Trends and variability of extreme climate indices in the Boucle du Mouhoun (Burkina Faso)

Songanaba ROUAMBA[1], Joseph YAMÉOGO[1*], Korotimi SANOU[1], Richard ZONGO[1] and Isidore Pawendkisgou YANOGO[1]
[1]University of Norbert ZONGO, Department of Geography, Koudougou, Burkina Faso

*Correspondence to: Joseph YAMÉOGO. E-mail: josephyameogo10@gmail.com.

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ABSTRACT: The main objective of this study is to analyse the trends and variability of extreme weather indices in the Boucle du Mouhoun region of Burkina Faso. To this end, meteorological data for the period 1991 to 2021 were obtained from the National Meteorological Agency of Burkina Faso. These meteorological data (rainfall, temperature) were integrated into the R-climdex software to generate extreme climate indices (rainfall, temperature). These data were then analysed by means of homogeneity tests (Pettitt and von Neumann ratio), trend tests (Mann-Kendall, Sen's slope) and the frequency of the return period of the extreme climate indices using XLSTAT (Statistical Software for Excel) 2023. The study shows that the precipitation indices are overall homogeneous (p-value ≥ 0.05) and that there is no significance (p-value ≥ 0.05) for the trend of the extreme precipitation indices from 1991 to 2021. Conversely, the temperature indices are not homogeneous (p-value ≤ 0.05), and a significant upward trend was observed for the maximum temperature index (p-value ≤ 0.05) and the minimum temperature index (p-value ≤ 0.05). The extreme climate indices also show considerable variability over the period 1991-2021. Moreover, the return periods for the occurrence of extreme climate indices are shorter, ranging from 0 to 10 years. It is therefore important that regional authorities in the area develop strategies to consolidate water infrastructures and provide financial support to producers, especially banana producers.

KEY WORDS: variability, climatic indices, trends, return periods, extreme climatic indices.

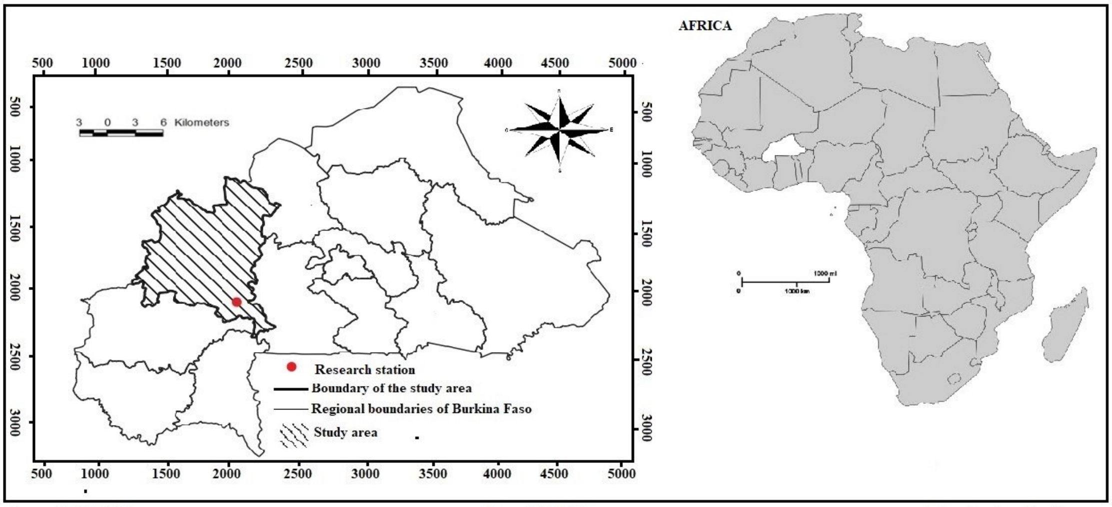
1. Introduction

Many countries around the world have recently experienced an increase in hydroclimatic extremes such as droughts, floods and heat waves (Wang et al., 2022). The impacts of climate change are more pronounced in developing countries due to lower incomes and adaptive capacities (Georgopoulou et al., 2017; Brouillet and Sultan, 2023). (Asrat and Simane, 2018) also note that farmers, in particular, may find it more difficult to adapt to climate change. In sub-Saharan Africa, climate variability has increased in recent decades (Mairura et al., 2021). It is characterised by widespread warming, a resumption of monsoon rains and an increase in the frequency of climatic extremes (Sultan and Gaetani, 2016). The observed effects of extreme weather events have increased in recent years (Ayanlade et al., 2022). Since the 1990s, there has been an increase in hydroclimatic events, with a mixture of intense precipitation, long periods of drought and sequences of floods (Salack et al., 2018). Extreme rainfall events have become more frequent and intense in the central Sahel of West Africa (Panthou et al., 2014). This situation has a negative impact on agricultural production. Indeed, the increase in extreme climate events has reduced millet production by 10-20% and sorghum production by 5-15% in West Africa (Sultan et al., 2019). During the dry season, irrigated rice yields in West Africa would fall by 45%. With adaptation, the reduction would be much smaller, around 15% (Van Oort and Zwar, 2017).

Burkina Faso, one of the countries in West Africa, is faced with the occurrence of extreme hydroclimatic events (Yanogo and Yameogo, 2023; Sougué et al., 2023). These events cause serious damage to agricultural production and hydraulic infrastructures (Bossa et al., 2020). Faced with this situation, many rural inhabitants are turning to banana production around small and large dams. The Boucle du Mouhoun region of Burkina Faso has thus become a banana-producing area. In the various villages of the region, particularly Lapara in the Boromo commune, the sale of bananas structures the daily life of the rural population (Yaméogo et al., 2022). Last year, heavy rains caused the Petit Balè dam to burst. This led to flooding. However, few studies have looked at extreme weather events in this region. However, a global study (Galberto et al., 2016) suggests that the recurrence of extreme rainfall has an impact on banana production. Small-scale studies on this topic are not widely used. The main objective of this study is to analyze the trends and variability of extreme weather indices in the Boucle du Mouhoun region of Burkina Faso.

2. Study area

The study area is the Boucle du Mouhoun region in the western part of Burkina Faso (Figure 1).



Source : BNDT, 2014 Date : 12/07/2023 Author : Yaméogo Joseph

Figure 1 Localization of study site.

The Boucle du Mouhoun region is located in the Sudano-Sahelian zone, but with three (3) climatic variants (MEEVCC, 2021). In the north of the region, the Sudano-Sahelian sector dominates, with average annual rainfall of 500 to 700 mm. In the centre, the northern Sudanian sector, with average annual rainfall of 700 to 900 mm. In the south, the Southern Sudan sector, with average annual rainfall of 1,000 to 1,400 mm. The synoptic station is located in the North Sudan sector.

3. Data and Methods

3.1. Climatic data

The National Meteorological Agency of Burkina Faso (NMA) was used to collect the rainfall data. The synoptic station of Boromo in the province of Balè, in the Boucle du Mouhoun region of Burkina Faso was used for the study, as it is located in the commune of Boromo. The period considered for the study is from 1991 to 2021, and the rainfall data collected is on a monthly time step. The table below shows the characteristics of the study station.

Table 1 Station characteristics used in this study.

Name of the station	Type de station	Type of data collected	Latitude	Longitude	Period of available data
Boromo	Synoptic	Monthly rainfall ; Monthly temperature	11.75	-2.9333	1991-2021

Source: National Meteorological Agency of Burkina Faso, Boromo, 1991-2021

In order to analyze extreme precipitation events, it is necessary to calculate extreme climate indices. The indices used are those recommended by the World Meteorological Organization's (WMO) Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) (Alexander et al., 2019). 27 indices were listed and calculated using RClimDex (Vincent et al., 2011), which can be downloaded from the website http://etccdi.pacificclimate.org/software.shtml.

These indices are widely used to study extreme events and have been successfully used by several authors in their work analyzing precipitation and temperature extremes in the West African sub-region (Ly et al., 2013; Diedhiou et al., 2018; Yarou et al., 2019), in Asia (Mondal et al., 2022; Zhang et al., 2022), in Europe (Malinović-Milićević et al., 2018; Popov et al., 2019; Gnjato et al., 2021); America (Akinsanola et al., 2020; Ceron et al., 2021; Lagos-Zúñiga et al., 2022). In order to take into account, the sensitivity of extreme climatic events affecting bananas in this study, the indices shown in Table 2 have been used.

Table 2 Extreme rainfall and temperature indices.

Element	Index	Descriptive Name	Definition	Unit
Temperature	TXx	Annual maximum temperature	Annual mean of TX	°C
	TXn	Annual minimum temperature	Annual mean of TN	°C
Precipitation	PRCPTOT	Annual precipitation	Annual total precipitation	mm
	SDII	Simple daily intensity index	Annual precipitation divided by number of wet days	mm/day
	CWD	Consecutive wet days	Maximum number of consecutive wet days (RR ≥ 1 mm)	days
	PXJA	Daily maximum rainfall	Maximum daily precipitation	mm
	R95p	Very wet days	Annual total PRCPTOT when RR>95th percentile	mm

Source: Vincent et al., 2011

3.2. Methods

3.2.1. Trend analysis methods

The Mann-Kendall (MK) test and Sen's slope estimator, linear regression and coefficient of determination (r^2) were used to examine trends in extreme climate indices. The Mann-Kendall test is commonly used to analyze trends in precipitation and temperature time series (Kumar and Sidana, 2017; Sridhara and Gopakkali, 2021). It has even been recommended by the World Meteorological Organization (WMO) (Diress and Bedada, 2021) because its power and significance are not affected by the actual distribution of the data (Hamed, 2009). The Mann-Kendall trend test (Mann, 1945; Kendall, 1975) is based on the correlation between ranks and sequences in a time series (Wang et al., 2020). According to the same authors, for a given time series $\{X_i, i = 1, 2..., n\}$, the null hypothesis H_0 is that it is independently distributed, and the alternative hypothesis H_1 is that there is a monotonic trend. Sen's slope estimator is always associated with the Mann-Kendall (MK) test (Aditya et al., 2021; Frimpong et al., 2022). Sen's slope estimator is used to examine the magnitude of change in the trend of selected extreme climate indices. Linear regression equations and their coefficient of determination (R^2) were also used to capture the trend of the indices over 30 years (1991-2021). XLSTAT (Statistical Software for Excel) 2023 was used to calculate the Mann-Kendall test and to generate the linear regression equations and the coefficient of determination (R^2).

3.2.2. Homogeneity tests

In the study of climate time series, homogeneity of data means the consistency of a series over time and reflects a robust analysis of the data series (Zhang et al., 2011). Two homogeneity tests (Pettitt and von Neumann ratio) were used to assess the homogeneity of the extreme climate index data. These tests, in particular the Pettitt test, detect breaks in the extreme climate index data. Two types of change point detection methods can be distinguished: real-time (or simply online) detection and retrospective detection (Dang et al., 2021). For the detection of change points in extreme climate indices, the retrospective detection method, including the Pettitt test was used in the study. The Pettit test is a parametric test based on the increasing order (r_i) of the elements in the series (Pettitt, 1979).

The test takes into account the following (Hänsel et al., 2016):

$$U_k = 2\sum_{i=1}^{k} ri - k(n+1),\ \text{k=1,.....,n.} \tag{1}$$

In addition, the statistics of the Pettit test are determined by:

$$U_k = \sum_{1\le k\le n}^{\max} \left|U_k\right| \tag{2}$$

According to the test, the null hypothesis is that the data are homogeneous, as opposed to the alternative hypothesis that there is a change in the data (Kocsis et al., 2020). This method is commonly used to find points of change in climate and hydrological datasets (Conte et al., 2019).

The von Neumann ratio is a measure of whether the extreme weather index data are homogeneous or not. Unlike the Pettitt test, the Von Neumann test does not provide any indication of the year of change point (Yildirim and Rahman, 2022). The von Neumann ratio (von Neumann, 1941) is a non-parametric test most often used to detect non-homogeneity over time (Ahmed et al., 2018). The test statistic can be described as (Ahmad & Deni, 2013):

$$N = \frac{\sum_{I=1}^{n-1}((Y_i - Y_{i+1})^2}{\sum_{i=1}^{n}(Y_i - \bar{Y})^2} \qquad (3)$$

If the sample or series is homogeneous, then the expected value E(N) = 2. If there is a break, then N must be less than 2, otherwise we can say that the sample varies. Otherwise, we can assume that the sample has a rapidly varying mean. XLSTAT 2023 is also used for the Pettitt and von Neumann ratio tests.

3.2.3. Return periods for extreme climate indices

The return periods of extreme climate indices for the period 1991-2021 are determined by frequency analysis. The return period of an extreme climate index is defined as the inverse of the annual exceedance probability (Mohymont & Demarée, 2006). According to Mohymont & Demarée, 2006, the mathematical formula is as follows:

$$RP = \frac{1}{Q\ (X \geq x^*)} \qquad (4)$$

Where:

X^*=Frequency of a rainfall event x*;

Q=The amount of rainfall (in mm);

RP=Return Period.

The same formula applies to temperature. We have replaced Q with T for temperature.

In order to operationalize the calculation of the return period, the theoretical probability of each observation has been calculated using the following formulae:

$$\text{P}=\frac{m-a+\text{b}}{N+1\text{-2a+b}} \qquad (5)$$

Where, P is probability of exceedance; m is rank, and N is number of years of record. For this study, the Weibull formula has been applied to P. So, a=0, and b=0. Therefore, the formula for P is now:

$$\text{P}=\frac{m}{N+1} \qquad (6)$$

The extrapolation of the return periods of the extreme climate indices was based on the logarithmic regression of the extreme climate indices as follows:

$$Y = a\ln(x) + b \qquad (7)$$

Simply replace x with a return period value, which can be in years or days for the CWD index (table 3).

Table 3 Extrapolation of the return periods of the extreme climate indices.

Return Period	Regression equation
50	a*ln (50) +b
75	a*ln (75) +b
100	a*ln (100) +b
125	a*ln (125) +b
150	a*ln (150) +b

Source: Authors, 2023

The return period was calculated using Excel 2023.

4. Results and discussion

4.1. Homogeneity in extreme climatic indices

Overall, the extreme precipitation indices show no temporal breaks between 1991 and 2021, except for the PXJA index, which shows a small break with medium significance ($p \leq 0.5$). The extreme temperature indices show clear breaks between 1991 and 2021. Indeed, the breaks are in 1999 for TXx and in 2001 for TXn (Table 4). The von Neumann ratio test also shows that most of the extreme precipitation indices are homogeneous. Only PXJA is not homogeneous. Extreme temperature indices, on the other hand, are inhomogeneous, with an upward trend in minimum temperatures from 2005 and in maximum temperatures from 2008. Table 4 below shows that the upward trend in maximum temperatures is less pronounced due to low significance ($p \leq 0.5$). This is not the case for minimum temperatures, which show a clear upward trend after 2005 ($p \leq 0.001$).

Table 4 Extreme climate indices applied to Pettitt and von Neumann ratio tests.

Index	Pettitt test			Years of change	Von Neumann ratio test		Interpretation
Extreme rainfall indices							
	k	t	*p-value*		N	*p-value*	
PRCPTOT	64	2007	0.775	-	2.17043241	0.687	Homogeneous
CWD	68	1999	0.930	-	2.58579183	0.951	Homogeneous
PXJA	67	1999	0.863	-	1.94299706	**0.432***	Non homogeneous
P95	58	1999	0.557	-	2.10448439	0.605	Homogeneous
SDII	72	2005	0.949	-	2.16314945	0.675	Homogeneous
Extreme temperature indices							
	k	t	*p-value*		N	*p-value*	
TXx	84	1999	**0.475***	2008	1.442514	**0.064***	Non homogeneous
TXn	165	2001	**0.001*****	2005	0.97158707	**0.001*****	Non homogeneous

*Source : NMA, 1991-2021 ; Note : **** p ≤ 0.001; *** p ≤ 0.05, **p ≤ 0.01; *p ≤ 0.5; - No break*

4.2. Trend of extreme climatic indices between 1991 and 2021

The extreme climate indices show different trends between 1991 and 2021, with virtually no clear trend emerging for the extreme precipitation indices (Table 5). However, there is a slight trend for the SDII index (p-value=0.5). However, the trend amplitude (Qi) has a positive value (0.372), indicating an upward trend. The extreme temperature indices show that there is a clear trend (TXx= p-value =0.378; TXn= p-value=0.004) with positive but slightly increasing trend amplitudes (TXx=0.006; TXn=0.026) (Table 5 below).

Table 5 Extreme climate indices applied to the Mann-Kendall and Sen's slope.

Extreme rainfall indices					
Mann-Kendall (MK) test	**PRCPTOT**	**CWD**	**PXJA**	**P95**	**SDII**
Tau de Kendall	0.080	-0.078	-0.023	-0.025	0.117
S	35	-33	-10	-11	51
Var(S)	3141.667	3105	3140.667	3141.667	3141.667
p-value	0.544	0.566	0.872	0.858	**0.372***
Sen’s slope	1.662	-0.050	-0.159	-0.88	0.033

Extreme temperature indices					
Mann-Kendall test	**TXx**	**TXn**			
Tau de Kendall	0.118	0.383			
S	48	155			
Var(S)	2842	2839			
p-value	**0.378***	**0.004*****			
Sen's slope	0.006	0.026			

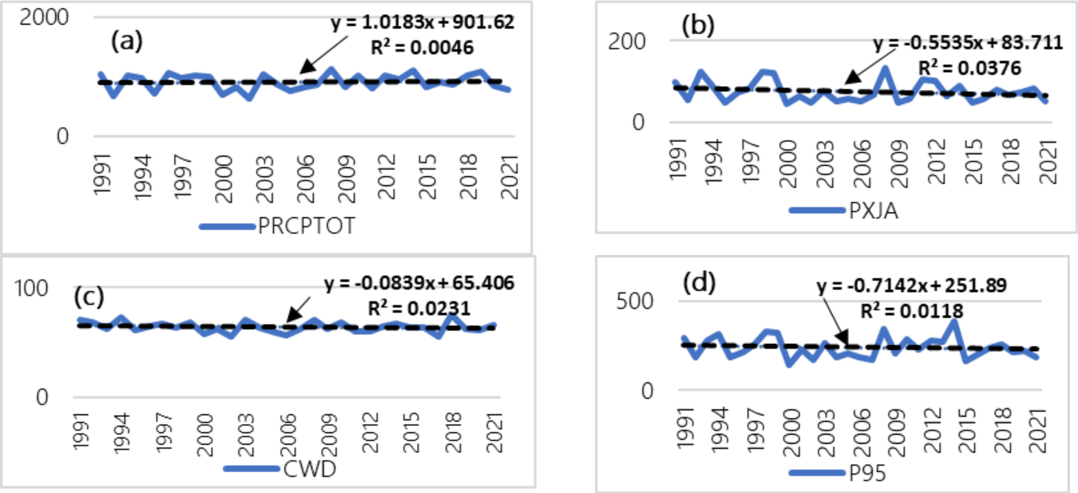
*Note : ****Trend is very significant at α = 0.001, **Trend is significant at α = 0.01, *Trend is significant at α = 0.05, * The trend is significant average at α = 0.5.*

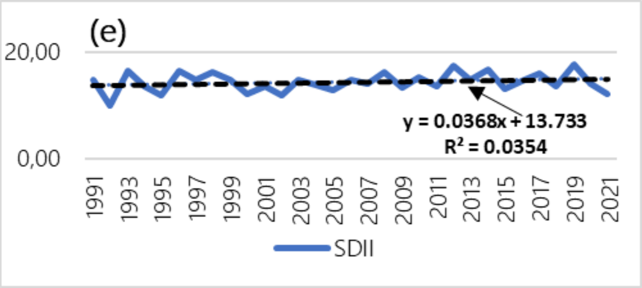
The results are in contrast with the work of Tazen et al. (2018) in Burkina Faso (case of the Centre region). In fact, the P95, CWD and SDII indices show trends as the p-value < 5%. Similar results were obtained by Agyekum et al. 2022 between Burkina Faso and Ghana. Indeed, the study also shows an upward trend in observed days with heavy and very heavy rainfall (R10 mm and R20 mm), very wet and extremely wet days (R95p and R99p), but a downward trend in consecutive wet and dry days (CWD and CDD). In Mali, similar observations were made by Fofana et al, 2022 with regard to PRCPTOT (upward trend, p-value=0.006). However, in the study area, PRCPTOT showed no trend according to the Mann-Kendall test (p-value=0.544 > 5%). In Ethiopia, on the other hand, rainfall trends are almost similar to those in the study area, with both increasing and decreasing trends observed in the time series studied (Shigute et al., 2023). This point was also made by Adeyeri et al. 2019 around Lake Chad (between Niger and Nigeria).

4.3. Temporal characteristics of extreme climatic indices

The extreme climate indices over the period 1991-2021 are highly variable (figure 2).

Extreme rainfall indices





Extreme temperature indices

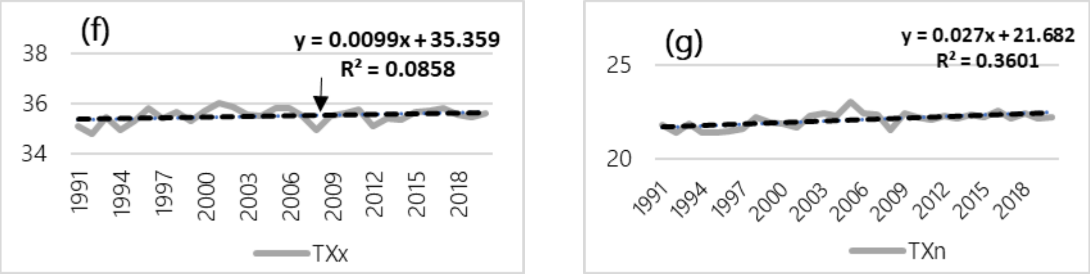


Figure 2 High variability of extreme climate indices over the period 1991 to 2021 *(Source : National Meteorological Agency of Burkina Faso, Boromo, 1991-2021).*

Two trends can be seen in Figure 2: first, in the case of extreme precipitation indices, a decrease is observed for CWD, P95 and PXJA, while an increase is observed for PRCPTOT and SDII. The second concerns extreme temperatures, where the indices show a significant increase between 1991 and 2021. However, Table 6 shows that the decade 2001-2010 corresponds to an overall decrease in precipitation indices. Conversely, the 2011-2021 decade shows an increase in extreme precipitation indices. This is in contrast to the extreme temperature indices, which show an increase in the 2001-2010 decade and a slight variability between TXx (decrease) and TXn (increase) in the 2011-2021 decade.

Table 6 Decade-by- decade trends in extreme climate indices.

Index	1991-2000	2001-2010	2011-2021
Extreme rainfall indices			
PRCPTOT	926.24	886.06	939.3
CWD	65.7	63	63.54
PXJA	85.39	65.29	81.37
P95	253.93	226.66	240.76
SDII	14.09	13.99	14.83
Extreme temperature indices			
TXx	35.36	35.63	35.55
TXn	21.73	22.28	22.29

Source: National Meteorological Agency of Burkina Faso, Boromo, 1991-2021

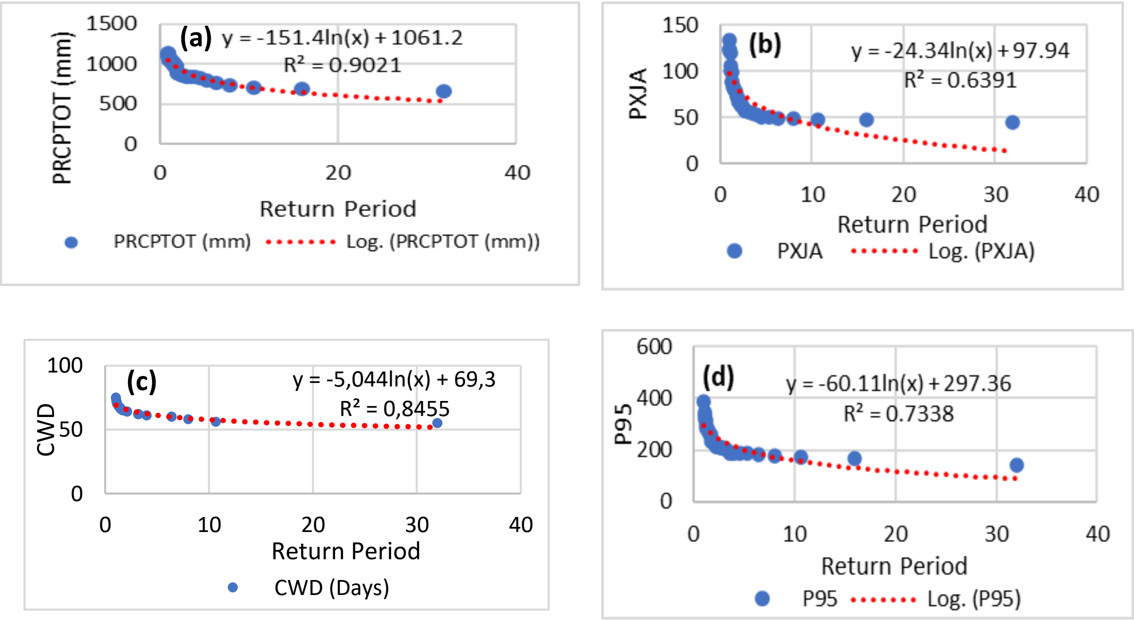
Results on the variability of extreme climate indices were also observed by Ly et al. 2013 in Sahelian West Africa. The authors found that indices such as CWD (maximum 5-day rainfall) increased between 1960 and 2010. Diatta et al. (2020) also found similar results for the variability of extreme climate indices (CDD, CWD, R10mm, R20mm, Rx1day, Rx5day, Prcptot and SDII).

4.4. Characterization of the return periods of extreme climatic between 1991 and 2021

Figure 3 below shows that the return periods of the extreme weather events (PXJA, PRCPTOT, P95, CWD, TXx, TXn) are relatively short, as most of the extreme weather indices (PXJA, PRCPTOT, P95, SDII, TXx, TXn) have return periods between 0 and 10 years. However, only the CWD index has a return period expressed in days, which is also short as the return period varies between 0 and 10 days during the rainy season. However, the trend lines are usually negative. This means that when the extreme weather indices fall, the return periods are long. The high coefficients of determination (R^2) show that this trend is strong. However, the SDII is the exception to the rule, as it increases over the years. Overall, the return periods of the climate indices in the area are between 0 and 10 years. This means that they will continue to occur in the coming years.

Several other studies in Africa converge with the results of this study. In Africa, extreme mean annual temperatures have shorter return periods (4 to 7 years) than maximum annual temperatures (6 to 10 years) (Turasie, 2021). In the Pra River catchment in Ghana, (Osei et al. 2021) found almost similar results to our study, with return periods of the CWD index ranging from 6 to 20 days over a 10-year period. In Kigali, Rwanda, the return periods of extreme maximum rainfall are increasing and vary between 5 and 50 years (Singirankabo and Iyamuremye, 2022). In Senegal, on the other hand, return periods of extreme rainfall tend to be between 100 and 150 years over the period 1951-2005. In the northeastern region of Brazil, return periods for the occurrence of intense rainfall events (IRE) are shorter, ranging from 5 to 10 years (Oliveira and Lima, 2019).

Extrapolation of the return periods from 50 to 150 years for the extreme climate indices shows a significant change in the indices (Figure 4). The extreme precipitation indices (PXJA, SDII) increase with the return periods. Conversely, PRCPTOT, P95, and CWD decrease with return periods. The same is true for the extreme temperature indices, which show a decrease in extreme temperatures over the years (return periods).



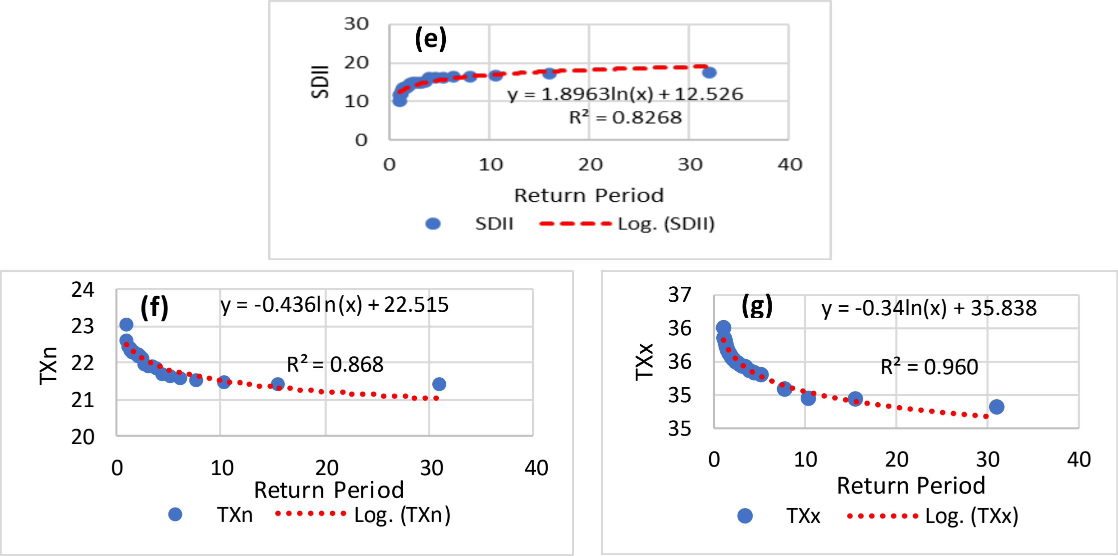
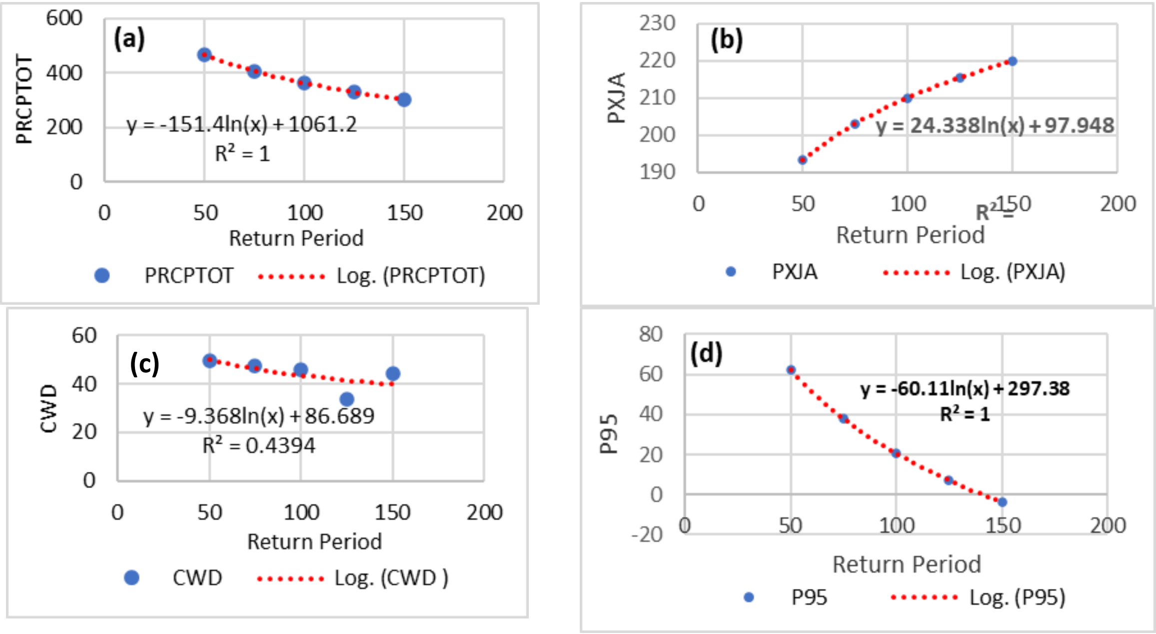
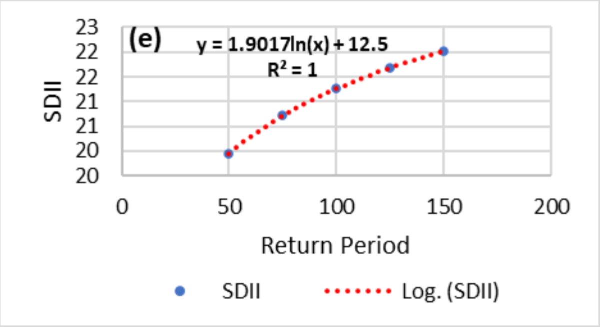


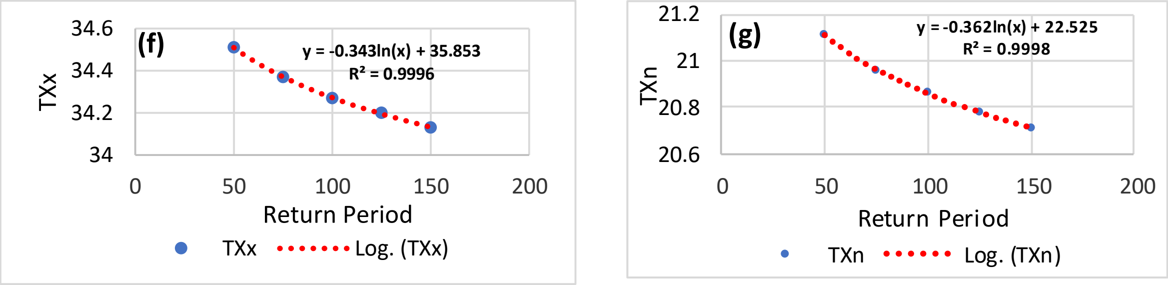
Figure 3. Return periods for extreme climatic indices between 1991 and 2021 (Source: National Meteorological Agency of Burkina Faso, Boromo, 1991-2021)

Extrapolation of 50-150 years return periods for precipitation indices





Extrapolation of return periods from 50 to 150 years for temperature indices



Source: National Meteorological Agency of Burkina Faso, Boromo, 1991-2021

Figure 4. Extrapolation of return periods from 50 to 150 years for extreme climatic indices

Figure 4 shows two (02) trends in the extreme precipitation indices: on the one hand, there is a decrease in PXJA and SDII, and on the other hand, PRCPTOT, P95 and CWD increase between 50 and 150 years. As for the temperature indices, there is a steady decrease in TXx and TXn.

5. Conclusion

The extreme precipitation indices are largely homogeneous, except for the SDII which shows a break, while the extreme temperature indices show breaks over the period 1991-2021. The trend of the extreme climate indices is upward for the extreme temperature indices and both upward (PRCPTOT, SDII) and downward (PXJA, P95, CWD) for the extreme precipitation indices. In addition, the extreme climate indices are highly variable between 1991 and 2021. The return periods of the extreme weather indices vary between 0 and 10 years. This implies that the trends in extreme weather indices will continue over the next decade. It is therefore important that measures are taken to help banana growers near the dams in the Mouhoun loop to avoid production losses.

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