extreme events in Burundi.

In recent decades, Burundi has observed increase in frequency and severity of droughts, torrential rainfall and devastating floods, mass movements, destructive tropical storms, among other extreme climate events. Some regions are more sensible to floods and mass movements' events while others are affected by drought events. The western part of Burundi is particularly prone and vulnerable to catastrophic events owing to the area's topography and geological components. Destructive floods and landslides have become common in the West especially in the metropolitan area of Bujumbura, in the plateau of the center, and in the South-East lowlands of Burundi whereas the Northern part is often affected by drought which affects the health of the population and constraints some people to leave their families for other regions. The floods of April 2009 have seriously impacted the west of Burundi including Bujumbura International Airport. Houses and many other basic infrastructures were destroyed; several hectares of crops have been damaged. On the 6th January 2010, the Gyneco-Obstetric Emergency Center (CURGO) in south of Bujumbura experienced devastating floods which overflowed and adversely damaged the hospital infrastructure and equipment (Moeyersons and Philippe 2012). The north of Burundi especially Kirundo and Muyinga Provinces are prone to drought events and its consequences. From 2000, many people have left the region towards different destinations due to the famine occasioned by severe drought.

In 2014, Burundi registered many cases of floods and mass movements especially in the western part where a historic flash floods affected Bujumbura on 9th February and nearly 1200 homes collapsed, 20,230 people were left homeless, 77 deaths were reported, and 182 people injured (African Development Bank (ADB) 2017).

Burundi has been experiencing extreme weather events in the two past decades that affect the socio-economic development sustainability of the country. Only few studies related to an assessment of extreme weather events characteristics in order to mitigate their impacts have been done. However, most of the studies on extreme events are done globally over East Africa, there is no specific case studied so far. It is needed to understand the current and future patterns of the extreme weather events for planning purposes that can consequently reduce the loss of lives and destruction of properties over Burundi.

Understanding of the occurrence of extreme weather events, especially in rainfall, is important for decision-making (Easterling et al. 2000). In order to assess and understand extreme events and related impacts, different approaches have been used. Understanding the precipitation patterns during MAM (long rains) and SON (short rains) has become the

preoccupation of scientists who conducted researches over East Africa; however, there is no specific studies over Burundi. In their study on extreme rainfall event over East Africa, Ongoma et al. (2016) found that the number of days that recorded heavy rainfall was decreasing; however, the number of heavy days seems to be increasing over Burundi during last decades. The metropolitan area of Bujumbura is the most affected by landslides, debris flow, and flash floods. According to Easterling et al. (2000), the vulnerability to the extreme events such as floods and storm in metropolitan areas is caused by the increasing of population and infrastructure. Due to the demographic pressure and the expansion of urban areas, the vulnerability of some regions on mass movements and flash floods is becoming very higher especially in the western part of Burundi. Statistical analysis has shown that an accurate estimate of frequency and distribution of events can significantly be used in planning policy and management system design (Goswami and Ramesh 2008). In his study on rainfall extremes, Koutsoyiannis (2004) found that the estimation of rainfall extremes is very important for major hydraulic structures. Kevin et al. (2003) reported that the character of precipitation depends not only on the nature of the storm but also on the available moisture. In the same perspective to deepening understanding on extreme events, Endreny and Imbeah (2009), Brunetti et al. (2001) and Trenberth et al. (2003a, b) observed that analysis of daily rainfall series is important since it helps to evaluate if changes in rainfall frequency are expected owing to change in the number of days reporting heavy rain. The research carried out by Omondi et al. (2014) over 10 countries of the Great Horn of Africa (GHA) showed that the total precipitation in wet days greater than 1 mm was significantly decreasing. Through his research on framework of sustainable management of Ntahangwa watershed, Sindayihebura (2012) observed that the rise of flows culminating at the point of flooding is more dangerous as the rainfall is more intense. Previous studies showed that the main impacts of extreme weather event such as floods and landslides are intensified by the amount of water in the soil which is a result of interactions between topography, soil properties, vegetation, water-routing processes, depth of water table, and meteorological conditions (Western and Blöschl 1999; Gómez-Plaza et al. 2001). The recent report on climate risk management in Burundi indicated that from 2010 to 2050, the extreme weather will be characterized either by rainier or drier periods (Sabushimike 2013).

According to local reports, it has been observed that more cases of extreme rainfall occur during November–December in Burundi. In the research carried out over East Africa, Manatsa et al. (2014) found that the floods and drought events that often occur during October–December are linked to the Mascarene high zonal movement of the eastern ridge. However, the question that comes to the mind is to know if the extreme events that have recently increased over Burundi are linked to Mascarene High. In consideration with the methods used to monitor and study

extreme events, it has been demonstrated that the trend analysis is very important to study extreme events over time. González Hidalgo et al. (2003) conducted a study over Valencia and found that annual rainfall trends depend on local factors that affect extreme events. Yang et al. (2018) discovered that some meteorological factors can be associated to the influence of local topography and a presence of the lake. In their study of rainfall variability over East Africa, Ongoma and Chen (2017) found that extreme rainfall generally occur during “short rains” period. Understanding the variability of extreme rainfall and its relationship with other climatic factors will allow planners to increase their ability for planning and predict flood events (Lü et al. 2017).

This study attempts to analyze spatial and temporal distribution of rainfall over Burundi, understand the variability and rainfall anomalies, analyze extreme rainfall, and then check whether there is any relation between the frequency of extreme events and occurrence of mass movements or flash floods. The outcome of this study provides useful information for territory management especially urban planners. The correct use of the information helps to minimize loss of lives and destruction of property and infrastructures.

In this study, the “Data and methodology” section gives a description of the study area, data, and methodology, the “Results and discussions” section demonstrates the results, and the “Conclusions” section contains concluding remarks.

Data and methodology

Study area

Burundi is located in Africa and is one of the East African Community countries. It lies between $2^{\circ} 15' - 4^{\circ} 30' S$ and $28^{\circ} 58' - 30^{\circ} 53' E$ (Fig. 1). Burundi straddles East and Central Africa bordering the Lake Tanganyika to the southwest. It is bounded on the north by Rwanda, on the east and south-east by The United Republic of Tanzania, and on the west by the Democratic Republic of Congo (DRC).

Located in East Africa, Burundi generally experiences bimodal patterns in a year (Ilunga et al. 2004; Manatsa et al. 2014; Ngarukiyimana et al. 2017; Ongoma and Chen 2017).

The climatology patterns are characterized by two wet seasons including long rains (MAM) and short rains (SOND) periods relatively separated by a long dry season (JJA) and a short dry season (JF). That situation can be linked to the double passage of the Inter-tropical Convergence Zone (ITCZ). However, the variability of rainfall is particularly associated to the variation of the topography. From the west to east, Burundi distinguishes diverse and complex topographical features. The lowlands is composed by series of plains of variable width from the south to the north west of the country with elevation in altitude that varies between 774 m (Lake Tanganyika rib) and 1000 m above mean sea level (a.m.s.l). It is generally a

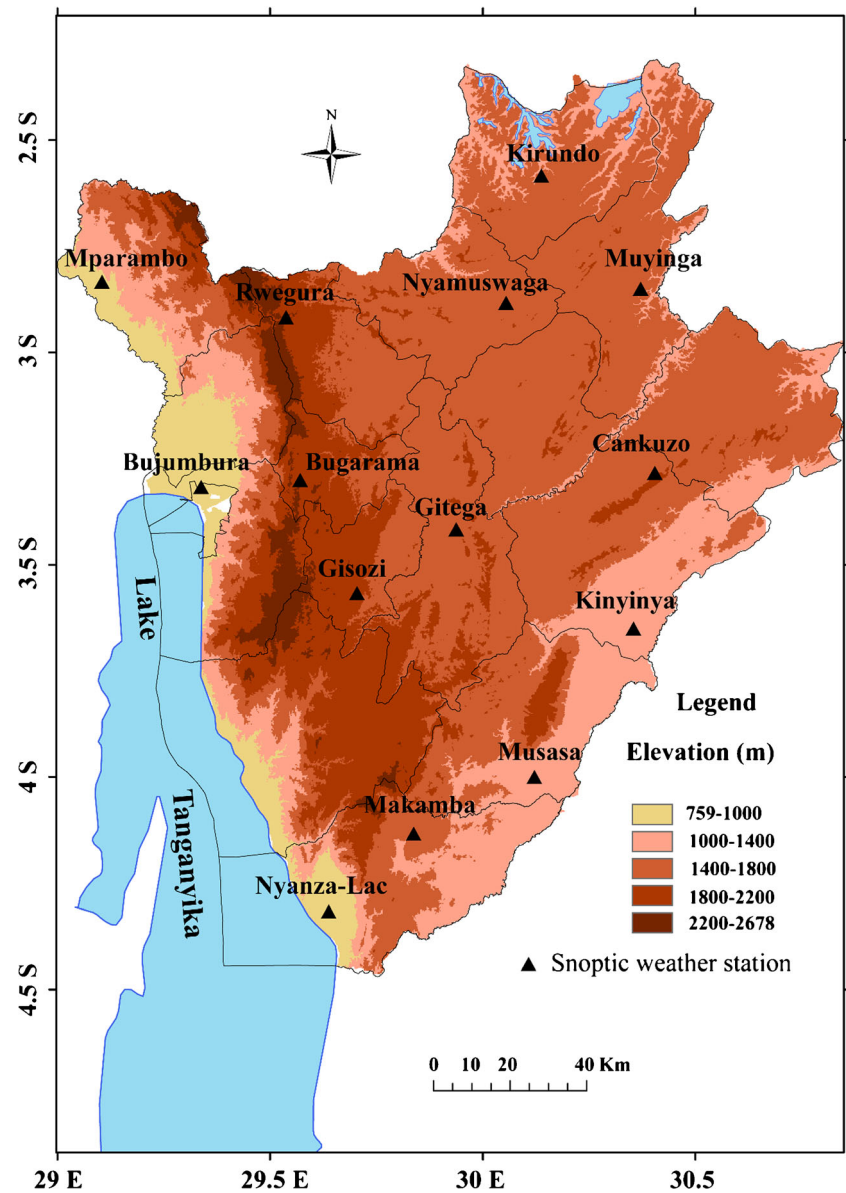
dry area with less than 1000 mm per year. The escarpments of Mirwa located between lowlands and Congo-Nile ridge are characterized by steep slopes and very narrow ridges with altitude average between 1000 m and 2000 m (a.m.s.l).

It receives annual rainfall varying between 1000 mm and 1400 mm (MWELUP 2011). The Congo-Nile Ridge is the asymmetrical and irregular ridge of Burundi topography and defines the delimitation between the Congo and the Nile basins. It registers more than 1400 mm of annual rainfall and characterized by a moderate temperate climate. The central plateau is characterized by elevation range from 1350 m to over 2000 m (a.m.s.l) in westward and southward. Annual rainfall varies between 1200 mm and 1400 mm. The depression is composed by two regions. The eastern depression includes valleys of the rivers located between Tanzania and Burundi (Malagarazi & Rumpungwe) while the depression of north includes the basin of Bugesera which extends to Rwanda and dominated by small lakes (Fig. 1). The annual rainfall average of these depressions is relatively about 1000 mm. Considering the studies conducted on east African climate variability, the inter-annual variability observed over Burundi can be also associated to El Niño South Oscillation (ENSO) and Indian Ocean Dipole (IOD) as demonstrated by researchers conducted over East Africa (Ogallo 1988; Indeje et al. 2000; Schreck and Semazzi 2004; Black et al. 2003). The extreme rainfall that is mainly followed by floods and drought events occurring in East Africa and in Burundi in particular is attributed to El Niño and La Niña events (Ongoma et al. 2018).

Data

The study used multiple datasets from different sources in order to analyze the rainfall variability and occurrence of extreme events. It utilized daily rainfall from Bujumbura International Airport (BIA) station covering a period of 51 years (1960–2010) and monthly rainfall obtained from 16 synoptic stations located in different parts of the study domain (Fig. 1 and Table 1) running from 1981 to 2010. Those observational data are provided by the Geographical Institute of Burundi (IGEBU). The study utilized also gridded data from European Centre for Medium-Range Weather Forecasts (ECMWF) known as Era-Interim data with horizontal resolution of $0.5^{\circ} \times 0.5^{\circ}$ (Dee et al. 2011; Berrisford et al. 2011; Bauer et al. 2011) for a period of 51 years running from 1960 to 2010. Monthly reanalysis data from Climate Research Unit (CRU) rainfall datasets (Harris et al. 2013) and Global Precipitation Climate Centre (GPCC) rainfall datasets (Schneider et al. 2013) were also used in the study in order to analyze the accuracy of observational data. The Era-Interim data, GPCC, and CRU datasets are chosen because of their performance in studying rainfall variability over East Africa (Ngarukiyimana et al. 2017; Ongoma et al. 2015; Ogwang

Fig. 1 Study area with topographical elevation (m). The black points represent synoptic weather stations



et al. 2015). All datasets were used to make global and detailed analysis in order to fill the gaps that station data may contain.

Methodology

The study aimed at investigating the relationship between the frequency of extreme rainfall and the occurrence of hazardous events such as mass movements (landslides, mud flows, debris flow, and shadow landslides) and flash floods. Series of methodologies were adopted to achieve the objective of this study.

Statistical methods

First of all, the study proceeded to evaluate the performance of the reanalysis data from CRU, GPCC, and

ECMWF with ground-based observational data. The correlation was systematically calculated between two different datasets using Spearman's correlation. The Spearman rank correlation coefficient was calculated with Eq. 1. The correlation takes values within the range $[-1, 1]$:

$$\rho = \frac{\sum_{i=1}^n (\text{observed}_{(i)} - \overline{\text{observed}}) (\text{model}_{(i)} - \overline{\text{model}})}{\sqrt{\sum_{i=1}^n (\text{observed}_{(i)} - \overline{\text{observed}})^2 \sum_{i=1}^n (\text{model}_{(i)} - \overline{\text{model}})^2}} \quad (1)$$

Where n is the observed times.

The statistical analysis was conducted with calculation of the frequencies of rainy days, rainfall intensity, daily average, monthly and annual rainfall, annual long-term average, etc.

The mean deviation was used to calculate the deviation of monthly or annual average compared to annual long-term

Table 1 Geographical coordinates of synoptic weather stations used in the study with information on annual, short rains (SOND), and long rains (MAM) mean rainfall (mm) from 1981 to 2010

No.	Station name	Longitude (E)	Latitude (S)	Altitude (m)	Annual mean rainfall	SOND mean rainfall	MAM mean rainfall
1	Gitega	29.92	- 3.42	1645	1157.2	110.1	129.3
2	Bujumbura (BAI)	29.32	- 3.32	783	773.7	72.8	89.4
3	Bugarama	29.55	- 3.30	2240	1522.1	156.5	183.4
4	Cankuzo	30.38	- 3.28	1652	1188.4	118.4	130.4
5	Gisozi	29.68	- 3.57	2097	1449.1	139.4	168.1
6	Imbo-SEM	29.35	- 3.18	820	735.8	72.9	98.7
7	Kinyinya	30.33	- 3.65	1308	1092.3	100.0	140.2
8	Kirundo	30.12	- 2.58	1449	1060.9	100.4	143.4
9	Makamba	29.82	- 4.13	1450	1132.6	118.7	151.5
10	Mparambo	29.08	- 2.83	887	914.0	88.3	122.1
11	Tora	29.57	- 3.73	2160	1530.7	141.7	179.0
12	Musasa	30.10	- 4.00	1260	1118.2	100.9	135.2
13	Muyinga	30.35	- 2.85	1756	1101.6	106.6	137.5
14	Nyamuswaga	30.03	- 2.88	1720	1210.7	125.8	158.6
15	Nyanza-Lac	29.62	- 4.32	820	1159.7	116.2	145.0
16	Rwegura	29.52	- 2.92	2302	1537.1	163.0	191.9

mean in order to see the trend variation in the series. The mean deviation was computed using Eq. 2;

$$Md = \frac{\sum_{i=1}^n |xi - \bar{x}|}{n} \tag{2}$$

where *Md* is the mean deviation, \bar{x} is the mean, and *xi* is the rainfall amount.

The standard deviation (Eq. 3) was used to analyze how the rainfall amount is spread from the mean. It was used to estimate the standard rainfall which can generate either mass movement or flash floods.

$$S = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (xi - \bar{x})^2} \tag{3}$$

The Eq. 4 was used to calculate the trend estimation to study the tendency of the daily, monthly, or yearly rainfall and rainy days.

$$Y_t = X_t\beta + e_t \tag{4}$$

where *Y_t* is an observed response and *X_t* includes values of daily, monthly, seasonal, or yearly rainfall. The partial regression coefficients in β represent the marginal contributions of individual predictors to the variation in *Y_t* and is effective when all of the other predictors are held fixed. The term *e_t* is a catch-all for differences between predicted rainfall and observed values of *Y_t*.

The non-parametric Mann-Kendall (MK) statistic test (Mann 1945; Kendall 1975) served to detect the trend in the data over the time. A significant level of 5% was considered

and the trend was detected by using two hypothesis: Ho expressing absence of the trend and Ha expressing the existence of a trend in the series. The Eq. 5 was used to calculate the Mann-Kendall statistic:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \tag{5}$$

Where *x_j* and *x_i* are sequential data values and *n* is the data length of the time series.

The variance of *S* was calculated using Eq. 6:

$$\text{Var}(S) = \frac{n(n-1)(2n+5)}{18} \tag{6}$$

The standardized anomaly was used to analyze different anomalies in time series. It was obtained by dividing the anomalies with the standard deviation as shown in Eq. 7.

$$y = \frac{(x_i - \bar{x})}{\sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^2}} \tag{7}$$

where *y* is the standardized anomaly and $(x_i - \bar{x})$ is the anomaly.

Ensemble empirical mode decomposition

The study used also the EMD which is proposed as an adaptive time-frequency data analysis method (Huang et al. 1998). Ensemble EMD (EEMD) is used as a self-adaptive data analysis methodology which is used to preprocess a rainfall data series (Qi et al. 2016; Bi et al. 2010).

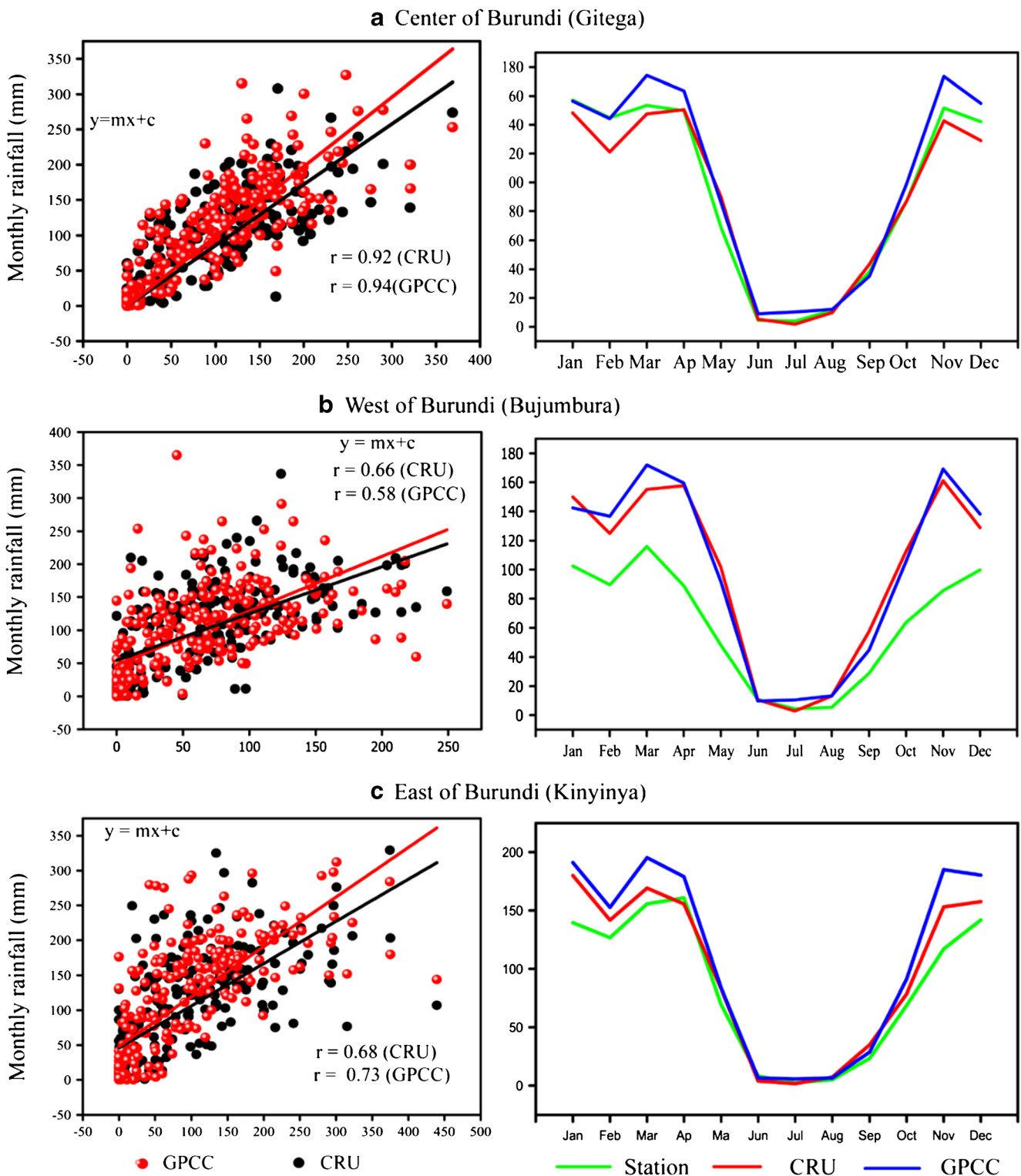
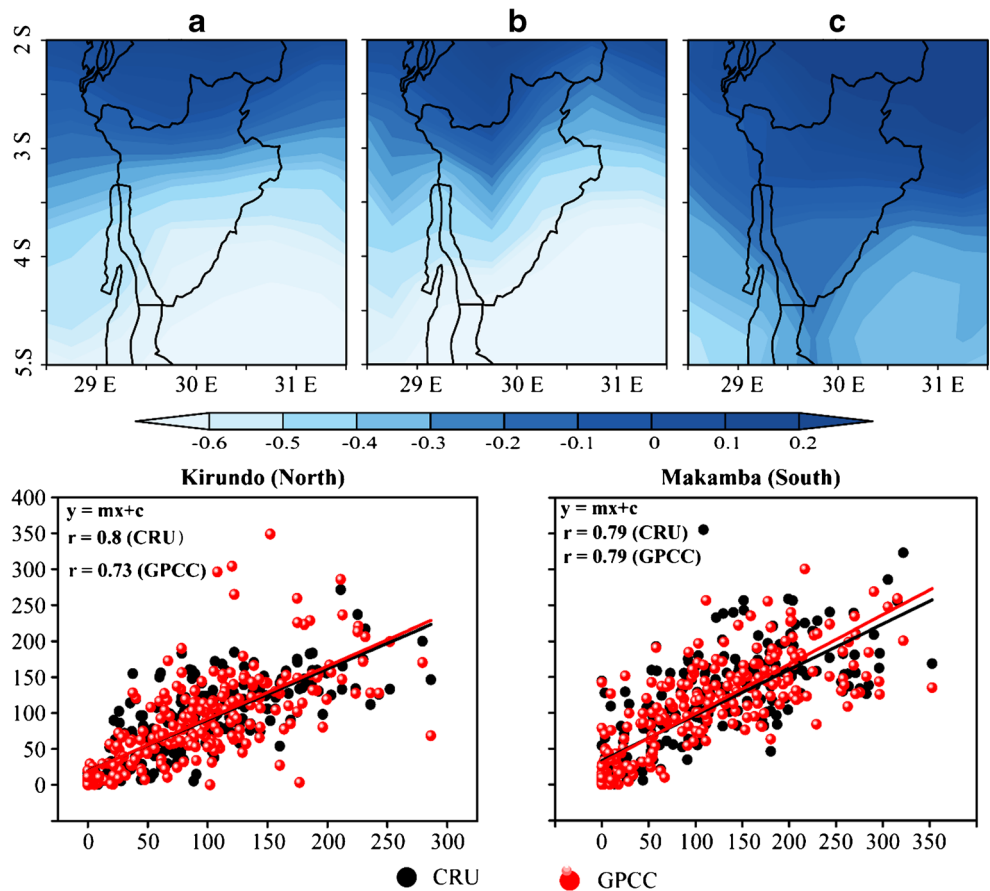


Fig. 2 Correlation coefficient of monthly gridded of three homogeneous rainfall zones over Burundi (left) with their annual rainfall cycle (right) based on CRU and GPCC datasets for a period of 30 years (1981–2010). The selected regions are **a** center, **b** west, and **c** east of Burundi

The main objective of using EEMD method is to process data with axial symmetry and decompose it into a series of intrinsic mode functions (IMFs) in

descending order by signal frequency. The last extracted IMF is the lowest frequency component of the signal. The specific steps of EEMD decomposition are the

Fig. 3 Correlation coefficient of monthly mean rainfall (a) and seasonal rainfall ((short rains (b), long rains (c)) between CRU and GPCC and the spatial correlation coefficient (CRU and GPCC) averaged in north and south of the study domain



white noise $n_i(t)$ added to original signal $x(t)$ which is given by Eq. 8:

$$x_i(t) = x(t) + n_i(t) \tag{8}$$

where $x_i(t)$ is the first signal after added to the white noise.

In order to eliminate the effect of adding white noise manually, the IMF components $C_{ij}(t)$ of the N-time EEMD decomposition are summed and the mean is taken as the final IMF component as given in the Eq. 9:

$$C_j(t) = \frac{1}{N} \sum_{i=1}^N C_{ij}(t) \tag{9}$$

where $C_j(t)$ represents the j th component obtained by subjecting the original signal to EEMD decomposition. The effect of white noise on the analysis signal follows the statistical laws below:

$$\delta = a/\sqrt{N} \tag{10}$$

where δ is the standard deviation which is the deviation of the input signal from the corresponding IMF component reconstruction result, a is the magnitude of the Gaussian white noise

and in that case the amplitude of the noise remains constant. In normal conditions, δ takes to 0.2 and N takes 100 (Zhu et al. 2013).

Finally, the original signal $x(t)$ can be decomposed into Eq. 11:

$$x(t) = \sum_{j=1}^N C_j(t) + r_n(t) \tag{11}$$

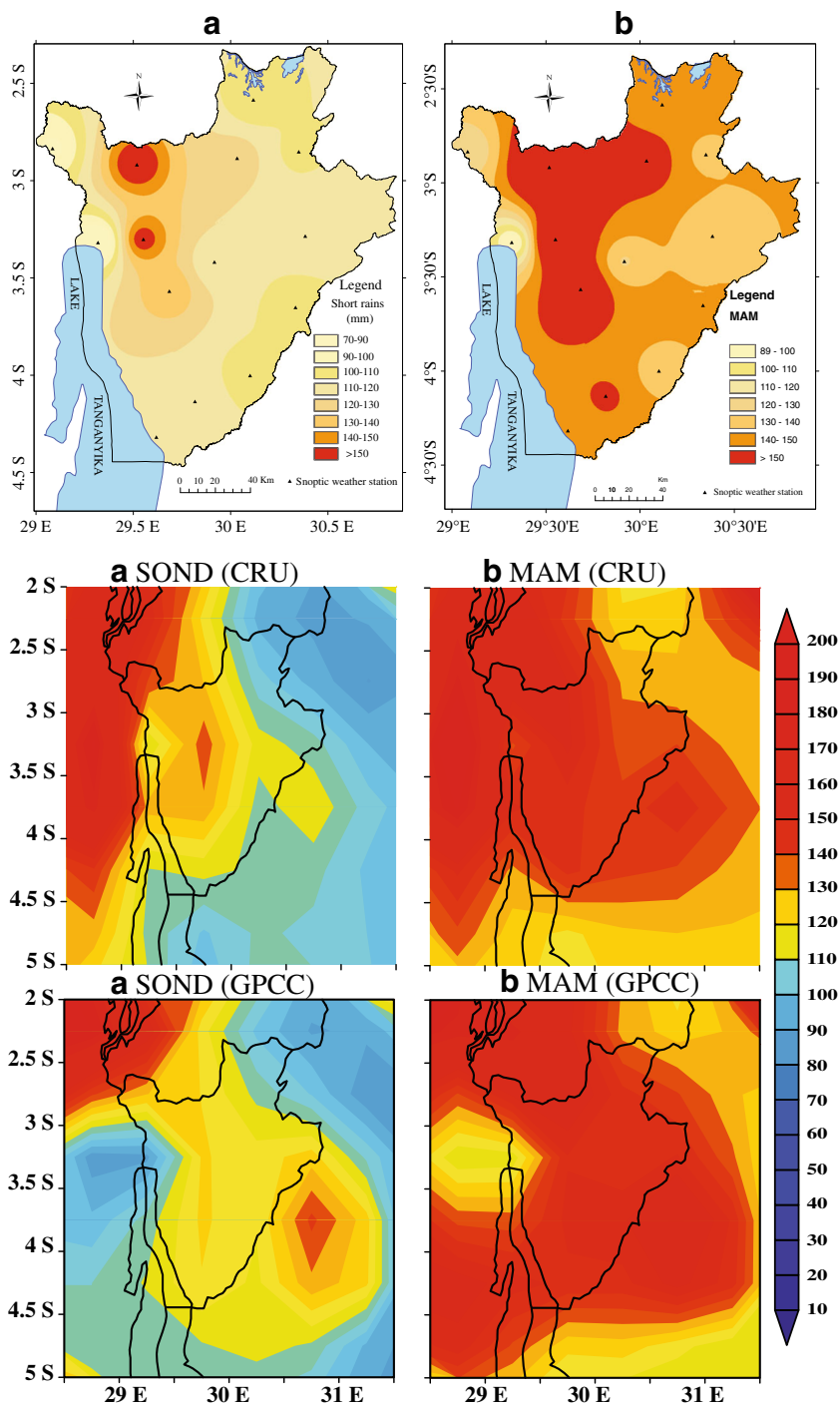
where $r_n(t)$ is the trend term RES, which represents the overall trend of the signal. Each component, $C_1(t), C_2(t), \dots, C_{n1}(t)$, respectively, shows the original signal in different time scales on the fluctuations of the original signal at different time scales, which represents the oscillation period from small to large scales. At the same time, EEMD can also carry out the significance test to give the confidence of each IMF component.

Results and discussions

Seasonal and annual rainfall variability

This study utilized different methods to analyze the climatology of Burundi. The Spearman rank correlation was applied to

Fig. 4 Spatial distribution of short rains (a) and long rains (b) over Burundi based on station data, CRU and GPCC for a period of 1981 to 2010. The station data are averaged over latitude 2° 15'–4° 30' S and longitude 28° 58'–30° 53' E and reanalysis data are averaged over latitude 2–5 S and longitude 28.5–31.5 E



reanalysis data and based station data to check their performance. It was found that the gridded datasets from Climate Research Unit (CRU) and Global Precipitation Climate Center (GPCC) datasets both are in agreement with station data with a correlation coefficient of 0.92 and 0.94 in center, 0.66 and 0.58 in west, 0.68 and 0.73 in east, 0.8 and 0.73 in north, and 0.79 in south for CRU and GPCC, respectively. Comparing different zones of the study domain, it can be seen that the ground-based observation data and reanalysis data have a

correlation in the north, in the center, and in the south of Burundi. Figure 2 shows the correlation between the datasets used through three different stations which are Gitega in center, Bujumbura in west, and Kinyinya in east.

It can be seen that both CRU and GPCC overestimate the rainfall in the western part of Burundi but perform well in the center and in the south over all seasons. However, in the northern part, the two metrics are likely to underestimate the amount of rainfall during MAM period and relatively

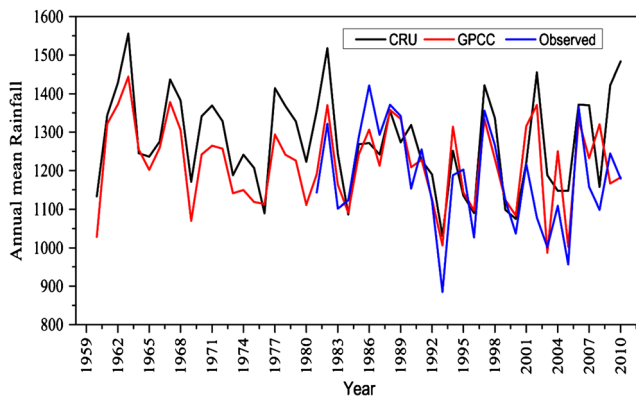


Fig. 5 Comparison of annual mean rainfall cycle (mm) over Burundi based on CRU and GPC for 51 years (1960–2010) and station datasets averaged for the period of 30 years (1981–2010)

overestimate short rains. In the eastern part, they have a consistent performance during long dry season but overestimate rainfall during MAM and SOND. With the same purpose, ground-based data and Era-Interim data have been compared and it was found that Era-Interim daily data performs well in all regions and delivers consistent results when analyzing daily rainfall and climatology over Burundi.

The temporal correlation over seasonal and annual rainfall is likely to underestimate the amount of rainfall over the southern and eastern part of the study domain though the spatial rainfall distribution exhibits a positive correlation (Fig. 3). The northern zone exhibits a positive correlation for both temporal and spatial correlations.

The ground-based observation rainfall data were interpolated to grid using inverse distance weighted (IDW) interpolation algorithm then compared to GPC and CRU data result. According to the results shown in Fig. 4, it can be seen that both ground-based observation and reanalysis data exhibit that short rains (SOND) register less rainfall while the long rains (MAM) period receives much rainfall. The statistical analysis carried out that the short rains registered more cases of irregularities especially from 1990s where it is observed that the first rains start in late September or in October and seriously affect crops' production in the north and north-east of the study domain. The spatial variation shows that the wet zone covers mountainous region in westward and the neighboring part of plateau while the north and north-east parts are relatively dry regions (Fig. 4). In this case, GPC dataset seems to capture consistent information in studying long short rains over the study domain.

Figure 5 shows the annual mean rainfall distribution over 51 years (1960–2010) for GPC and CRU data with ground-based observation data over 30 years (1981–2010). Annual mean rainfall has been varying along the time. The rainfall has significantly decreased especially during the last decades accompanied with occurrence of unexpected extreme weather events. Though the GPC and CRU seem to overestimate the

annual mean rainfall from the year 2001, all the datasets used reveal the continuous decrease of rainfall along the period of study as shown in Fig. 5. The year 1993 is the driest year ever registered with annual mean rainfall amount less than 885.1 mm. The western part of Burundi, one of the regions which are vulnerable to extreme rainfall, registered a very significant decrease for both rainy days and amount of rainfall recorded according to data collected from Bujumbura International Airport for the period 1960 to 2010.

The spatial distribution of annual monthly mean cycle rainfall shows that from 1960 to 2010, the western lowlands, eastern and northern depressions experienced less rainfall (Fig. 6). However, comparing the results given by reanalysis data, it is found that CRU (Fig. 6a) captured well the rainfall amount over the study domain and is in agreement with station data results (Fig. 6c). The area covering the high altitude of Burundi receives more rainfall amount along the study period. The spatiotemporal distribution of annual monthly mean rainfall showed that there is a very significant decrease of rainfall especially from 1990s, the CRU data is more expressive and shows the decline of rainfall. However, the GPC data shows a simple shift of rainfall on global level (Fig. 7c). The period after 1990 registers a significant rainfall decrease in most of the regions of the study area as shown by the result from the comparison between the period 1960–1990 and 1990–2010 using GPC and CRU reanalysis datasets (Fig. 7).

Inter-annual anomalies

In order to understand the rainfall variability over Burundi, a linear regression method was used to examine the trend within the station data to check whether there is increase or decrease of rainfall over the period of study. First of all, we proceeded by analyzing all the stations one by one, then analyzed stations from homogeneous zones, and finally conducted regional and global analysis. The analysis of homogeneous regions exhibits a decreasing trend which means that the rainfall is decreasing over the studied domain. Five of six homogeneous stations selected have a statistically significant decreasing trend (Fig. 8). For the period of study, Burundi registered more cases of abnormal rainfall. Some stations have a relative decreasing trend while others exhibit a significant decreasing trend. However, most of the stations observed define a decrease of rainfall amount except the southern part of Burundi where the annual precipitation has increased (Fig. 8f), all other regions register a rainfall deficit especially from 1990s.

Despite the frequency of extreme weather events in the west of Burundi, the study finds a relative decrease trend in west annual or seasonal mean rainfall (Fig. 8) while the mountainous area including Congo-Nile ridge and its surrounding exhibited a statically significant decreasing trend. Due to the

Fig. 6 Annual monthly mean rainfall (mm) over Burundi obtained by CRU (a), GPCC (b), and ground-based observation data (c) averaged for the period 1981 to 2010

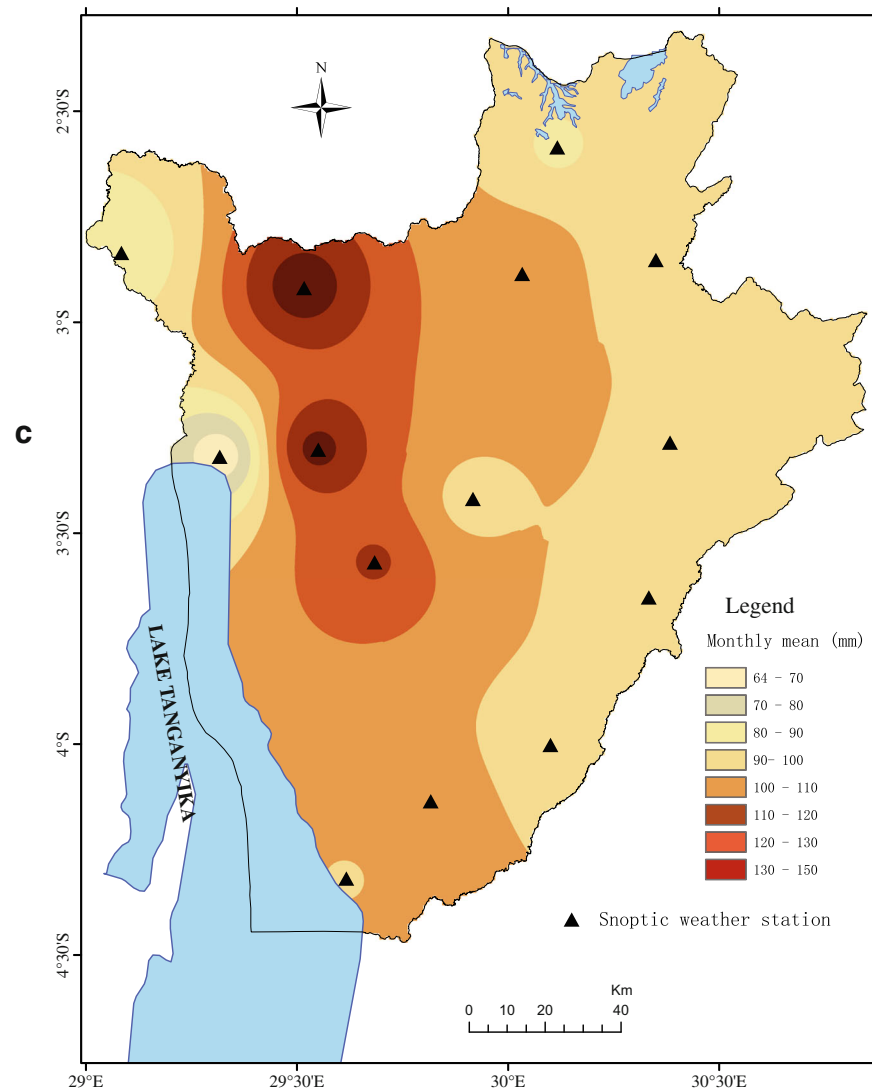
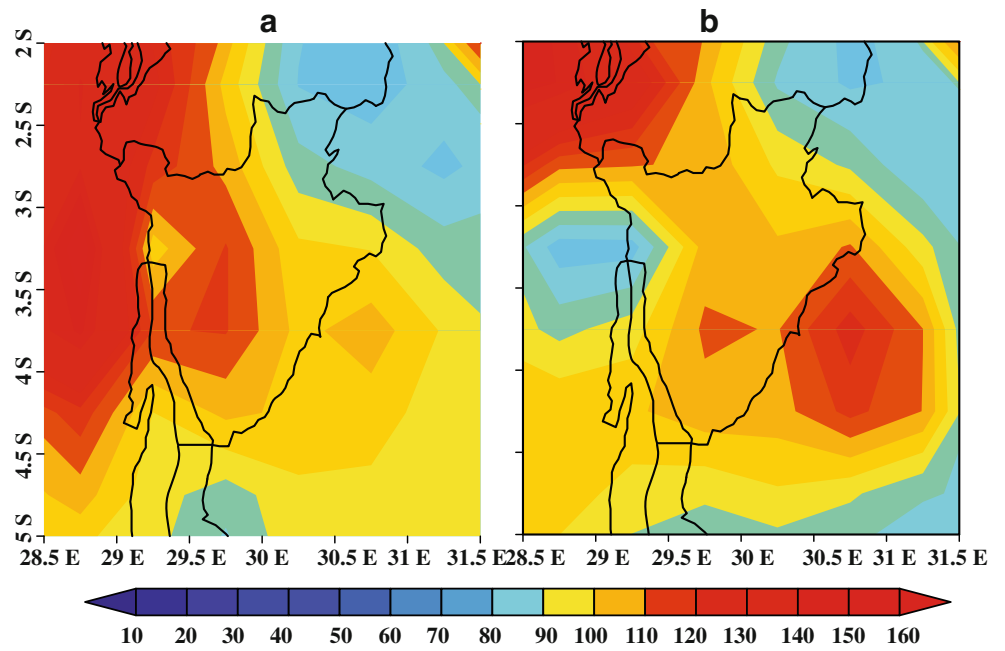
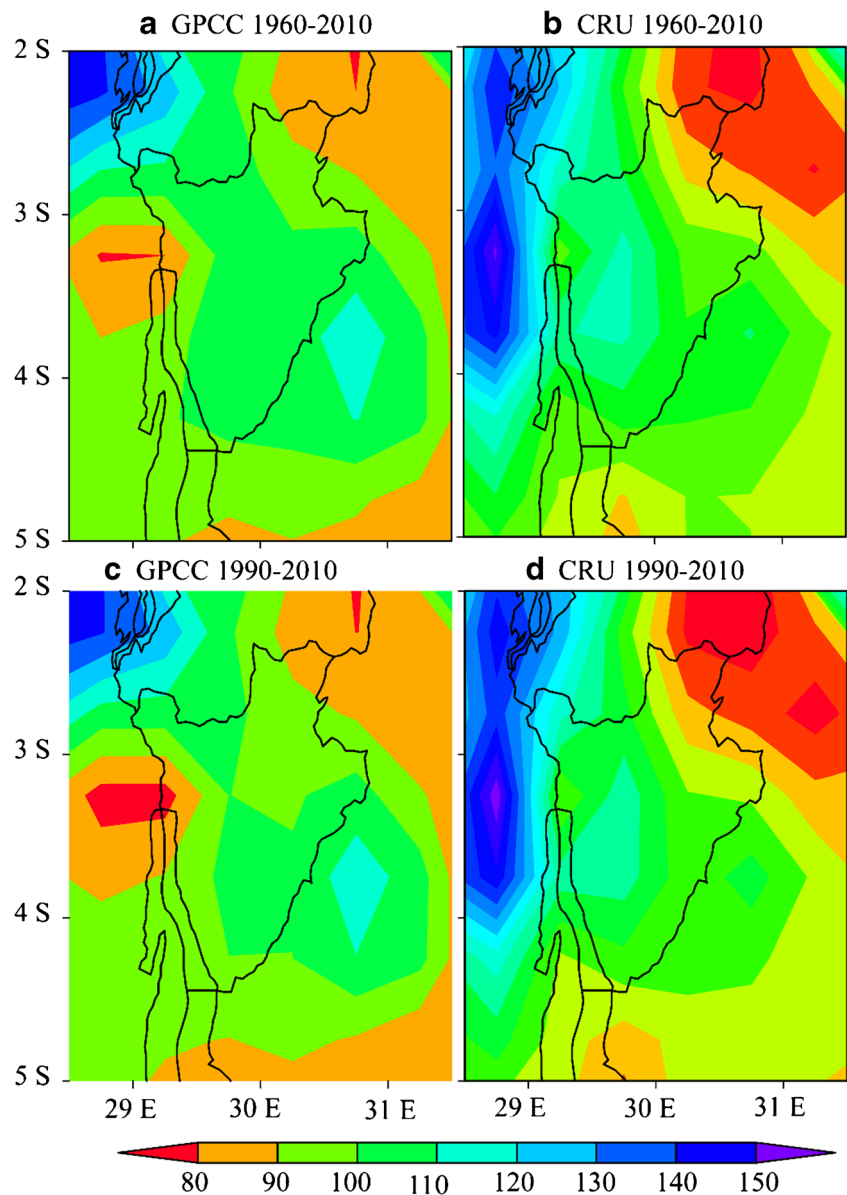


Fig. 7 Spatial distribution of monthly mean rainfall for the period 1960–2000 in comparison with monthly mean rainfall for 1990–2010 based on GPCC (a, c) and CRU (b, d) datasets



lack of data for some months, some stations were omitted in this study for accurate analysis. For most of the stations analyzed, it can be seen that there is a significant variability along the 30 years especially during the two last decades. The year 1993 registered the lowest rainfall in all the stations. That period is linked to the longest dry season that was prolonged until the end of October or early November in northern and eastern regions of Burundi.

During the period 1981–2010, the global annual mean analysis showed that for most of the stations, 1986, 1987, 1988, 2006, 1997, 1989, and 1982 are the wettest years, with annual rainfall more than 1300 mm while 1993 is the driest year with annual rainfall less than 1000 mm (Fig. 5). The western part of Burundi is recorded to be the driest region with less than 800 mm of annual mean rainfall amount and the wettest region covers mountainous area including its surrounding with more

than 1500 mm of annual mean rainfall amount. The global decrease of precipitation is associated with the drought period which abnormally long in some areas that triggers the diminution of water resources as witnessed recently in the decline in the water level of the hydroelectric power of Rwegura from 2005 to 2014. It has been observed that the period 1990–2005 experienced a significant decrease that correspond to the diminution of water level of the Lake Tanganyika in the west and the drought to the northern part of Burundi and neighboring countries Rwanda and Tanzania (Ngarukiyimana et al. 2017; Chang'a et al. 2017). In global view, the annual mean diminution of last decades can also be linked to the ENSO that affected East Africa as well as Burundi (Ogallo 1988; Indeje et al. 2000; Ogwang et al. 2015).

A seasonal standardized anomalies show that different regions exhibit a consistent variability within the study period.

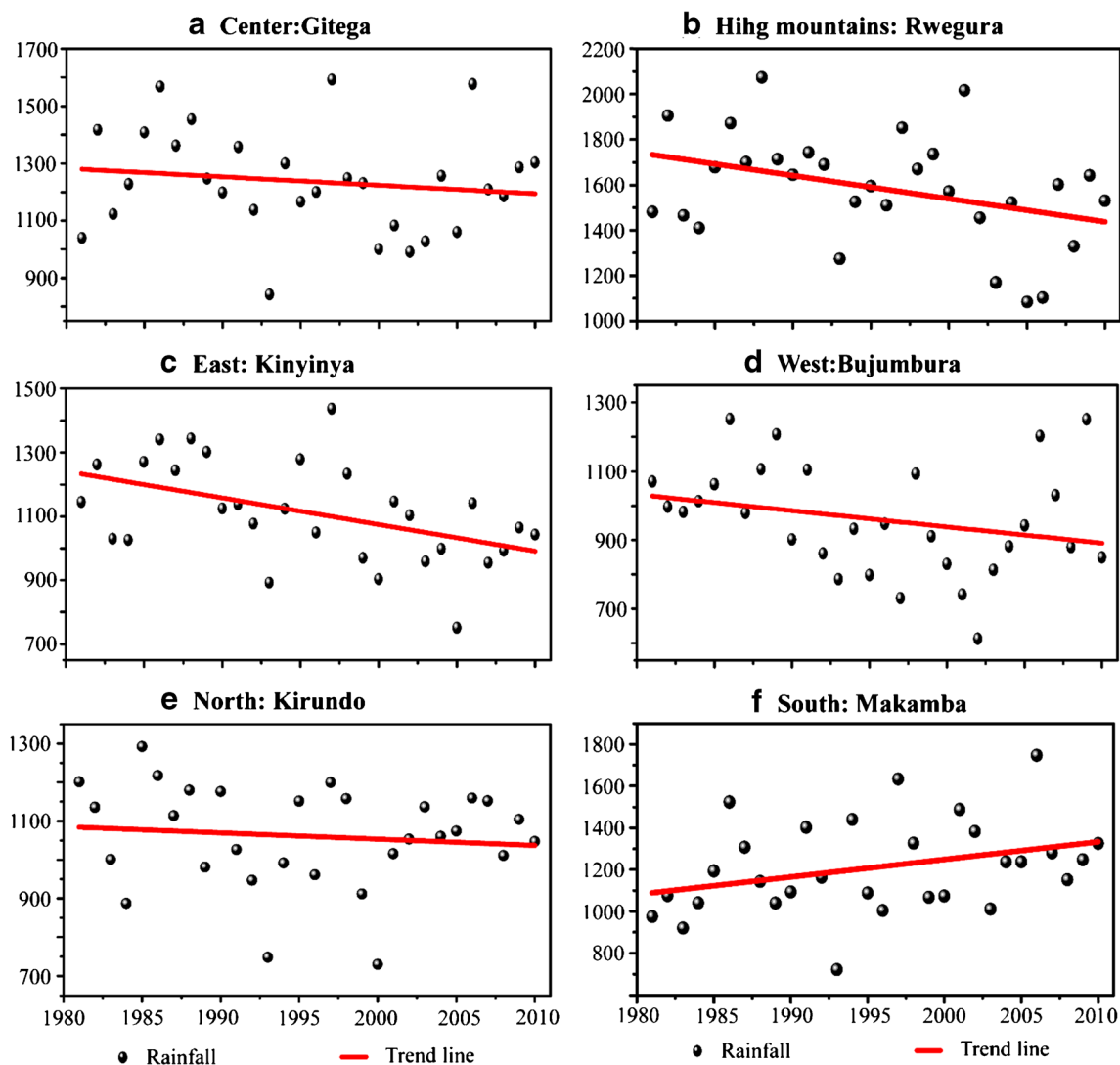


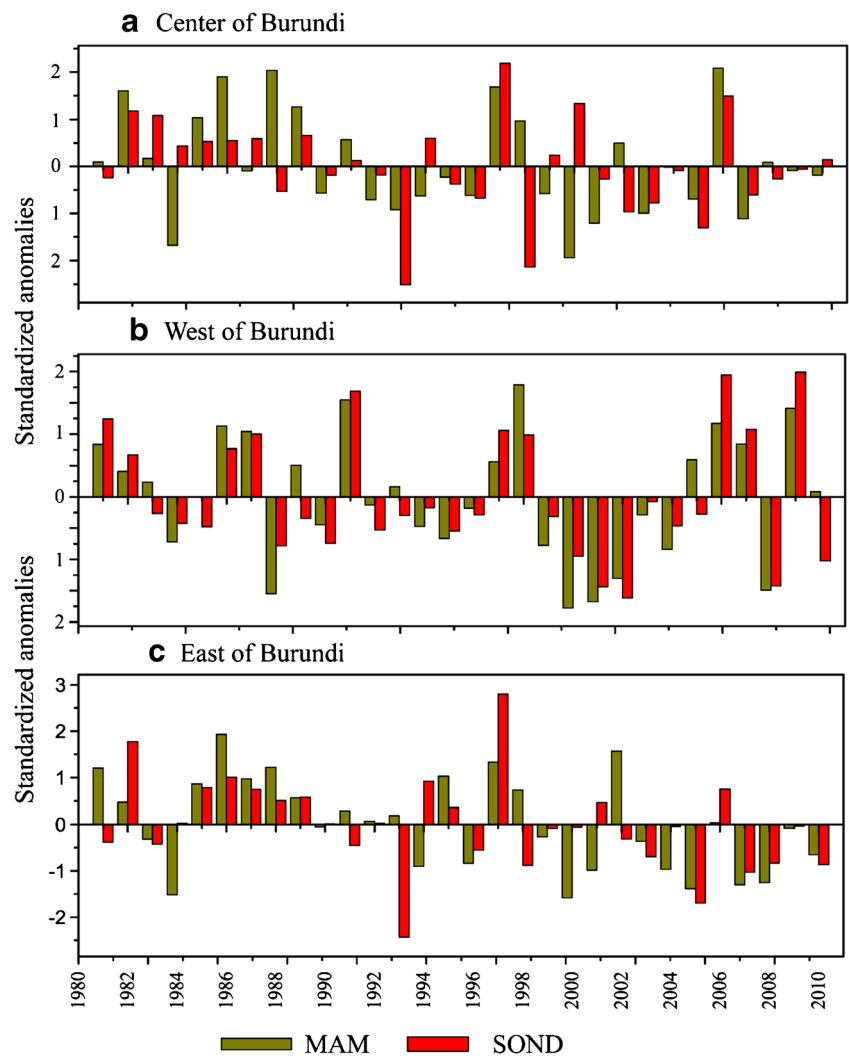
Fig. 8 Trend analysis of six selected homogeneous zones over the study domain for a period of 30 years. The selected regions are **a** center, **b** mountainous zone, **c** east, **d** west, **e** north, and **f** south

In Fig. 9, it can be seen that both long rains and short rains prone to a high variability. However, it seems that the short rains are highly varying compared to long rain (Fig. 9). That situation can help to explain the occurrence of extreme events such as drought in northern and eastern part of Burundi and the occurrence of mass movements combined with flash floods in the western part especially in the metropolitan area of Bujumbura and its surrounding. The analysis of inter-annual variability of the mean of SOND and MAM exhibits a strong anomaly starting from 1990.

The study has carried out that some data stations can hide the real anomaly signs while analyzing decrease or increase of rainfall over time. To overcome that situation, all the stations' results are considered and compared together before averaging or making global analysis. It was found that all the regions experienced high variability and

decrease of short rains and long rains from 1990s. Most of the country receive the first rain in September; however, there is a decline of first rain especially in the north, east, and west which effect crops production and cause the repetitive famine in the north of Burundi. The result analysis shows that the west, the east, and the north of Burundi are more affected by decrease of rainfall especially during first cultural season (SOND). It has been found that although some regions show a small trend increase or decrease within the study period, other exhibit a very significant decrease and it has also been found that the stations with a very significant decreasing trend are the ones that experienced more extreme events. The stations located in north experienced drought events while the west of Burundi experienced extreme rainfall cases accompanied by flash floods, landslides, debris flow, etc.

Fig. 9 Long rains and short rains standardized anomalies over the center (a), the west (b), and the east (c) of Burundi from 1981 to 2010



Occurrence of extreme rainfall over the western part of Burundi

In order to understand the frequency of extreme rainfall over Burundi, the study analyzed the western part of Burundi which prone to more cases of extreme rainfall compared with other regions. Statistical analysis done with daily rainfall from Bujumbura showed the decrease of daily rainfall.

Table 2 Daily rainfall frequencies from 1960 to 2010 at Bujumbura International Airport station

Rainfall (mm)	Frequency	Percentage (%)
< 5	16,214	87.76
[5–15]	1575	8.52
[15–30]	489	2.65
[30–60]	158	0.86
> 60	40	0.22
Total	18,476	100

Table 2 shows that from 1960 to 2010, 87.77% of rainy days registered a volume of rainfall less than 5 mm, rainy days with a volume between 5 and 15 mm represent 8.53%, 2.6% correspond to the rainy days whose volume is between 15 and 30 mm, rainfall between 30 and 60 mm represents 0.86% whereas daily rainfall equal or greater than 60 mm represents only 0.21%.

In the west of Burundi, the daily rainfall analysis has carried out that two successive rainy days of more than 20 mm can directly affect the stability of steep slopes and cause mass movements. Among 4990 wet days observed during 51 years, only 158 cases of heavy rains (30–60 mm) were recorded (Table 2). The study defined the wet day as a daily rainfall $R \geq 1$ mm referring to the indices defined by Expert Team on Climate Change Detection and Indices (ETCCDI). However, this study considered a “very heavy rainfall” a daily rainfall with the range of 30–60 mm and “extreme rainfall” a daily rainfall equals or above 60 mm. The extreme rainfall represents the proportion of 0.22% (Table 2). From 1960 to 2010, 4 cases of rainfall greater than 100 mm were recorder (Table 3).

Table 3 Periodicity of “extreme rainfall” recorded at Bujumbura station from 1960 to 2010

Year	Date	Rainfall	Year	Date	Rainfall	Year	Date	Rainfall
1961	5-Feb	67.8	1971	31-Jan	96.2	1991	18-Dec	61.7
	9-Dec	84.2		25-Feb	60		7-Mar	60.7
	10-Dec	70.6	1977	29-Apr	93	1999	29-Dec	71.2
	27-Dec	92		30-Nov	61.6		16-Nov	77
1962	6-May	60	1980	4-Dec	68.6	2004	31-Mar	64.8
1965	7-Nov	77.9		18-Dec	60.3	2006	31-Dec	110
1966	23-Mar	95.8	1982	1-Dec	94.6	2007	13-Jan	63
1967	18-May	81.8	1984	9-Dec	60.4	2008	5-Feb	75.2
	24-Nov	62.1		8-Apr	88.1		4-Jun	79.8
1969	29-Jan	76.4	1989	16-Mar	64.4	2009	11-Nov	142
1970	6-Jan	63.7		6-Apr	60.6		22-Dec	121.7

Although the west of Burundi registers annual mean rainfall less than 1000 mm (MRDTE 2007), it is known as one of the regions which are more affected by heavy rainfall especially during the two last decades. The study found that most of extreme rainfall occur in November–December (Fig. 10). The variation in precipitation can be related to changes in various weather systems that affect the study domain especially during the short rains period. A changing weather system is one of the main factors triggering mass movements and flash floods affecting the western part of Burundi in general and the city of Bujumbura in particular.

Figure 10 shows that more cases of extreme rainfall occurred in November–December (55%), 30% occurred in January–February that is linked to the period of short dry season in Burundi (MWELUP 2011), 25% occur during the “long rains” period (MAM). However, only 1 extreme rainfall event occurred in June which is normally the beginning of dry season in Burundi. It has been recorded in 2008 which is among the wettest years of the 2000th decade.

The year 2009 is known as a special year for the whole period of study. It registered two extreme rainfall events within a very short period (142 mm on November 11th and 121.7 mm on December 22th). The rainfall amount of 142 mm is the

highest rainfall amount ever recorded in Burundi as shown (Table 3).

Based on the results provided by Fig. 10, with the purpose of understanding the cause of extreme rainfall over Burundi, especially in the western part, the study utilized CRU and GPCP datasets, to compare the spatial distribution of rainfall amount of October, November, and December during the year 2009. Figure 11 shows October, November, and December rainfall distribution based on CRU and GPCP. It is seen that CRU shows that the region was wet during November which in agreement with previous analysis and ground-based data results.

The study found that although Bujumbura station did not show a significant trend within 30 years of observation (1981–2010), the result given by the analysis of 51 years (1960–2010) showed a very significant decreasing trend of both rainfall and rainy days as shown by Fig. 12. It shows the temporal distribution of annual precipitation in comparison with annual monthly mean of rainy days. It carried out that there is a very significant decrease of both rainfall and rainy days from 1990s. The two last decades are characterized by a very high variability with either drought event or and flood events. The number of rainy days has decreased significantly from 1990. The period 1990 to 2010 is characterized by a very significant decrease of the number of rainy days and the rainfall amount especially in the western part of Burundi. It corresponds to the period where Burundi registered more cases of drought events in northern and eastern parts, landslides and floods in western parts of Burundi. There is a very significant decrease of rainfall and rainy days especially from 1990 (Fig. 12). The 1990s decade is the driest period over Burundi. Although some authors confirm that the Great Horn of Africa (GHA) which includes Burundi will likely experience an increase of rainfall (Shongwe et al. 2011; Tierney et al. 2015), the trend (Fig. 12) indicates a continuous decrease with more variability during last decades. Those years are 1998 (883.5 mm), 2006 (1027.9 mm), and 2009 (1231.7 mm). The years 1995 and

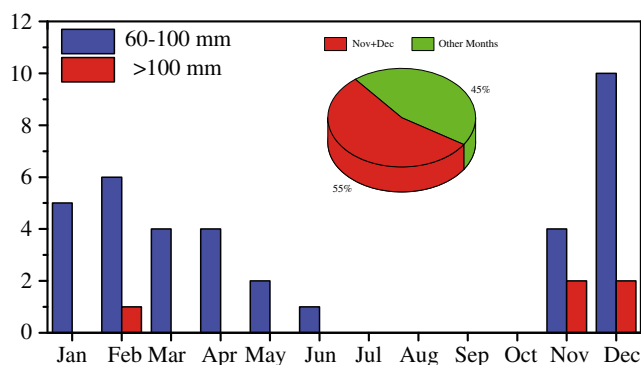
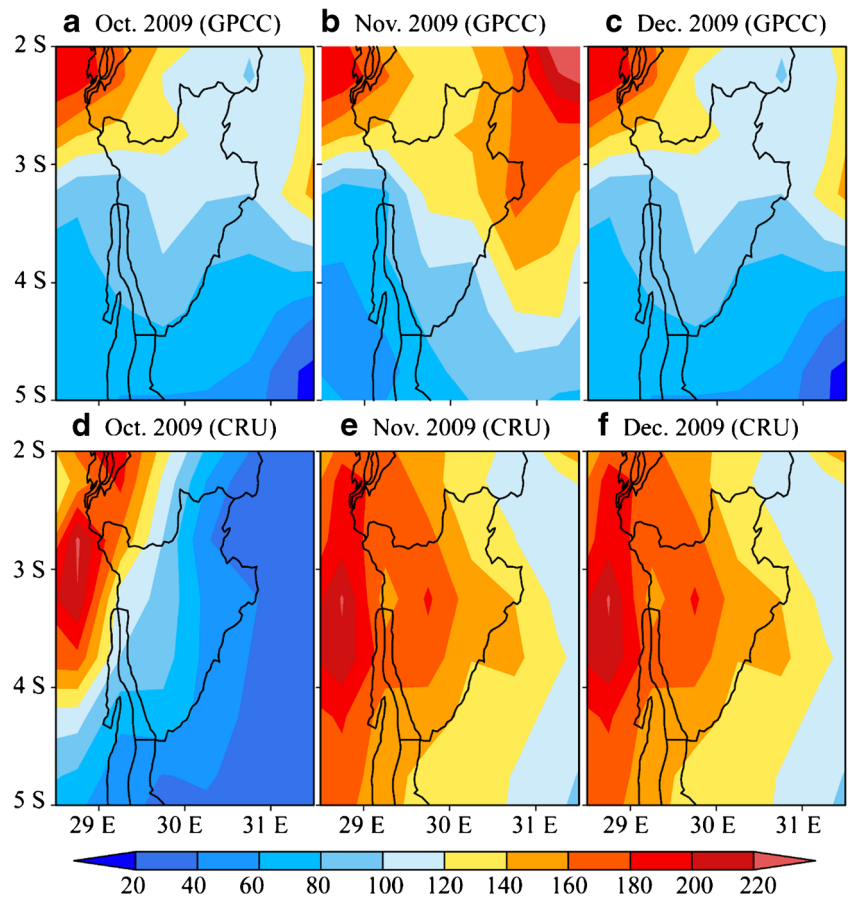


Fig. 10 Distribution of monthly frequencies of extreme rainfall from 1960 to 2010 as observed at Bujumbura International Airport

Fig. 11 Spatiotemporal comparison of rainfall between (a) October, (b) November, and (c) December 2009 based on GPCC and (d) October, (e) November, and (f) December 2009 for CRU datasets over Burundi



1997 are the driest years of the period studied (Fig. 12). This situation is linked to the climate variability that affected not only Burundi but also the East Africa (Omondi et al. 2014; Ogwang et al. 2014; Ongoma and Chen 2017).

Decreasing or increasing of rainy days is an important index in studying climate variability. The rainy days in Bujumbura have decreased significantly compared to the average of the first 30 years (from 1960 to 1989). The average of the rainy days from 1960 to 2010 is 140 days. The annual

long-term mean of rainy days in 30 years is 153 days (from 1960 to 1989), while the average of rainy days from 1990 to 2010 is 121 days, thus a decrease of 32 days.

However, according to result analysis, there is no relationship between the number of rainy days and the amount of rainfall recorded. Some years registered more rainfall in few days like 2009 in which the rainfall amount reached 1231.7 mm in only 100 days while others registered a very low rainfall amount during many rainy days. It is for example

Fig. 12 Decreasing of annual mean rainfall and annual monthly mean of rainy days during 51 years of observation over the west of Burundi (station of Bujumbura International Airport)

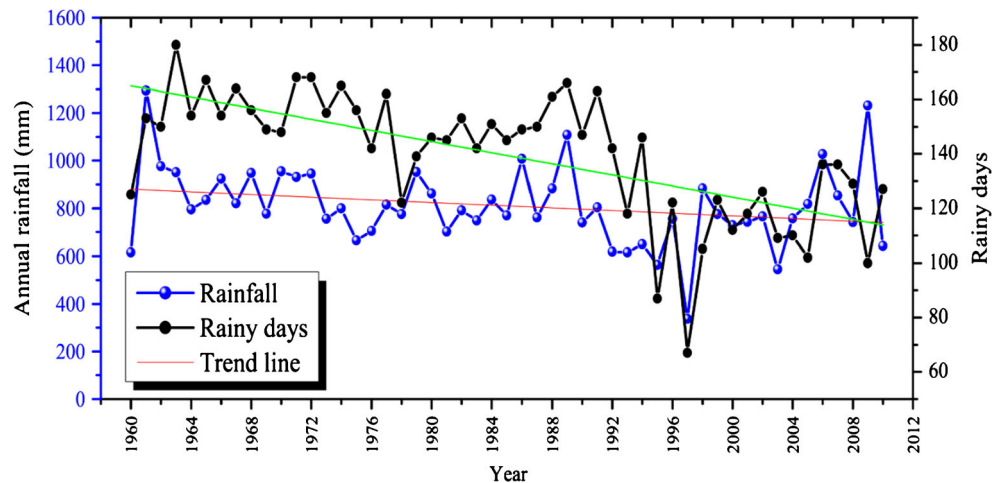
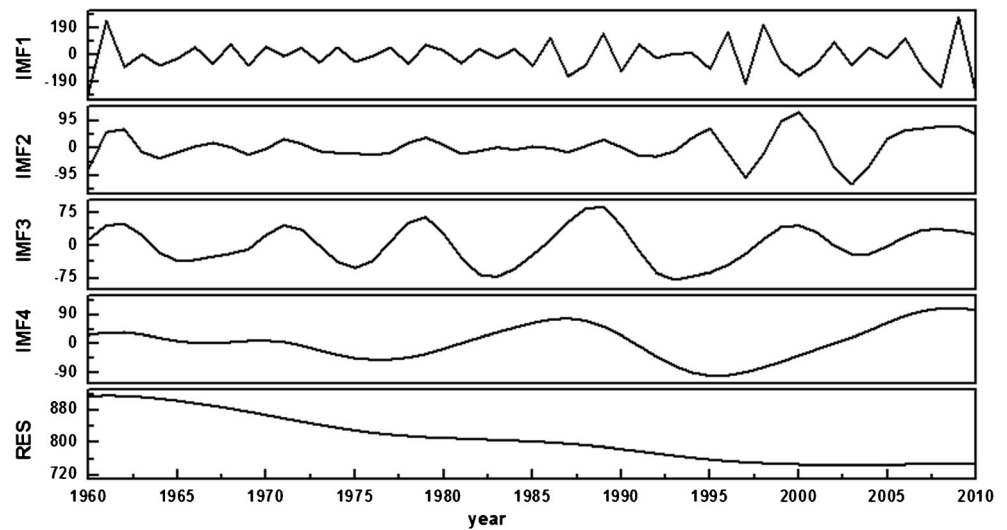


Fig. 13 Annual rainfall cycle analysis based on ensemble empirical mode decomposition (EEMD) results



the case of the year 1973 that registered more rainy days (155) with less rainfall, 756 mm (Fig. 12).

Multi-time scale change of yearly rainfall

In order to understand the time scale change of yearly rainfall and the frequency of extreme rainfall, the EEMD method was applied to Bujumbura station data. The original rainfall data was decomposed into a series of 4 IMFs. After adding white noise to the data, signal-to-noise ratio and the number of samples of the original signal are 0.2 and 500. The result shows that multi-time scale sequence of yearly rainfall is changing along the studied period (Fig. 13). IMF1 reflects the same result as the trend line of the time series represented in Fig. 12 that corresponds to the period where occurred many cases of extreme rainfall triggering landslides and flash floods over Burundi especially in the west.

The extracted IMFs are shown in Fig. 14 which enables the analysis of the oscillation signal and sequence variation along the studied period.

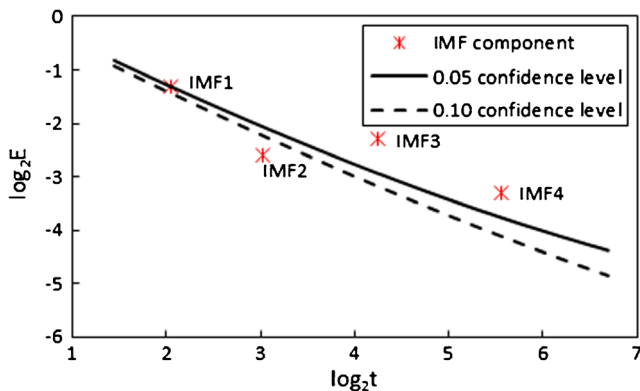


Fig. 14 Significance test of each IMF component signal of annual rainfall, where E is the average normalized energy and t is the averaged period

Combining Fig. 14 and Table 4, it can be seen that the inter-annual scale given by IMF1 showed a scale change within a period of 2.3 years with a correlation coefficient of 0.685 and the covariance rate of 33.65%. The oscillation signal is high during the period 1960–1962, 1988–1991, 1996–2002, and 2006–2010. IMF1 shows that more sequence variation has increased during the last decades especially from 1996 which is characterized by high amplitude. The period from 1965 to 1985 is quite stable.

IMF2 indicates that the variance contribution rate of the 5.9-year cycle is 21.36% with a correlation coefficient of 0.437. The amplitude is varying between 1961–1963 and 1996–2010 whereas during the period 1964–1992, the oscillation signal is relatively constant.

Within a period of 9.6, IMF3 represents the variance contribution rate 20.19% and shows a correlation coefficient of 0.493.

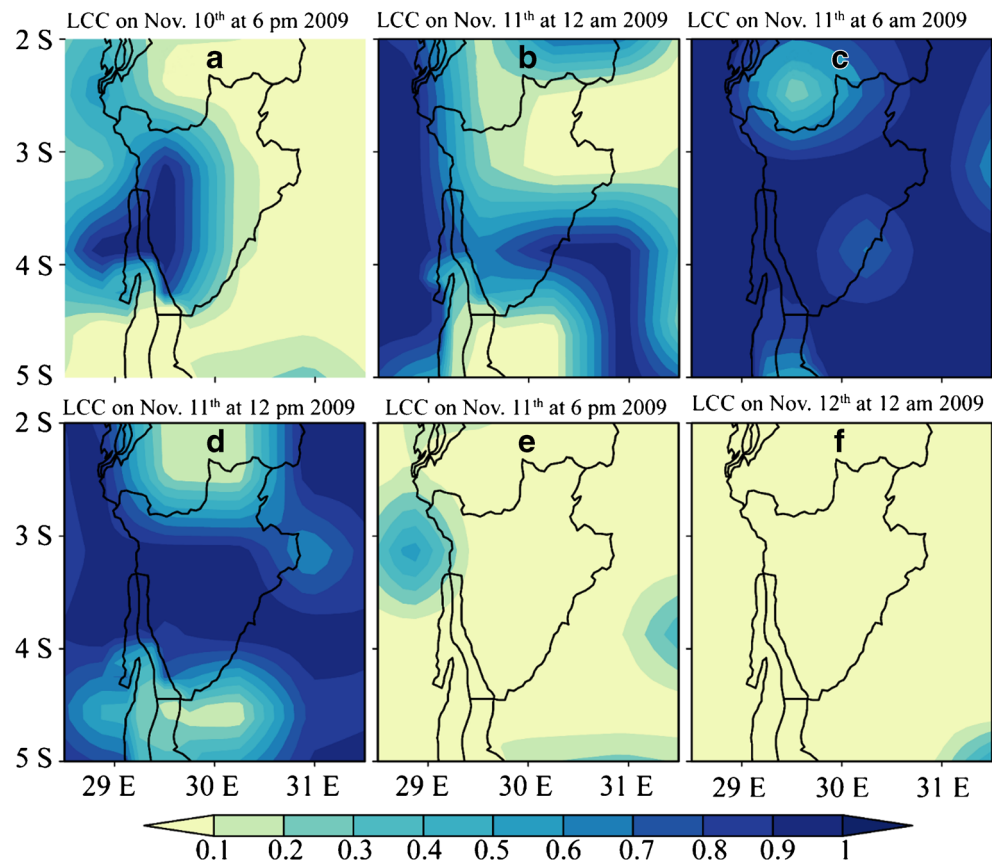
The IMF4 with a periodicity of 21.7 years shows a variance contribution rate of 14.43% and a correlation coefficient of 0.447. The oscillation signal is characterized by a period of weak amplitude from 1960 to 1975 and a period of large amplitude corresponding to 1976–1993 and 1995–2010.

The RES shows a continuous decrease in the overall period of time. RES carried out the same results as the linear trend

Table 4 Period, contribution rate, and correlation coefficient of IMF components of the yearly rainfall sequence in the west of Burundi

IMF component	IMF1	IMF2	IMF3	IMF4	RES
Period/a	2.3	5.9	9.6	21.7	
Variance contribution rate/%	33.65	21.36	20.19	14.43	10.37
Correlation coefficient	0.685	0.437	0.493	0.447	0.333

Fig. 15 Spatial distribution of low clouds cover (LCC) averaged on November 10th 2009 at 6 pm (a), November 11th 2009 at 12 am (b), November 11th 2009 at 6 am (c), November 11th 2009 at 12 pm (d), November 11th 2009 at 6 pm (e), and November 12th 2009 at 12 am (f) based on Era-Interim reanalysis datasets with a spatial resolution of $0.5^\circ \times 0.5^\circ$



shown in Fig. 12 which depicts that the annual rainfall is decreasing especially during the last decades.

The analysis of confidence test revealed that the significance level is 0.05 or 0.10, respectively. After calculating the confidence level, it was found that IMF1 corresponds to 0.05 which is a genuine confidence level, thus 95% of confidence interval (Fig. 14). IMF3 and IMF4 fall above 95% of confidence interval. IMF2 is lower than 90% confidence interval; however, the result given by IMF2 is not significant. Only the results given by IMF1, IMF3, and IMF4 are significant and served to analyze the oscillation signal during the studied period.

Influence of Congo basin and local factors to the climate variability over Burundi

From recent research, some scientists confirmed that there is an influence of moisture flux from Congo basin that affect East Africa including Burundi. Otieno and Anyah (2013) used velocity potential to measure the causes of precipitation anomalies and found that Congo basin is projected to generate flux moisture that may influence climate variability of East Africa. In their study, Camberlin and Philippon (2002) found that the west wind from Congo basin contribute to predict March–May (MAM) rainfall in East Africa.

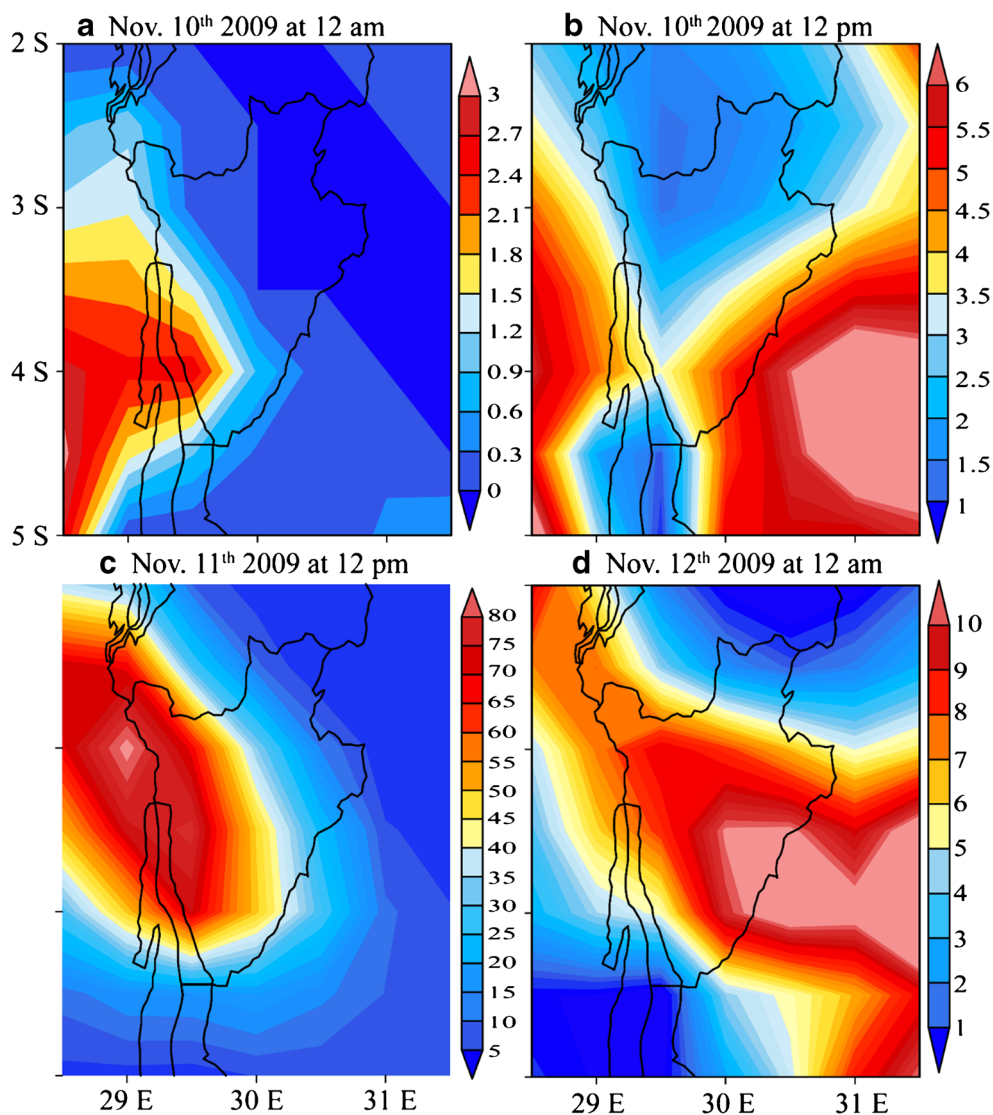
Based on the period of occurrence of extreme rainfall, this study analyzed the dynamic of low clouds cover, daily mean

rainfall, and zonal air mass circulation over the west of Burundi before, during, and after November 11th 2009 date where occurred the highest daily rainfall amount (Table 3).

The analysis results showed that from November 11th 2009 in very early morning, the air mass was flowing from Congo basin towards Burundi and a cyclone is installed over the region around 6 am in morning causing very a heavy rainfall. Figure 15 shows the situation of low clouds cover over Burundi and neighboring countries on November 10th 2009 at 6 am, on November 11th at 12 am, 6 am, 12 pm, and 6 pm, and on November 12th at 12 am in 2009. It shall be reminded that November 11th 2009 is the date known to be the daily rainfall with a volume of precipitation ever recorded in Burundi (142 mm). On that day from early morning at 12 am, the Congo basin was covered by low clouds with a very high convergence as shown by Fig. 17.

It is carried out that there was a strong convergence over Congo basin towards Burundi on November 11th 2009. The west of Burundi was totally covered by low clouds from 6 am to 12 pm which exactly correspond to the duration of the event (Fig. 15c, d). From November 10th 2009, the daily precipitation was too low below 5 mm. However, as shown by Fig. 16, the daily mean rainfall was over 80 mm on November 11th 2009 at 12 pm according to Era-Interim data (Fig. 16c). This result carried out Era-Interim data is in agreement with the information provided by ground station data provided by

Fig. 16 Spatial distribution of daily mean rainfall averaged on November 10th 2009 at 12 am (a), November 10th 2009 at 12 pm (b), November 11th 2009 at 12 pm (c), and November 12th 2009 at 12 am (d) based on Era-Interim datasets with a spatial resolution of $0.5^\circ \times 0.5^\circ$



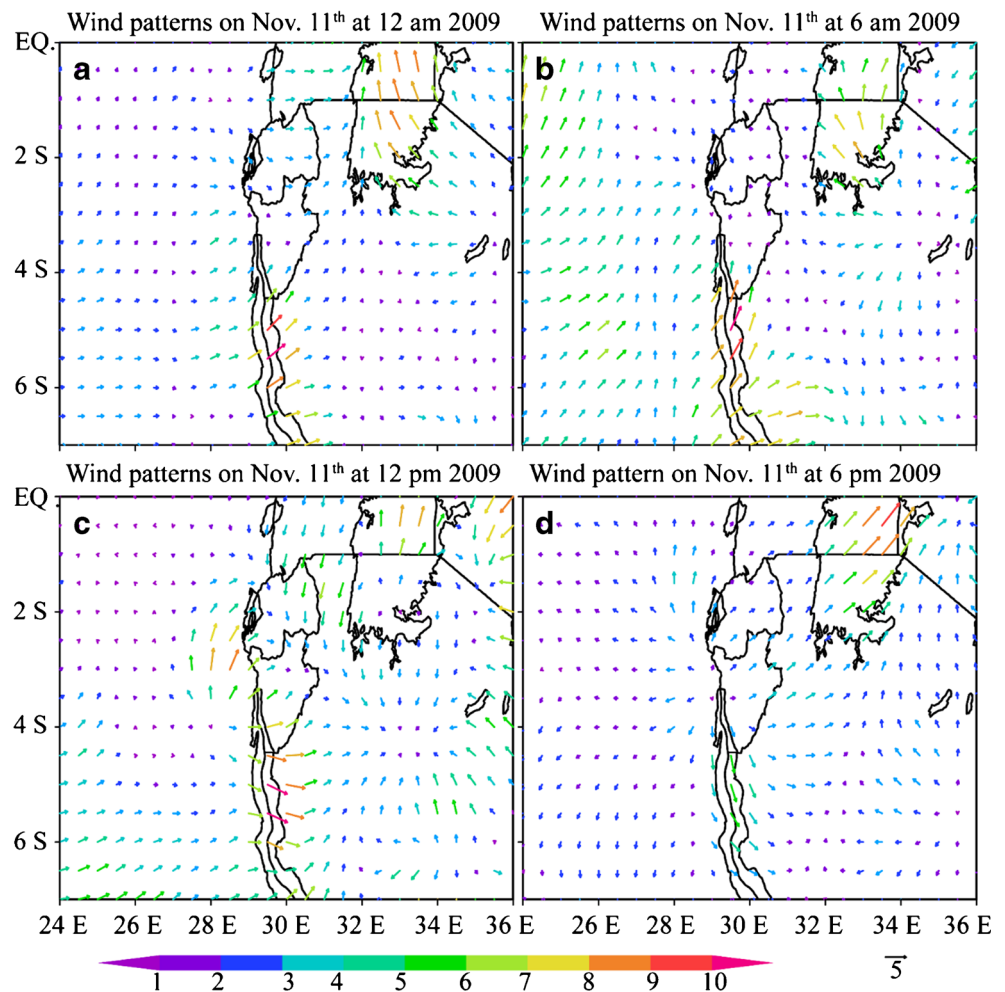
Bujumbura International Airport station. After 12 pm, the west of Burundi was dominated by a strong anticyclonic wind that sudden swept out the low clouds and the precipitation as shown by (Fig. 15e, f, Fig. 16d, and Fig. 17d). The air mass circulation over the region in preceding days showed that Inter-tropical Convergence Zone (ITCZ) was over Congo basin. The observed circulation anomaly is amplified by the local topography of the west of Burundi. The local circulation combined with local topography and air mass from Congo basin can generate a sudden convection that cause damage in few hours.

Conclusions

The understanding of characteristics of rainfall and spatiotemporal distribution of extreme rainfall events in Burundi is key to undertake response measures that enhance preparedness

and early warning system in short and long term about occurrence of floods or mass movements in order to reduce the risks. The climatology features, annual mean, monthly mean, short rains, long rains, and daily rainfall analysis allowed to investigate the variability and rainfall anomaly over Burundi for a period of 30 years (1981–2010) for the whole country and a period of 51 years (1960–2010) for the western part which highly prone to landslides and flood events. In order to study with accuracy the rainfall variability and extreme events over the study domain, we used station data, Climate Research Unit (CRU), Global Precipitation Climate Centre (GPCC), and Era-Interim datasets. It has been found that CRU and Era-Interim datasets have a good caption of observed rainfall information than GPCC datasets. Their performance was calculated with Spearman's rank correlation. It was found that CRU has a good performance when analyzing monthly data whereas Era-Interim has good performance to analyze daily rainfall. Different results analysis showed that

Fig. 17 Zonal wind patterns on November 11th 2009 at 12 am (a), November 11th 2009 at 6 am (b), November 11th 2009 at 12 pm (c), and November 11th 2009 at 6 pm (d) over Burundi and surrounding regions based on Era-Interim datasets with a spatial resolution of $0.5^\circ \times 0.5^\circ$



the rainfall is significantly decreasing especially in the western, eastern, and northern part of Burundi.

The analysis of annual, yearly monthly mean and monthly rainfall showed that most of the regions have registered a high variability and a significant decrease of rainfall amount except the southern part which shows a relative increase of rainfall within the last decades. The studied period showed the existence of rainfall anomaly in both short rains (SOND) and long rains (MAM) especially from 1990s. The rainfall anomaly also varies from one region to another. The western part registered a high variability characterized by a very significant decreasing trend while the center has a relative decrease. The analysis of daily rainfall allowed to extract information about extreme cases that occurred within the studied period. It has been found that heavy rains and extreme rainfall events over the western part of Burundi mainly occur during November, December, and January. Daily, monthly, seasonal, and annual analysis showed a continuous decrease of rainfall. Mann-Kendall trend test helped checking whether there exist a trend in time series. EEMD served to make a deep analysis of rainfall variability and the method carried out a high rainfall variability especially in 1990s.

According to the results of our research, there is a relationship between extreme rainfall and meteorological events that occurred over Burundi within the last decades. The saturation of the soil during December increases the vulnerability of some regions with steep slopes to mass movements and causes flash floods in lowlands which the extreme rainfall events mostly occur in November, December, and relatively in January. 37.5% of extreme rainfall occurred in December.

The rainy days analysis showed a continuous decrease trend from 1990. It has been found that there is no relative correlation between rainfall and the number of rainy days. We demonstrated that the number of rainy days does not directly influence the rainfall amount.

The sudden climate variability and occurrence of extreme rainfall over Burundi result of the combination of air mass from Congo basin, the topography, and the local circulation were influenced by the presence of the Lake Tanganyika. There is a permanent circulation anomaly over the Rift valley between Burundi and Democratic Republic of Congo and the anomaly becomes very influent during the short rains period especially October–December.

Annual mean or monthly mean analysis cannot show extreme event. For better understand the relationship between the frequency of extreme rainfall and the occurrence of extreme events, the analysis of daily rainfall from different stations over Burundi should be analyzed in association with gridded data. Although the Era-Interim daily data is found to give a good caption of rainfall patterns, one ground-based data is not enough to give more significant results. As physical patterns vary from region to another, daily rainfall for each station is necessary to validate reanalysis data which provide a very good spatial caption. A good gridded data can help to identify which area is susceptible either to mass movement or to floods and then help in preparedness and prevention of damage. Future studies should also focus on the circulation patterns over Burundi during September–December in order to understand why most of extreme cases occurs within that period.

It is very important to understand the occurrence of extreme events in order to assess its impact on livelihood and on sustainable development of the communities. Policies that are able to combine mass movements and flood risk management with the intention of nature conservation, urban management, and agricultural production are likely to offer the best long-term solutions.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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