American Journal of Climate Change, 2025, 14(2), 288-315
https://www.scirp.org/journal/ajcc
ISSN Online: 2167-9509
ISSN Print: 2167-9495

Analysis of Extreme Rainfall Events in the Oti Watershed, Togo (West Africa)

Koungbanane Dambré[1,2]*, Kodja Japhet Domiho[2], Lemou Faya[1], Totin Vodounon Henri Sourou[2,3], Amoussou Ernest[2,3]

[1]Laboratory of Biogeographic Research and Environmental Studies, Department of Geography, University of Lome, Lome, Togo
[2]Laboratory Pierre PAGNEY, Climate, Water, Ecosystems and Development (LACEEDE), Université d'Abomey-Calavi, Cotonou, Benin
[3]Laboratory of Tropical Climatology & Ethnoclimatology, Department of Geography and Regional Planning, Université de Parakou, Parakou, Benin
Email: *dambrekoungbanane@gmail.com, fayalemou31@gmail.com, japhdom@gmail.com, totinsourouhv@gmail.com, ernestamoussou@gmail.com, totinsourouhv@gmail.com, ernestamoussou@gmail.com

How to cite this paper: Dambré, K., Domiho, K. J., Faya, L., Sourou, T. V. H., & Ernest, A. (2025). Analysis of Extreme Rainfall Events in the Oti Watershed, Togo (West Africa). *American Journal of Climate Change, 14,* 288-315.
https://doi.org/10.4236/ajcc.2025.142015

Received: January 27, 2025
Accepted: May 18, 2025
Published: May 21, 2025

Abstract

Global climate change, characterised mainly by an upsurge in extreme rainfall events, is affecting the precarious economies of most vulnerable countries. The aim of this study is to analyze extreme rainfall events in the Oti watershed, which is characterised by high climatic variability. Daily observed and simulated rainfall and temperature data from two models (CCLM4.8 = Climate Limited-area Modeling Community 4.8 and REMO = Regional Model) in the Cordex programme were used. The data is subjected to statistical processing methods. Climatic indices were calculated using RclimDex software. The results obtained show a spatio-temporal variability in observed and simulated rainfall that follows an increasing north-south gradient. A break in stationarity was observed in 1998 in the rainfall data series, showing a change in the behavior of maximum daily rainfall from 1961-2022. Both models overestimate observed rainfall, with deviations of 1.95 for the CCLM4.8 and 8.53 for the REMO. This shows that the CCLM4.8 is more realistic in reproducing observed rainfall, is therefore validated for the rainfall projection. The rainfall indices show a non-statistically significant increase in PRCPTOT, R99p, RX1day, RX5 days and CWD on the one hand, and a decrease in the SDII, R10 mm, R20 mm and R95p indices on the other for the observed rainfall. For simulated rainfall, the RCP 8.5 and RCP 4.5 scenarios predict an upward trend in some indices and a downward trend in others from 2025 to 2069. Thus, the RCP 8.5 scenario predicts an increase in Rx1day, SDII and R99P from 2025 to 2069. The RCP 4.5 scenario also predicts an upward trend in Rx1day, Rx5days and R99P over the same period. This study provides a clearer picture of how extreme rainfall could change, and is a tool to help plan and manage flood risk in the Oti watershed in Togo.

Keywords

Climate Change, Rainfall Indices, Rainfall Trends, Simulated Rainfall, Oti Watershed

1. Introduction

West Africa is one of the regions of the world most vulnerable to climate change. The often-disastrous impacts of climate variability and extremes over the last thirty years are a good illustration and warning sign of this vulnerability. Thus, if West Africa is vulnerable to climate variability and change, it is because some of its physical and socio-economic characteristics predispose it to be disproportionately affected by the negative effects of climate variation (Niasse et al., 2004). Furthermore, the capacity to monitor and understand the consequences of extreme climatic events (droughts and floods) in terms of their temporal and spatial variability is fundamental if West African countries are to acquire the knowledge they need to assess their vulnerability and develop effective early warning systems to support mitigation and adaptation policies (Tadouna et al., 2024). The frequency of extreme events in today's climate will change with warming, with heat extremes becoming more frequent (almost certain), cold extremes becoming less frequent (extremely likely) and precipitation extremes becoming more frequent in most places (very likely) (IPCC, 2021). Extreme weather events in 2024 resulted in the highest number of new annual displacements since 2008. They destroyed homes, essential infrastructure, forests and farmland, and harmed biodiversity (World Meteorological Organization (WMO), 2025). The report of WMO (2024) notes the worsening effects of climate and weather. According to forecasts by the Intergovernmental Panel on Climate Change (IPCC, 2001), some extreme events (flooding, drought, heat waves, heavy rains, tropical cyclones) will increase in frequency and intensity during the 21st century as a result of changes in climatic averages and/or climate variability. All climate projections predict an intensification of average warming, in addition to changes in rainfall and also a greater frequency and intensification of extreme events (IPCC, 2014). Extreme climatic events have a major impact on people's livelihoods, leading to desertification, land degradation, reduced agricultural yields, loss of biodiversity, depletion of livestock and population displacement International Bank for Reconstruction and Development (IBRD, 2024). Floods and drought account for around a third of all displacements observed in the most densely populated regions of West Africa (Guo et al., 2024; Kevin & Yamani, 2024). A significant consequence of climate change in West Africa is human migration, accounting for over 50% of global migration flows (Disaster Displacement, 2018), which manifests itself on a variety of scales, from internal displacement to cross-border migration, exacerbating conflict and violence in the region (IOM UN MIGRATION, 2020). In addition, West Africa has been identified as one of the region's most vulnerable to climate change due to its exposure to climatic hazards. According to a report by the Food and Agriculture Organization (FAO, 2024), heatwaves and floods have a different impact on women and men and exacerbate income disparities.

Many climate projections have shown that West Africa will experience a significant rise in temperatures associated with high variability in rainfall (Ozer et al., 2017). These climate changes could have harmful consequences for the environment, such as flooding or drought, reduced water availability and crop yields, and loss of biodiversity (Ly et al., 2013). The extreme weather and climate events will condition vulnerability to future extreme events by modifying already fragile ecosystems (Descroix et al., 2015). Indeed, West African climates are subject to strong spatio-temporal variability or change depending on the time scale and analysis, the consequences of which are detrimental to sustainable development (Katz & Brown, 1992). This spatial and temporal distribution of extreme rainfall events is not homogeneous and can lead to significant negative socio-economic and environmental impacts. Several studies (Tapsoba, 1997; Panthou et al., 2014; Donat et al., 2016; Ozer et al., 2017; Biasutti, 2019) on climate change in general and rainfall in particular have shown that climate change has been characterized by an intensification of rainfall and a recurrence of extreme events. The question of future changes in the frequency or intensity of these events, particularly as a result of increased concentrations of greenhouse gases in the atmosphere, is therefore a major one (Sylla et al., 2012; Nouaceur, 2020; Crétat et al., 2013).

Climate change in Togo is leading to an increase in mean temperature, high variability in rainfall and an increase in the occurrence of extreme conditions such as floods and droughts (Badjana et al., 2014; Koungbanane et al., 2019). The Oti watershed in Togo is no exception to the extreme rainfall events associated with current climate variability. The occurrence of daily rainfall has repercussions on its hydrological dynamics and exceptional flooding, which has a serious impact on the livelihoods of the local human population (Komi et al., 2016). These extreme rainfall events in the watershed have repercussions for all the ecosystems, and the human populations affected suffer the consequences, leading to migration and hampering the achievement of the Sustainable Development Goals. The Sustainable Development Goals (SDGs) are a global call to action to eradicate poverty, protect the planet and ensure that all human beings live in peace and prosperity.

Climate change, characterized mainly by an upsurge in extreme rainfall events, is affecting the precarious economies of most Sub-Saharan African countries (Ozer & Perrin, 2014; Gemenne et al., 2017; Gbohoui et al., 2018). These changes related to precipitation and temperature, as well as non-linear effects on humidity and evapotranspiration, have consequences for the quantity and quality of water resources and agriculture (IPCC, 2001; Zakari et al., 2019) and therefore for people's lives. In this respect, the Oti watershed in Togo is of particular concern, because, in addition to the high vulnerability of its populations, extreme weather and climate events are by far the most frequent cause of casualties among the various natural hazards.

Populations are often surprised by the onset of drought on the one hand, and the occurrence of floods on the other, with dramatic consequences for the physical environment, human settlements and socio-economic systems. Nowadays, planners and engineers continue to use tools and guides dating back to the 1960s to assess extreme hydroclimatic events (Nka Nnomo, 2016; Kodja, 2018), whereas in the current context of global and environmental changes added to demographic growth, this approach seems to be obsolete and deserves to be updated with modern tools adapted to current climate trends and land use. This would make it possible to cope with flood episodes that are detrimental to environmental and human systems (Paturel et al., 2003; Koumassi et al., 2014; Komi et al., 2016).

The aim of the present study is to analyse extreme rainfall events in the Oti watershed in Togo. In other words, the aim is to help decision-makers manage flood risk, which is why this study includes projections of future rainfall using data from two regional climate models (CCLM et REMO) from the CORDEX West Africa program under different RCP4.5 and RCP8.5 climate scenarios. By calculating indices for future periods, the study will provide policy-makers with a clearer picture of how extreme rainfall could change and help with risk planning and management in Togo. This study was based on the standardized precipitation indices (SPI), the climatic indices designed to characterize extreme climatic events.

2. Materials and Methods

2.1. Study Area

The Oti river basin in Togo is located in the north of the country, in the Volta river basin, and drains part of the catchment areas of the countries bordering Togo, namely Burkina Faso, Benin and Ghana. At the Mango outlet, the Oti basin covers an area of 3.652 square kilometres and is located between 11˚05' and 10˚96' N and 0˚12' and 0˚95' E (**Figure 1**).

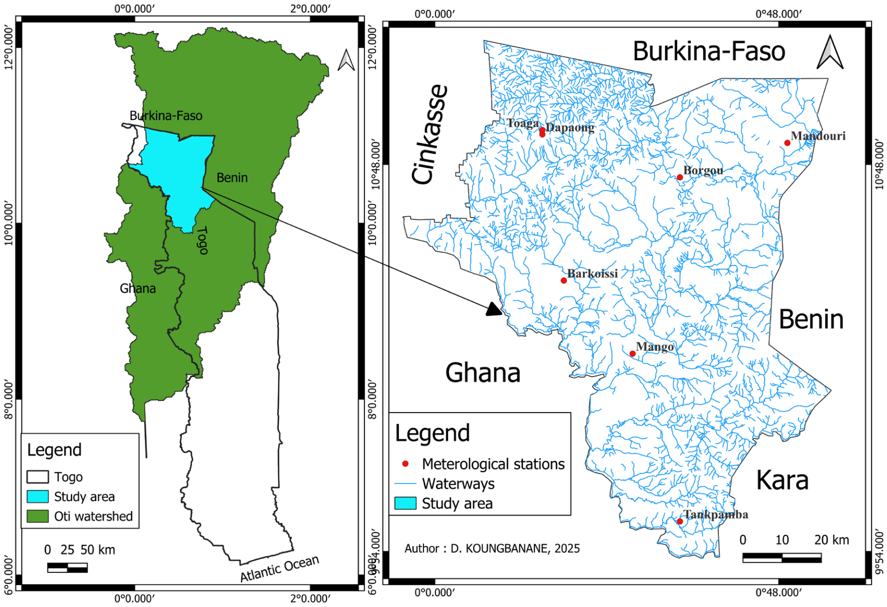

Figure 1. Location of the Oti watershed in Togo.

The topography of the watershed is based on a morphology that includes the Gourma peneplain, the Dapaong-Bombouaka plateaus and the Oti plain. The total elevation ranges from 106 to 506 meters. Its relatively dense hydrographic network is controlled by the Oti River. The Oti river, the main water collector (167 kilometers long in Togo), rises in northern Benin on the eastern slopes of the Atacora chain, under the name of Pendjari. He follows a south-west-north-east orientation, crosses the Atacora region, and then reverses and returns south-west, arriving in Togo, where it takes the name of the Oti (Mul et al., 2015). The Oti river forms the natural border between Togo and Benin from its confluence with the Koumongou River, south of the Galangachi classified forest, to the Ghanaian commune of Sabari, south of which the Oti river flows into Lake Volta. Its tributaries are the Wabga, Namiélé and Sansargou on its right bank. Its left bank tributaries are the Koumongou, Kéran and Kara. The riverbed of the Oti is cut into the clay formations and here and there bordered by a forest gallery. When the Oti overflows its banks during the rainy season, it causes major flooding with serious consequences for the people living along its banks.

The map shows the meteorological stations (Barkoissi, Borgou, Dapaong, Mandouri, Mango, Tankpamba and Toaga) used for this research in the Oti watershed.

According to the 5th General Census of Population and Housing (5thRGPH) in 2022, the Oti watershed had a population of 1.143.520. Several activities are practiced by these populations. These include agriculture, livestock, fishing, hunting, handicrafts, commerce, tourism, sand and gravel extraction, and transportation. However, agriculture seems to be the main activity of the people living in the watershed.

2.2. Data

2.2.1. Observation Data

The data used for this study are cumulative daily rainfall and air temperatures (maximum and minimum). They are collected from seven meteorological stations (Barkoissi, Borgou, Dapaong, Mandouri, Mango, Tankpamba, Toaga) of the National Agency for Meteorology in Togo (ANAMET) covering the period 1961-2022.

Table 1 summarizes the weather station characteristics of the observed and simulated data used for this study.

Table 1. Coordinates of meteorological stations used.

Stations	Type of station	Geographical coordinates	
		Latitude (N)	Longitude (E)
Barkoissi	Rainfall	10˚53	0˚3
Borgou	Synoptic	10˚76	0˚56
Dapaong	Synoptic	10˚85	0˚25
Mandouri	Synoptic	10˚85	0˚85
Mango	Synoptic	10˚36	0˚46
Tankamba	Rainfall	9˚96	0˚57
Toaga	Climatological	10˚87	0˚25

2.2.2. Simulation Data

To analyze extreme weather events in the Oti watershed, it is necessary to use the results of climate model data in comparison with observed data. Data from climate models were used to analyze extreme hydroclimatic events in comparison with historical and observed data. They are also used to assess the performance of data from these models in analyzing extreme rainfall events as indicators of flooding in the study area. Simulation data from two models (CCLM4.8 and REMO) from the Coordinated Regional Climate Dawnscaling Experiment (CORDEX) West Africa program, which provides high-resolution data in the form of 0.44˚ × 0.44˚ grids, i.e. approximately 50-km × 50-km, are also used. These data cover the period from 2006 to 2100. The data is simulated in two phases, taking into account the historical aspect from 1961 to 2022 without the RCP (Representative Concentration Pathways) scenarios and the future aspect from 2025 to 2069 with the combination of RCP 4.5 and RCP 8.5 for the simulations. The priority simulations carried out as part of the CORDEX project concern only two of the RCPs defined, namely the RCP 4.5 and RCP 8.5 scenarios. These particular scenarios correspond to the B1 and A1B scenarios of the old Greenhouse Gas evolution profiles (SRES = Special Report on Emissions Scenarios) (Nka Nnomo, 2016). They represent optimistic and pessimistic climate change scenarios for the 21st century, respectively (Herbst & Rautenbach, 2016). For this reason, both scenarios are used in this study.

2.3. Methods

2.3.1. Data Quality Control

In order to ensure the homogeneity and reliability of the climatic data chronicles, data criticism and control are the basic processes to which this research is dedicated. For example, data from the raw precipitation and temperature files were systematically checked. This check eliminates values with gaps and does not guarantee the accuracy of the data retained.

The missing data from the stations selected for this research were then reconstituted to obtain the most complete series possible, constituting the operational database used for subsequent calculations. Stations with significant data gaps (several months or years with >5% missing data) were simply deleted. On the other hand, stations with <5% missing data were used without filling in, as they have a daily time step. This method avoids the artificialization of data, while eliminating any risk of introducing vitiated and fanciful figures (Klassou, 1996; Totin, 2010).

Data quality control has been performed to help identify any recording errors that may exist in the daily data (Balliet, 2017; Atcheremi et al., 2018). Thus, the principle consists of:

- replace the daily maximum temperature of the erroneous values by −99.9, if it is lower than the daily minimum temperature;
- not more than 365 daily observations per year;
- no more than 28 observations in the month of February, whatever the year;
- replace missing or negative data (for rainfall) with −99.9 before quality control by the software Rclimdex.

2.3.2. Interpolation of Rainfall Data in the Oti Watershed in Togo

There are several methods for interpolating rainfall data (simple arithmetic mean, linear interpolation, Thiessen polygon interpolation and ordinary block Kriging). The most robust and most widely used in recent years in tropical regions, particularly in West Africa, are linear interpolation and interpolation by Thiessen polygons (Kodja, 2018). For the purposes of this study, the Thiessen polygon interpolation method was used for both observed and model-simulated rainfall data. The weighted average precipitation P for the basin is then calculated by summing the precipitation Pi from each station, multiplied by their weighting factor (area Si), divided by the total surface area S of the basin. The average rainfall over the basin is therefore written as:

$$P = \frac{\sum P_i S_i}{S} \tag{1}$$

With P: average rainfall (mm); P: rainfall at the station within the polygon (mm); S_i: surface area of the polygon (km^2) and S: total surface area of the watershed (km^2).

The various zones of influence are determined by geometrically dividing the basin on a topographical map. Once the available stations have been plotted on a map, a series of straight lines is drawn between adjacent stations. Perpendiculars are drawn at the center of each of these lines (perpendicular bisectors); the intersections of these perpendiculars form polygons. Within each polygon, the precipitation level selected is that recorded at the station located within it. The sides of the polygons and/or the watershed represent the limits of the area (and weight) assigned to each station. The area of each S_i polygon is determined planimetrically or numerically.

Following analysis of the two precipitation models simulated in CORDEX, data from the 50-km × 50-km grids of the two regional models were interpolated. These grids cover a variable surface area, but have only one geolocalized value, generally at the center of the grid. Spatial interpolation consists in calculating the value of a simulated field on a destination grid point (also known as the target grid), based on the values of the simulated field on the meshes of the source grid, which may be closer or further away. Several interpolation methods are available, based on weighting methods that take into account the distance between source and target grid points, or the altitude of the source grid point.

2.3.3. Method for Determining Stationarity Break in the Series

The Pettitt (1979) test was applied to determine the break year and the comparison of means in order to analyze the temporal stability of rainfall series over the 1961-2022 period, using Khronostat 1.01 software. This test was confirmed by Buishand's test and Hubert's segmentation. Pettitt's method for detecting breaks in the stationarity of time series was used in this study to identify current trends in interannual rainfall compared with the average for the period under consideration. It consists in splitting the main series of N elements into two sub-series at each time t between 1and $N-1$.

The main series is broken at time *t* if the two subseries have different distributions. The null hypothesis H0 of no break is tested using a non-parametric test.

The Pettitt test has been chosen for its use in numerous studies of stationarity change detection in West Africa (Hubert & Carbonnel, 1987), its power, especially with regard to the break test on the mean (Lubes-Niel et al., 1998), and its robustness (Lubès et al., 1994). It was then applied in the Oti basin using Khronostat 1.01 software. Then (Xi) I = 1 at t and $t + 1$ at N belong to the same population (Lubès et al., 1994). This test is based on the variable U_t and N is defined by:

$$U_{t,N} = \sum_{i=1}^{t} \sum_{j=t+1}^{N} D_{ij} \tag{2}$$

where D_{ij} = sgn(xi-xj) with sgn(Z) = 1 if (Z) > 0; 0 if $Z = 0$ and -1 if $Z < 0$. Let KN be the variable defined by the maximum absolute value of $U_{t,N}$ for t varying from 1 to $N - 1$. If K denotes the value of KN taken from the series studied, under the null hypothesis, the probability of exceeding the K value is given approximately by: Prob($KN > K$) is approximately equal to 2exp(-$-6K^2/N^3 + N^2$).

For a given first-species risk a, if Prob($KN > K$) is less than a, the hypothesis is rejected.

Hubert's segmentation procedure is also used in this work. Its principle is to divide the rainfall series into segments (m) significantly different from the mean of the neighbouring segment(s). This approach involves searching for multiple changes in the mean. Thus, if the procedure does not produce an acceptable segmentation of order greater than or equal to 2, the main hypothesis of stationarity is accepted. By means of a specific algorithm, this segmentation provides one or more break dates separating contiguous segments whose means are significantly different (Hubert et al., 1998). In fact, the hydrometeorological series segmentation procedure proposed by (Hubert et al., 1989) is interpreted as a stationarity test, the main hypothesis being that the series studied is stationary.

The parametric t-test is used to compare two means and two sub-series of respective numbers $\bar{X}_1$ and $\bar{X}_2$ obtained on either side of the breakpoint. This parametric test is used to assess the significance of the regression coefficient.

The statistic used in this test is:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\left(S_2\left(\frac{1}{n_1} + \frac{1}{n_2}\right)\right)}} \tag{3}$$

$\bar{X}_1$ = Average before year of breakup;

$\bar{X}_2$ = Average after breakup;

n_1 = Number of elements in the first series;

n_2 = Number of elements in the second series.

where denotes the weighted variance of the whole group of the two samples, i.e.:

$$S_2 = \frac{\sum_{i=1}^{n_1}\left(X_{1,i} - \bar{X}_1\right)^2 + \sum_{i=1}^{n_2}\left(X_{2,i} - \bar{X}_2\right)^2}{n_1 + n_2 - 2} \tag{4}$$

2.3.4. Bias Calculation Method

In order to assess the performance of the two models (CCLM and REMO) of the CORDEX programme in reproducing as well as possible the interannual variability of annual rainfall on the one hand, and for the analysis of extreme rainfall events in the future on the other hand, the calculation of biases is necessary. The bias calculation method involves calculating the difference in means between simulated and observed rainfall (Yèkambèssoun et al., 2016; Kodja, 2018). It is used to identify the best simulation model that best matches the analysis of future projections of mean rainfall and extremes (Taïbi-Freddal, 2016; Yira et al., 2016). It evaluates the deviation of simulated rainfall from observations and is obtained by the following formula:

$$Bias = \frac{PSim - PObs}{PObs} \tag{5}$$

where $PSim$ = simulated precipitation and $PObs$: observed precipitation.

2.3.5. Choice of Climatic Indices Used

Several indices were used to analyze extreme rainfall events. These indices are relatively simple ways of assessing changes in extreme rainfall events that affect the natural and human environment (Frich et al., 2002). It was in this context that the CLIVAR (Climate Variability and predictability) group (World Meteorological Organization, 2012) of the WCRP (World Climate Research program) of the World Meteorological Organization proposed a list of twenty-seven (27) indices calculated from daily series of surface variables (rainfall and temperature). The purpose of these indices is to characterize extremes, frequency, amplitude and persistence. In the context of this study, the calculation of these indices is based on rainfall, and nine indices have been calculated to analyze extreme rainfall events as proposed by the ETCCDI (Expert Team on Climate Change Detection and Indices) expert group (**Table 2**). This analysis method is commonly used to study extreme events (Hountondji et al., 2011; Filahi et al., 2015; Djossou et al., 2020). These indices have already been used in several studies to analyze extreme climatic events, such as those by (Gachon et al., 2005; Dubuisson & Moisselin, 2006; Issaou, 2014; Gbohoui et al., 2018).

Table 2. Characteristics of rainfall indices calculated.

Indices	Indicator name	Definitions	Unit
Rx1days	Max 1-day precipitation amount	Monthly maximum 1-day rainfall	Mm
Rx5days	Max 5-day precipitation amount	Monthly maximum consecutive 5-day rainfall	Mm
SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days (defined as PRCP ≥ 1.0 mm) in the year	Mm/day
Rx10 mm	Number of days with heavy precipitation	Annual number of days with PRCP ≥ 10 mm	Day

Continued

Rx20 mm	Number of days with very heavy precipitation	Annual number of days with PRCP ≥ 20 mm	Day
CWD	Consecutive wet days	Maximum number of consecutive days with RR ≥ 1 mm	Day
R95P	Very wet days	Annual total PRCP when RR > 95th percentile	Mm
R99P	Extremely wet days	Total annual PRCP when RR > 99th percentile	Mm
PRCPTOT	Annual Total Precipitation in Wet Days	Yearly total PRCP in wet days (RR ≥ 1 mm)	Mm

2.3.6. Trend Analysis

Trends were analyzed using linear regression between the different rainfall indices and time over the entire series. The slopes estimated in this way were grouped into three classes ([$p > 0.05$] insignificant, [$0.01 < p < 0.05$] significant and [$p < 0.01$]) highly significant, indicating upward or downward trends. The threshold is defined on the basis of the Student's t statistic, which is used to test the hypothesis of a slope equal to 0. The trend is therefore qualified as significant if the probability p of the t-test applied to the regression slope is less than 0.05, while it is not significant if it exceeds the 0.05 threshold.

2.3.7. Determination of Standardized Precipitation Index

To analyze extreme values, methods derived from the calculation of SPI "Standardized Precipitation Index" were used. SPI indices are used to measure the deviation from the long-term average at a point scale, based on station data. The Standardized Precipitation Index (SPI) (McKee et al., 1993) is used in this study. It has advantages in terms of statistical consistency and has the ability to describe both short-term and long-term extreme rainfall events across different time scales (McKee et al., 1993). It should be noted that the probabilistic nature of the SPI index allows it to be comparable between different sites (McKee et al., 1993). Based on daily rainfall for multiple time scales, these standardized indices (WMO, 2012) were calculated. In this case, the standardized index is based on the equiprobability of the transformation of rainfall values, aggregated at k-months, into normal standard values, with k generally set according to the objectives of the analysis, for example: $k = 1, 3, 6, 9, 12, 24, 36$ months (Cancelliere & Bonaccorso, 2009).

McKee et al. (1993) originally proposed a Gamma transformation for calculating the SPI index. This index is used at monthly or fortnightly time steps. Thus, the classic standardized index (noted Z) was used, but with a change of time step to the daily scale. It is a reduced-centered index, as indicated by the following formula:

$$Z = \frac{Xi - M}{S} \tag{6}$$

With Xi: rainfall in year i; M: mean interannual rainfall over the reference period and *S*: standard deviation of interannual rainfall.

These indices are used to define thresholds for extreme rainfall events, based on the classification of threshold values for the intensity of extreme rainfall events in **Table 3** of McKee et al. (1993).

Table 3. Classification of SPI values and event categories.

SPI threshold values	Extreme event category
2.00 and more	Extreme humidity
1.5 à 1.99	Severe humidity
1 à 1.49	Moderate humidity
0 à 0.99	Light humidity
−2.00	Extreme drought
−1.5 à - 1.99	Severe drought
−1 à - 1.49	Moderate drought
0 à - 0.99	Light drought

Source: Adapted from Aghrab (2003) and Mckee et al. (1993).

3. Results

3.1. Interannual Trends in Maximum Daily Rainfall from 1961-2022

In the context of climate change and the recurrence of extreme weather events, it is important to analyze trends in maximum daily rainfall so as to be able to take measures to prevent extreme rainfall events from damaging human and environmental systems.

Figure 2 illustrates the interannual variability of maximum daily rainfall in the Oti watershed in Togo.

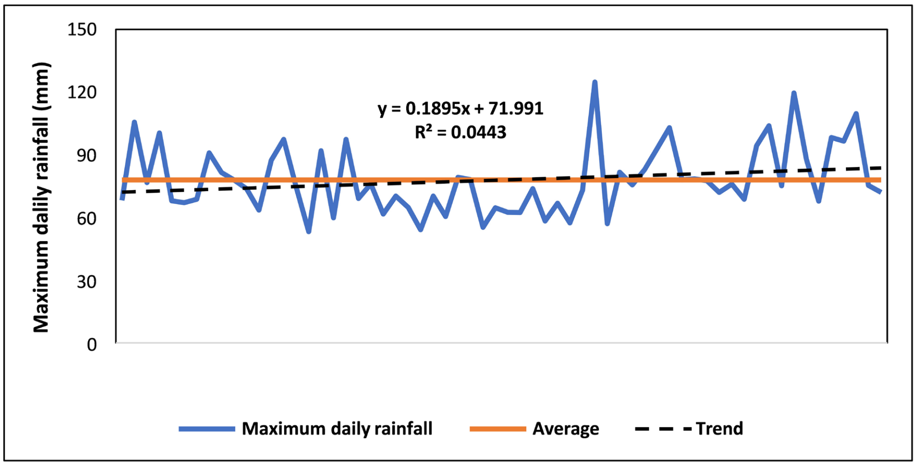

Figure 2. Interannual variation in maximum daily rainfall from 1961-2022.

Analysis of **Figure 2** reveals interannual variability in maximum daily rainfall in the Oti watershed in Togo. This indicates a non-statistically significant upward trend in maximum daily rainfall, with a positive slope. The calculated *p*-value (0.20) is above the significance level at the alpha value threshold of 0.05. Maximum daily rainfall varies from 53.22 to 124.90 mm in the watershed. The maximum daily rainfall for the entire series was 124.9 mm in 1999. The lowest value for maximum rainfall is 53.22 mm recorded in 1976. It should be noted that it is the accumulation of rainfall maxima that amplifies extreme rainfall events in the Oti watershed in Togo. This in turn increases run-off followed by flooding.

3.2. Stationarity Break in Maximum Daily Rainfall Series

Detection of breaks in the rainfall series by the Pettitt, Buishand and Hubert segmentation tests shows a change in the evolution of the rainfall chronicles. These three tests show a break in stationarity in the series. The null hypothesis of no break was rejected at the 95% and 90% confidence levels, with a probability of exceeding the critical value of 1.30E−02. **Figure 3** shows the Pettitt test applied to the annual maximum rainfall series (1961-2022) in the Oti watershed.

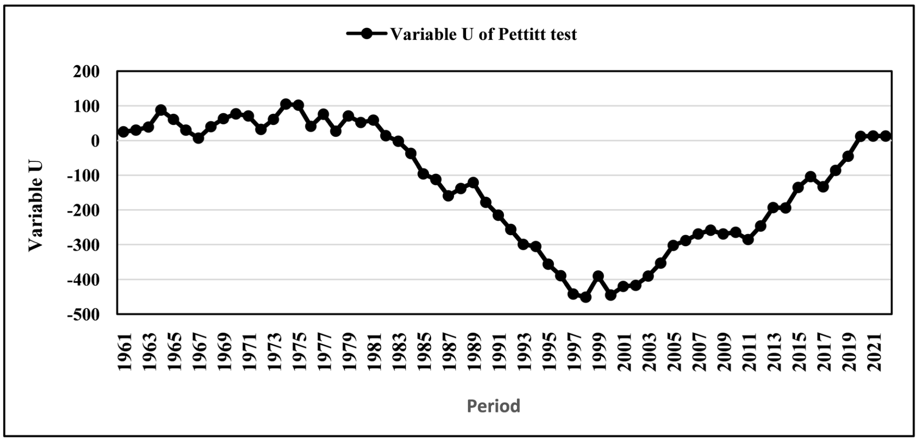

Figure 3. Break in stationarity of maximum daily rainfall.

Analysis of **Figure 3** shows that, at the 99% threshold according to the Pettitt tests, annual rainfall levels show interannual variability, with a break in rainfall in 1998. The break was observed in 1998, showing a change in the rainfall series, dividing the series into two sub-periods, confirmed by Hubert segmentation with Scheffé test significance level of 1%. The first subperiod (1961-1998) is marked by a dry phase, with a mean rainfall of 72.72 mm and a standard deviation of 13.44. In fact, the 1961-1998 sub-period is divided into two phases, the first of which is characterized by a wet period (1961-1979) with an average rainfall of 79.19 mm. The second phase (1980-1998) was a dry period, with maximum daily rainfall dropping by 12.95 mm to an average of 66.24 mm. This decline is followed by a slight upturn in rainfall that begins in 1999 and continues until 2022. By contrast, the second sub-period (1999-2022) in the series is characterized by a wet phase, with mean precipitation of 86.26 mm and a standard deviation of 17.08, confirming a slight upturn in precipitation in the watershed. This upturn in precipitation is accompanied by extreme rainfall events.

3.3. Interannual Variability of Observed and Simulated Rainfall from 1961 to 2005 in the Oti Watershed in Togo

The need for information on climate change at regional and local scales is one of the crucial concerns for assessing the impact of climate change on human and natural systems, and for developing sound national adaptation and mitigation strategies. The "Coordinated Regional climate Downscaling Experiment" (CORDEX) was set up to fill this gap and reduce uncertainties in the analysis of climate information. This program aims to produce reliable climate scenarios for impact studies over most of the world's landmass, using Regional Climate Models (RCMs).

Figure 4 shows the interannual variability of observed and simulated rainfall in the Oti watershed in Togo, based on data from the African Cordex program.

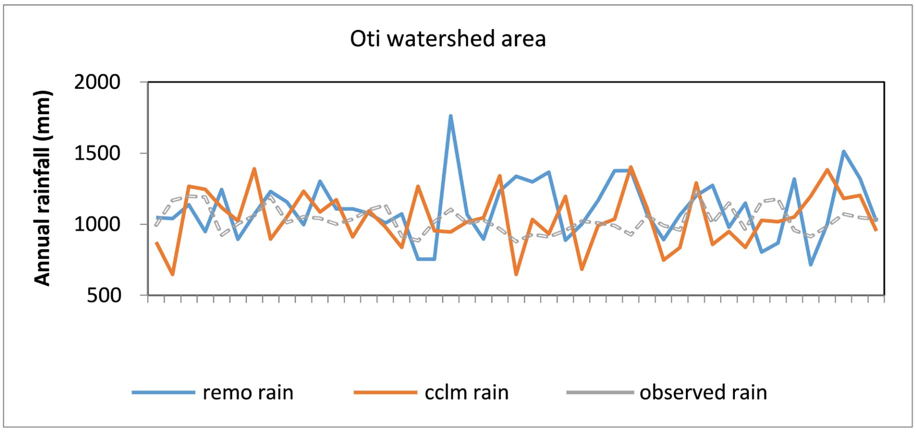

Figure 4. Interannual variability in observed and simulated rainfall in the Oti watershed in Togo from 1961 to 2005.

Analysis of **Figure 4** shows that the cumulative rainfall simulated by the models and that observed have almost the same trend. **Figure 4** shows that both models overestimate observed rainfall in the study area. It should be noted that the CCLM4.8 model overestimates observations less than REMO. This is justified by the difference values of 1.95 for CCLM4.8 and 8.53 for REMO. Cumulative annual rainfall varies from 715.3 mm to 1762.2 mm for REMO, while the CCLM4.8 shows cumulative precipitation ranging from 646.7 to 1402.1 mm. At the same time, observations vary from 878.4 mm to 1233.3 mm.

3.4. Rainfall Regime of Observed and Simulated Rainfall Amounts with the Output of the African Cordex RCM 1961-2005 for the Oti Watershed in Togo

The Oti watershed in Togo has a tropical Sudanian climate. It is the displacement of the Intertropical Front (ITF) that explains the seasonal nature of the climate, marked by alternating rainy and dry seasons. The rainfall regime provides information on the amount of monthly rainfall recorded in a given year and the periods of rainfall extremes in the watershed. The aim here is to compare the observed and simulated rainfall patterns of the models in order to see which model best represents the reality of observations in the Oti watershed in Togo.

Figure 5 shows the rainfall pattern of observed and simulated rainfall amounts from 1961 to 2005. This will enable the REMO and CCLM4.8 models and the mean climatological regime of the study area as a whole to be evaluated to see whether these models are suitable for the seasonal study.

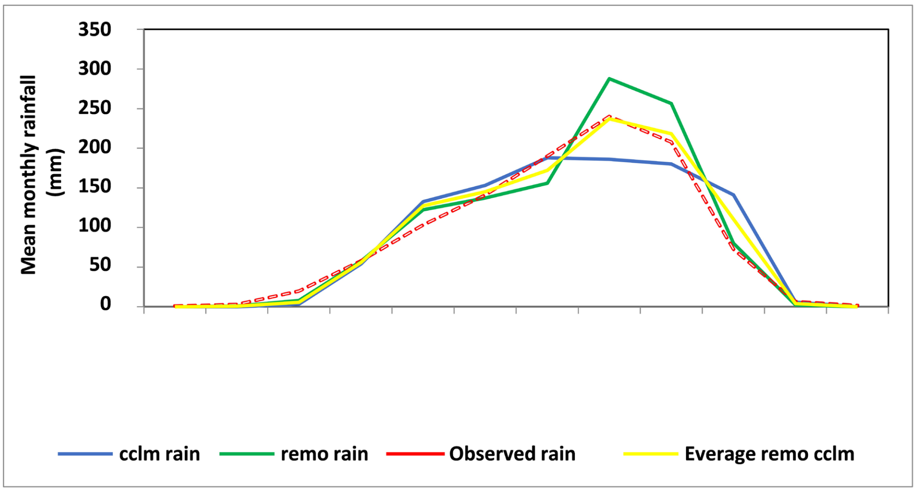

Figure 5. Schematic diagram of observed and simulated rainfall based in the Oti watershed in Togo.

Figure 5 shows that the two models are close to the observed rainfall and tend to represent the rainfall regime towards a unimodal rainfall regime for the observed rainfall in the Oti watershed, which peaks in August. The REMO model overestimates the observations, while the CCLM4.8 model underestimates them by 6.27 and 0.01 respectively. It should be pointed out that they reproduce the seasonal variability of rainfall within the same region and in the same sector in different ways, which is likely to influence the variability of cumulative rainfall and the choice of the appropriate model. From this observation, it should be noted that CCLM4.8 reflects the reality of observations and is suitable for seasonal analysis in the Oti watershed in Togo. The CCLM4.8 model was therefore chosen to project rainfall in the Oti watershed in Togo.

3.5. Rainfall Projections under RCP 4.5 and RCP 8.5 Scenarios for the Period 2025-2069

Climate projections are needed to analyze future rainfall extremes under the RCP 4.5 and RCP 8.5 scenarios for the period 2025-2069 in the Oti watershed. The CORDEX program in West Africa offers data from several models and concerns historical data and data projected to 2100. For this study, the analysis of extreme rainfall data is carried out taking into account the period 2025-2069 with the RCP

4.5 and RCP 8.5 scenarios for the Oti watershed in Togo. This period covers 44 years and is linked to the reference period (1961-2005) for evaluating the performance of the RCM.

Figure 6 shows the precipitation trends for 2025-2069 in the CCLM4.8 model according to the RCP 8.5 and RCP 4.5 scenarios.

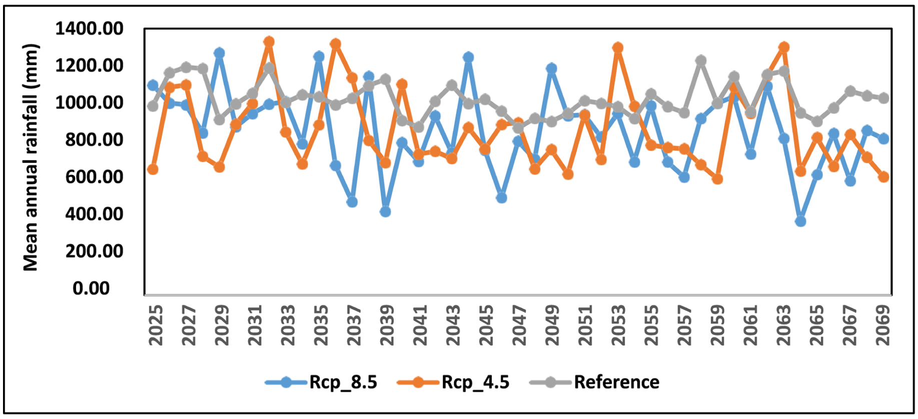

Figure 6. Observed and simulated rainfall trends.

Analysis of Figure 6 reveals interannual variability in future rainfall for the RCP 4.5 and RCP 8.5 scenarios and the reference rainfall for the period 2025-2069 in the Oti watershed in Togo. The RCP 4.5 and RCP 8.5 scenarios underestimate the reference rainfall, with differences of −0.15 for each RCP. This shows that with RCP 4.5 and RCP 8.5, rainfall in the CCLM4.8 model will decrease by 2025-2069.

3.6. Changes in Maximum Daily Rainfall Under RCP 4.5 and 8.5 Scenarios for the Period 2025-2069

Figure 7 shows daily rainfall variability in the Oti watershed in Togo from 2025 to 2069.

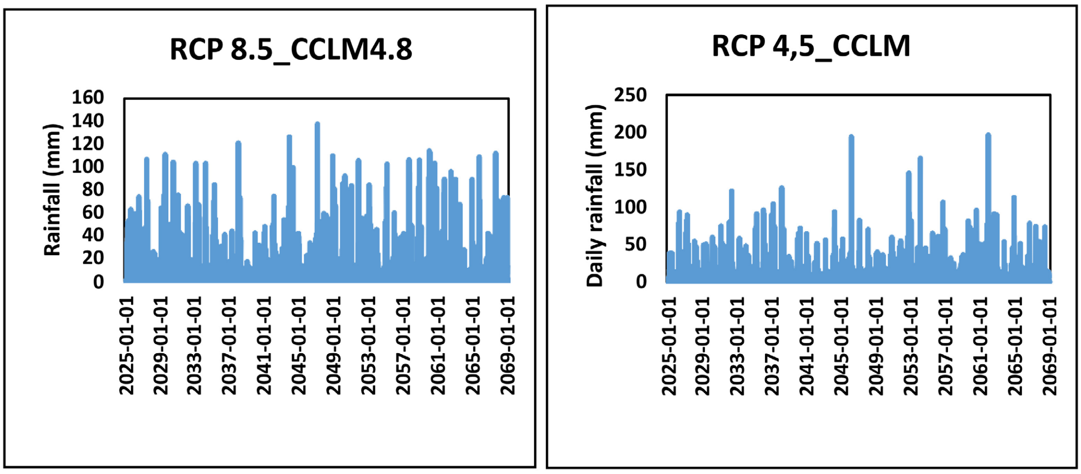

Figure 7. Interannual variability of extreme daily rainfall.

Figure 7 shows the daily rainfall variability projected from 2025 to 2069 in the Oti watershed in Togo. The simulated daily rainfall varies from 1 mm to 137.95 mm with an average of 2.36 mm for the RCP 8.5 scenario and from 1 to 196.52 mm with an average of 2.38 mm for the RCP 4.5 scenario. The change in daily rainfall by 2069 will therefore be accompanied by an increase in run-off and, consequently, recurrent flooding over this period.

3.7. Interannual Variability of Standardized Precipitation Index

A study of the projected interannual variability of precipitation from 2025-2069, using rainfall indices and their smoothing by five-year rolling averages in the Oti basin (Figure 8) with RCP 8.5 and RCP 4.5, shows that positive anomalies characterize wet years and negative anomalies present dry years.

Analysis of Figure 8 reveals that the period from 2025 to 2069 is marked by two rainfall phases in the two scenarios (RCP 8.5 and RCP 4.5). For RCP 8.5, the first phase runs from 2025 to 2038, reflecting a wet period. Of the 14 years in this period, 10 have recorded positive standardized precipitation indices and only 4 negative anomaly indices. Average rainfall during this period for RCP 8.5 is 962.05 mm. At the same time, for RCP 4.5, the first phase runs from 2025 to 2037, i.e. 13 years with 8 years of positive anomalies and 5 years of negative anomalies. The average rainfall over this period for RCP 4.5 is 954.56 mm. Generally speaking, positive anomalies are frequently observed during this wet period.

On the other hand, the second phase is marked by a dry period for both scenarios (RCP 8.5 and RCP 4.5), reflecting the rainfall deficit. The dry period runs from 2039 to 2069, i.e. 30 years of rainfall deficit for the RCP 8.5 scenario. This period is characterized by a high frequency of negative anomalies. Over the 30 years, 19 years have negative anomalies and 11 are positive. Average rainfall during this dry phase is 818.52 mm. RCP 4.5 is also marked by a long dry period from 2038 to 2069, with average rainfall of 837.46 mm. Over the 31-year period, 21 years recorded negative anomalies and 10 years positive anomalies.

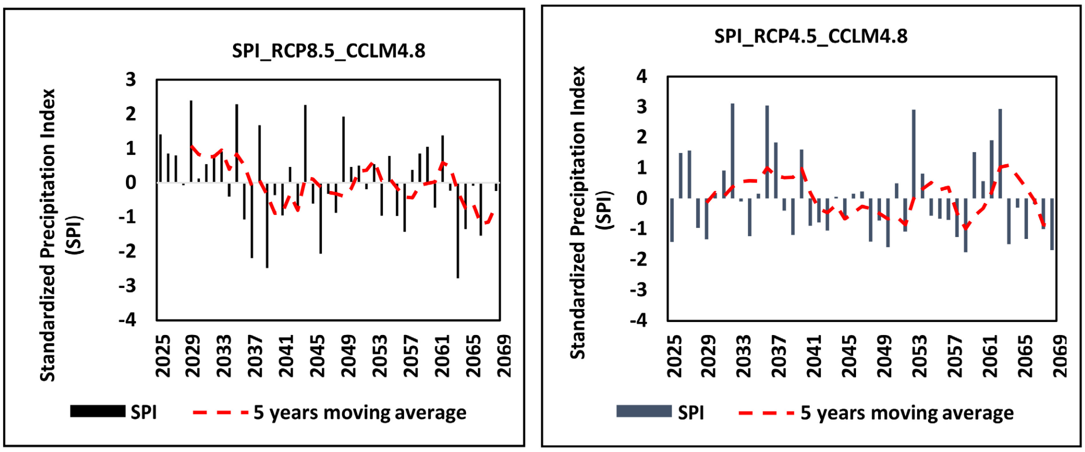

Figure 8. Intercomparison of RCP 8.5 and RCP 4.5 from standardized precipitation index.

3.8. Spatial Variation of Observed and Simulated Mean Annual Rainfall

In the case of the flood risk study, it is important to project the rainfall field in the Oti watershed in order to see the sectors that will record the most rainfall by 2069. This makes it possible to determine the amount of rain that will fall on the watershed under both RCP 8.5 and RCP 4.5.

Figure 9 shows the distribution of observed and simulated mean annual rainfall fields in the Oti watershed for 1961-2005 and 2025-2069.

Analysis of **Figure 9** shows that rainfall increases from north to south, indicating a variation in mean annual rainfall in the watershed. The reference rainfall varies from 975 mm in the north to 1131 mm in the south and is distributed along an increasing north-south gradient. RCP 8.5 varies spatially from 816 mm in the north to 924 mm in the south and RCP 4.5 varies from 825 mm to 935 mm. In fact, the south is the wettest part of the basin, with average annual rainfall in excess of 1000 mm. The north-east (Mandouri) receives little rainfall, with average annual rainfall always below 1000 mm.

Generally speaking, the south of the watershed (downstream) will record more rainfall than the north (upstream) according to the RCP 4.5 and RCP 8.5 scenarios of this model. The models predict an increase in rainfall from the north to the south of the watershed, indicating a more accentuated decrease near Mandouri in the northeast and to the northwest at Dapaong.

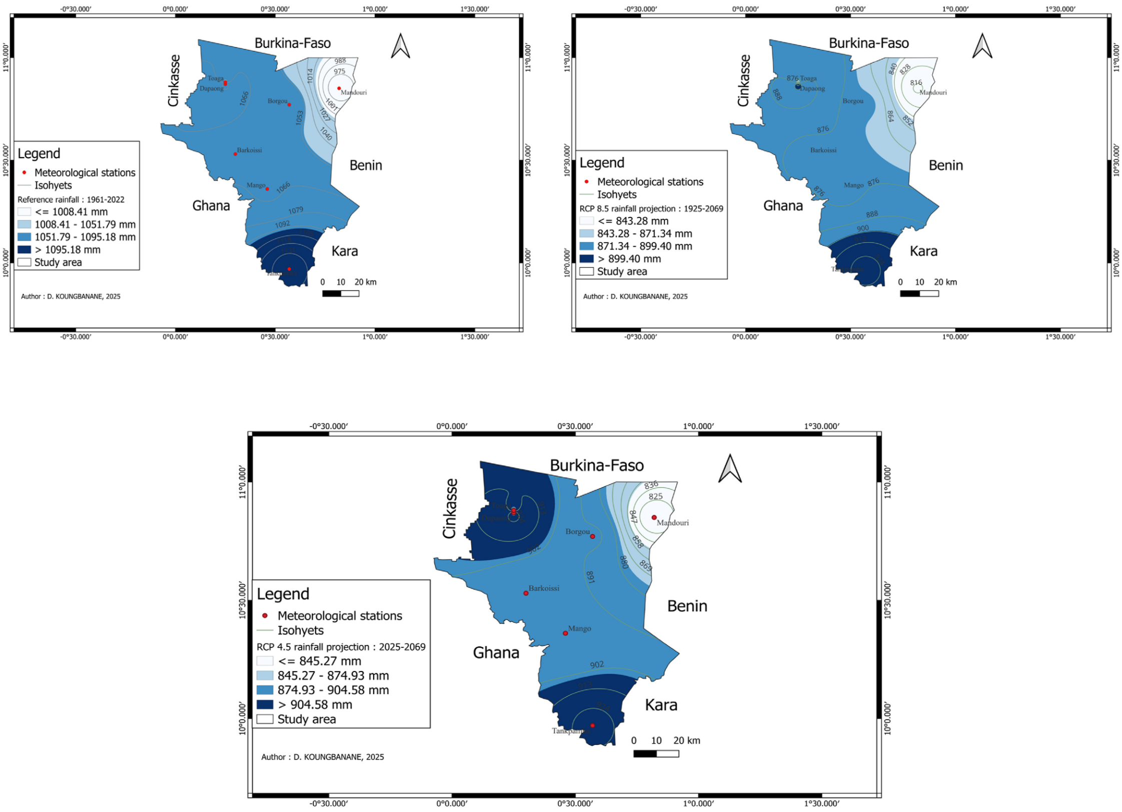

Figure 9. Average annual rainfall fields observed and simulated by the CCLM4.8 model.

3.9. Variability of Extreme Rainfall Events with Observed Rainfall

Table 4 shows the nine climatic indices calculated to characterize extreme rainfall events observed in the Oti watershed in Togo. These are PRCPTOT, SDII, R10 mm, R20 mm, R95P, R99P, Rx1day, Rx5days and CWD.

Table 4. Characteristics of the 1961-2022 climate index trend.

Observed rainfall		
Indices	**Slope**	***p*-value**
PRCPTOT	0.93	0.40
SDII	−0.01	0.27
Rx10 mm	−0.04	0.37
Rx20 mm	−0.01	0.70
R95P	−0.17	0.83
R99P	0.33	0.49
Rx1days	0.16	0.20
Rx5days	0.02	0.90
CWD	0.03	0.34

Analysis of Table 4 shows that total annual rainfall in rainy days (PRCPTOT) in the Oti catchment in Togo is increasing and varies from 665.5 mm to 1373.5 mm. The positive value of the slope (0.93) confirms the non-statistically significant increase, with an estimated *p*-value of 0.40. In contrast, the daily rainfall intensity (SDII) showed a non-significant decrease with a *p*-value of 0.27. The indices for the number of days with rainfall of more than 10 mm (R10 mm) and 20 mm (R20 mm) show a non-significant downward trend, with *p*-values of 0.37 and 0.70 respectively. Rainfall amounts associated with the 95th percentile vary from 28.4 to 511.1 mm and are considered to be very heavy rainfall events in the study area. These 95th percentile rainfall amounts show a non-significant downward trend, with a *p*-value of 0.83. On the other hand, at the 99th percentile, rainfall amounts vary from 1 to 260.4 mm and are described as extremely heavy in the catchment area. This index shows a statistically insignificant upward trend, with a *p*-value of 0.49.

There is an upward trend in the maximum total rainfall indices for one rainy day (Rx1day) and five consecutive rainy days (Rx5days). The respective p-values are 0.20 and 0.90. Analysis of the maximum number of consecutive days of rainfall in excess of 1 mm in the watershed provides a better understanding of the extreme rainfall phenomenon. The CWD shows a non-significant upward trend, with a p-value of 0.34.

3.10. Variability of Simulated Extreme Rainfall Events in the Oti Watershed between 2025 and 2069

Table 5 shows the characteristics of the trends in extreme rainfall events simulated using nine climate indices under the RCP 8.5 and RCP 4.5 scenarios from 2025 to 2069.

Table 5. Trend characteristics of nine climate indices.

Simulated rainfall indices				
RCP 8.5			**RCP4.5**	
Indices	Slope	*p*-value	Slope	*p*-value
Rx1days	0.36	0.29	0.33	0.46
Rx5days	−0.001	0.99	0.59	0.34
SDII	0.002	0.91	−0.004	0.79
Rx10 mm	−0.14	0.01	−0.09	0.11
Rx20 mm	−0.06	0.09	−0.03	0.23
CWD	−0.11	0.05	−0.10	0.17
R95P	−1.30	0.54	−0.88	0.62
R99P	1.82	0.16	0.48	0.73
PRCPTOT	−4.77	0.05	−2.59	0.28

Analysis of Table 5 shows that, according to the CCLM4.8 model, climate indices such as Rx1day, SDII and R99P will show a non-significant upward trend from 2025 to 2069 for RCP 8.5, as shown by their slope and *p*-value. The rest of the indices will show an insignificant downward trend. For the RCP 4.5 scenario, on the other hand, the Rx1day, Rx5days and R99P will rise over the same period and the rest of the climate indices will fall.

4. Discussion

This study analyses extreme rainfall events in the Oti watershed in Togo using simulated data from two models (CCLM4.8 and REMO) from the CORDEX program and observed station data. The results show interannual variability in observed and simulated rainfall. The rainfall of the two models overestimates observed rainfall. Between the two models, the CCLM4.8 overestimates the observations less than REMO in relation to the calculated biases. This enabled the CCLM4.8 to be validated for projecting future rainfall in the study area, as it is more realistic than REMO. These results corroborate the research of (Tramblay et al., 2012) who find that regional climate models (RCMs) reproduce rainfall differently for the same study area. This point was raised by (Mascaro et al., 2015; Taïbi-Freddal, 2016; Kodja, 2018), when they found that some models overestimate observations while others underestimate them.

An uneven distribution of observed and simulated mean annual rainfall is recorded over the whole Oti watershed in Togo, following a decreasing south-north gradient showing a significant accumulation of water downstream of the watershed. This situation could be explained by the orographic effect, as the south benefits from the effect of orographic rainfall from the extension of the Togo mountains. Similarly, the Atacora to the east plays an amplifying role in rainfall in the Oti watershed and the transfer of water from upstream to downstream. This phenomenon has already been reported by (Klassou, 1996; Amoussou, 2010; Houessou, 2016) in the Mono basin in Benin and Togo.

According to the CCLM4.8 model, rainfall is set to fall over the period 2025-2069 under the RCP 4.5 and RCP 8.5 scenarios. This is in line with the study by (Diallo et al., 2012), whose results from three regional models under the RCP4.5 and RCP8.5 scenarios show a general downward trend in average rainfall in West Africa. Similarly, (Tall et al., 2019) predict a decline in rainfall for the distant future. The study showed a non-statistically significant upward trend in maximum daily rainfall in the Oti watershed in Togo. However, the link between cumulative maximum rainfall and runoff in the Oti watershed should be emphasized. The cumulative daily maximum can have repercussions on runoff. This finding has already been reported by (Totin et al., 2016; Koumassi, 2014; Amoussou et al., 2012; Amoussou, 2015; Kodja, 2018). For these authors, maximum daily rainfall is an indicator for assessing rainfall hazards in the wet season or during periods of high rainfall intensity, which leads to flooding.

The results also show monthly variability in rainfall across the watershed, indicating that the wettest or rainiest months are August and September. This indicates the unimodal nature of the climate in the study area, with a single rainy season and a single dry season. The same observation was made by (Baritsé, 1986; Kankpénandja, 2002; Adéwi, 2012; Badjana et al., 2014) in the Oti Basin in Togo. These wettest months constitute the period during which cumulative rainfall causes high water followed by flooding in the Oti watershed in Togo. This observation corroborates the results of (Totin et al., 2016; Kodja, 2018) in the Ouémé watershed in Benin. The period from May to October is marked by a slight dip in August. Overall, this is the period during which cumulative rainfall contributes to replenishing water stocks in soil horizons and replenishing underground reservoirs. This phenomenon would be more noticeable in the downstream part of the basin due to the differential hydrodynamics associated with the geological bedrock in place and the topography of this part of the basin. These results confirm those of Atchadé (2014); Kodja (2018) in Benin. Under these conditions, any change in rainfall patterns during these months would disrupt the hydrogeological functioning of the basin, with slightly more acuity in the downstream part of the basin. Similarly, the REMO model overestimates observations and the CCLM4.8 underestimates them, reflecting the different reproduction of seasonal rainfall variability within the same area. This corroborates with the results of Taïbi et al. (2015); Kodja (2018).

The results for the nine climate indices calculated to characterise extreme rainfall events in the Oti watershed in Togo show that the PRCPTOT, R99P, Rx1day, Rx5days and CWD indices showed a non-statistically significant increase between 1961 and 2022. The upward trend in these indices is characteristic of extreme rainfall events in the watershed. This increases runoff and consequently the recurrence of floods in the Oti watershed in Togo. This corroborates the results of (Issaou, 2014) in Togo. These results are consistent with those of (Houngue̒ et al., 2019), who reported a clear increase in extreme rainfall, extremely heavy rainfall and consecutive maximums over 1, 2, 3, 5 and 10 days in the Ouémé delta (Benin). In addition, (Dike et al., 2020) noted a significant increase in total rainfall on wet days over the 39-year observation period, as well as in cumulative rainfall over 5 consecutive days.

In addition, the SDII, R10 mm, R20 mm and R95p indices show an insignificant downward trend from 1961-2022. The downward trend in these indices should help to reduce flooding in the watershed. On the other hand, flooding has recurred in recent decades in the Oti watershed in Togo. It is therefore likely that the increase in flooding is linked to an increase in vulnerability, particularly in the absence of territorial planning, rather than to the hazard, as various studies have already suggested (Descroix et al., 2013; Ozer, 2014; Hangnon et al., 2015). The same observations were made by (Ozer et al., 2015). The Rx1 day, SDII and R99P rainfall indices simulated by the CCLM4.8 model will show an upward trend from 2025 to 2069 for RCP 8.5. This corroborates the results of several studies (Koala et al., 2023; Famien, 2020; Sarr, 2017). For the RCP 4.5 scenario, Rx1day, Rx5 ays and R99P will also increase over the same period, while the rest of the climate indices will decrease. This finding corroborates the results of work by (Totin, 2009), based on the PRECIS/ECHAM4-A2 model, (Houngue̒ et al., 2019) using the UKhadCM3 model and (Kodja, 2018). Thus, increased rainfall according to PCR 4.5 and PCR

8.5 with extreme rains could lead to flood risks in the study area. Abiodun et al. (2017) had previously shown that the projected rising rainfall trend of the general circulation model leads to a likely increase in extreme rainfall events in West Africa.

5. Conclusion

The analysis of extreme rainfall events in the Oti watershed in Togo with simulated and observed rainfall shows a spatio-temporal variability of the annual mean rainfall fields as well as the daily maximum rainfall. The distribution of rainfall follows a decreasing south-north gradient in the watershed. The simulated rainfall overestimates the observed rainfall with a difference of 1.95. According to the CCLM4.8 model, rainfall will decrease during the period 2025-2069 depending on whether we are with the RCP 4.5 and RCP 8.5 scenarios. So, this study will also enable us to prepare accordingly in terms of climate variability adaptation and mitigation strategies, in order to avoid the scale of impacts using past and current climate, as well as possible future impacts as the climate continues to vary and change. This provides an early warning of extreme rainfall events.

The examination of the different rainfall indices calculated from the observed rainfall to characterize extreme rainfall events in the watershed shows a statistically non-significant upward trend in PRCPTOT, R99P, Rx1day, Rx5days and

CWD on the one hand, and a non-significant decrease in the SDII, R10 mm, R20 mm and R95p indices on the other hand. For the simulated rainfall, climate indices such as Rx1day, SDII and R99P will experience a non-significant upward trend from 2025 to 2069 for RCP 8.5. In the same sense, the RCP 4.5 scenario predicts an increase in the Rx1day, Rx5days and R99P indices. The trend in these indices justifies the recurrence of floods and consequently flooding in the Oti watershed in Togo. This study provides a clearer picture of how extreme rainfall could change and constitutes a tool to support planning and flood risk management in the context of climate change and the high vulnerability of populations in the Oti watershed in Togo.

The strength of this study lies in the analysis of extreme rainfall events using observed station data and regional climate model data. This study used innovative methodology such as SPI, climate indices and multivariate methods such as the Pettitt test.

The limitation of this study is that it used only the two models' data to analyze extreme rainfall events in the study area. In addition, it did not include an analysis of flows in the watershed as a function of the evolution of extreme rainfall events. The limitation of this study is the failure to determine return periods through frequency analysis of maximum daily rainfall.

Acknowledgments

This document was produced with the financial support of the Pice Albert II of Monaco Foundation. The contents of this document are solely the liability of Dambré Koungbanane and under no circumstances may be considered as a reflection of the position of the Prince Albert II of Monaco Foundation and/or the IPCC.

Conflicts of Interest

The authors declare no conflicts of interest.

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