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Analyses of Past Extremes Precipitation–Evapotranspiration Indices Over Sub-Saharan Countries

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Extreme weather and climate events including extreme precipitation have increased in frequency, intensity, and severity due to climate change and hit vulnerable communities disproportionately hard. However, there is a gap in the understanding of the characteristics of extreme precipitation and their effects on socio-economic activities in sub-Saharan Africa societies. The study utilized climate hazards group infrared precipitation with station data (CHIRPS) to analyze the climate characteristics from 1981 to 2019 over Senegal, Burkina Faso, Tanzania, and Malawi. Standardized precipitation evapotranspiration index (SPEI) and standardized precipitation index (SPI) were used to classify the precipitation and water balance anomalies with respect to the long-term observations. It was found that Burkina Faso and Senegal have a similar climate signal with more rainfall in Burkina Faso. Malawi recorded more rainfall than Tanzania. All the four countries recorded a high rainfall

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variability of extreme events. Standardized hydro climatic indices have shown that these sub-Saharan countries have suffered severe droughts which have negatively affected the socio-economic activities among the rural populations.

Keywords: Extreme precipitation; sub-Saharan countries; climatic events; variability; socioeconomic impacts.

1. Introduction

Extreme weather events (EWEs) result from deviations in weather or climate variables beyond the usual range of historical patterns (IPCC 2012). These EWEs are short-lived, abrupt, occur very rarely, lasting only from several hours to several days. Their frequency, intensity, and severity increased due to climate change and hit vulnerable communities disproportionately hard (WMO 2020). EWEs have been noted to propel adaptation to climate change (Travis 2014). Among these extreme events, those from precipitation (droughts and floods) are the most severe in terms of damages. Sub-Saharan Africa is not on the fringes of this situation, and several socioeconomic activities are affected by extreme rainfall, including the agricultural sector, among others. Indeed, sub-Saharan Africa's food systems are exposed to floods, heatwaves, pests and prolonged dry spells and or drought (Vogel *et al.* 2019). Over the past decade, sub-Saharan Africa experienced extreme weather and climate events (heat waves, cold waves, heavy rains, cyclones, periods of drought and flooding, and severe storms) which affected livelihoods (Kotir 2011). Effects of climate change and EWEs frequencies have socioeconomic repercussions on the well-being of human societies being affected worldwide (Sylla *et al.* 2018). The fifth report of the intergovernmental panel on climate change (IPCC), for instance, noted that extreme climate events have substantially affected natural ecosystems and biodiversity, water supply and food production, and loss of infrastructures and settlements, among several others (IPCC 2014). There is a lack of understanding on the characteristics of extreme precipitation and evapotranspiration, and their effects on socio-economic activities in sub-Saharan Africa societies.

Increased susceptibility, as well as the severity and frequency of climatic catastrophes, puts low-income populations at risk of disasters. Understanding characteristics and effects of extreme precipitation on social economic activities provides a basis to reduce the risk, devise appropriate responses and build community resilience. Extreme weather occurrences, such as torrential rain, pose a threat to the social ecological system because of the potential for negative economic effects and the destruction of property, infrastructure, and crops (Bauer *et al.* 2018). In addition, droughts in Africa cause severe problems, such as crop failure, food shortages, famine, epidemics and event mass migration

(Peng *et al.* 2020). There is a general lack of consolidated information that characterizes extreme precipitation and how such precipitation affects social economic activities.

In this study, we will focus on extreme precipitation and evapotranspiration indices; they are the most common extreme events that affect both west and southeast African countries. Therefore, the study aims to provide a status-quo of extreme precipitation and evapotranspiration events in Senegal and Burkina Faso, Tanzania and Malawi.

2. Data and Methods

2.1. *Study area*

The study area (Figure 1) represents two countries of West Africa (Senegal and Burkina Faso) and two countries of Eastern Africa (Malawi and Tanzania). These countries are in the sub-Saharan African area. Two distinct seasons characterize Senegal's climate, as follows: A dry season from roughly October to May and a rainy season from June to September. The mean annual rainfall from 1950 to 2010 was 600 mm; with a maximum of 1300 mm in the south, and a minimum of 300 mm in the north (Mbaye *et al.* 2019). In Burkina Faso, we have two seasons (wet and dry). A two-month wet season in the far north (beginning in June or July) gradually shifts to a longer six-month wet season to the south (May–October). Rainfall peaks in August. The dry season (December–March) brings dust-laden Harmattan trade winds from the northeast that reduce humidity and can produce severe dust and sand storms (USAID 2017).

The climate of Tanzania is hot and humid with rain season starting from March to May, a semi-temperate type of climate in mountainous areas where short rains are found in October, November, and December (OND) and long rains during in March, April, and May (MAM). Furthermore, plateau regions are drier with seasonal variations of temperature (Tumaini 2009). As for Malawi, it has a subtropical climate which is characterized by seasonal changing wet (November to April) and dry (May to October) conditions. The general climate pattern is altered by altitude, relief and lake influence (Vincent *et al.* 2014).

2.2. *Data*

We use the climate hazards group infrared precipitation with station data (CHIRPS) to analyze the climate characteristics from 1981 to 2019 over Senegal, Burkina Faso, Tanzania, and Malawi. We did not use rainfall stations (*in situ*) because of the difficulty of getting the daily time series from national meteorological services, we used gridded observational datasets (CHIRPS) estimated from rain gauges and satellite observations. The spatial resolution of these daily data is 25 km (Funk *et al.* 2014). Furthermore, we have also used the climatic research unit time series data (CRU TS) (Harris *et al.* 2020).

2.3. *Methods*

The standardized precipitation evapotranspiration index (SPEI) and standardized precipitation index (SPI) were used. These indices allow to classify the precipitation and the water balance anomalies with respect to the long-term observations. These indices can be used to determine the duration and the magnitude of drought conditions with respect to normal conditions in a variety of natural and managed systems such as crops, ecosystems, rivers, water resources, etc. (https://spei.csic.es/). As for the evapotranspiration (both evaporation and transpiration) that is considered within the SPEI index, it is based on monthly precipitation and potential evapotranspiration from the climatic research unit of the University of East Anglia. The FAO-56 Penman–Monteith estimation of potential evapotranspiration was used. This method is considered a superior method, so this index is recommended for most uses including long-term climatological analysis.

The SPI values for any given location and accumulation period, are classified into seven different precipitation regimes (from dry to wet), as shown in Table 1.

The SPEI classification is similar to that of SPI. The resulting different SPI indicators allow for estimating different potential impacts: when SPI is computed for shorter accumulation periods (e.g., 1–3 months), it can be used as an indicator for immediate impacts, such as reduced soil moisture, and flow in smaller creeks; when SPI is computed for medium accumulation periods (e.g., 3–12 months), it can be used as an indicator for reduced stream flow and reservoir storage; when

Table 1. SPI Classification (Source: European Commission 2020)

Anomaly	Range of SPI Values	Precipitation Regime
Positive	$2.0 < \text{SPI} <= \text{MAX}$	Extremely wet
	$1.5 < \text{SPI} <= 2.0$	Very wet
	$1.0 < \text{SPI} <= 1.5$	Moderately wet
None	$-1.0 < \text{SPI} <= 1.0$	Normal precipitation
Negative	$-1.5 < \text{SPI} <= -1.0$	Moderately dry
	$-2.0 < \text{SPI} <= -1.5$	Very dry
	$\text{MIN} <= \text{SPI} <= -2.0$	Extremely dry

SPI is computed for longer accumulation periods (e.g., 12–48 months), it can be used as an indicator for reduced reservoir and groundwater recharge. Furthermore, climate indices were also computed in order to investigate the characteristics of extremes events in four sub-Saharan countries. The details on these indices are given in Table 2. These indices are among the recommended extreme indices by the World Meteorological Organization (WMO) and expert team on climate change detection and indices (ETCCDI) technical document enclosing "Guidelines on analysis of extremes in a changing climate".

Moreover, statistical trend analysis has been done on a monthly basis. We use the Mann–Kendall (MK) trend test, the standard error mean (SE_{mean}), the skewness, the kurtosis and the coefficient of variation.

2.3.1. *Mann–Kendall test*

The MK test is a non-parametric test used for trends analyses. This test has been suggested by the WMO to assess trends in environmental data time series as the test is suitable for cases where the trend may be assumed monotonic and therefore no seasonal aspects are presented in the data (Rustum *et al.* 2017).

The MK trend test is initiated by computing the statistic S using the following equation:

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

Table 2. Extreme Climate Indices

Climate Index Name	Index Meaning	Unit
Simple daily rainfall intensity index (SDII)	Let PR_{wj} be the daily precipitation amount on wet days, $PR >= 1$ mm in period j. If W represents the number of wet days in j, then $SDII_j = \frac{\left(\sum_{w=1}^{W} PR_{wj}\right)}{W}$	mm
Maximum number of CDDs	Let PR_{ij} be the daily precipitation amount on day i in period j. Count the largest number of consecutive days where $PR_{ij} < 1$ mm	Day
Maximum number of CWDs	Let PR_{ij} be the daily precipitation amount on day i in period j. Count the largest number of consecutive days where $PR_{ij} > 1$ mm	Day
Very wet days (95P)	95th percentile of precipitation on wet days means the value above which 5 percent of the daily precipitation events are found	mm
Extremely wet days (99P)	99th percentile of precipitation on wet days means the value above which 1 percent of the daily precipitation events are found	mm

where n is the number of data x_j and x_i are the sequential data values and sgn(·) is the sign function, which can be calculated by the following equation:

$$\mathrm{sgn}(x_j - x_i) = \begin{bmatrix} 1 & x_j - x_i > 0 \\ 0 & x_j - x_i = 0 \\ -1 & x_j - x_i < 0 \end{bmatrix}. \tag{2}$$

A negative value indicates a downward trend and a positive value of S indicates an upward trend. For $n > 10$, S is considered as normal distribution. The mean of S is zero and its variance can be calculated as follows:

$$\mathrm{var}(s) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)}{18}, \tag{3}$$

where m is the number of tied groups each with t_i tied observations. A set of data that has the same value is a tied group. The standardized test statistic (Z_{MK}) is calculated as

$$Z_{\mathrm{MK}} = \begin{bmatrix} \dfrac{S-1}{\sqrt{\mathrm{Var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{Var}(S)}}, & S < 0 \end{bmatrix}. \tag{4}$$

Thus, in a two-sided trends test, the null hypothesis should be accepted if at the level of significance ($\alpha = 5$ percent). The positive value of Z_{MK} indicates an upward trend and the negative value of Z_{MK} indicates a downward trend, where the value of Z_{MK} is the Mann–Kendall test statistic that follows a standard normal distribution with mean 0 and variance 1 (Rustum *et al.* 2017). The Z_{MK} value can be related to a p-value of a specific trend. A p-value is a measure of evidence against the null hypothesis of no change. The for trend, the null hypothesis of no trend H_0 is accepted if $-Z_{1-\alpha/2} \leq Z_{\mathrm{MK}} \leq Z_{1-\alpha/2}$, where α is the significance level that indicates the trend strength.

The trends were calculated based on the significant level, in which the trend is considered statistically significant at 95 percent confidence level ($\alpha = 0.05$). This means that the trend is statistically significant if the p-value is less than α.

2.3.2. *Standard error of the mean*

The SEM is calculated by taking the standard deviation and dividing it by the square root of the sample size. Standard error gives the accuracy of a sample mean by measuring the sample-to-sample variability of the sample means. The SEM describes how precise the mean of the sample is as an estimate of the true mean of the population. As the size of the sample data grows larger, the SEM decreases versus the SD; hence, as the sample size increases, the sample mean estimates the true mean of the population with greater precision

$$\mathrm{SEM} = \frac{\sigma}{\sqrt{n}}, \quad \text{where } \sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}}, \tag{5}$$

where $\bar{x}$ is the sample's mean, n is the sample size and σ is the standard deviation.

2.3.3. *Skewness and kurtosis*

The skewness coefficient (Sk) and the kurtosis coefficient (K) are classically defined for a variable x on a population of size n by

$$Sk = \frac{1}{\sigma^3} \frac{\sum (x_i - \mu)^3}{n}, \tag{6}$$

$$K = \frac{1}{\sigma^4} \frac{\sum (x_i - \mu)^4}{n} - 3, \tag{7}$$

where μ is the sample's mean and σ is the standard deviation.

The Sk coefficient evaluates the lack of symmetry of a distribution while the kurtosis coefficient (K) evaluates the dispersion of "extreme" values with reference to the normal distribution.

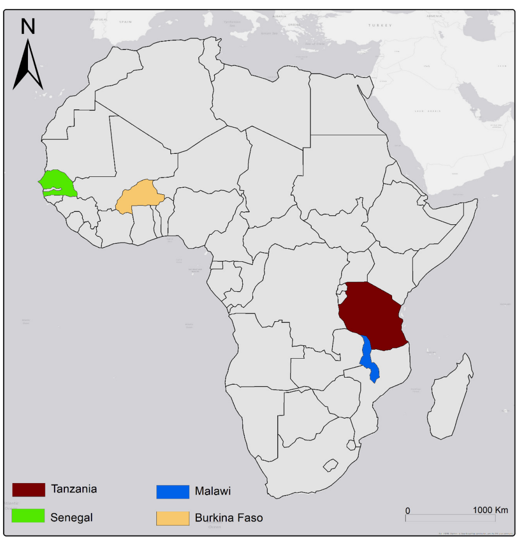


Figure 1. Map of Studied Countries

2.3.4. *Coefficient of variation*

The coefficient of variation (*CV*) represents the ratio of the standard deviation to the mean, and it is a useful statistic for comparing the degree of variation from one data series to another, even if the means are drastically different from one another

$$CV = \frac{\sigma}{\mu}, \tag{8}$$

where σ is the standard deviation and μ is the mean.

3. Results and Discussions

3.1. *Annual cycle of rainfall*

Figure 2 shows the annual rainfall cycle in 4 sub-Saharan countries from 1981 to 2018. Burkina Faso and Senegal, which have a tropical and Sahelian climate, present an unimodal appearance with the maximum precipitation recorded in August with the highest rainfall peak in Burkina Faso. The main rainy season is found in June, July, August and September (JJASO). In Burkina Faso, the rainy season begins earlier than in Senegal. The maximum precipitation in these months can be explained by the effect of the west African monsoon. It is a periodic wind system resulting from a temperature and energy gradient on the surface between the continental part and the ocean basin and which affects West Africa every year for a few months (May–August) and brings air laden with humidity to the continent, which is the source of intense rains in this part of the continent (Cissé *et al.* 2016).

The seasonal cycle of rainfall in Malawi and Tanzania, which have a variable tropical (subtropical) and equatorial humid (temperate tropical) climate, respectively, presents a bimodal pattern of precipitation. It presents an opposite signal

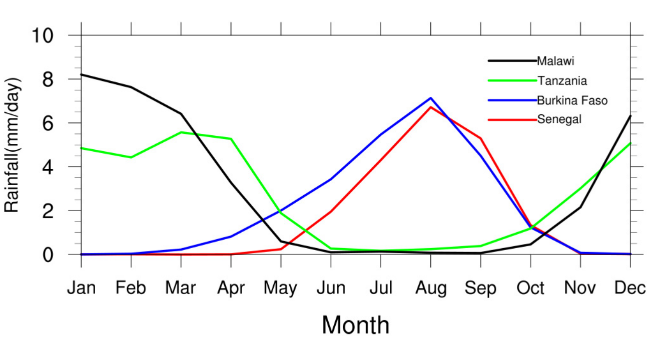


Figure 2. Annual Cycle of Rainfall

when compared to Burkina Faso and Senegal. The rainy season begins in October until May and the dry season extends from June to September for these two countries of South-East Africa (Glad 2010).

The heavy rainfall was recorded between December and April with maximum in January for Malawi and March–April for Tanzania. It rains more in two countries than in Senegal and Burkina Faso. The highest rainfall amount in this south-eastern part of Africa may be due to tropical forests with their substantial effect for rainfall generation, and the tropical cyclones which penetrate the interior from the Indian Ocean and more easily affect the south of the country, bringing wind and torrential rains in Malawi (Blais *et al.* 2011).

3.2. *Standardized precipitation–evapotranspiration index*

The SPEI indices are given in Figures 3–6, for Senegal, Burkina Faso, Tanzania and Malawi, respectively, with lags of 3, 6, 12 and 24 months. The red color represents the dry periods and the blue color exhibits relatively wet periods. The climate classification is given in Table 1. Senegal (Figure 3) gets more dry than

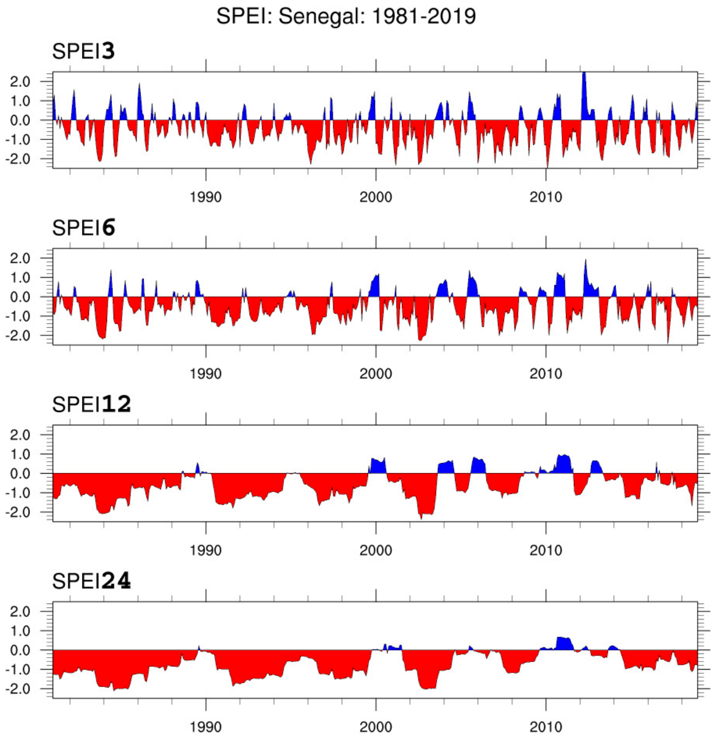


Figure 3. Standardized Precipitation-Evapotranspiration Index Over Senegal

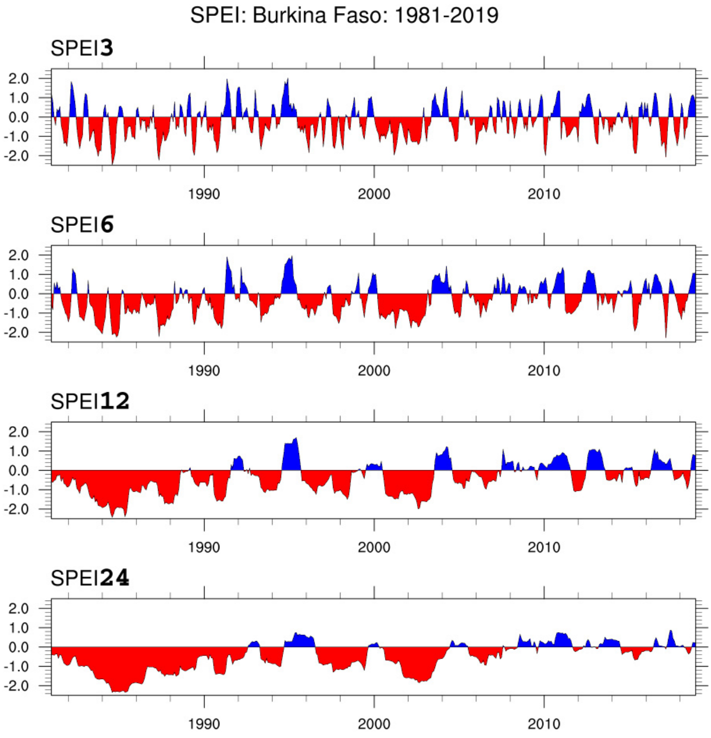


Figure 4. Standardized Precipitation-Evapotranspiration Index Over Burkina Faso

wet periods on the 3- and 6-month timescales. The years 2010 and 2017, respectively, for the 3-to-6-month timescales are considered extremely dry with a drought intensity less than –2. This situation reveals meteorological and agricultural droughts in Senegal during these periods. The wettest periods were obtained in the decades 1981–1990 and 2000–2010. 2013 is the wettest year with SPEI index greater than 2. As for 12–24 monthly timescales, the two first decades were very dry which indicates dry conditions for hydrological streams and groundwater reservoirs. These worst conditions are pronounced over the lag 24 months. This means that the more the timescale increases, the more noticeable the dry sequences are. Like all the other countries of the Sahel, Senegal also suffered for a long period of very dramatic droughts before and after the 1970s. This means that the evaporation rate is generally higher than the annual rainfall amount in Senegal. These drought conditions and climate variability have increased the vulnerability to EWEs for smallholder food producers, subsistence farmers and agricultural workers (FAO 2016). Climate change constitutes a major risk for the agricultural sector, which employs almost 60 percent of the active population and contributes to

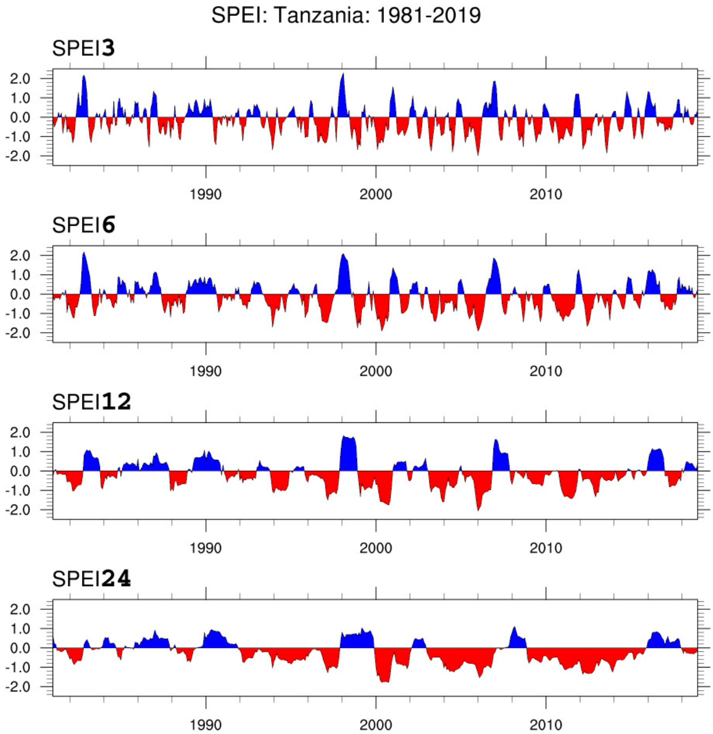


Figure 5. Standardized Precipitation-Evapotranspiration Index Over Tanzania

8 percent of GDP (IRD 2016). According to Diop and Bacci (2016), global warming will impact potential areas for the development of vegetable crops in the regions of Thiès, Diourbel, and Fatick. The most favorable areas are in the littoral zone. Furthermore, melon, potato, pepper, and chilli crops are more sustainable in these localities compared to the temperature increases. Tomato, cabbage, and eggplant are more sensitive to temperature increases, with potentially confined areas on the coast of the Thiès and Fatick regions (Diop and Bacci 2016). The World Bank predicted that climate change would reduce the average yields of 11 global field crops in sub-Saharan Africa by 15 percent by 2046–2055 compared to the period 1996–2005 (IPCC 2019).

In Burkina Faso (Figure 4), there is a fluctuation of dry and wet years, even if the number of dry periods is greater than those of wet periods. The high rates of potential evapotranspiration (PET) are much more visible over the decade 1981–1990 on the 6-month scale; the years 2021, 2002, and 2003 were very dry. This have negatively affected socio-economic activities. On the time scales 12 and 24, the figure reveals there are three periods: an extremely dry period (1981–1992),

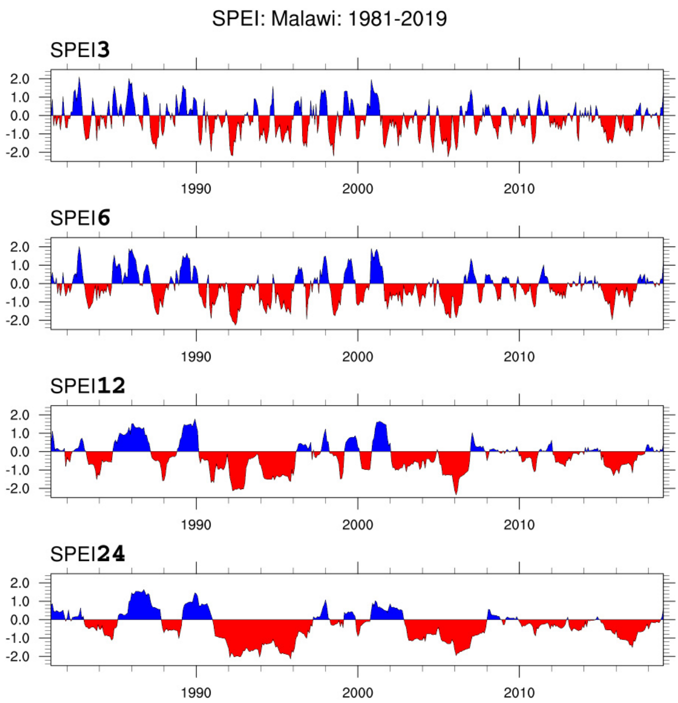


Figure 6. Standardized Precipitation-Evapotranspiration Index Over Malawi

a period of moderate drought (1992–2008) with a few wet months and at the end another period considered to be relatively wet (2008–2018). During this last decade, the humid sequences are the most dominant for the timescales of 12 and 24 (SPEI-12 and 24). The surface and groundwater have suffered less during the two last decades than the two first periods. Moreover, these droughts have reduced cover plant, agricultural yields and affects the survival of communities by exposing them to food insecurity and poverty (Kaboré *et al.* 2019).

As the timescales increase, wet and dry conditions, as well as their persistence, become increasingly clearer. The most severe drought was recorded between 2002 and 2013 with several monthly averages of SPEI approaching -1.5, which confirms the work of Bae *et al.* (2020). As for Tanzania (Figure 5), and Malawi (Figure 6), it is noteworthy a high inter-annual variability of SPEI. The inter-annual variation of SPEI3 is much greater than that of SPEI6, so that the dry events of SPEI3 are much more intense but with short periods of drought unlike the SPEI6 timescale where more dry months are recorded. Very humid months are also observed during the years 1983, 1998 and 2007 for the two-time scales (SPEI3 and SPIE6).

According to Traore and Owiyo (2013), such extreme droughts tend to have a cascading impact; they first caused a lack of water affecting seedling and crop yields, which then affected the availability of food for people and feed for livestock. This situation has led them to be more vulnerable and further limited their capacity to cope with future droughts. On the SPEI12 and SPEI24 time scales, we obtain moderately dry and humid months, except for the months of 1998 which are very wet on the 12-month scale (SPEI12). The dry months are much more numerous than the wet months for these last scales. The periods 2009–2016, 1991–1998 and 2000–2008 are considered to be the driest (moderately dry) and that of 1983–1991 is estimated to be slightly wet particularly in Tanzania. Furthermore, similar variations and climate conditions were observed in Malawi. However, for SPEI12 and SPEI24 indices, the frequency of hydrological droughts increases with the duration. The periods 1991–1996, 2002–2007 and 2010–2018 exhibit the driest hydrological conditions.

The analysis of these different figures has revealed that all investigated sub-Saharan countries have experienced drought conditions, in different magnitudes. Hydrological droughts were very severe in Tanzania and Malawi for the periods 2000–2018 while the west African countries such Senegal and Burkina Faso have faced more water deficits during the two first decades from 1981 to 2000, particularly for the SPE12 and SPEI 24. Moreover, the climatic conditions were relatively humid in Tanzania and Malawi when compared to Burkina Faso and Senegal for the indices SPEI3 and SPEI6.

Moreover, the dominance of drought conditions from 2010 to 2019 in Malawi has negatively affected agricultural production outcomes. According to an assessment of the extent to which farmers in Malawi suffer crop production losses due to extreme weather. Drought and flood shocks had large negative impacts on maize yields and value of crop production per hectare, according to data from the integrated household panel survey (IHPS) between 2013 and 2016, results show drought-induced maize yield declines of 32–34 percent and value per hectare declines of 42–44 percent. The flood shock was significantly worse, resulting in 54 percent lower maize yields and a 58 percent decrease in value per hectare (McCarthy *et al.* 2021).

3.3. *Standardized precipitation index*

Figure 7 represents the temporal variation of the SPI on the scale of 3, 6, 12 and 24 months in Senegal. The analysis of SPI3 and SPI 6 shows important fluctuations of rainfall anomalies where the highest wet indices were found between 2000 and 2018.

The wet periods are slightly higher than those which are dry for these first two-time scales (SPI3 and SPI6). The drought is much more marked for the first two

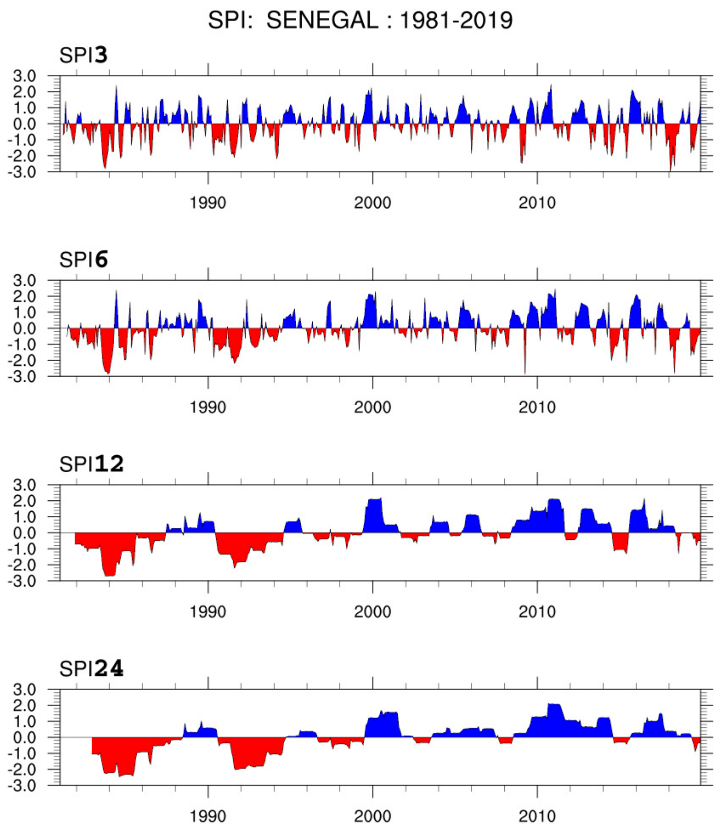


Figure 7. Standardized Precipitation Index Over Senegal

decades (1981–2000) than the first two decades (2000–2018). As for the last two timescales (SPI12 and 24), wet and dry spells are increasingly visible and more noticeable compared to the 3- and 6-month timescales. The intensity and duration of the drought are very important for the period from 1981 to 2000. During these years, the countries of West Africa suffered a sharp decrease in rainfall. From 2000 to 2019, there was a "return of wet conditions" marked by a multitude of positive rainfall anomalies. Furthermore, the dry and warm conditions have led to an increase in evaporative demand which was already amounted to 1,435 million m^3 in 2000; a decline in freshwater resources. Moreover, in regions such as Fatick, Kaolack, Ziguinchor and Kolda, there is a reduction in areas under traditional rice cultivation due to an increase in water and soil salinity. The long period of drought favored the settlement of populations brought by the rural exodus to the outskirts of cities, in areas generally classified as non-built. The sealing of these traditional infiltration areas explains the urban flooding that occurs with below normal rainfall. This is the case of large cities which have problems with the evacuation of their rainwater. In addition, the fight against floods is now part of the national priorities and sanctioned by heavy investments such as in Dakar where the Jaxaay Plan required funding of +50 billion CFA francs between 2006 and 2012 for an objective of building 3,000 social housing units in Keur Massar (Dakar region). In 2025, cereal production could drop by 30 percent following the reduction of agricultural land (Funk *et al.* 2012).

Burkina Faso has a similar inter-annual variability of SPI3 and SPI6 (Figure 8) compared to Senegal. The period 1981–1999 was the driest for all time scales. In addition, the remaining period was characterized by relatively humid conditions even though there are dry years recorded. With regard to the last two timescales SPI12 and SPI24, there was still drought like Senegal. Bobadoye (2018) has shown negative SPI values over Senegal and Southern Burkina-Faso. This was very

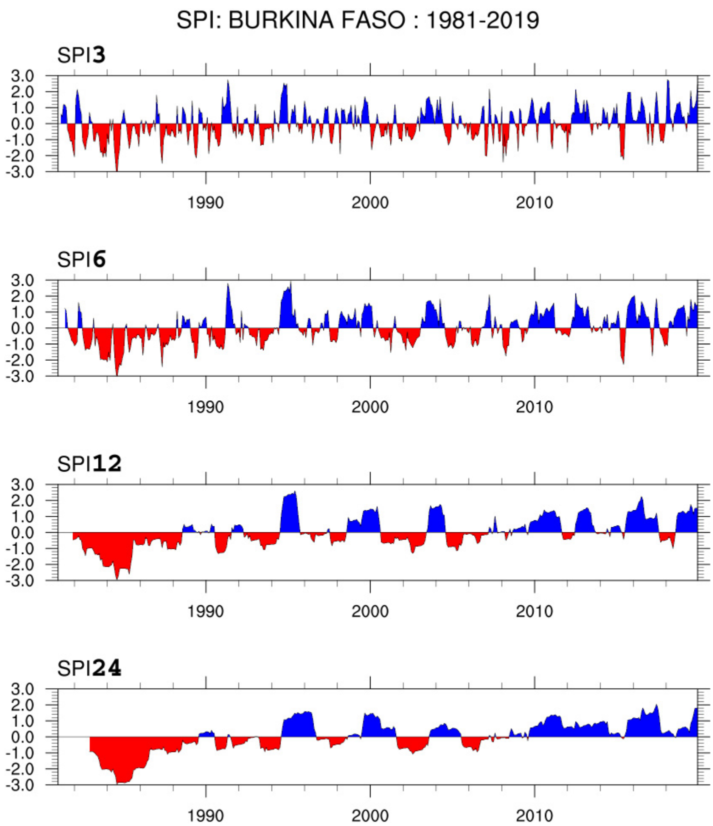


Figure 8. Standardized Precipitation Index Over Burkina Faso

persistent in Burkina Faso for the first two decades (1981–2000), even if we noted wet months around 1995–1997. From 2000 to 2018, there was a return of very wet conditions on the 12-to-24-month time scales. These positive anomalies could be due on the one hand to intense rains which can cause extreme events and on the other hand due to a long rainy period in this part of Africa. Furthermore, the number of flood events increased to five per year in the 2000s (Tazen *et al.* 2018).

The last period starting from 2010 to 2018 was wet specifically with SPI24. This reveals that there was enough rainfall for the recharge of ground water. In Tanzania (Figure 9), there was also an important inter-annual variation of SPI as shown in SPEI. The climate conditions were relatively normal in the first decade (1981–1990), moderate and even very intense in the second and third decade (1990–2000 and 2000–2010). In the last decade, the dry sequences are less frequent compared to wet episodes. The dry episodes are much more frequent than the wet sequences at the scale of 3 and 6 months. In other words, this means that

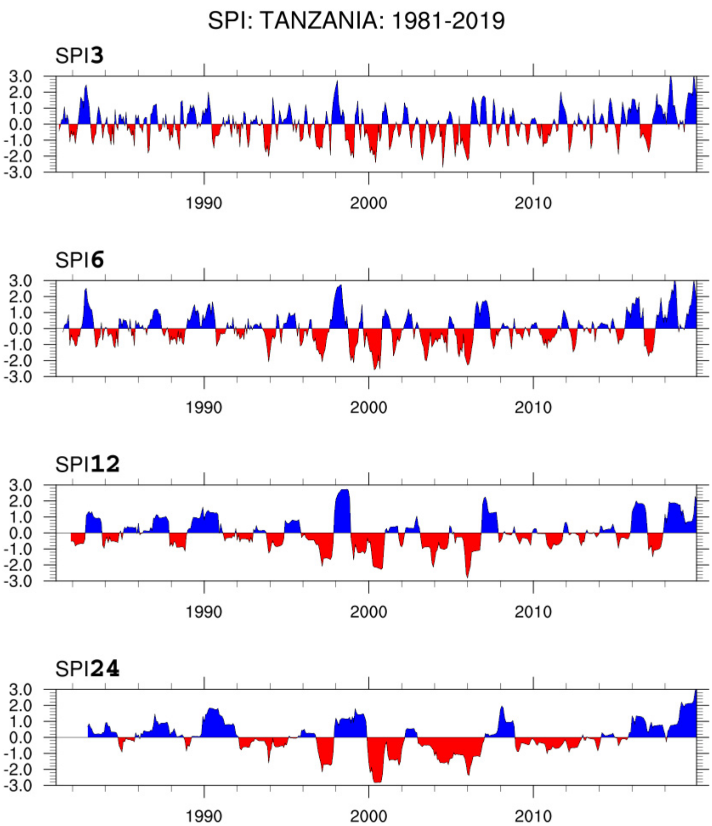


Figure 9. Standardized Precipitation Index Over Tanzania

the number of dry years is greater than the number of wet years within the same period. Severe dry years are interspersed with moderately wet years. Furthermore, for the scales 12 and 24 months, the highest magnitudes of wet conditions were obtained from the 12-month SPI in 1999 and the 24-month SPI in 2018, while the greatest water deficits were noted from the 12-month SPI in 2006 and the 24-month SPI between 2000 and 2001.

On the 12 and 24 monthly timescales, dry and extremely dry years were found between 2000 and 2008; and a period of normal drought (2009–2016). Moreover, the period 2016–2018 was very wet.

Malawi also exhibits similar inter-annual fluctuations (Figure 10) as shown in Tanzania. No significant change is detected in the severity of the drought when comparing the results for the different time scales (SPI3 and SPI6). The drought is considered normal for the first decade (SPI = 1) and after that, moderate to extreme droughts were found for the SPI3 and SPI6. For the 12- and 24-month time

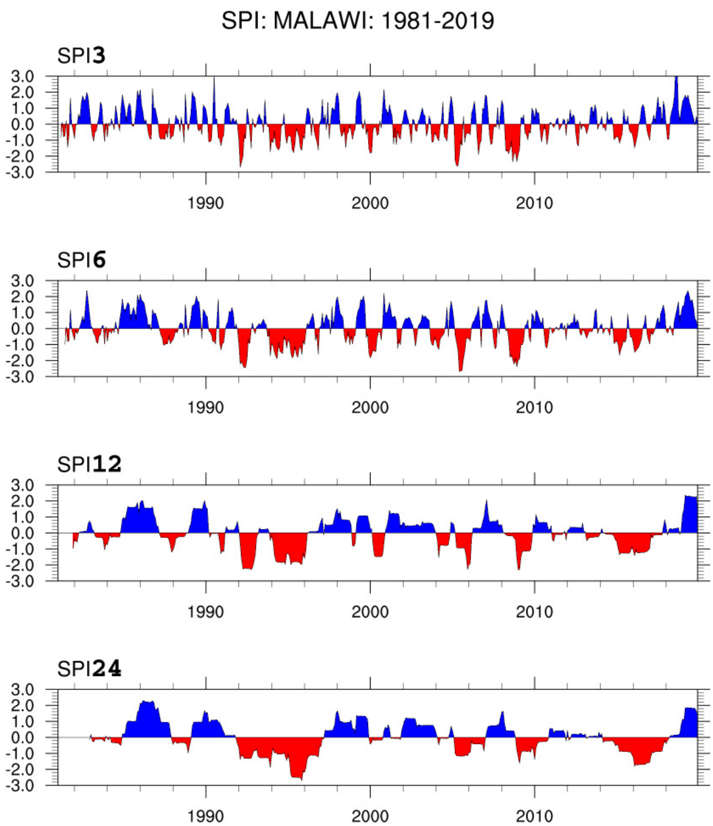


Figure 10. Standardized Precipitation Index Over Malawi

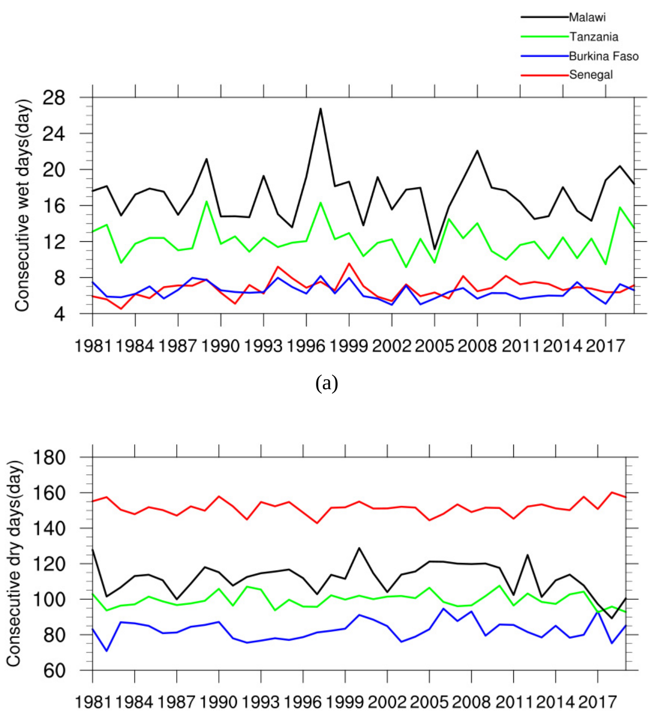
scales (SPI12 and SPI24), there is a clear appearance of dry and wet periods. Comparing the severity, magnitude and duration of droughts, we found well-marked drought spells (1992–1996 and 2014–2016).

These climate conditions have more negative impacts on women because they are already considered marginalized in socioeconomic, institutional, cultural engagements and political participation. It is further revealed that drought during the growing season decreases non-assistance consumption per capita by 5–12 percent, and excess rainfall at the onset of the growing season reduces food consumption by 1.8 percent%, while excess rainfall later in the growing season appears to increase consumption; vulnerability to poverty is generally higher than static poverty during a good weather year. In years of extreme droughts, such as 2016, the recorded poverty rates are higher than vulnerability. The Malawi vulnerability assessment committee (MVAC) indicated a total 6.5 million severely affected people in 24 of 28 districts, later revised upwards to 6.7 million (an estimated 40 percent of Malawi's total population) according to Baquie and Habtamu (2020).

3.4. *Inter-annual variations of extreme climate indices*

Figure 11 shows the inter-annual variations in the number of wet (CWD) and dry (CDD) days, respectively, from 1981 to 2018. These indices are characterized by considerable variations. From Figure 11(a), Malawi and Tanzania have more consecutive wet days (CWDs) than Senegal and Burkina Faso. The mean of the maximum number of CWDs in Senegal and Burkina Faso varies between 4 and 9 days, this could be due to their short rainy season. For Tanzania and Malawi, the number of CWDs range between 9–17 and 11–27 days, respectively. The large number of CWDs in Malawi and Tanzania can be explained by the length of their rainy season and also by the influence of the Indian monsoon.

As for dry periods (Figure 11(b)), the study of the inter-annual variations of CDD, reveals that among the considered countries, Senegal is the area which has more consecutive dry days (CCDs; it varies between 140 and 160 days). This large number of CCDs in Senegal could be explained by the fact that the rainy season has become very short compared to the long dry season according to Faye and Sané (2015). After Senegal, it follows Malawi and Tanzania which have the maximum number of CCDs which varies between 90 and 130 days. In this South-East African zone, the rainy days are frequent. Finally for Burkina Faso, we have the lowest values of the number of CCDs. In this part of the Sahel, the rainy season is long compared to Senegal, and there are a lot of wet days with weak amounts. The number of dry days is around 50–90 days during the rainy season. The south-west of Burkina Faso is known to record substantial rainy days.



(a)

(b)

Figure 11. Inter-Annual Variations of the Maximum Number of Consecutive Wet Days (CWD) and Dry Days (CDD)

These findings are consistent with the number of wet days, the rainfall intensity, and the total rainfall amount as shown in Figure 12. Malawi and Tanzania have more wet days and their total rainfall is very high compared to those countries from West African countries (Senegal and Burkina Faso). In addition, we have noticed that more wet days led to more annual cumulative precipitation. Senegal has fewer wet days followed by Burkina Faso; these countries record a low cumulative annual rainfall compared to the countries of the South–East. The lowest rainfall amounts were recorded in 1983 (400 mm in Senegal), in 1982–1983 (600 mm in Burkina Faso), in 2005 (750 mm in Malawi), and Tanzania (500 mm).

In Figure 13(a), the 95th percentile of wet days ranges between 18 and 33 mm in all countries.

As regards the daily rainfall intensity, Burkina shows the weakest rainfall intensities. The other three countries are in the same range with a daily average which is close to 10 mm/day. Tanzania and Senegal have the most intense rainfall

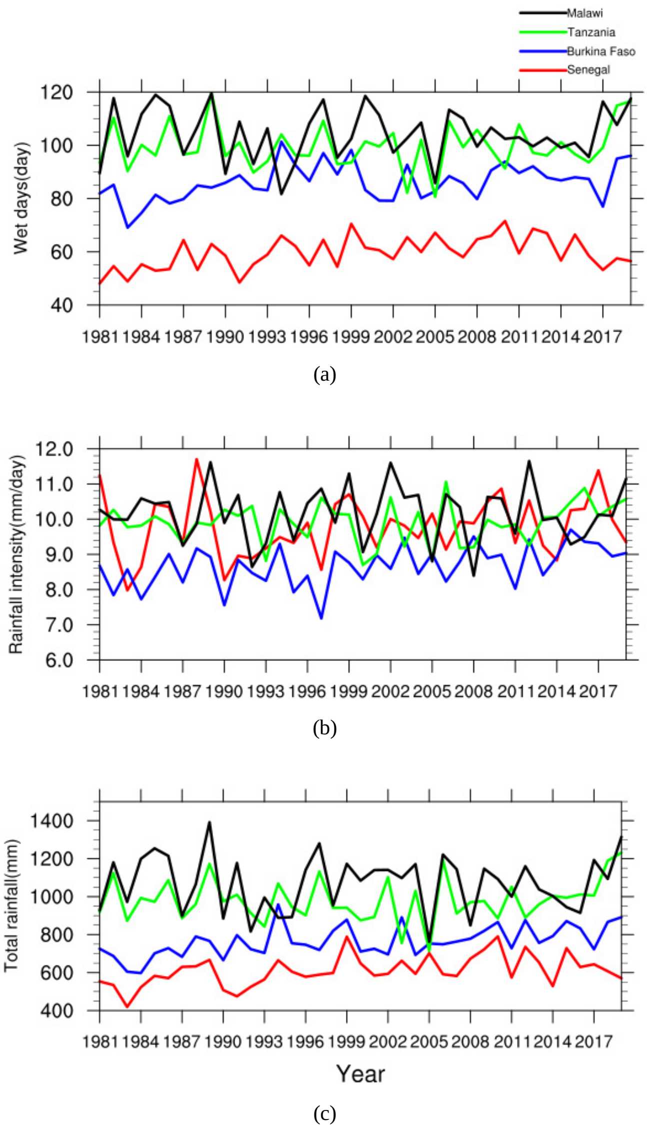
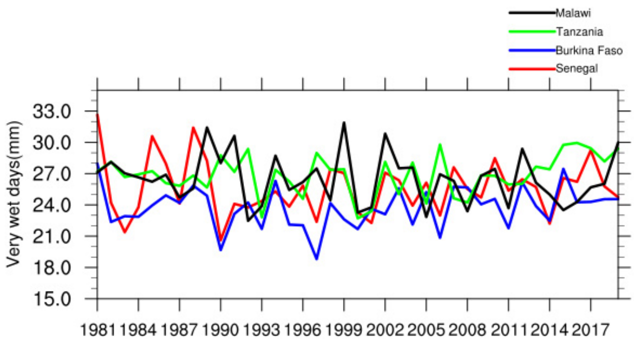


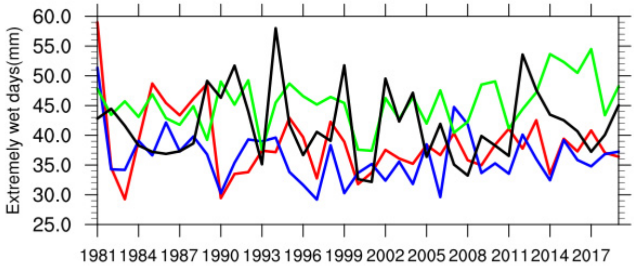
Figure 12. Interannual Variations of (a) Wet Days, (b) Rainfall Intensity, and (c) Total Rainfall

intensities of over 11 mm/day. The years 1989, 1999, 2002 and 2012 in Tanzania and 1981, 1988 and 2017 in Senegal are years of high rainfall intensity.

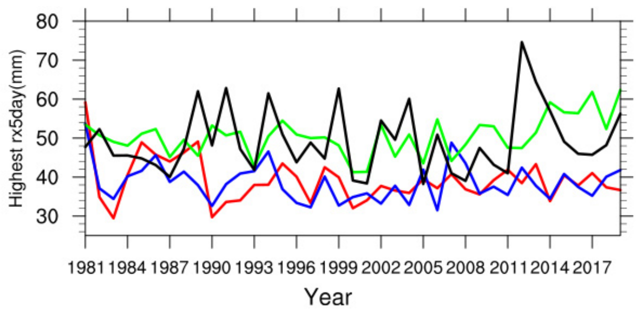
The greatest numbers of very wet days are recorded in 1981 for the countries of West Africa (Senegal and Burkina Faso), 1999 and 2014–2015, respectively, for Malawi and Tanzania. Figure 13(b) represents the annual variation of the extremely wet days (99th percentile) of sub-Saharan countries. In this figure, the



(a)



(b)



(c)

Figure 13. Inter-Annual Variations of Very Wet Days (95th), Extremely Wet Days (99th), and Total 5 Days Precipitations

minimum amount of extremely wet days is greater than 30 mm in these different countries.

During this period the highest values of extremely wet days are noted in 1981 in Senegal (59 mm), in 1994 in Malawi (58 mm), in 2017 in Tanzania (55 mm) and in 1981 in Burkina Faso (51 mm). In the general framework, we note that the countries of the South–East (Malawi and Tanzania) record the greatest extremely wet events than those of West Africa (Senegal and Burkina Faso). Burkina Faso and Senegal showed a decreasing trend while it increased in Malawi and Tanzania.

In this latest country, the increase in extreme climatic events is likely to pose significant damage to the agriculture sector, water sector and other socioeconomic livelihoods of people over many regions in Tanzania (Luhunga 2022). Moreover, Vischel *et al.* (2019) have shown a significant intensification of the Sahelian rainfall regime with more extreme events, larger size storms. The heavy amounts of rain could be at the origin of the adverse consequences like flooding (Sadio *et al.* 2020). Malawi has suffered with these extreme climate conditions. In its economy that is heavily dependent on the agricultural sector, not only are rural livelihoods, but non-farm and urban households are also vulnerable given the strong production and price linkages between agriculture and the rest of the economy. Malawi loses 1.7 percent of its gross domestic product on average every year due to the combined effects of droughts and floods (Pauw *et al.* 2010). Recent observable events indicate that the frequency of EWEs in Malawi has increased — more droughts and floods have occurred in the last two decade (2000 – 2020) than in the past three decades before (1970 – 2000). Up to 25 percent of the population has experienced drought seven or more times during the 2000–2010 period, with similar trends in flood affected populations. Climate change is exerting increasing stress on Malawi's ecosystems and infrastructure to the point of threatening to erode hard-won developmental gains (Government of Malawi 2018).

As for the accumulated 5 days precipitation (Figure 13(c)), we found a clear interannual variation of this rainfall index. The annual amount of this rainfall varies between 30 and 80 mm in all countries, except in Senegal, where we noticed an accumulation less than 30 mm in 1983. According to Figures 11(a) and 12(b), the year 1983 is the year that we noted respectively less CWDs and with a low daily intensity of rain in Senegal. We also observe the maximum cumulative 5 days of rain during the year 2012 in Malawi with a quantity greater than 70 mm because during this year, the daily intensity of the rain is close to 11.8 mm. Furthermore, we found a slight increase and a slight decrease in this index during the last five years in Tanzania and Burkina Faso, respectively.

3.5. *Trends analyses*

In Table 3, we show the *p*-values of the Mann–Kendall test at the 5 percent confidence level for SPEI in each country for the study period. The trend analysis is significant in all time scales of the SPEI in Burkina Faso, as for Senegal and Tanzania the results are significant under SPEI12 and SPEI 24, while in Malawi, it

Table 3. *p*-Values of SPEI (03, 06, 12, and 24)

Country	SPEI03	SPEI06	SPEI12	SPEI24
Tanzania	0.1387663	0.06942144	0.00287502	1.1543E−07
Malawi	0.06394297	0.21207959	0.19481508	0.00010869
Senegal	0.07367929	0.13762145	3.2581E−13	1.8955E−25
Burkina Faso	0.01238558	1.0305E−09	1.2034E−24	9.8683E−41

is only under SPEI 24. We underline that more bigger the time scale is, more the test is significant over all countries. Then, the changes are more pronounced in Burkina Faso and Senegal in general. It is also noticed that the first decades of the study period are characterized by decreasing SPEI trend toward negative values; and the last decades of the study period are characterized by slight increasing SPEI trend toward positive values. The long droughts conditions are "relative reduced" from 1981 to 2019. This can be due to the partial rainfall recovery observed during these last decades.

The trend analysis of heavy rainfall events (95th percentile) is given in Tables 4–7. The trend analysis is significant in June and October in Burkina Faso; while in Senegal, there is no significant monthly trend. This weak significance in West Africa (Burkina Faso and Senegal) can be due to the fact the time series of the data is marked by two different periods: 1981–2000 where there is a decreasing trend and from 2000 to 2018, and there is a light increase trend. The missing values in the tables (particularly in Senegal) are due to traces of rainfall. Furthermore, we found *p*-values below than 5 percent in Tanzania and Malawi during April and July, June and August, respectively. Moreover, we have also got similar results for

Table 4. Heavy Rainfall Statistics in Burkina Faso (95th Percentile)

Month	*p*-Value	Tau	Slope	SE_{mean}	Skewness	Kurtosis	*CV*	Min	Mean	Max
Jan	1.000	−0.022	−0.009	0.093	−0.049	2.004	0.18	1.16	1.64	2.03
Feb	0.084	0.203	0.018	0.147	1.650	5.988	0.33	1.40	2.70	5.59
Mar	0.425	0.090	0.025	0.244	0.623	3.229	0.32	2.19	4.71	9.01
Apr	0.208	−0.142	−0.031	0.302	0.475	2.778	0.27	3.68	6.85	11.25
May	0.809	0.028	0.010	0.641	2.212	9.394	0.34	6.59	11.86	28.55
Jun	0.004	−0.323	−0.111	0.578	1.500	5.580	0.18	14.31	20.10	32.16
Jul	1.000	−0.001	0.000	0.638	0.445	3.507	0.14	20.83	28.25	39.01
Aug	0.866	0.020	0.005	0.729	0.863	4.362	0.14	23.65	33.15	46.65
Sep	0.287	0.120	0.053	0.609	0.375	4.279	0.16	14.88	23.28	35.36
Oct	0.047	0.223	0.074	0.420	0.539	2.574	0.26	5.33	9.94	15.87
Nov	0.183	0.150	0.020	0.201	0.648	2.906	0.33	1.95	3.78	7.34
Dec	0.833	−0.028	−0.002	0.095	1.399	5.441	0.29	1.11	1.88	3.71

Table 5. Heavy Rainfall Statistics in Senegal (95th Percentile)

Month	*p*-Value	Tau	Slope	SE_{mean}	Skewness	Kurtosis	*CV*	Min	Mean	Max
Jan										
Feb										
Mar										
Apr	0.652	0.074	0.006	0.168	1.127	3.063	0.35	1.38	2.23	4.02
May	0.904	−0.015	−0.006	0.458	1.079	4.012	0.39	2.75	7.38	15.05
Jun	0.217	−0.139	−0.067	0.666	1.471	7.633	0.26	7.95	15.79	32.28
Jul	0.717	−0.042	−0.030	0.618	−0.194	2.117	0.16	17.11	24.78	32.34
Aug	0.904	−0.015	−0.009	0.976	2.031	9.103	0.19	24.13	32.25	57.78
Sep	0.663	0.050	0.035	0.707	0.477	2.853	0.17	17.83	25.89	37.26
Oct	0.468	0.082	0.029	0.522	0.685	3.273	0.31	4.88	10.53	18.36
Nov	0.392	0.113	0.009	0.109	1.187	3.493	0.31	1.28	1.94	3.51
Dec	0.133	−0.524	−0.131	0.122	0.144	1.677	0.23	1.04	1.42	1.90

the extremely wet day events (99th percentile) in Burkina Faso (Table S1) where the trends were significant in two months (June–October). This finding is similar with the results of De Longueville *et al.* (2016) who suggested that the changes in rainfall patterns have remained moderate, particularly concerning of the occurrence of extreme events from 1950 to 2013 in Burkina Faso. In Senegal, there are no significant trends in all months (Table S2) in the whole period. This can be explained by the mix of wet periods, dry periods, intermediate and recovery periods. The dry climatic phase was extended over almost 30 years; due to the geographical position of this country in relation to the West African Monsoon

Table 6. Heavy Rainfall Statistics in Tanzania (95th Percentile)

Month	*p*-Value	Tau	Slope	SE_{mean}	Skewness	Kurtosis	*CV*	Min	Mean	Max
Jan	0.236	−0.134	−0.053	0.545	0.341	3.319	0.157	14.77	21.66	30.82
Feb	0.681	−0.047	−0.021	0.454	0.050	3.014	0.143	13.89	19.81	26.50
Mar	0.345	−0.107	−0.051	0.665	1.944	8.828	0.159	20.56	26.08	43.35
Apr	0.002	0.341	0.265	0.909	−0.060	2.593	0.147	25.66	38.66	49.73
May	0.904	−0.015	−0.016	0.978	−0.013	2.702	0.281	8.94	21.75	34.89
Jun	0.425	−0.090	−0.013	0.158	0.017	2.553	0.138	5.38	7.15	9.36
Jul	0.011	−0.285	−0.030	0.154	2.118	9.984	0.169	4.46	5.71	9.88
Aug	0.439	−0.088	−0.010	0.133	0.253	2.472	0.129	4.96	6.42	8.20
Sep	1.000	0.001	0.001	0.248	1.128	4.956	0.213	4.81	7.27	12.57
Oct	0.961	0.007	0.002	0.546	0.787	2.694	0.269	8.34	12.67	20.46
Nov	0.468	0.082	0.077	0.956	−0.130	2.188	0.258	10.58	23.18	34.12
Dec	0.981	0.004	0.003	0.732	−0.756	3.421	0.174	13.81	26.32	35.61

Table 7. Heavy Rainfall Statistics in Malawi (95th Percentile)

Month	*p*-Value	Tau	Slope	SE_{mean}	Skewness	Kurtosis	*CV*	Min	Mean	Max
Jan	0.226	−0.136	−0.066	0.664	0.640	3.301	0.169	16.68	24.48	36.28
Feb	0.116	−0.177	−0.087	0.650	−0.538	2.914	0.158	15.38	25.76	32.87
Mar	0.942	0.009	0.015	1.114	1.072	3.265	0.247	19.15	28.15	46.21
Apr	0.077	0.198	0.212	1.781	1.298	4.933	0.336	19.04	33.06	70.57
May	0.595	−0.061	−0.025	0.547	2.435	10.542	0.408	4.56	8.39	23.27
Jun	0.015	−0.274	−0.030	0.123	0.858	3.286	0.160	3.75	4.79	7.08
Jul	0.772	−0.034	−0.004	0.188	2.571	9.740	0.258	3.37	4.55	8.91
Aug	0.006	−0.306	−0.021	0.106	0.837	2.853	0.173	2.92	3.81	5.45
Sep	0.545	−0.069	−0.009	0.242	2.594	11.324	0.362	2.62	4.17	10.84
Oct	0.287	−0.120	−0.058	0.553	0.655	2.301	0.410	3.78	8.43	16.24
Nov	0.514	−0.074	−0.047	0.772	0.349	2.757	0.283	6.07	17.01	26.82
Dec	0.110	−0.179	−0.101	0.840	−0.091	5.824	0.217	7.20	24.13	40.09

movement to the northern areas of Sahelian Africa (Nouaceur and Murarescu 2020). Moreover, we found significant trends in Tanzania (April and July) and Malawi (February, June, and August) as shown in tables (Tables S3 and S4). The empty boxes in tables, indicate that there are no values which allow to calculate the indices.

As for maximum number of CDD, there is an increase in dry periods from June to July in Burkina Faso (Table 8); while in Senegal, they are found in August and September (Table 9). These dry conditions usually cause agricultural damages in rural areas; because in these west African countries, agriculture is mainly based on rainfall, and these months are critical rainy months for crops. In contrast to

Table 8. CDD Statistics in Burkina Faso

Month	*p*-Value	Tau	Slope	SEmean	Skewness	Kurtosis	*CV*	Min	Mean	Max
Jan	0.536	−0.071	0.000	0.022	−2.013	6.359	0.00	30.45	30.90	31.00
Feb	0.699	−0.045	−0.009	0.240	−0.271	2.475	0.06	23.32	26.40	28.97
Mar	0.276	0.123	0.059	0.503	0.052	2.198	0.14	16.18	22.58	29.04
Apr	0.468	−0.082	−0.051	0.530	0.629	3.131	0.23	9.38	14.17	23.86
May	0.161	−0.158	−0.045	0.335	0.889	3.285	0.28	4.56	7.52	13.07
Jun	0.001	−0.382	−0.045	0.193	0.919	3.358	0.23	3.24	5.22	8.22
Jul	0.040	−0.231	−0.020	0.099	0.253	2.551	0.16	2.79	3.89	5.37
Aug	0.073	−0.201	−0.015	0.103	0.995	4.413	0.18	2.56	3.47	5.40
Sep	0.077	−0.198	−0.021	0.173	1.543	7.479	0.23	2.93	4.65	8.91
Oct	0.266	−0.126	−0.077	0.704	0.315	2.367	0.33	6.21	13.51	24.19
Nov	0.753	0.036	0.003	0.233	−0.171	1.970	0.05	24.65	27.39	29.75
Dec	0.717	0.042	0.004	0.160	−2.088	8.021	0.03	26.05	30.03	31.00

Table 9. CDD Statistics in Senegal

Month	*p*-Value	Tau	Slope	SEmean	Skewness	Kurtosis	*CV*	Min	Mean	Max
Jan	0.831	−0.030	0.000	0.003	−3.923	18.928	0.00	30.90	30.99	31.00
Feb	0.543	0.076	0.000	0.067	1.263	2.691	0.01	27.80	28.20	29.00
Mar	0.351	−0.131	0.000	0.000	−6.002	37.026	0.00	30.99	31.00	31.00
Apr	0.561	0.066	0.001	0.045	−1.705	5.892	0.01	28.75	29.75	30.00
May	0.681	0.047	0.013	0.293	0.111	2.382	0.07	21.85	25.78	29.39
Jun	0.646	0.053	0.031	0.503	−0.068	2.245	0.26	6.10	12.32	18.13
Jul	0.809	−0.028	−0.009	0.254	0.188	2.281	0.24	3.36	6.67	10.10
Aug	0.010	−0.290	−0.039	0.238	1.008	3.501	0.30	2.29	4.99	8.96
Sep	0.012	−0.282	−0.036	0.177	0.794	5.038	0.23	2.40	4.86	8.45
Oct	0.073	−0.201	−0.083	0.496	0.600	2.714	0.26	7.44	12.12	19.90
Nov	0.885	−0.018	−0.001	0.140	−1.390	5.319	0.03	25.80	28.89	29.94
Dec	0.470	0.084	0.000	0.009	−2.254	9.539	0.00	30.72	30.96	31.00

southern countries (Tanzania and Malawi), where there are no significant trends for dry spells (Tables 10 and 11). This can be explained by the fact that rainfall trend is not homogeneous across the region; some areas are experiencing a slight decreasing rainfall trend, while other areas are experiencing a slight increasing rainfall trend (Kijazi *et al.* 2021).

In addition, Burkina Faso has experienced significant rainfall intensity from July to October (Table S5 supporting information). The high rainfall intensity has led to flood events which have caused considerable damage to all sectors: infrastructures, health, agriculture, and so forth (Tazen *et al.* 2018). They underlined that several died, 670 classrooms were destroyed, the main water purification plants for the city were rendered inoperable, and around 150,000 people were affected during the 2009 flood in Burkina Faso.

As for Senegal, there is no significant trend in rainfall intensity by considering the whole period 1981–2019 (Table S6 supporting information); but the last decade of this period is wetter than the previous decades (not shown here). Several studies over West Africa have shown a kind of "rainfall recovery" since the years 2000. Nouaceur and Murarescu (2020) found wet cycle, drought periods, intermediate and rain resumption from 1957 to 2014 over West Africa. After the year 2000, several West African countries have faced severe floods events such as that in September 2009, where Burkina Faso and Senegal have faced catastrophic floods. In Senegal, flood shocks defined as annual rainfall higher than one standard deviation from the 50-year average are associated with a 35 percent decrease in total and food per-capita consumption and 17 percent point increase in extreme poverty. In Burkina Faso, rainfall variability is significantly associated with migration, particularly for men, who are likely to move from areas with poor rainfall to other

Table 10. CDD Statistics in Tanzania

Month	*p*-Value	Tau	Slope	SEmean	Skewness	Kurtosis	*CV*	Min	Mean	Max
Jan	0.885	−0.018	−0.006	0.349	0.088	1.963	0.321	2.83	6.79	11.23
Feb	0.056	0.215	0.053	0.309	0.408	2.609	0.296	3.45	6.51	11.01
Mar	0.276	−0.123	−0.030	0.353	0.371	1.996	0.334	2.70	6.60	11.03
Apr	0.439	0.088	0.023	0.346	0.587	2.669	0.221	6.10	9.81	14.60
May	0.298	−0.117	−0.035	0.333	0.121	2.070	0.135	11.95	15.37	19.42
Jun	0.358	−0.104	−0.013	0.153	0.134	3.496	0.038	22.34	24.85	27.32
Jul	0.561	0.066	0.003	0.092	−0.180	2.422	0.022	24.76	26.17	27.18
Aug	0.809	−0.028	−0.004	0.136	0.075	3.468	0.034	23.43	25.26	27.63
Sep	0.246	−0.131	−0.015	0.156	0.209	2.309	0.044	20.33	22.11	24.32
Oct	0.961	0.007	0.000	0.316	0.236	3.403	0.120	12.36	16.47	22.24
Nov	0.904	−0.015	−0.007	0.351	0.343	2.886	0.200	7.01	10.97	17.08
Dec	0.699	−0.045	−0.014	0.405	0.566	3.179	0.346	3.29	7.30	14.05

rural areas that are wetter (Henry *et al.* 2004). Gardens cultivated by women's groups are granted by their husbands or relatives male. Normally these lands are of poorer quality, and they are lands that have been left fallow and are less profitable. In addition, they do not have the strength required to use soil conservation techniques such as stony cords, implying that their land is most damaged during floods or heavy rains. Climate change aggravates the degradation of soils and cultivated land, and the women's plots are often the most affected. Indeed, they often cultivate a personal plot of land of lower quality (quality of the land, access to water, etc.). They do not benefit from the necessary equipment and inputs (chemical fertilizers, compost and improved seeds) still used on the family farm. In

Table 11. CDD Statistics in Malawi

Month	P-Value	Tau	Slope	S.E. Mean	Skewness	Kurtosis	CV	Min	Mean	Max
Jan	0.168	−0.155	−0.026	0.169	0.660	3.235	0.34	1.38	3.08	6.11
Feb	0.483	0.080	0.015	0.296	1.148	3.691	0.45	1.68	4.09	9.70
Mar	0.753	0.036	0.011	0.375	1.351	4.600	0.38	2.76	6.24	12.93
Apr	0.790	−0.031	−0.017	0.611	0.471	3.090	0.27	6.79	14.02	24.18
May	0.246	−0.131	−0.048	0.396	0.580	3.573	0.14	13.50	18.22	25.17
Jun	0.663	−0.050	−0.006	0.129	−1.535	5.827	0.03	23.55	26.36	27.42
Jul	0.298	−0.117	−0.020	0.186	−0.013	2.301	0.04	23.41	26.11	28.38
Aug	0.217	−0.139	−0.031	0.261	−0.580	3.414	0.06	22.09	26.90	29.61
Sep	0.110	−0.179	−0.023	0.172	−1.000	4.515	0.04	24.00	27.35	29.17
Oct	0.371	0.101	0.037	0.478	0.102	2.257	0.15	14.63	20.50	27.18
Nov	0.753	0.036	0.017	0.672	0.210	2.435	0.34	3.40	12.23	22.39
Dec	0.287	−0.120	−0.033	0.320	0.350	2.293	0.40	1.92	5.05	9.41

addition, the techniques such as stony cords, which require great physical strength, do not apply to women's plots. Therefore, the heavy rain and runoff wash away much of the vegetation cover (Romero *et al.* 2011). Tanzania recorded increased rainfall intensity during April and July significantly. As for Malawi, its only in July where we found significant rainfall intensity (Tables S7 and S8 supporting information). These findings reveal that these sub-Saharan countries are likely to experience significant challenges from climate-related stresses about the future climate condition and socioeconomic livelihoods of people (Luhunga *et al.* 2020).

4. Conclusion

The study aimed to examine the extreme precipitation over four sub-Saharan countries from 1981 to 2018 using CHIRPS datasets. Burkina Faso and Senegal, which have a tropical and Sahelian climate, present a unimodal appearance with the maximum precipitation recorded in August with the highest rainfall peak in Burkina Faso. The main rainy season is found in June, July, August and September (JJASO). Regarding the seasonal cycle of rainfall in Malawi and Tanzania, which have a variable tropical (subtropical) and equatorial humid (temperate tropical) climate, respectively, presents a bimodal pattern of precipitation. It presents an opposite signal when compared to West African countries. All these countries have experienced meteorological and hydrological droughts which may have significantly impacted the socioeconomic activities of rural populations. Further works are recommended to investigate these extremes in the coming decades in order to analyze their potential impacts by using climate change scenarios data.

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Supplemental Materials

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References

Anyamba, A, Small JL, Britch SC, Tucker CJ, Pak EW, Reynolds CA and Linthicum KJ (2014). Recent weather extremes and impacts on agricultural production and vector-borne disease outbreak patterns. *PLoS ONE*, 9(3): 23–24.

Azzarri, C and Signorelli S (2020). Climate and poverty in Africa South of the Sahara. *World Development*, 125: 104691.

Bae, J (2020). Weather impact, migration factors, intention using machine learning algorithms. Discussion paper: 2020/34.

Baquie, S and Habtamu, F (2020). Vulnerability to poverty following extreme weather events in Malawi. Policy research working paper: No. 9435. World Bank, Washington, DC.

Bauer, T, Ingram V, De Jong W and Arts B (2018). The socio-economic impact of extreme precipitation and flooding on forest livelihoods: Evidence from the Bolivian Amazon. *International Forestry Review*, 20(3): 314–331.

Blais, A (2011). Study of the impact of the main modes of climate variability in Africa over the last thirty years through remote sensing data of photosynthetic activity of vegetation, Host laboratory: UMR 5210 CNRS, Center de Research in Climatology, University of Burgundy.

Bobadoye, A (2018). Assessing vulnerability to climate change and the impact of drought on vegetation productivity in West Africa. PhD Climate Change and Adaptation, University of Nairobi.

Cissé, S, Eymard L, Ottlé C, Ndione JA, Gaye AT and Pinsard F (2016). Rainfall intraseasonal variability and vegetation growth in the Ferlo Basin (Senegal). *Remote Sensing*, 8: 66.

De Longueville, F, Hountondji YC, Kindo I, Gemenne F and Ozer P (2016). Long-term analysis of rainfall and temperature data in Burkina Faso (1950–2013). *International Journal of Climatology*, 36: 4393–4405.

European Commission (2020). Copernicus European Drought Observatory (EDO). https://edo.jrc.ec.europa.eu/documents/factsheets/factsheet_spi.pdf [January 8, 2022].

FAO (2016). The State of Food and Agriculture: Climate Change, Agriculture and Food Security. Rome: FAO.

Faye, C and Sané T (2015). Climate change in the Casamance watershed: Climate change and trends, impacts on water resources and adaptation strategies, in Waters and Societies Facing Climate Change in the Casamance Basin. The Harmatan, L'HARMATTAN, 2015 5–7, rue de l'École-Polytechnique, 75005 Paris.

Funk, CC, Peterson PJ, Landsfeld, MF, Pedreros DH, Verdin JP, Rowland JD, Romero BE, Husak GJ, Michaelsen JC and Verdin AP (2014). A quasi-global precipitation time series for drought monitoring. U. S. Geological Survey Data Series 832. http://dx.doi.org/110.3133/ds832.

Funk, C *et al*. (2015). The climate hazards infrared precipitation with stations — A new environmental record for monitoring extremes. *Scientific Data*, 2: 150066.

Glad, A (2010). Weather and hydrological conditions leading to severe drought in Malawi. Master's thesis, University of Oslo, Problemveien 7, 0315 Oslo, Norway.

Government of Malawi (2018). National resilience strategy 2018–2030: Breaking the cycle of food insecurity in Malawi. Lilongwe, Malawi: Department of Disaster Management Affairs.

Harris, I *et al*. (2020). Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Scientific Data*, 7: 109.

Henry, S, Schoumaker B and Beauchemin C (2004). The impact of rainfall on the first out-migration: A multi-level event-history analysis in Burkina Faso. *Population and Environment*, 25(5): 423–460.

IPCC (2012). *Changes in Climate Extremes and their Impacts on the Natural Physical Environment*, Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M and Midgley PM (eds.), Cambridge University Press, The Edinburgh Building, Shaftesbury Road, Cambridge CB2 8RU, England, p. 582.

IPCC (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability: Part B: Regional Aspects*, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Barros VR, Field CB, Dokken, MD Mastrandrea, KJ Mach, TE Bilir DJ, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR and White LL (eds.), Chapter 21: Regional Context, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 688.

IPCC (2019). Global warming of 1.5°C: An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, Masson-Delmotte, V, Zhai P, Pörtner H-O, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, Connors S, Matthews JBR, Chen Y, Zhou X, Gomis MI, Lonnoy E, Maycock T, Tignor M and Waterfield T (eds.).

Kijazi, AL, Chang'a LB, Muruke WT, Ndaki MM, Babyegeya MM, Kisama SY and Juma OH (2021). Best practices and lessons learned in the implementation of global framework for climate services — Adaptation programme in Africa: Tanzania-experience. *Atmospheric and Climate Sciences*, 11: 749–766.

Kotir, JH (2011). Climate change and variability in sub-Saharan Africa: A review of current and future trends and impacts on agriculture and food security. *Environment, Development and Sustainability*, 13(3): 587–605.

Luhunga, PM and Songoro AE (2020). Analysis of climate change and extreme climatic events in the lake Victoria region of Tanzania. *Frontiers in Climate*, 2: 559584.

Luhunga, PM (2022). Projection of extreme climatic events related to frequency over different regions of Tanzania. *Journal of Water and Climate Change*, 13(3): 1297–1312.

Maulidi, F and Kasiya S (2019). Analytical work to develop a gender responsive conceptual framework and guidelines for the efficient use of ICTs in scaling-up initiative. Lilongwe, Malawi.

Mbaye, ML, Sylla MB and Tall M (2019). Impacts of 1.5 and 2.0°C global warming on water balance components over Senegal in west Africa. *Atmosphere*, 10(11): 712.

McCarthy, N, Kilic T, Brubaker J, Murray S and de la Fuente A (2021). Droughts and floods in Malawi   World Bank. Environment and Development Economics 2021-01-25 CC BY-NC-ND 3.0 IGO. http://dx.doi.org/10.1017/S1355770X20000455.

Narcise, KP, Bruno B, Paulin O, André K, Léopold S and Amadé O (2019). Perceptions du changement climatique, impacts environnementaux et stratégies endogènes d'adaptation par les producteurs du Centre-nord du Burkina Faso. *VertigO*, 19(1): 28. DOI: https://doi.org/10.4000/vertigo.24637.

Nouaceur, Z and Muraresc O (2020). Rainfall variability and trend analysis of rainfall in west Africa (Senegal, Mauritania, Burkina Faso). *Water*, 12(6): 1754.

Pauw, K, Thurlow J and van Seventer D (2010). Droughts and floods in Malawi: Assessing the economy wide effects. International Food Policy Research Institute (IFPRI). http://www.ifpri.org/publications/results/taxonomy%3A468.

Peng, J, Dadson S, Hirpa F, Dyer E, Lees T, Miralles DG, Vicente-Serrano SM and Funk C (2020). A pan-African high-resolution drought index dataset. *Earth System Science Data*, 12: 753–769.

Romero, YL *et al*. (2011). A relation between extreme daily precipitation and extreme short-term precipitation. *Climatic Change*, 106: 393–405.

Sadio, PM, Mbaye ML, Diatta S and Sylla MB (2020). Hydroclimatic variability and change in the Casamance river basin (Senegal). *La Houille Blanche*, 6: 89–96.

Sylla, MB, Faye A, Giorgi F, Diedhiou A and Kunstmann H (2018). Projected heat stress under 1.5°C and 2°C global warming scenarios creates unprecedented discomfort for humans in west Africa. *Earth's Future*, 6(7): 1029–1044.

Tazen, F, Diarra A, Kabore FWR, Ibrahim B, Traoré B, Traoré K and Karambiri K (2018). Trends in flood events and their relationship to extreme rainfallin an urban area of Sahelian west Africa: The case study of Ouagadougou, Burkina Faso. *Flood Risk Management*, 12: e12507.

Travis, WR (2014). Weather and climate extremes: Pacemakers of adaptation? *Weather and Climate Extremes*, 5(1): 29–39.

Tumaini, E (2009). Research project submitted in fulfilment of the requirements for the post graduate diploma in meteorology, Department of Meteorology, University of Nairobi School of Physical Science.

USAID (2017). Climate risks in food for peace geographies: Burkina Faso. Climate Risk Profile.

Vincent, K, Dougill AJ, Mkwambisi DD, Cull T, Stringer LC and Chanika D (2014). Analysis of existing weather and climate information for Malawi. Report, final version.

Vischel, T, Panthou G, Peyrillé P, Roehrig R, Quantin G, Lebel T, Wilcox C, Beucher F and Budiarti M (2019). Precipitation extremes in the West African Sahel: Recent evolution and physical mechanisms. In Venugopal, V, Sukhatme J, Murtugudde R and Roca R (eds.). Tropical Extremes: Natural Variability and Trends. Amsterdam: Elsevier, pp. 95–138.

Vogel, C, Steynor A and Manyuchi A (2019). Climate services in Africa: Re-imagining an inclusive, robust and sustainable service. *Climate Services*, 15: 100107.

WMO (2020). State of climate services 2020 report: Move from early warnings to early action. https://public.wmo.int/en/media/press-release/state-of-climate-services-2020-report-move-from-early-warnings-early-action?s=03 [October 13, 2020].