

Analysis of past and projected changes in extreme precipitation indices in some watersheds in Côte d'Ivoire

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ABSTRACT

The purpose of this study is to analyse trends in annual rainfall extremes over five watersheds within Côte d'Ivoire using observed (1976–2017) and projected (2020–2050) rainfall data from the fourth version of the Rossby Centre regional atmospheric model, RCA4, for the representative concentration pathways RCP 4.5 and RCP 8.5. Four rainfall extreme indices, namely, the consecutive dry days (CDD), maximum annual rainfall (Pmaxan), very wet day (R95p), and maximum 5-day rainfall (Rx5days), were considered for trend analysis by using the non-parametric modified Mann–Kendall test and the distribution mapping bias-correction technique to adjust the simulated regional climate model of the simulated daily precipitation. As a result, it is found that during the period 1976–2017, there was a significant downward trend in the drought-related index (CDD) at the Bagoue, Baya, Agneby, and Lobo watersheds. The Baya and N'zo watersheds also experienced a significant downward trend under the RCP 4.5 and RCP 8.5 scenarios. The flood-related indices (Pmaxan, R95p, and Rx5days) show a clear downward trend in the recorded data for almost all the considered watersheds and generally a significant upward trend for both cases. These findings indicate that the watersheds are vulnerable to climate-induced disasters.

Key words: extreme rainfall, modified Mann–Kendall, RCA4, RCPs, trend analysis

HIGHLIGHTS

- This article is an original work.
- This article analyses the past and projected changes in extreme precipitation indices.
- This article allows us to see the past and projected changes in extreme precipitation indices under different climate zones in Cote d'Ivoire.
- This article allows us to see a great change in extreme precipitation indices under different climate zones in Cote d'Ivoire in the near future.

1. INTRODUCTION

Extreme hydrological events such as floods and droughts have become more frequent in recent decades as a result of climate change. Indeed, according to the IPCC (2001), global warming has indeed led to a level of extreme temperature events in many parts of the world. In Africa, hydrological extremes were observed with almost recurrent frequency over the last few decades. The northern part of Africa is faced with increasingly dry trends, although these trends are not significant (Donat *et al.* 2014). In sub-Saharan Africa, several studies have been devoted to the analysis of climate extremes. Some have shown an increase in extremes, as was the case in Niger (Velia *et al.* 2018), Burkina Faso (Okafor *et al.* 2021), Nigeria (Adeyeri *et al.* 2019), and Côte d'Ivoire (Assa *et al.* 2020). On the contrary, decreasing trends in extremes are reported in Nigeria by Oguntundé *et al.* (2011), in Guinea-Conakry by Aguilar *et al.* (2009), in eastern Niger by Ozer *et al.* (2009), as well as in Côte d'Ivoire by Soro *et al.* (2016). These works demonstrate contrasted patterns of climate extremes throughout the west African region, necessitating a detailed assessment of trends in extremes across the region.

In the specific case of Cote d'Ivoire, extreme events, especially floods, have become annual natural disasters resulting in significant material damage and loss of lives (Assoma *et al.* 2016; Kouassi *et al.* 2020). According to Assoko *et al.* (2020),

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Côte d'Ivoire endured extended periods of drought in 2018 in many of its cities, including Bouaké, Korhogo, Tiébissou, Niakaramandougou, Odienné, etc. This made it difficult for the nation to supply these towns with drinking water. In contrast to these cities, disastrous floods caused horrendous devastation in Abidjan, Zuenoula, Bouaflé, Tiassalé, Toulepleu, N'douci, Sassandra, Fresco, Gagnoa, Korhogo, Ferké, and Agboville (RNC 2021). Therefore, more understanding of extreme phenomena to minimize their consequences through trend analysis of past data and monitoring their evolution in the near future has become urgent for the country. It is the focus of this study, which selected five catchments (Lobo, N'zo, Agneby, Kouto, and Baya) for the trend analysis of extremes. The selected watersheds have been the subject of several studies, notably on climate variability and water resources (Affoué *et al.* 2016; Kouakou *et al.* 2016; Adja *et al.* 2019; N'Guessan Bi *et al.* 2020). However, most of these variability studies analysed data that stopped in the 2000s without much insight into trend analysis. But trend analysis is important because it offers the opportunity to know the short-, medium-, and long-term evolution of hydrological extremes to provide adaptive solutions to reduce the vulnerability of low-income people. In addition, the selection of the five catchments located in different climatic zones offers the possibility of comparing outputs and drawing conclusions on the differences and similarities of extreme events in different climatic areas.

Therefore, this research aimed to analyse the extreme rainfall trends in the context of future climate change over five selected watersheds in Côte d'Ivoire. It focused on assessing historical trends in climate extremes as well as future changes for the period 2020–2050 under two climate scenarios, namely RCP4.5 and RCP8.5, by using data from the fourth version of the Rossby Centre regional atmospheric model, RCA4. This study is particularly significant because it provides a chance to understand how hydrological extremes have evolved in the past and will evolve in the future. This knowledge will allow researchers to come up with adaptable solutions to lessen the study areas' susceptibility to the effects of extremes. Furthermore, to avoid severe floods and droughts, a better understanding of predicted future changes in water supply in connection to extreme variables is required. This is owing to the fact that the effects of climate change are already having an influence on the country, with a dramatic increase in erosion, resulting in the circulation of undesired sediments or the leaching of agricultural toxins that might contaminate the water due to the recurrence of floods. Furthermore, during low-water periods, the amount of water decreases as the temperature rises, resulting in accelerated heating of the water, which promotes the growth of algae in the various watercourses. As a result, the study will provide information that will allow policies and strategies to be developed to assist the study region in preparing for any potential challenges induced by climate change, and to plan for floods and droughts, which can affect population food supplies, as well as flooding, pollution, river bank collapse, and erosion.

2. MATERIALS AND METHODS

2.1. Study area

Côte d'Ivoire is a country located in West Africa, bordered by Liberia, Guinea, Mali, Burkina Faso, and Ghana. The study area is situated in Côte d'Ivoire and comprises five watersheds, which are N'zo, Nibéhibé, Agneby, Bagoue, and Baya (Figure 1).

The N'zo watershed is located in the western part of the country, near the border with Liberia and situated between latitudes 6°50' and 7°50' North and longitudes 7°15' and 8°05' West (Michel *et al.* 2021). It covers an area of approximately 4,300 km² (Oularé *et al.* 2017). It has unimodal rainfall season with mean annual rainfall of between 1,600 and 2,000 mm (Amichiatchi *et al.* 2023). The N'zo River is the main river in the watershed, and it is fed by several smaller streams and tributaries.

The Lobo watershed in Nibéhibé is situated between 6°17' and 6°44' West longitude and 6°46' and 7°41' North latitude in the central-western region of Côte d'Ivoire with an area of 6,923 km² (Toure *et al.* 2022). According to the Ministry of Water and Forests of Côte d'Ivoire (2018), the watershed is mainly rural, with agriculture being the primary economic activity. Crops such as cocoa, coffee, and palm oil are grown in the area, and there is also some livestock production. It is home to around 1,103,059 people (INS 2014; Kamenan *et al.* 2020) and is primarily rural, with agriculture as the primary economic activity. A dry season from November to February and a wet season from March to October with little temperature variation define the basin's transitional equatorial climate (Yao 2015). The Nibéhibé River is the main river in the watershed, and it flows into the Bandama River, which is the largest in the country.

The Agneby watershed is located in the southern part of the country, covering an area of approximately 4,000 km² (Ministry of Water and Forests 2018). The West African Monsoon is responsible for shaping the local climate (Kouakou *et al.* 2016). The local climate of the Agneby watershed is shaped by the seasonal south-north oscillation of two air masses: the

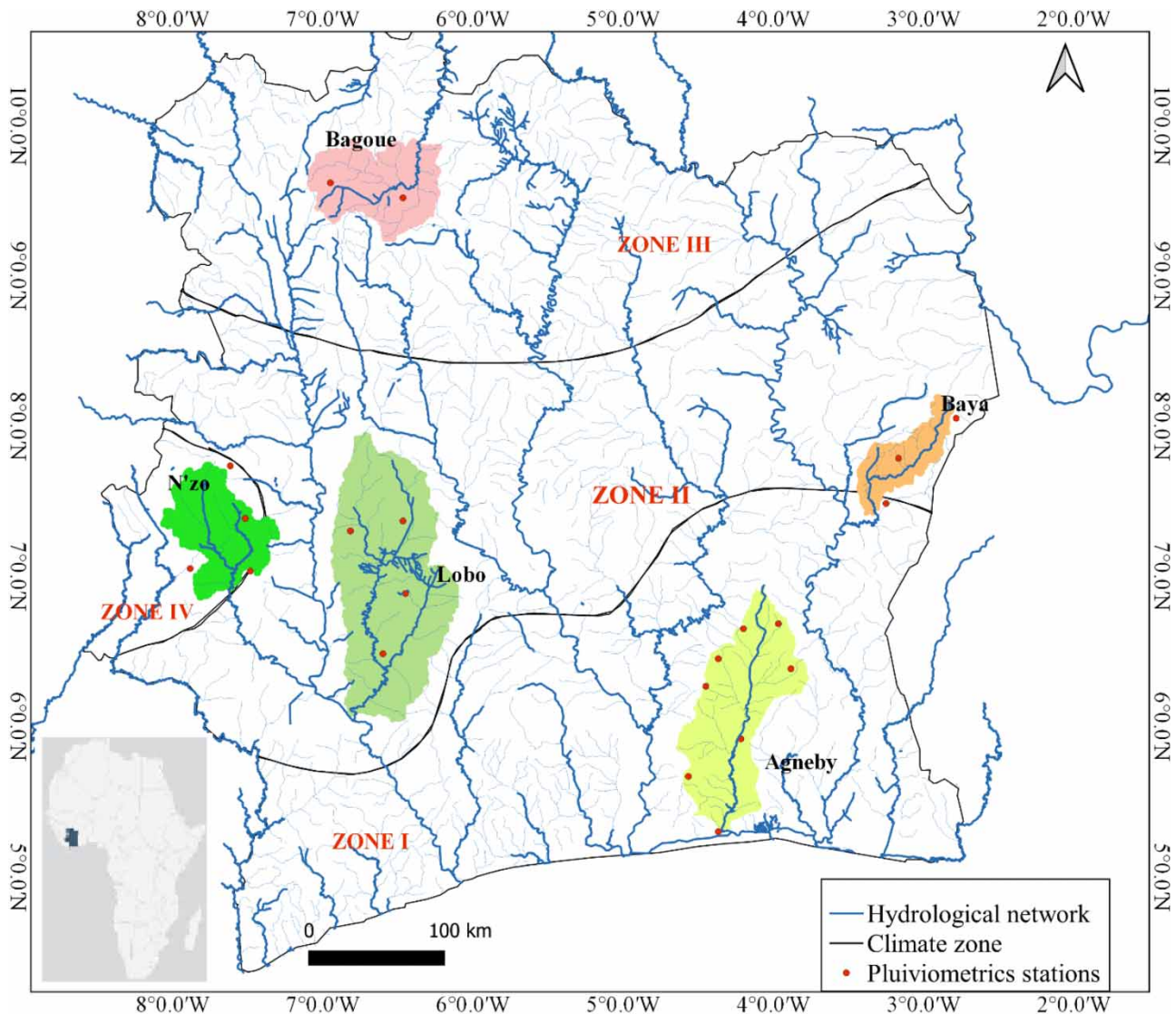


Figure 1 | Location of the five selected watersheds within the different climatic zones in Côte d'Ivoire.

dry continental air mass known as harmattan and the moist oceanic monsoon (Kouakou *et al.* 2016). The Agneby River is the main river in the watershed, and it flows into the Ébrié Lagoon, which is connected to the Gulf of Guinea (Ministry of Water and Forests 2018).

The Bagoue watershed is located in the northern part of the country, covering an area of approximately 33,430 km² extending from Côte d'Ivoire to Mali and Niger (N'da SA *et al.* 2015). The Bagoue watershed is characterized by the two-season Sudano-Guinean climate – a wet season from May to October and a dry season from November to April (Soro *et al.* 2014). The Bagoue River is the main river in the watershed, and it flows into the Sassandra River, which is the second-largest in the country.

The Baya watershed is located in the northeastern part of the country, covering an area of approximately 6,324 km² (Mangoua *et al.* 2015). Baya watershed has a humid tropical climate with 1,200 mm annual rainfall (Amichiatchi *et al.* 2023). The Baya River is the main river in the watershed, and it flows into the Comoé River, which is the third-largest in the country (Ministry of Water and Forests 2018).

Overall, these five watersheds in Côte d'Ivoire are important for their ecological, economic, and social value (Ministry of Water and Forests 2018). They provide important habitats for wildlife, support agriculture and other economic activities, and are important sources of water for people and ecosystems (Ministry of Water and Forests 2018). However, they also face a

range of challenges, including climate change, pollution, and deforestation, which can have negative impacts on their ecological and social value (Ministry of Water and Forests 2018).

2.2. Data used

This research used two types of data. The first type consists of daily recorded rainfall data from 21 rainfall stations spread over the selected watersheds from 1976 to 2017. The data were obtained from the database of the Airport, Aeronautical, and Meteorological Exploitation and Development Company (SODEXAM) of Côte d'Ivoire. Stations were chosen based on the number of years of observation, allowing us to have good spatial representativeness and statistical information, as shown in Table 1. The missing data were filled by using rainfall data from Africa Rainfall Climatology 2.0 (ARC2™) estimated by the Climatology 2.0 (ARC2™) rainfall data estimated by the National Oceanic and Atmospheric Administration (NOAA) (Xie & Arkin 1996, p. 843; Novella & Thiaw 2013, p. 590) and before using the Africa Rainfall Climatology 2.0 (ARC2™) data to fill in the missing data from the ground stations (SODEXAM), correlation tests between the different datasets were performed using Pearson's correlation coefficient (r) (Coulibaly *et al.* 2019).

The second type of data used is daily precipitation data from several datasets of scenarios downscaled by a high-resolution regional climate model (RCM) with a typical horizontal resolution of 50 km. The RCM used was from the fourth version of the Rossby Centre regional atmospheric model, RCA4, developed at the Swedish Meteorological and Hydrological Institute (SMHI). The RCA4 was used to downscale three global climate models (GCMs), namely, CNRM-CERFACS-CNRM-CM5 at a resolution of $1.4^\circ \times 1.4^\circ$, IPSL-IPSL-CM5A-MR at a resolution of $1.25^\circ \times 2.5^\circ$, and MPI-M-MPI-ESM-LR at a resolution of $1.9^\circ \times 1.9^\circ$ under the coordinated Regional Climate Downscaling Experiment (CORDEX-Africa). Two sets of scenarios with representative concentration pathways (RCPs), namely, RCPs 4.5, the mean scenario, which supposes that strategies for reducing greenhouse gas emissions cause radiative forcing to stabilize at 4.5 W/m^2 , and RCPs 8.5, the gloomy scenarios that consider increased greenhouse gas emissions causing radiative forcing that would reach 8.5 W/m^2 by the year 2100, for only the near future period (2020–2050), were considered in this study. RCP 4.5 and RCP 8.5 have been widely used in West Africa in many studies on climate change impact, variability, and extreme events (Nikiema *et al.* 2016) and have provided information about future changes under different RCPs and global warming levels. The RCMs used were chosen for their

Table 1 | Selected stations within the catchments

Watersheds	Stations	Latitude	Longitude	Data range
Agneby	Agboville	5.9	−4.2	1976–2017
	Akoupe	6.3	−3.8	
	Arrah	6.6	−3.9	
	Bongouanou	6.6	−4.2	
	Cechi	6.2	−4.4	
	Dabou	5.3	−4.3	
	M'batto	6.4	−4.3	
	Sikensi	5.6	−4.5	
Bagoue	Boundiali	9.5	−6.4	1980–2017
	Madinani	9.6	−6.9	
Baya	Bondoukou	8.1	−2.7	1976–2017
	Kun-Fao	7.4	−3.2	
	Tanda	7.7	−3.1	
Lobo	Daloa	6.8	−6.4	1983–2017
	Issia	6.5	−6.6	
	Pelezi	7.3	−6.8	
	Vavoua	7.3	−6.4	
N'zo	Bangolo	7.03	−7.4	1983–2017
	Biankouma	7.7	−7.6	
	Man	7.4	−7.5	
	Zeregbo	7.05	−7.8	

performance in West Africa, specifically for their potential to properly capture the rainfall regimes of West Africa. (Akisanola *et al.* 2017; Kwawuvi *et al.* 2022).

2.3. Inter-annual variation of historical rainfall

According to Dorsouma & Requier (2008), climate variability refers to the natural intra- and inter-annual variation in climate that significantly modifies the climate. Rainfall data are influenced by this variability, which often compromises the results of certain studies. Thus, for a good inventory of time series and a better observation of inter-annual fluctuations, seasonal variations are often eliminated by using a non-recurrent low-pass Hanning filter of order 2 (a weighted moving average). This method consists of filtering the data to eliminate seasonal variations to better illustrate deficit and surplus periods on an inter-annual scale. This exercise was achieved with the recommended equations of Tyson *et al.* (1975) and used by Blé & Emile (2021), Yao (2015a 2015b), and Amichiatchi *et al.* (2023) with good results. Under this method, each term of the series is calculated by the equation:

$$X_t = 0.06x_{t-2} + 0.25x_{t-1} + 0.38x_t + 0.25x_{t+1} + 0.06x_{t+2} \quad (1)$$

where x_{t-2} and x_{t-1} are totals of the observed rainfalls of two terms immediately preceding the term x_t and x_{t+2} and x_{t+1} totals of the observed rainfall of two terms immediately following the term x_t .

The weighted rain totals of the first two (X_1 and X_2) and the last two (X_{n-1} and X_{n-2}) terms of the series are calculated by using Equations (3)–(6) (n being the size of the series):

$$X_1 = 0.54x_1 + 0.46x_2 \quad (2)$$

$$X_2 = 0.25x_1 + 0.50x_2 + 0.25x_3 \quad (3)$$

$$X_{n-1} = 0.25x_{n-2} + 0.50x_{n-1} + 0.25x_n \quad (4)$$

$$X_n = 0.54x_n + 0.46x_{n-1} \quad (5)$$

To better visualize the periods of deficit and surplus, the flow is centred and reduced using the following equation:

$$Y_t = \frac{(X_t - m)}{\sigma} \quad (6)$$

Y_t is the average rainfall, X_t is the total annual weighted rain, m is the mean of the series of weighted means, and σ is the standard deviation of the series of weighted moving averages.

2.4. RCMs performance evaluation and bias correction

Prior to use of the RCA4 model outputs for this study, GCMs' performances were evaluated on a daily time scale. R package 'qmap' was used to perform the bias correction. It is a tool used to extract data from regional and GCMs and bias-correct that data. The distribution map error correction method was used in this study to adjust the simulated RCM climate values to match the observed values (Switanek *et al.* 2016; Seth *et al.* 2015). This method has been widely used in the bias correction of RCMs (Dobler & Ahrens 2008; Piani *et al.* 2010) and is capable of correcting other statistical properties with a better outcome. The package used the overlapping technique by considering the observed data (1976–2005) and simulated rainfall data for the future time period (2020–2050) for the RCP4.5 and RCP8.5 scenarios. The difference between simulated and observed climate variables for the historical period is minimized, and the adjusted data should roughly match the observed ones. The flexibility provided by R Package 'qmap' makes it easier to analyse climate model data and improve observational replication.

A statistical method for evaluation of model performance that includes the mean absolute error (MAE) and percent of bias (PBIAS) was used to assess the effectiveness of the RCM using the following equations:

$$MAE = \frac{\sum_{i=1}^n |y_i - x_i|}{n} \quad (7)$$

where MAE is the mean absolute error, y_i is prediction, x_i is the true value, and n is the total number of the data.

$$\text{Percent of bias (PBIAS)} = \frac{\sum_{i=1}^n [S_i - O_i]}{\sum_{i=1}^n O_i} \times 100 \quad (8)$$

A PBIAS value of 0 indicates that there is no systematic difference between the amounts simulated and observed, whereas a large PBIAS value indicates that the RCM rainfall amount is significantly different from the one that was observed. Overestimation of the observed variables is indicated by a positive PBIAS, while underestimation is indicated by a negative PBIAS. The range for the statistical measures $\text{MAE} = 0$ to ∞ , with lower values showing better performance, showed how well the RCM simulates the observed rainfall (Bessah *et al.* 2020).

2.5. Description and extraction of extreme rainfall indices

The extreme climate indices used in this study are based on indicators from the Expert Team on Climate Change Detection and Monitoring (ETCCDI), which have been used in numerous other studies worldwide (e.g., Yao *et al.* 2018; Okafor *et al.* 2021). The maximum annual rainfall (Pmaxan), which was extracted annually, and the consecutive dry days (CDD), which was extracted taking into account the maximum number of consecutive days with daily rainfall less than 1 mm (1 mm) from the database, were the four (4) indices chosen to characterize extreme rainfall. Using moving averages, the maximum 5-day rainfall (Rx5days) was determined annually from the average daily rainfall over 5 consecutive days. The very wet day (R95p) was extracted, taking into account the rainfall period starting in the middle of March and ending in November regarding all the watersheds.

A detailed description of the four selected extreme rainfall-related indices (i.e., Pmaxan, R95p, Rx5 days, and CDD) is presented in Table 2. The extraction of the extreme rainfall data was done using Rstudio software.

2.6. Trend detection

To avoid outliers and the effect of autocorrelation, the modified Mann–Kendall (MMK) test was used to identify trends in the extreme precipitation indices for both scenarios (RCP 4.5 and RCP 8.5) with respect to the historical period. The principle is based on a modification of the S statistic in the Mann-Kendall (MK) test. Based on this, Hamed & Rao (1998) proposed a modified version of the original MK test in which the variance of the test statistic is modified to account for autocorrelation in the series. The statistic to adjust the variance is given as follows:

$$\text{Var}(S) = \frac{1}{18} (n(n-1)(2n+5)) \frac{n}{ns^*} \quad (9)$$

where ns^* is the effective number of observations to account for autocorrelation in the data.

$$\frac{n}{ns^*} = 1 + \frac{2}{n(n-1)(n-2)} \sum_{s=1}^m (n-s) \quad (10)$$

The test was done on Rstudio with ‘*mmkh*’ as the computational code, with the null hypothesis (H_0) being ‘no trend’ and the alternative hypothesis (H_1) corresponding to the presence of a trend in the series at a 5% significance level.

Table 2 | Rainfall extreme indices

Index	Name	Definition	Unit
Pmaxan	Maximum rainfall	Maximum annual rainfall	mm
R95p	Very wet day	Annual total rainfall when RR >95%ile	mm
Rx5 days	Maximum 5-day rainfall	Maximum 5-day rainfall	mm
CDD	Consecutive dry days	Maximum number of consecutive days with daily rainfall <1 mm	day

3. RESULTS

3.1. Inter-annual variation of historical rainfall

The results of applying Hanning's second-order low-pass filter to the observed rainfall in each climatic zone of the country are depicted in Figure 2. There is a significant degree of inter-annual variability in the rainfall. Wet and dry periods alternate at each of the studied stations (surplus zone, deficit zone). Since 1993, the N'zo and Bagoue watersheds have experienced more deficit years, whereas the Baya, Agneby, Lobo, and N'zo watersheds have experienced surplus years. Over the course of time, there are alternating data variations in the Baya and Lobo watersheds.

3.2. Evaluation of the performance RCM data

The evaluation of the RCM data's performance is depicted in Figure 3. It is evident that the best statistics are those with after bias correction. Before, the MAE ranged from 0 to 1,600, depending on each model, and after bias correction showed a value between 0 and 600, depending on each model. The PBIAS, before the bias correction, indicated at some stations an overestimation or underestimation of the values, but after the bias correction, almost all of the values indicated '0,' meaning that there was no systematic difference between simulated and observed amounts.

3.3. Trend analysis of observed data

Figures 4 and 5 show the results of the trend analysis on the observed data for the extreme rainfall index of the study area with respect to each station in each watershed. The trend analysis has shown that the study watersheds are experiencing a disturbance for this index and at all the stations with a significant decreasing trend. At all the stations, the Pmaxan indices show a 43% decreasing trend, while the Rx5days, CDD, and R59p show, respectfully, 43, 57 and 38% decreasing trend.

3.4. Trend analysis of RCM data

3.4.1. RCP 4.5 scenario

Figures 5 and 6 show the results of the trend analysis on RCP 4.5 data of Pmaxan, Rx5day, CDD, and R95p extreme rainfall indexes for the study area under each climate zone, with a non-significant trend for CNRM out of the three models (CM5A, CNRM, and

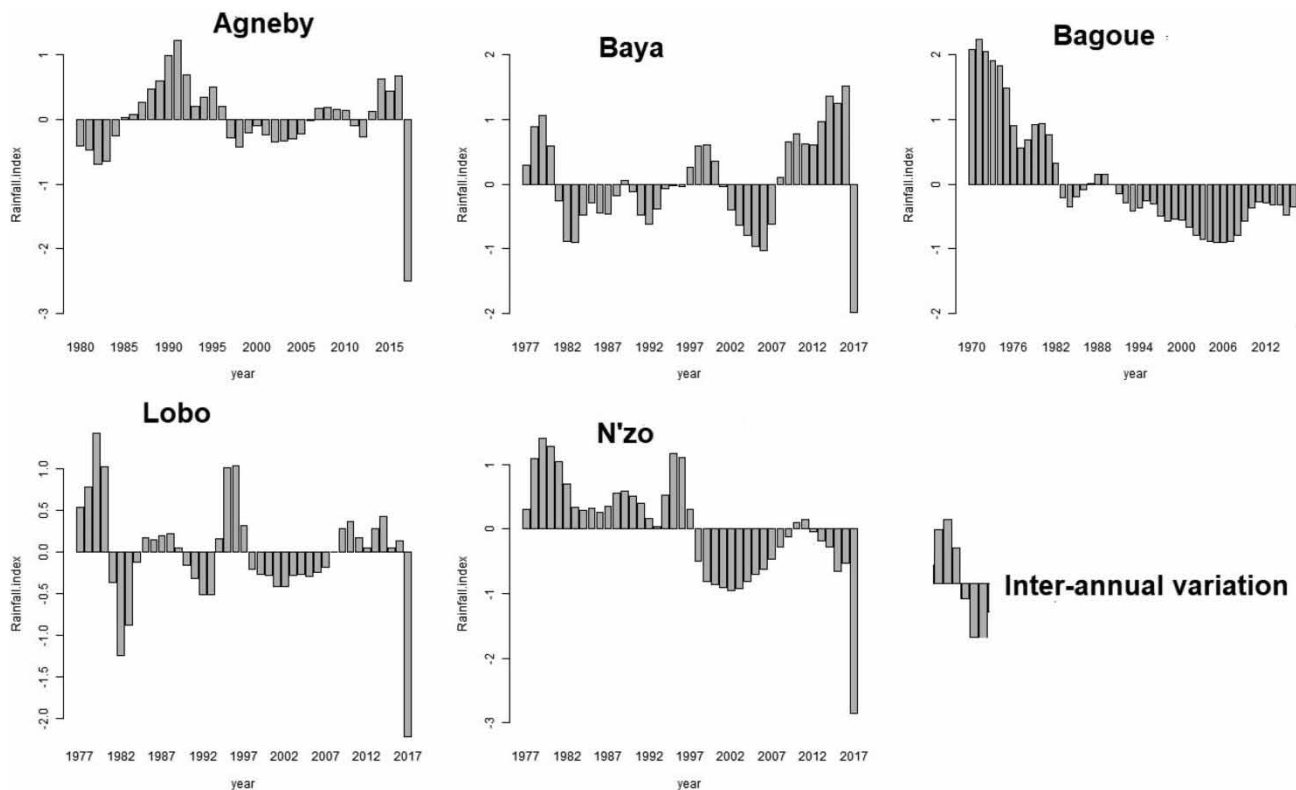


Figure 2 | Inter-annual variation of rainfall in each watershed using the non-recursive low-pass Hanning filter of order 2.

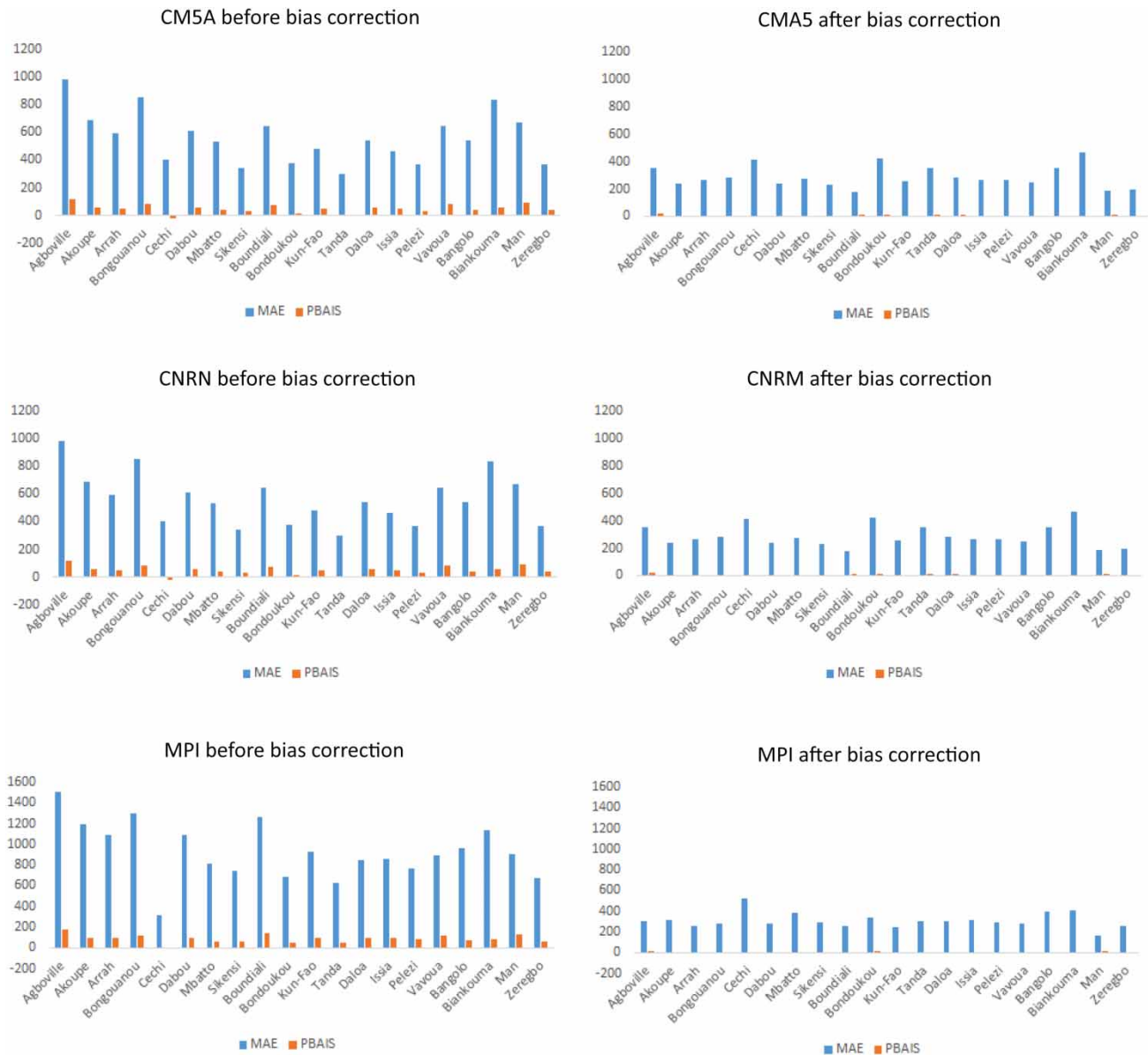


Figure 3 | Evaluation of the performance of RCMs data before and after bias correction.

MPI). The climate zone I with the Agneby watershed can see a significant upward trend with CM5A and MPI at Akoupe, Arrah, Agboville, Dabou, and Sikensi stations concerning the indexes (Rx5days, Pmaxan, and R95p). At climate zone II, Lobo, and Baya watersheds, the model CM5A showed a significant upward trend at Bondoukou, Kun-Fao, and Tanda at Baya watershed, and Issia at Lobo watershed regarding the Pmaxan indices, but a non-significant trend for the MPI model. It is possible to notice, at the Bagoue watershed for climate zone III, a significant upward trend at Boundiali and Madinani stations concerning Pmaxan, Rx5days, and R95p indices for only the CM5A model. CNRM and MPI showed a non-significant trend. N'zo watershed at climate zone IV in the western part of the country also showed a significant upward trend for Pmaxan and R95p and a significant downward trend for the CDD index at Zerego and Man stations for the climate models CM5A and MPI. The ensemble model showed a significant result at Lobo and N'zo watersheds concerning Pmaxan, Rx5days, and CDD indices at Issia, Daloa, and Zerego stations.

3.4.2. RCP 8.5 scenario

Figure 7 below shows the results of the trend analysis on the RCP 8.5 data of Pmaxan, Rx5day, CDD, and R95p extreme rainfall indexes of the study area under each climate zone with three models (CM5A, CNRM, and MPI). The climate zone I with

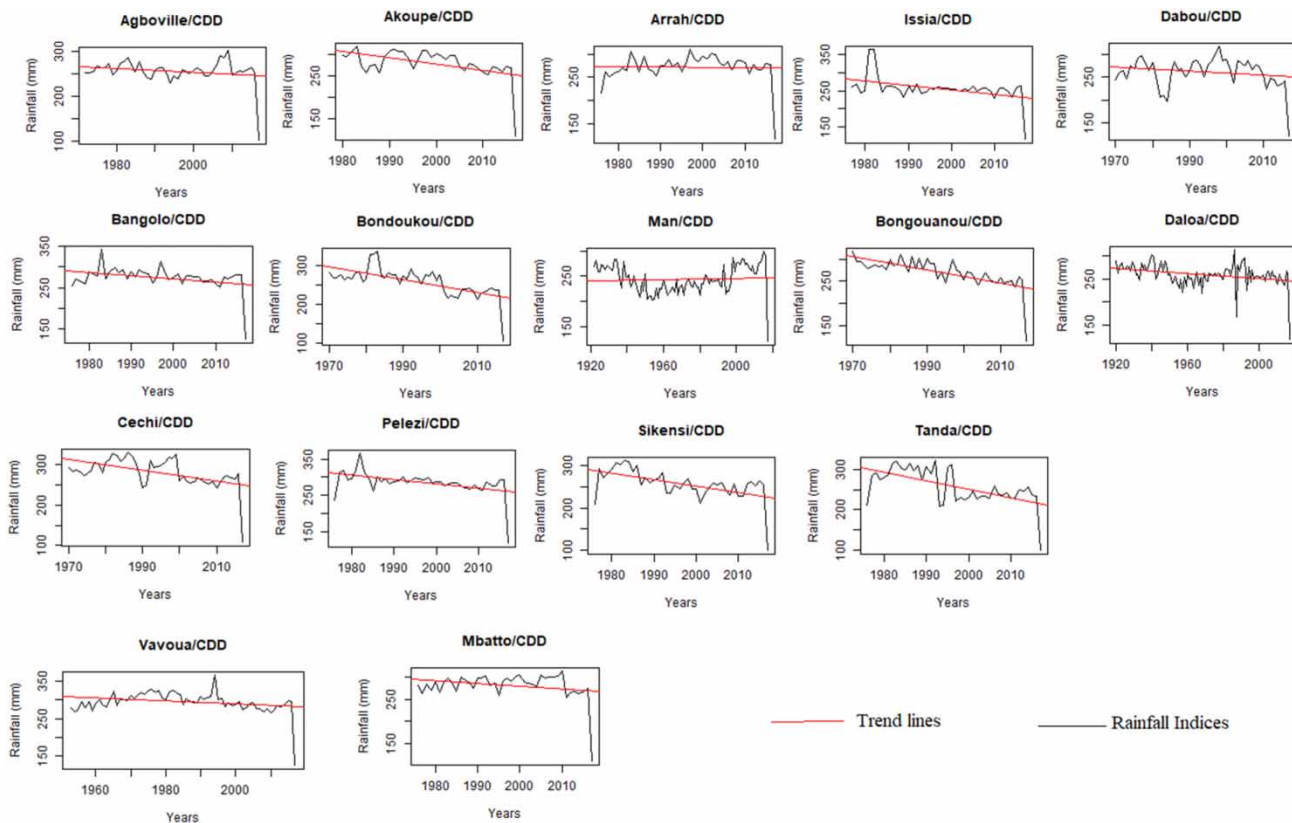


Figure 4 | Significant trend result for CDD index for observed data from 1976 to 2017.

the Agneby watershed can see a significant upward trend with CM5A and CNRM at Akoupe, Arrah, Agboville, Cechi, and Sikensi stations, respectively, concerning the Rx5days index. At the climate zone II, Lobo, and Baya watersheds, the models showed a significant upward and downward trend. The CM5A presented a significant upward trend at Bondoukou, Kun-Fao, Tanda, and Issia for the Baya and Lobo watersheds, respectively, regarding the Pmaxan index. CNRM allowed us to see at Kun-Fao, Daloa, and Issia a mixed trend (decreasing and increasing trend) for the CDD indices at Lobo watershed and an increased trend for Pmaxan at Kun-Fao station for Pmaxan at Baya watershed. For the MPI model, only Kun-Fao station presented a significant upward trend for the Baya watershed; other stations presented a non-significant trend. It can be noticed that at the Bagoue watershed for climate zone III, there is a significant upward trend for only the CM5A model regarding Pmaxan, R5days, and R95p indices, while at Madinani and Boundiali stations, CNRM and MPI show a non-significant trend. N'zo watershed in climate zone IV in the western part of the country also showed a significant upward trend for Pmaxan, Rx5days, and R95p at Zeregbo and Man stations for the climate models CM5A and CNRM. The ensemble model generally showed a significant result at Lobo and N'zo watersheds concerning Pmaxan, Rx5days, R95p, and CDD indices.

4. DISCUSSION

The goal of this study was to look at how extreme rainfall indices have changed over time (both flood and drought related) in each of the climatic zones of Côte d'Ivoire. The observed and simulated future data used for this analysis are for the periods 1976–2017 and 2020–2050, respectively.

• Trend analysis for the observed period 1976–2017

The drought index, which is characterized by the dry season duration, has experienced changes in each climate zone in the past. With the observed data, the CDD index showed a significant downward trend at the Bagoue watershed in the north, Baya in the east, Agneby in the south, and Lobo in the southwest. The significant downward trend in this drought index

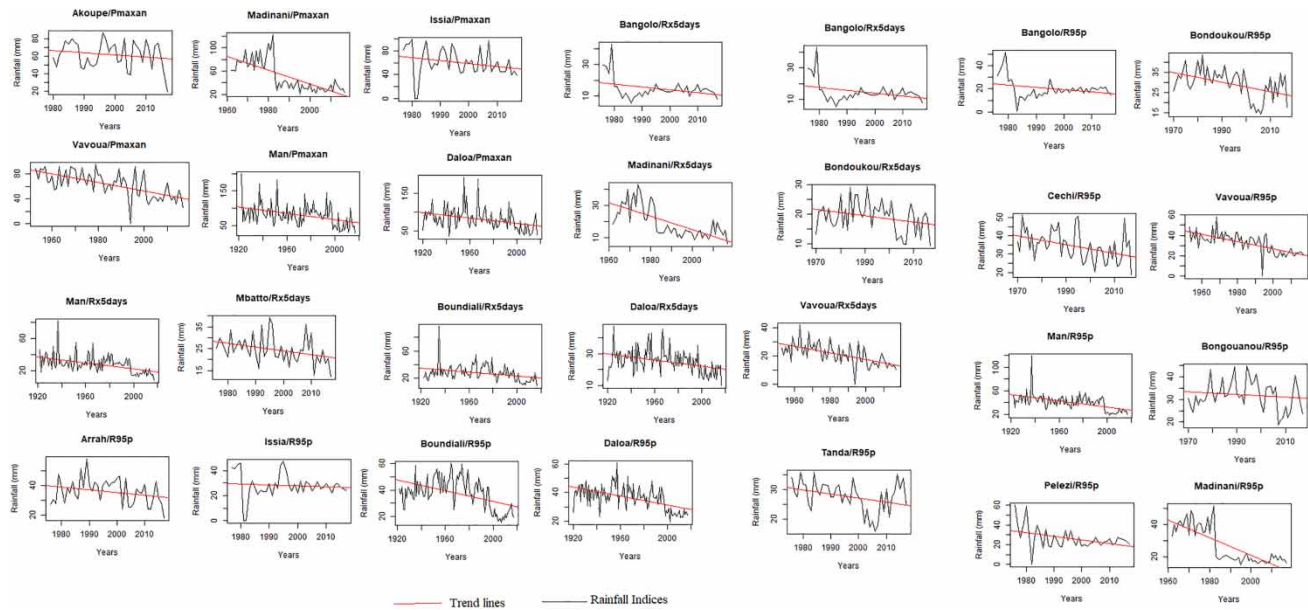


Figure 5 | Significant trend analysis result for Pmaxan, Rx5days, and R95p indices for observed data from 1976 to 2017.

could be explained by the fact that the climate has been marked by a long period of variation dominated by either a long rainy season or a long moderate season, which has considerably reduced the length of the dry period, especially after the severe drought period of the 1970s in West Africa. This change in the drought index trend is in line with findings from the study by [Agyekum et al. \(2022\)](#), who observed a decrease in the trend of dry consecutive days over the Volta watershed from 1985 to 2014 at an annual scale. This result could be explained by the fact that the climatic variability of each climate zone in the country is not the same everywhere. The whole country is then watered by normal rainfall all the time, thus decreasing the dry days.

The flooding phenomena were analysed by three extreme indices (Pmaxan, R95p, and Rx5days). After trend analysis of these data, the indices characterizing flooding all showed a general multiform trend with a downward trend on the observed data. The significant downward trend observed could be explained by the fact that the early and subsequent recovery of rainfall after the major droughts was not strong enough to influence these extreme indices over the entire study area. These extreme rainfall indices were, therefore, dominated by normal rainfall in each climatic zone and the high rainfall variability in the entire country. This observation is similar to findings by [Coulibaly \(2021\)](#), who also found a statistically significant decrease in annual rainfall over the period 1951–2017 in Cote d'Ivoire. Furthermore, [Balliet et al. \(2016\)](#) found a significant mixed trend (increase and decrease) in the Rx5days index in the Goh region of Gagnoa over the period 1961–2010. The significant upward trend of extreme rainfall observed in the N'zo watershed could be due to the geographical location of this watershed. Indeed, located in the forested and mountainous area of the country, there is sufficient rainfall, a resumption of rainfall, and backing for an upward trend in indices of extreme rainfall. Thus, the frequency of flooding in this area could increase the phenomenon of soil erosion due to runoff. [Yao et al. 2022](#) have also found an upward trend on the R95p index in their study in the southwest of Côte d'Ivoire, which is in line with our finding.

• Trend analysis under RCP scenarios for near future

In the same way, under the RCP 4.5 and RCP 8.5 scenarios, the CDD shows a significant downward trend at Man station in the N'zo watershed, and under the RCP 8.5 scenario, the number of consecutive dry days will decrease at Kun-Fao station in the Baya watershed in eastern Cote d'Ivoire, reflecting a rather uncertain projection of the climate model for the near future. The long duration of the consecutive dry days predicted by both scenarios (RCP 4.5 and RCP 8.5) will greatly impact Ivorian agriculture, the source of the national economy, with a great delay in the agricultural calendar. Crops that need water, such as rice, cassava, and yams, will be greatly disrupted. The development of new cropping strategies with insufficiency or sufficiency in water use will be needed because of the great uncertainty of the index, which could threaten the supply of

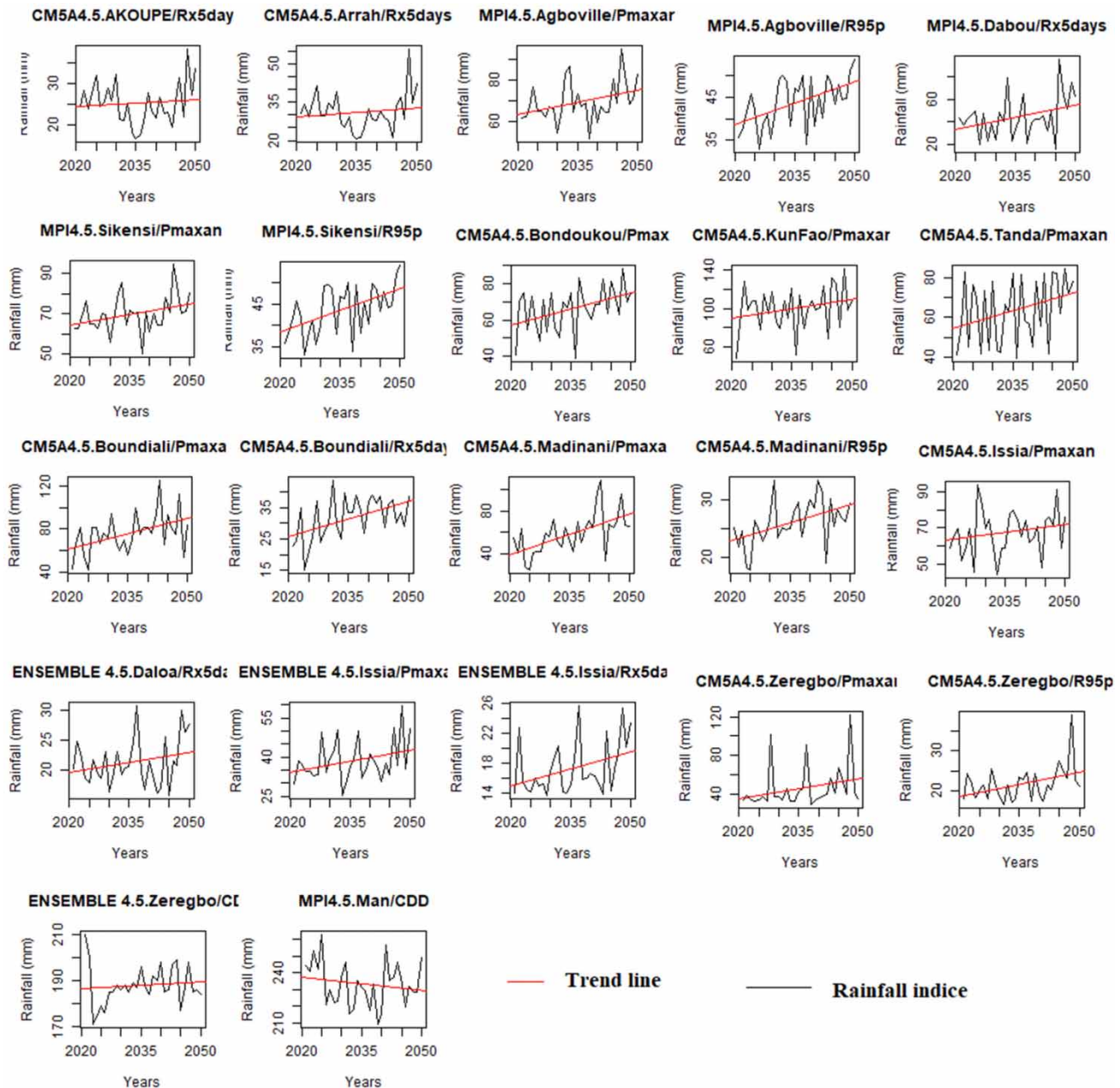


Figure 6 | Significant trend analysis result on RCP 4.5 data of Pmaxan, Rx5day, CDD, and R95p extreme rainfall indexes for Agneby and Bagoue watersheds under each climate zone.

pasture and animal feed. Some regions will experience longer and more intense droughts due to rising temperatures and decreasing rainfall. Therefore, in an uncertain climate, it is more than urgent that adaptation strategies are known to all sections of the population.

The flooding phenomena were analysed by three extreme indices (Pmaxan, R95p, and Rx5days) with future data from 2020 to 2050 under two scenarios (RCP4.5 and RCP8.5). The trend analysis of the indices under RCP4.5 and RCP8.5 showed an increasing trend under each climate zone.

The different flood indices used (Pmaxan, R95p, and Rx5days) have generally shown a projected mix trend (upward and downward trend), with the most important trend being the non-significant trend under the two scenarios (RCP 4.5 and 8.5) in each of the study areas in the near future (2021–2050). Thus, under both scenarios, the Bagoue watershed in the

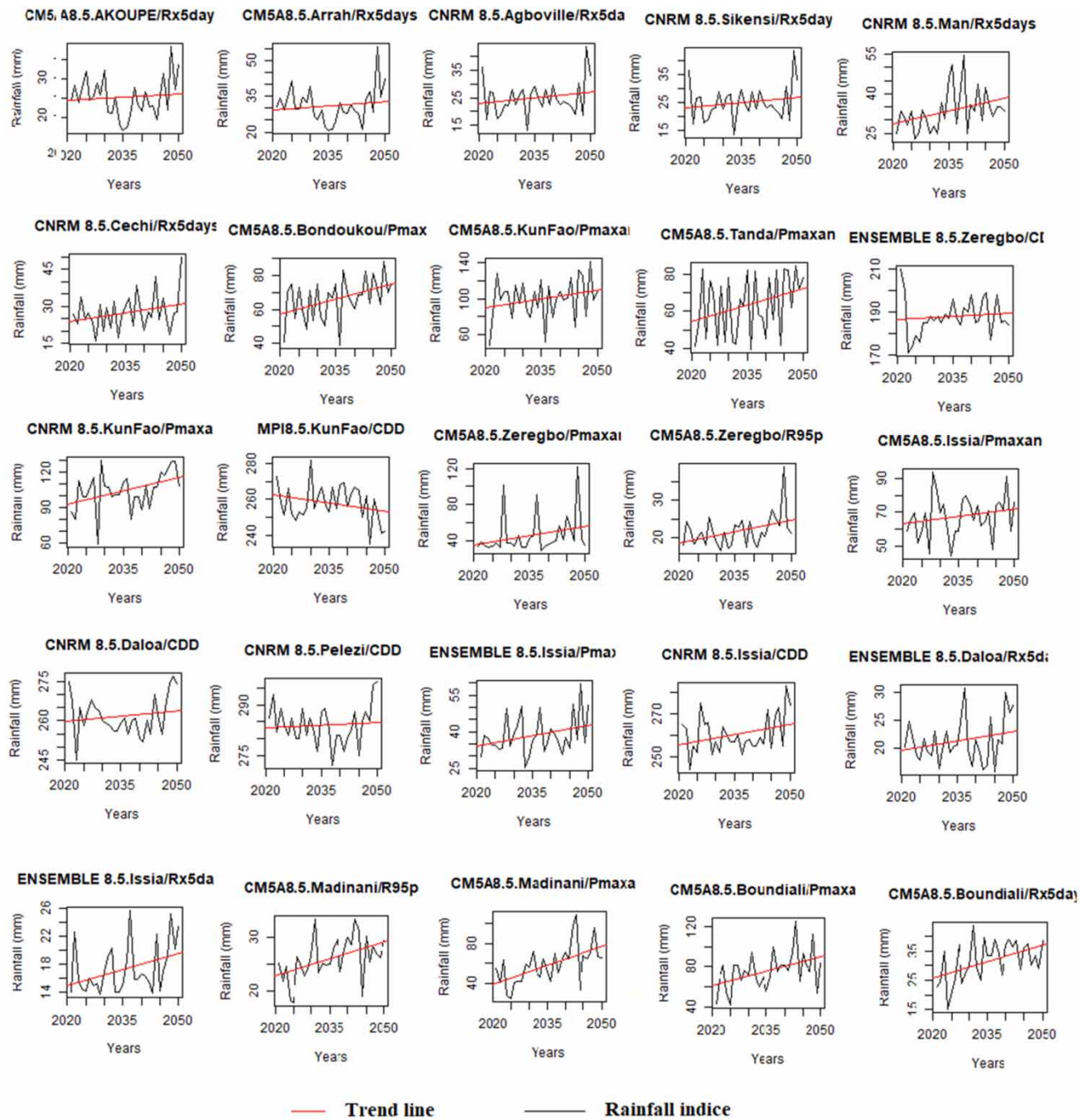


Figure 7 | Significant trend analysis result on RCP 8.5 data of Pmaxan, Rx5day, CDD, and R95p extreme rainfall indexes for the watersheds under each climate zone.

north, the Agneby watershed in the south, the N'zo watershed in the mountainous west, and the Baya watershed in the east are expected to experience a significant upward trend in flooding in the near future. This could be explained by the expected impact of climate change on rainfall due to the severe climatic variability experienced in these climatic zones. This result is reported by several recent works over other parts of Africa, such as those by [Teshome *et al.* \(2022\)](#) over Africa, [Okafor *et al.* \(2021\)](#) in the Dano catchment, Burkina Faso, and [Adeyeri *et al.* \(2019\)](#) over the Komadugu-Yobe watershed, Lake Chad region. [Okafor *et al.* \(2021\)](#) observed increasing trends in Rx5day under both RCPs 4.5 and 8.5 scenarios in their study. The inhabitants of the Bagoue watershed are maize and rice farmers, whose livelihoods could be damaged by the expected

floods, thus directly impacting the socioeconomic activities of the riparian population. The Baya watershed is marked by yam cultivation, the Agneby by cassava, and the N'zo by rain-fed rice, all of which are the main economic activities of the riparian population and could be affected by floods with environmental and socioeconomic damaging effects resulting from the impact of climate change in these areas.

5. CONCLUSION

We analysed, at an annual scale, the trends of four extreme rainfall indices trends using the MMK statistical test at a 5% confidence level using observed rainfall over the period 1976–2017 and RCM simulations under two scenarios (RCP 4.5 and 8.5) for the near future (2020–2050) in five river watersheds in Cote d'Ivoire. The simulated RCM climate data were bias corrected, and the performance evaluation was carried out using the distribution mapping method. The results of the trend analysis showed that all the indices characterizing flooding and the dry season duration (CDD index) depicted general downward trends in the observed data from 1976 to 2017. Under the RCP 4.5 scenario for the near future, the CDD is expected to experience a significant upward trend at Zeregbo station in the N'Zo watershed and at Agboville, Dabou, and Sikensi stations in the Agneby watershed, and a non-significant trend under RCP 8.5 in each of these areas. Under the RCP 4.5 scenario, all the indices characterizing flooding, such as the Pmaxan and Rx5days indices, are expected to show a significant upward trend in the Bagoue watershed for both indices and in the Agneby watershed for the Rx5days index. For the R95p index, under the same scenario, it is expected to show a significant mixed trend, either upwards in the Bagoue watershed or downwards at Sikensi station in the Agneby watershed. Under the RCP 8.5 scenario, the N'zo watershed in Man station and the Baya watershed in Tanda station will experience a significant upward trend in the Pmaxan and R95p indices. The Rx5days index will have a significant mixed trend, either upward at Man station in the N'zo watershed or downward at Akoupe and Arrah stations in the Agneby watershed.

The trend analysis of extreme precipitation indices (drought and flood) provided a good understanding of the evolution of past and future droughts and floods in each climate zone of the Cote d'Ivoire. However, at the local scale, the downscaled climate model projections tended to be inaccurate for the near future period, where they showed a large variability between datasets. It is important to note then that changes in climate extremes are of greater interest to decision makers at the local scale as they imply changes in the types of hazards that are often of greatest concern to communities. As a result, further research should include a comprehensive database of observed extremes as well as a variety of techniques for trend analysis at various time steps (such as monthly and decadal) employing a variety of time series techniques to predict extremes on a monthly and seasonal scale. This would be beneficial to farmers and still help the Ivorian economy. The knowledge will enable policy planning and strategies to prepare for the potential challenges that will emanate from the impacts of climate change in the study area. Climate change, as we all know, is a global issue with local consequences. The lines of adaptation will allow us to cope with and plan for drought by generating new crop kinds that give a profitable possibility.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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