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Climatic Indices' Analysis on Extreme Precipitation for Tanzania Synoptic Stations

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Abstract

Like other countries in East Africa, Tanzania has been affected by extreme precipitation incidences both socially and economically. Determining the trend and variability features of extreme precipitation in the country is crucial. This study used data from 28 meteorological stations for 1981-2020 period to give an annual and seasonal analysis of the patterns of 10 ETCCDI's extreme precipitation indices over the regions. At annual scale, the results showed that increasing trends had high frequency percentage than the decreasing ones, collecting about 76% in total. The decreasing trend was approximately 24%, and most of the stations with increasing percentage in trend are concentrated in Northern coast, Central, West, North-eastern highlands and Lake Victoria Basin. Most of the stations depicted negative trend are concentrated over Southern region. This highlights that extreme precipitation events have increased over the country for the period 1981-2020. At seasonal scale, during October to December (OND); the patterns of extreme precipitation climatic indices except R99p, showed positive significant increasing trend over Lake Victoria Basin and some Western parts of the country. In general, spatial patterns indicate decrease of precipitation over most parts of the country during OND. The seasonal average time series depicted non-significant positive trend during March to April (MAM) season, except for Consecutive Wet Days (CWD) which showed non-significant decreasing trend. Over the highest mountain in Africa, Kilimanjaro; the study has revealed significant decrease in Annual total-wet Precipitation (PRCPTOT), the number of heavy (very heavy) days of precipitation R10 mm (R20 mm) and

Consecutive Wet Days (CWD) during MAM season. While the maximum one-day precipitation amount (RX1 day) was observed to decrease significantly over the Mountain during OND season. The result is very important in risk assessment and preparedness perspective in planning climate change mitigation and adaptations for different sectors like Tourism, Agriculture, Water and Energy.

Keywords

Extreme Precipitation, Climatic Indices, Tanzania, Mann-Kendall, ETCCDI, Trend

1. Introduction

Extreme precipitation has a number of negative effects, including serious infrastructure damage from flooding, landslides, loss of life and property (Chang'a et al., 2020a; TMA, 2022). The majority of recent studies and records from climatological data from many regions of the world point to a rise in the frequency and severity of extreme precipitation and other severe occurrences, such as floods and droughts (IPCC, 2023; Masson-Delmotte, 2018). Others studies project that as a result of global warming, the hydrological cycle is anticipated to become more intense, which is likely to rise in the frequency of intense precipitation and raise the danger of flooding (Pötner et al., 2022; Shongwe et al., 2009; Tabari, 2020).

Since precipitation is one of the most important variables in the climate system (Baede et al., 2001; Ding, 2001), it is essential to look into its variability and intensity for understanding its attribution to climate change (O'Gorman, 2015; Shiu et al., 2012). The study's significance stems from the fact that extreme precipitation events, which are defined as a marked and unusual precipitation event occurring during a period of hours to a longer period of several days, with total precipitation largely exceeding local average conditions of that period (WMO, 2015), lead to extreme hydrological events which have significant negative economic and social effects due to the harm they inflict on agriculture, human settlements, ecosystems, human health, and water supply sources, among others (Kai, Ngwali, et al., 2021a; Mafuru, 2018). Like other countries in East Africa, Tanzania has been also suffering from extreme precipitation both socially and economically as documented by (Chang'a et al., 2020b; Kai, Osima, et al., 2021b; Mafuru, 2018; Racoma et al., 2022). Also, research on extreme precipitation is relevant to several Sustainable Development Goals (SDGs), including Goal 2 on Zero Hunger (Huck, 2022), Goal 11 on Sustainable Cities and Communities (United Nation-HLPF, 2018) and Goal 13 on Climate Action (Advocates for International Development, n.d.).

Since the likelihood that some extremes will rise in frequency, widespreadness and intensity over the 21st century have increased (Alcamo et al., 2007), it is necessary to find a statistically significant change in some aspect of the climate system in order to detect climate change in observational records. It should be noted that for more than a decade, the World Meteorological Organization (WMO) and the National Meteorological and Hydrological Services (NMHSs) have focused on developing an effective early warning system for climate anomalies and related extremes in order to increase national capacities for managing climate risk (World Climate, 2007). To achieve the analysis of extremes in a changing climate, Expert Team on Climate Change Detection and Indices (ETCCDI) has created and disseminated climatic indices of climate variability and change from the stratosphere to the surface and subsurface ocean; it also promotes the comparison of observations and simulated data (Zhang et al., 2006; Zhang et al., 2004). The indices delineate certain attributes of extremes, such as persistence, amplitude and frequency. There are 27 extremes indices in total, 16 for temperature and 11 for precipitation in the core set and is recommended by WMO to be used worldwide (Zhang et al., 2004).

Like other parts of the world, in order to comprehend how climate change is affecting the regions of Tanzania as recommended by number of studies (Chang'a et al., 2017; Jiang et al., 2016), it is essential to look into extreme precipitation indices. Studies like (Luhunga, 2022) over Tanzania, (Ojara et al., 2021; Osima et al., 2018) over East Africa have used some climatic indices to study extreme events. Focusing on Tanzania, analysis on seasonal and annual extreme precipitation need to be understood. Unlike to previous studies, this study explores possible changes in the frequency, intensity, and duration of extreme precipitation over the country involving 28 synoptic stations by using 10 ETCCDI Climatic indices on precipitation for the period 1981-2020 both annually and seasonally. Knowledge on extreme precipitation is very important in risk assessment and preparedness perspective. It makes it possible for authorities to prepare for and react to probable flood events, landslides, and other natural disasters. This research is organized as follows; the data and methodology are briefly explained in Sect. 2, Sect. 3 provides Results and Discussion on spatial and average time series of annual and seasonal extreme precipitation climatic indices over Tanzania. Conclusion is given in Section 4.

2. Data and Methodology

2.1. Study Area

Tanzania is found in East Africa between latitudes 1˚ and 12˚S and longitudes 29˚ and 41˚E (**Figure 1**). The country has automatic as well as observational weather stations including agrometeorological and synoptic stations (**Table 1**). The country's complex geographic landscape is a significant contributor to the region's climatic variety. Numerous factors, such as the East African Monsoon, the El Nino Southern Oscillation (ENSO), the westerlies from the Congo, tropical cyclones, and the Inter-Tropical Convergence Zone (ITCZ), influence the distribution and variability of precipitation. One of the primary factors influencing the distribution and unpredictability of precipitation in Tanzania and

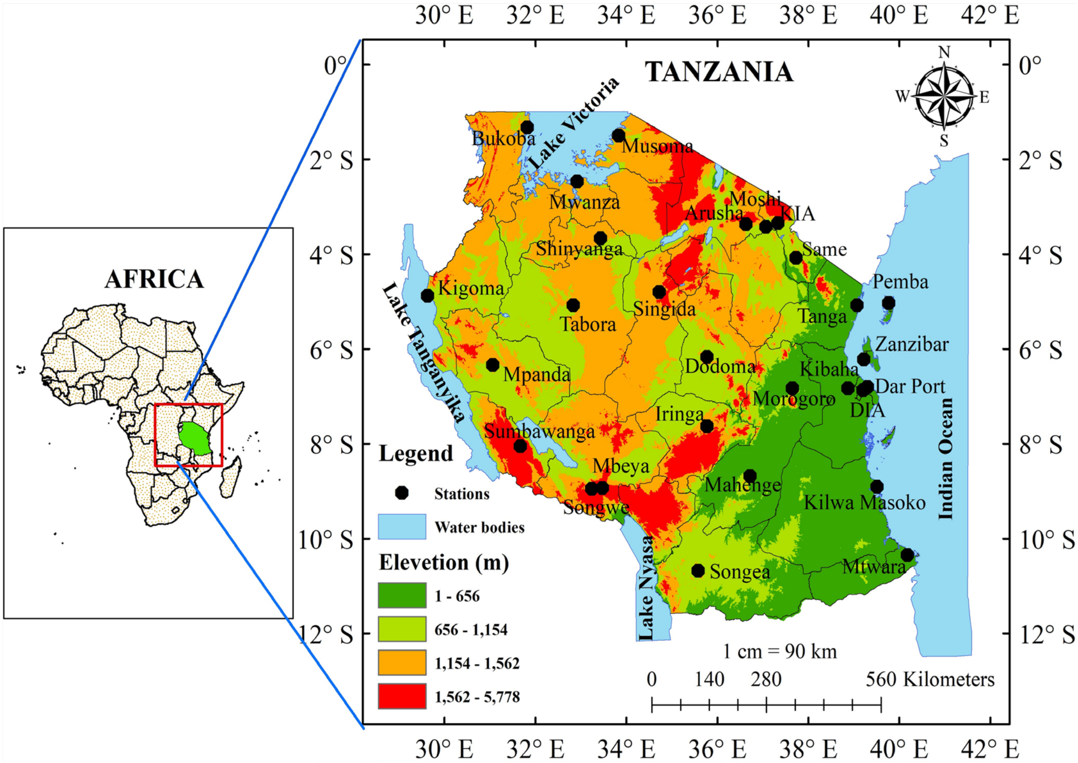


Figure 1. Study area; Tanzania map showing distribution of synoptic stations with their elevation.

throughout East Africa is the ITCZ's passage north and south over the equator (Kebacho, 2022; *Statement on the Status of Tanzania Climate*, 2020). The ITCZ migrates to southern regions of Tanzania from October to December, reaching the southern part of the country in January-February and reverses northwards in March, April and May. Due to this movement, some areas experience single and double passages of the ITCZ (*Statement on the Status of Tanzania Climate*, 2019; TMA, 2022). Areas that have only single passage are referred to as unimodal areas. These include the southern, southwestern, central, and western regions of the country, which have precipitation from November to April or May (NDJFMA, also known as Msimu). Those with double passages are called Bimodal regions, including the Zanzibar Islands (Unguja and Pemba), Lake Victoria basin and the Northern-eastern highlands. There are two separate seasons for precipitation in these areas. The short season (also known as Vuli), which begins in October and lasts through December (OND), and the long rains (also known as Masika season), which often begins in March and lasts through May (MAM). For bimodal regions, January and February are the transition months (relatively dry), whereas June, July, August and September are dry months for the entire country (*Statement on the Status of Tanzania Climate*, 2020).

2.1.1. Data Source

This study utilized daily precipitation data from CHIRPS (Climate Hazards Group Infrared Precipitation with Station) version 2.0 with worldwide coverage of 50˚S - 50˚N latitude and spatial resolution at 0.05˚ - 0.05˚ latitude-longitude grid from 1981 to present (Funk et al., 2015). CHIRPS generates a gridded rainfall time series by combining in-house climatology, CHPclim, 0.05˚ resolution satellite images, and in-situ station data for trend analysis and seasonal drought monitoring. The daily precipitation data from CHIRPS (1981-2020) were then extracted by using Climate Data Tool (CDT) into respective 28 synoptic stations used for the study (**Table 1**). CDT is an open-source, R-based software with an

Table 1. List of the synoptic stations used in the study and their geographical location and information.

No	Station name	Station No.	Latitude (˚S)	Longitude (˚E)	Elevetion (m)
1	Arusha	09336033	3˚22'	36˚38'	1372
2	Bukoba	09131002	1˚20'	3˚22'	1144
3	DIA	09639029	6˚52'	39˚12'	53
4	Dodoma	09635001	6˚10'	35˚46'	1120
5	Iringa	09735013	7˚38'	35˚46'	1428
6	Karume (Pemba)	09539026	5˚15'	39˚49'	24
7	KIA	09337115	5˚25'	37˚4'	891
8	kigoma	09429018	4˚53'	29˚40'	822
9	Mbeya	09833001	8˚56'	33˚28'	1758
10	Morogoro	09637076	6˚50'	37˚39'	526
11	Moshi	09337004	3˚21'	37˚20'	813
12	Mtwara	10040004	2˚28'	32˚55'	113
13	Musoma	09133000	1˚30'	33˚48'	1147
14	Mwanza	09232009	2˚28'	32˚55'	1140
15	Same	09437003	4˚5'	37˚44'	860
16	Songea	10035010	10˚40'	35˚35'	1036
17	Songwe	09833036	8˚55'	33˚16'	1264
18	Tabora	09532012	5˚5'	32˚50'	1182
19	Tanga	09539015	5˚5'	39˚4'	49
20	Kibaha	09638027	6˚50'	38˚58'	25
21	Mahenge	09836027	8˚40'	36˚43'	1500
22	Sumbawanga	09731028	7˚35'	31˚36'	1824
23	Handeni	09538088	5˚26'	38˚2'	756
24	Singida	09434042	4˚48'	34˚43'	1307
25	Shinyanga	09433063	3˚39'	33˚24'	1877
26	Kilwa MET	09639010	6˚50'	39˚18'	14
27	mpanda	09639064	6˚21'	31˚4'	1099
28	Zanzibar	09639028	6˚13'	39˚13'	18

Source: Tanzania Meteorological Authority (TMA).

easy-to-use graphical user interface developed and maintained by the International Research Institute for Climate and Society (IRI), Columbia University and is being used by over 20 countries primarily in Africa (Dinku et al., 2022).

2.1.2. Data Quality Control

Since Data Quality Control (QC) is a prerequisite for indices calculations, Data quality check was carried out by using RClimDex (Zhang et al., 2004). RClimDex is a library that offers a user-friendly programming interface in R for the purpose of computing the 27 core indices of extreme climate as defined by ETCCDI. All missing values are replaced into an internal format by the library and R will recognize and replace all unreasonable values including precipitation less than zero and outliers.

2.2. Methodology

2.2.1. Calculation of Indices

Ten precipitation indices recommended by the ETCCDI that examine the frequency, intensity and duration of extreme annual precipitation events were calculated using RClimdex software package. Different studies like (Costa et al., 2020; Ortiz-Gómez et al., 2020) in America, (Jiang et al., 2016) in Asia, (Croitoru et al., 2016) in Europe, (Ayugi et al., 2021; Ojara et al., 2021) in East Africa and (Luhunga, 2022) in Tanzania have used this method. The best of this method lies in avoiding inhomogeneities in calculation of percentiles when they are applied to the base-period. These indices are accessible at (http://etccdi.pacificclimate.org/indices.shtml) and are listed in Table 2. Under ETCCDI, indices are calculated relative to an annual cycle of thresholds over the entire time series. For seasonal analysis of the Climatic indices on extreme precipitation, the European Climate Assessment & Dataset project (ECA&D) analysis was used. This Analysis involves the calculation

Table 2. Definitions of 10 ETCCDI Core Climatic Indices used for the study (Zhang et al., 2004).

No	ID	Indicator name	Definition	UNITS
1	RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
2	RX5day	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
3	SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days in the year	mm/day
4	R10mm	Number of heavy precipitation days	Annual count of days when PRCP ≥ 10 mm	days
5	R20mm	Number of very heavy precipitation days	Annual count of days when PRCP ≥ 20 mm	days
6	CDD	Consecutive dry days	Maximum number of consecutive days with RR < 1 mm	days
7	CWD	Consecutive wet days	Maximum number of consecutive days with RR ≥ 1 mm	days
8	R95p	Very wet days	Annual total PRCP when RR > 95^{th} percentile	mm
9	R99p	Extremely wet days	Annual total PRCP when RR > 99^{th} percentile	mm
10	PRCPTOT	Annual total wet-day precipitation	Annual total PRCP in wet days (RR ≥ 1 mm)	mm

Daily precipitation is represented by RR; RR ≥ 1 mm represents a wet day while RR < 1 mm represents a dry day.

of extreme indices in accordance to agreed procedures specified by ETCCDI (Project Team ECA&D, 2021).

2.2.2. Trend Analysis

To examine temporal variability in extreme precipitation events, we used the Mann-Kendall (MK) non-parametric trend test (Mann, 1945; Sen, 1968). The World Meteorological Organization has endorsed this test and it is frequently used to find monotonic trends in hydrometeorological time series (Costa et al., 2020; Luhunga, 2022). The MK test is appropriate for non-normally distributed data and is less susceptible to outliers. It can also account for missing data and is easy to use and reliable. The MK test was used to determine whether the trend in the precipitation series is statistically significant ($p \leq 0.05$) at a significance level of $\alpha = 0.05$. Because is a reliable estimator of the magnitude of a trend (Yue et al., 2002), the Theil and Sen approach was used to evaluate the trend's magnitude slope (Croitoru et al., 2016; Dang et al., 2009).

3. Results and Discussion

3.1. Annual Analysis of the Extreme Precipitation Indices during the Study Period 1981-2020

The findings from analysis of 28 synoptic stations were investigated and summarized in **Table 3**, the results of time series of annual station mean of the extreme precipitation indices for the years 1981 to 2020 were also compiled. The average frequency percentages of the 10 precipitation indices at the 28 stations under analysis are as follows, according to the strength of the trend: significant

Table 3. The results of the Trend test (%) of Annual average extreme precipitation for each index for 28 Synoptic Stations in Tanzania (1981-2020).

Indices	Increasing Trend			Decreasing Trend			No Trend (%)
	Sig (%)	Non-Sig (%)	Total (%)	Sig (%)	Non-Sig (%)	Total (%)	
RX1day	35.7	53.6	89.3	0.0	10.7	10.7	0.0
RX5day	17.9	67.9	85.8	0.0	14.2	14.2	0.0
SDII	32.1	53.6	85.7	0.0	14.3	14.3	0.0
PRCPTOT	28.6	60.7	89.3	0.0	10.7	10.7	0.0
R95p	42.9	46.4	89.3	10.7	0.0	10.7	0.0
R99p	39.3	46.4	85.7	3.6	10.7	14.3	0.0
R10mm	14.3	64.3	78.6	0.0	21.4	21.4	0.0
R20mm	25.0	67.9	92.9	0.0	7.1	7.1	0.0
CDD	0.0	32.2	32.2	10.7	57.1	67.8	0.0
CWD	3.6	32.1	35.7	0.0	64.3	64.3	0.0

Statistical Significance: $\alpha = 0.05$ (Sig = Significant, Non-Sig = non-significant).

increasing trend 24%, non-significant increasing trend 52%, significant decreasing trend 3%, non-significant decreasing trend 21%, and no trend 0% (Figure 2). The results showed that increasing trends had high frequency percentage than the decreasing ones, collecting about 76% in total. The decreasing trend was approximately 24%, and most of the stations with increasing percentage in trend are concentrated in Northern coast, Central, West, North-eastern highlands and Lake Victoria Basin. Most of the stations depicted negative trend is concentrated over Southern region.

The stations annual mean time series of the extreme precipitation indices in Tanzania from 1981 to 2020 are represented in Figure 4; 6 indices, namely the RX1day (maximum 1-day precipitation), RX5day (maximum 5-day precipitation), SDII (simple daily intensity index), very wet days of precipitation (R95p), extremely wet days of precipitation (R99p) and very heavy precipitation days (R20mm) showed a positive statistically significant increasing trend (Figures 4(a)-(f)). From the year 1981-2020, both RX1day and RX5day were increasing at the rate of 3.2 mm and 5.6 mm per decade respectively, with a significant positive trend of 35.7% and 17.9% of the stations respectively (Table 3), these stations were concentrated over Northern coast, central regions and western side of the country (Figure 3(a) and Figure 3(b)). 53.6% and 67.9% of the stations showed non-significant increasing trend for RX1day and RX5day, while 10.7% of RX1day and 14.2% of RX5day were observed to have negative trend but statistically non-significant. The same case to SDII, majority of the stations depicted positive trend, of which 32.1% were statistically significant and 53.6% were non-significant (Table 3). Most of the stations of the index SDII were concentrated all over the country except for South-western highlands and southern region in which 14.3% of the stations had downward non-significant trend. In general, majority of the stations for SDII were increasing at the rate of 0.2 mm/decade for the whole time period of the study.

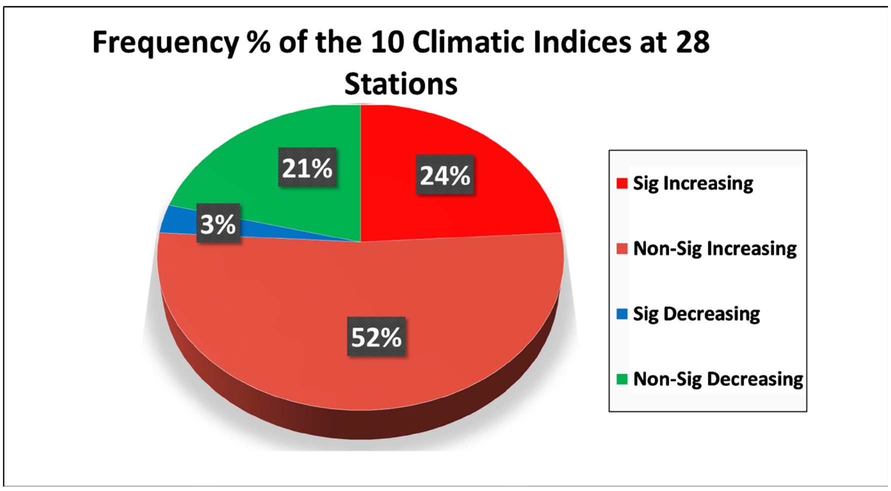
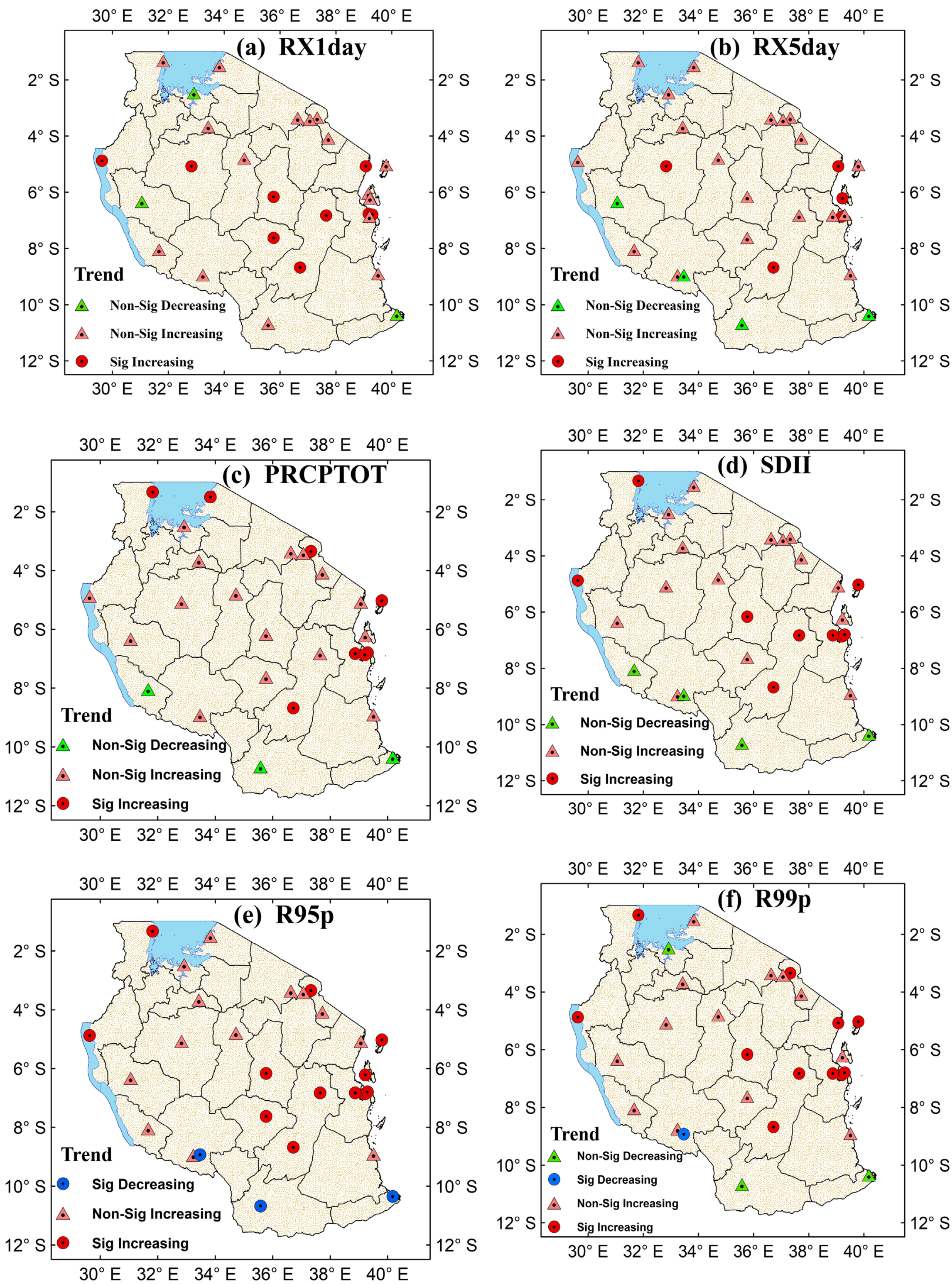


Figure 2. The frequency of annual average trends of extreme precipitation climatic indices for 28 Stations in Tanzania for the period 1981-2020. (Sig = significant, Non-Sig = non-significant).


(a) RX1day
Trend
Non-Sig Decreasing
Non-Sig Increasing
Sig Increasing
(b) RX5day
Trend
Non-Sig Decreasing
Non-Sig Increasing
Sig Increasing
(c) PRCPTOT
Trend
Non-Sig Decreasing
Non-Sig Increasing
Sig Increasing
(d) SDII
Trend
Non-Sig Decreasing
Non-Sig Increasing
Sig Increasing
(e) R95p
Trend
Sig Decreasing
Non-Sig Increasing
Sig Increasing
(f) R99p
Trend
Non-Sig Decreasing
Sig Decreasing
Non-Sig Increasing
Sig Increasing
30° E 32° E 34° E 36° E 38° E 40° E
2° S 4° S 6° S 8° S 10° S 12° S

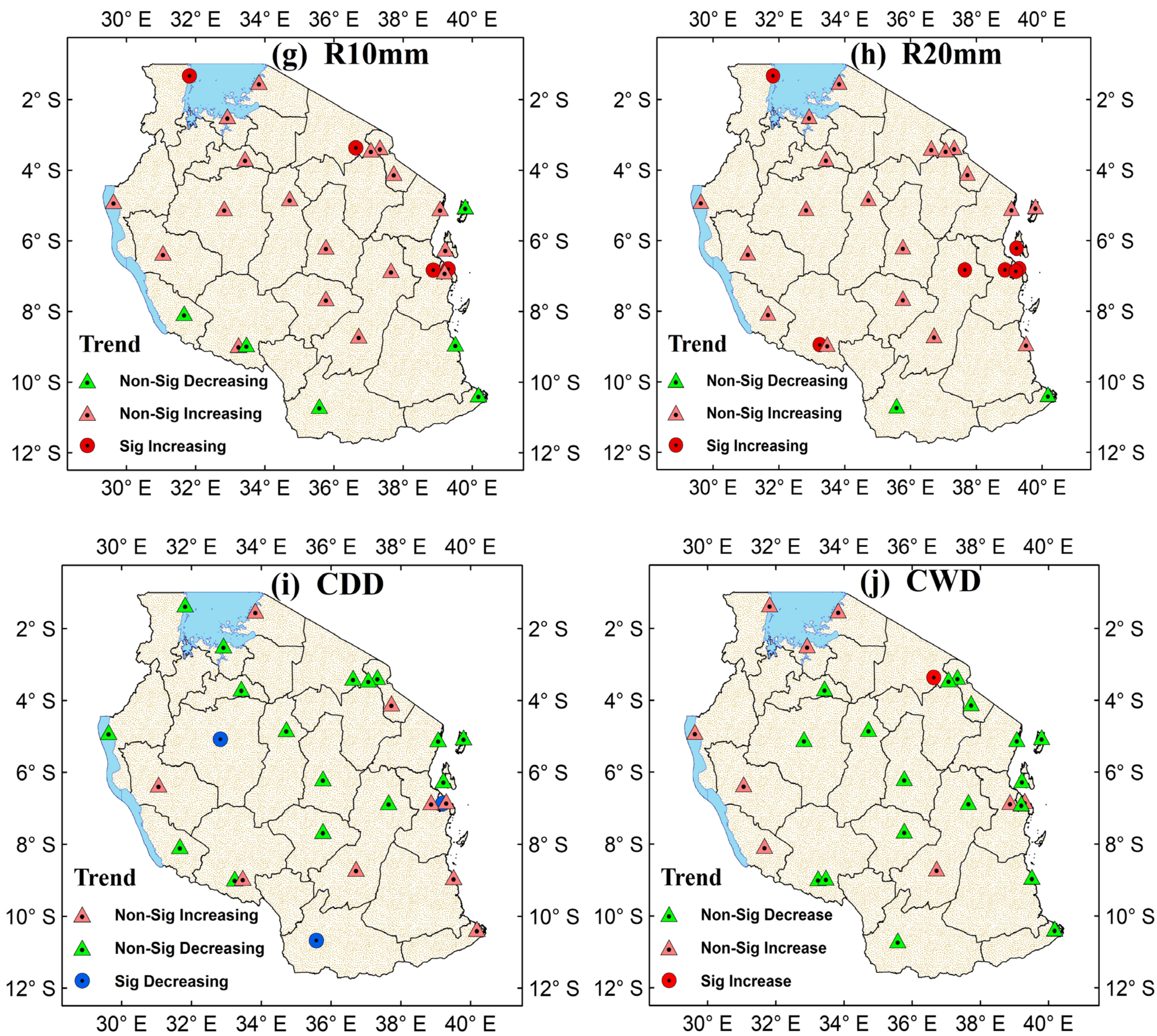
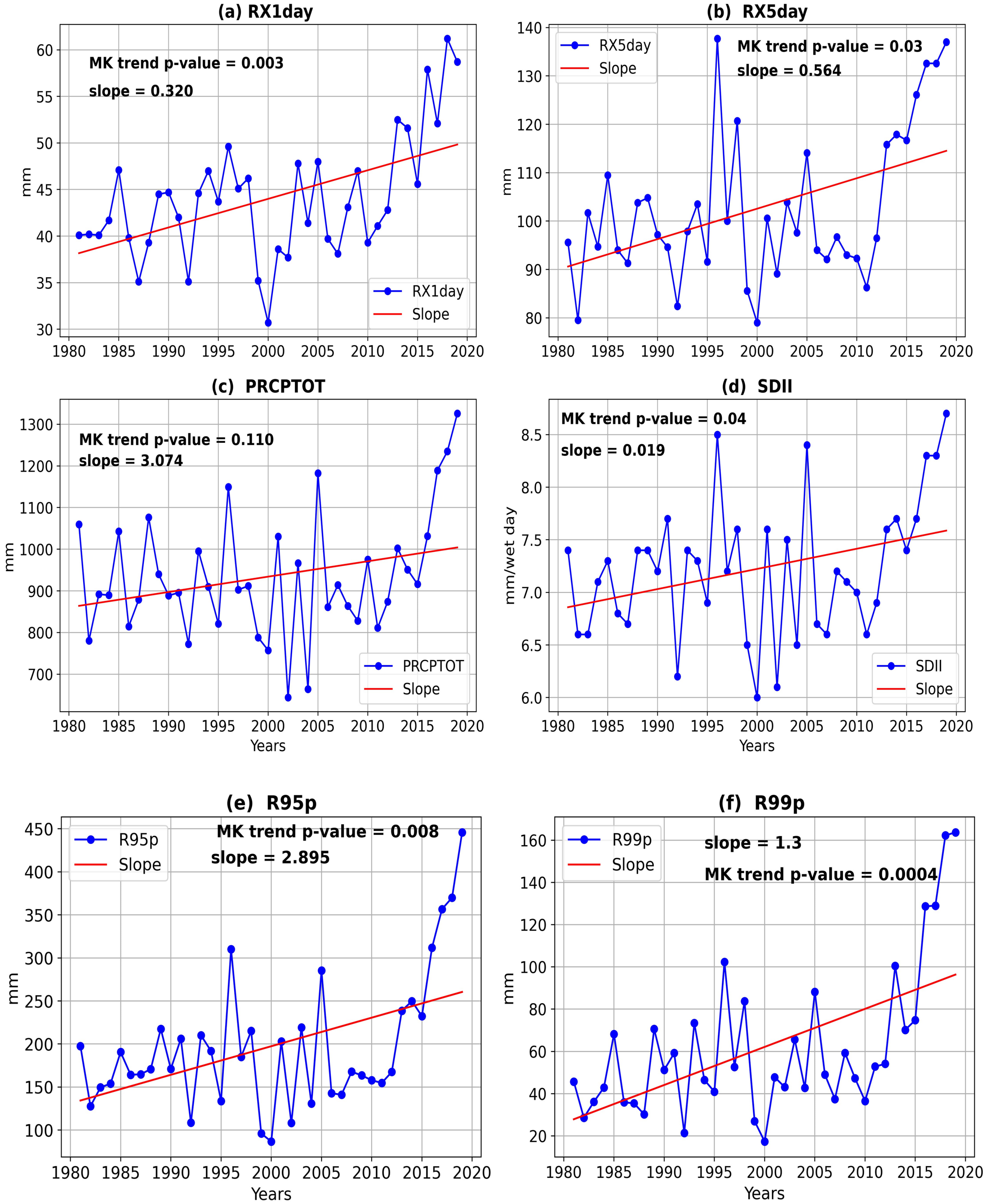


Figure 3. Spatial features of the annual average trends of extreme precipitation climatic indices in Tanzania (1981-2020).

The results also showed that R95p and R99p had similar spatial features with negative trends over South-western highlands and Southern region of the country. For R95p, 12 stations (42.9%) showed positive significant trend, 13 stations (46.4%) had non-significant positive trend while few (10.7%) had significant negative trend. For R99p, 39.3% and 46.4% of the stations were significantly and non-significantly increasing respectively, while only 3.6% was tested to decrease significantly. For both R95p and R99p, the three stations with significant negative trend were Songwe, Mtwara and Songea (Figure 3(e) and Figure 3(f)). Also, precipitation when the amount of rainfall is greater than R95th and R99th percentile was observed to increase at 29 mm/decade and 13 mm/decade respectively for the annual mean time series (Figure 4(e) and Figure 4(f)). Another statistically significant increase in trend was shown by the R20mm index which was increasing at the rate of 0.7 days/decade for annual time series of all stations

(Figure 4(g)). The significant increasing trend was contributed by 7 stations (25%), non-significant trend 19 stations (67.9%) and only 2 stations (7.1%) highlighted non-significant decreasing trend.



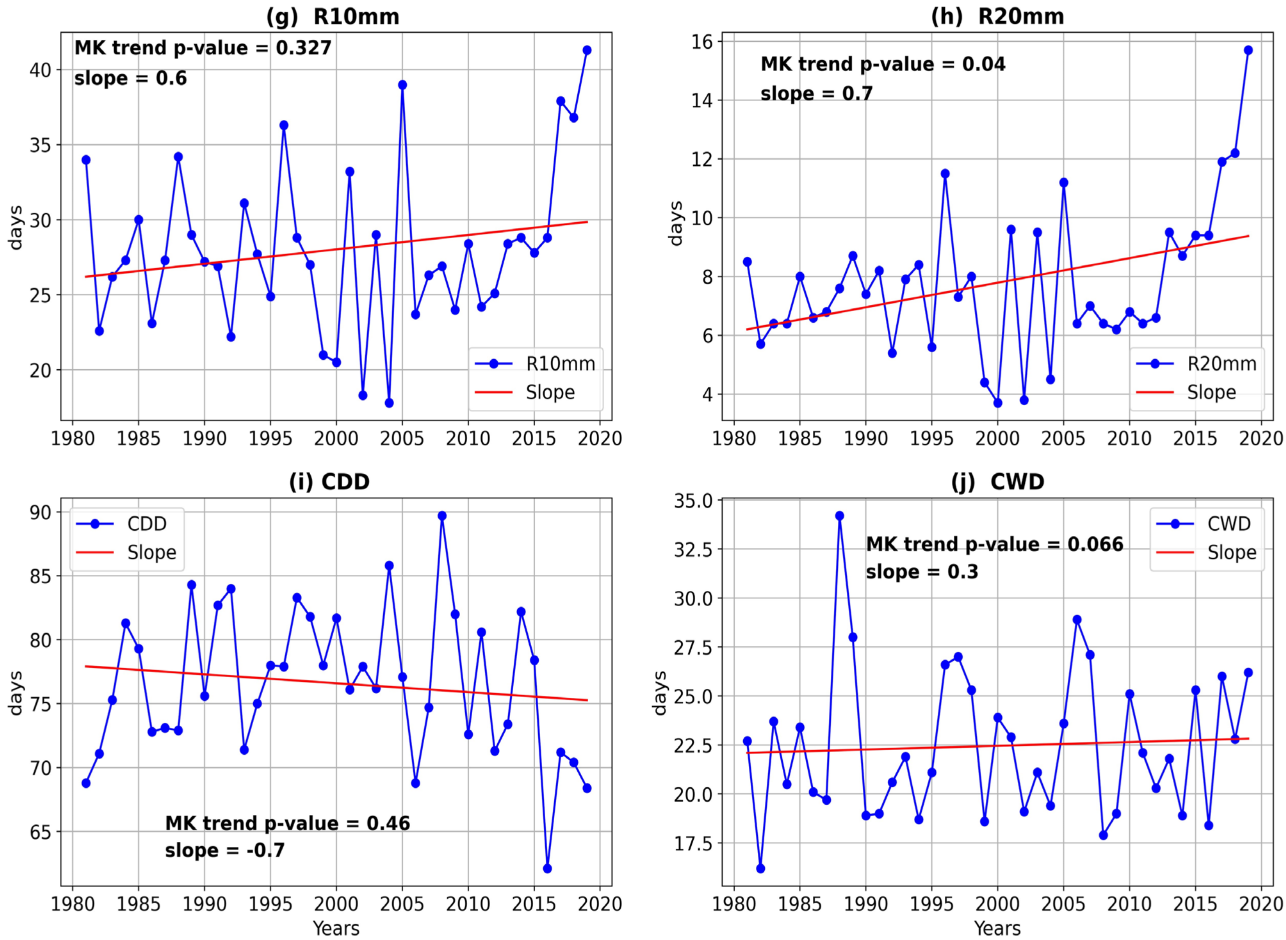


Figure 4. Time series of the annual average trends of extreme precipitation climatic indices in Tanzania (1981-2020).

On the other hand, annual time series of the stations showed that the indices PRCPTOT, R10mm and CWD have increased statistically non-significant at the rate 3.1 mm/decade, 0.6 days/decade and 0.3 days/decade respectively (Figure 4(c), Figure 4(g) and Figure 4(j)). For PRCPTOT, 89.3% of the stations showed upward trend and 10.7% had non-significant negative trend. The positive trend of PRCPTOT and R10mm was mostly contributed with many stations over the country except for South-western highlands and Southern region which depicted the negative trend (Figure 3(c)). Most of the stations under average Wet Consecutive days (CWD) were observed to decrease over the country except for areas around Lake Victoria Basin, West and some parts of Northern coast (Figure 3(j)). Only CDD was observed to decrease non-significantly from annual mean time series at 0.7 days/decade (Figure 4(i)). A total of 19 stations (67.8%) over the country were observed to decrease of which 10.7% had significant negative Trend (Table 3).

Further analysis of the result showed that among the threshold indices; R10mm, R20mm and CWD were all increasing except CDD which was decreasing (Figures 4(g)-(j)). CWD was slightly increasing at 0.3 days/decade, R10mm at 0.6 days/decade and CDD was decreasing at 0.7 days/decade. About

10.7% of the stations for this index had negative significant trend and 57.1% had non-significant decreasing trend. Many stations (64.3%) of CWD index showed insignificant negative trend. R10mm and R20mm showed positive trend of 78.6% and 92.9% in total respectively (**Table 3**), and most of their stations are concentrated to different parts of the country except for the southern region (**Figure 3(g)** and **Figure 3(h)**).

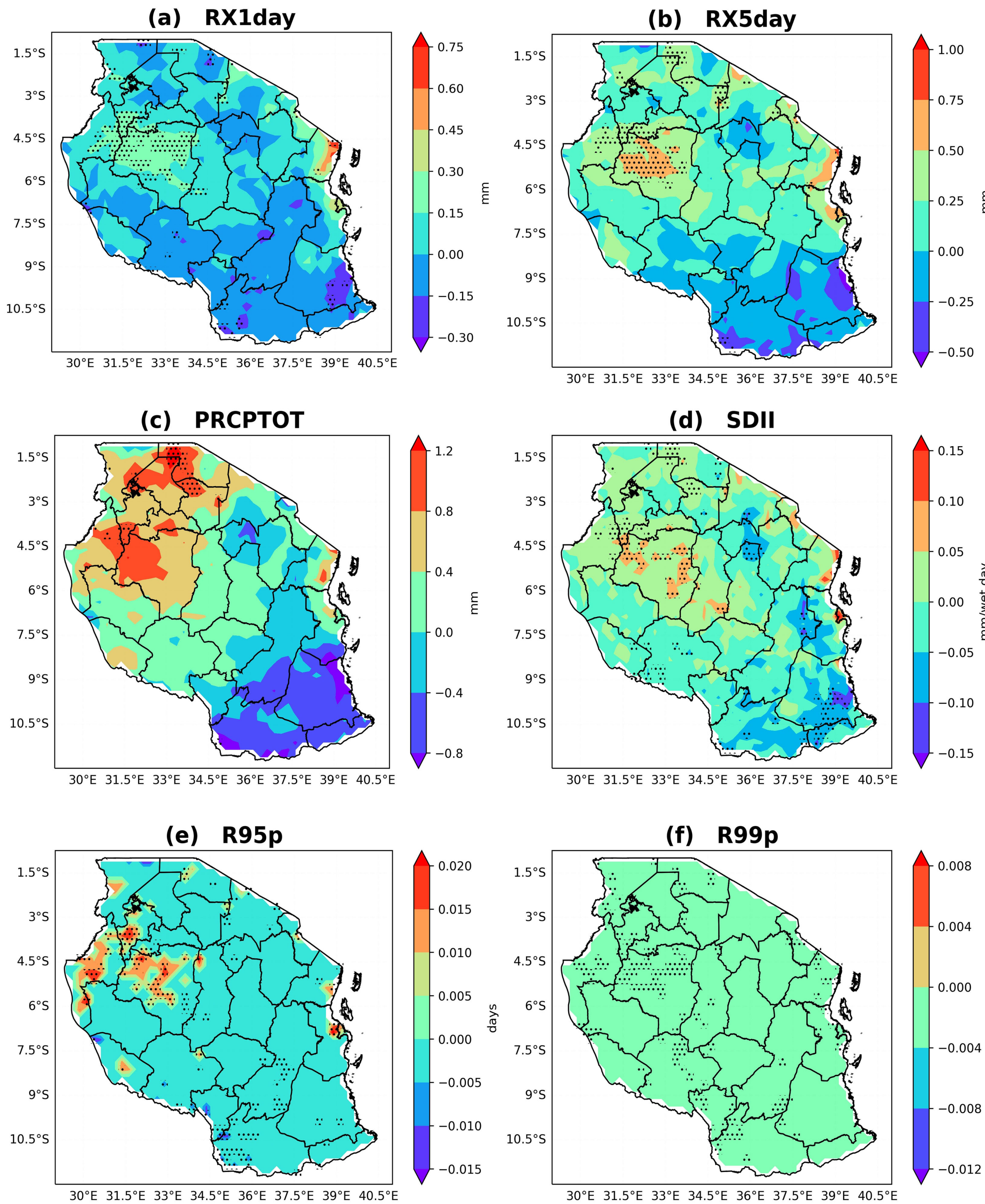
3.2. Seasonal Analysis of the Climatic Indices on the Extreme Precipitation

3.2.1. Trend Analysis of Climatic Indices during OND Season

The results of the seasonal analysis showed that RX1day and RX5day increased significantly at the rate of 1.5 - 4.5 mm/decade and 2.5 - 7.5 mm/decade over some parts of Tabora, Kigoma and areas around Bukoba respectively. While a downward significant trend of 1.5 - 3.0 mm/decade was observed over some parts of Songea, Sumbawanga and Mtwara for RX1day and Songea at the rate of 2.5 - 5.0 mm/decade for RX5day (**Figure 5(a)** and **Figure 5(b)**). PRCPTOT showed a positive significant trend at the rate of 8.0 - 12.0 mm/decade over some parts of Kigoma and Mara with non-significant downward trend over southern region, while SDII depicted increasing significant trend at the rate of 0.5 - 1.5 mm/wet day per decade over some parts of western zone, Lake Victoria basin, Arusha and Kilimanjaro but decreasing significantly over southern region (**Figure 5(c)** and **Figure 5(d)**). During the season, days related to R95p showed positive significant increasing trend over some western parts of the country, northern-eastern highlands and northern coast, while significant downward trend was observed over the southern region. All over the country, days related to R99p showed to decrease significantly in most parts of the country. The R95p also had significant negative trend in many parts of the country except western parts which were observed to increase significantly at 0.1 - 0.5 days/decade (**Figure 5(e)** and **Figure 5(f)**). The spatial analysis of the trend showed that most parts of Lake Victoria basin and Kigoma are increasing significantly at the rate of 0.2 - 0.8 days/decade for R10mm while for R20mm, some parts of West, Lake Victoria basin and Arusha were characterized by significant positive change ranging 0.2 - 0.5 days/decade and both depicted significant and non-significant negative trend over southern parts (**Figure 5(g)** and **Figure 5(h)**). CDD were observed to increase non-significantly in most parts of the country except Musoma and some parts of Shinyanga. Except some parts of West and Lake Victoria basin which showed significant increasing trend (0.4 - 0.8 days/decade), majority parts of the country depicted non-significant decreasing trend in Consecutive Wet days (CWD) (**Figure 5(i)** and **Figure 5(j)**).

During OND season, the seasonal average time series RX1day, RX5day, PRCPTOT, SDII and CWD showed an increasing trend but statistically non-significant (**Figure 6**). While CDD had decreasing non-significant trend, the seasonal average SDII, R95p, R99p, R10mm and R20mm had no trend at all.

RX5day showed a highest increase change of 1.6 mm/decade followed by PRCPTOT (0.7 mm/decade), RX1day (0.2 mm/decade). CWD was increasing at the rate of 0.09 days/decade while CDD was decreasing at the rate of 0.3 days/decade (Figure 6).



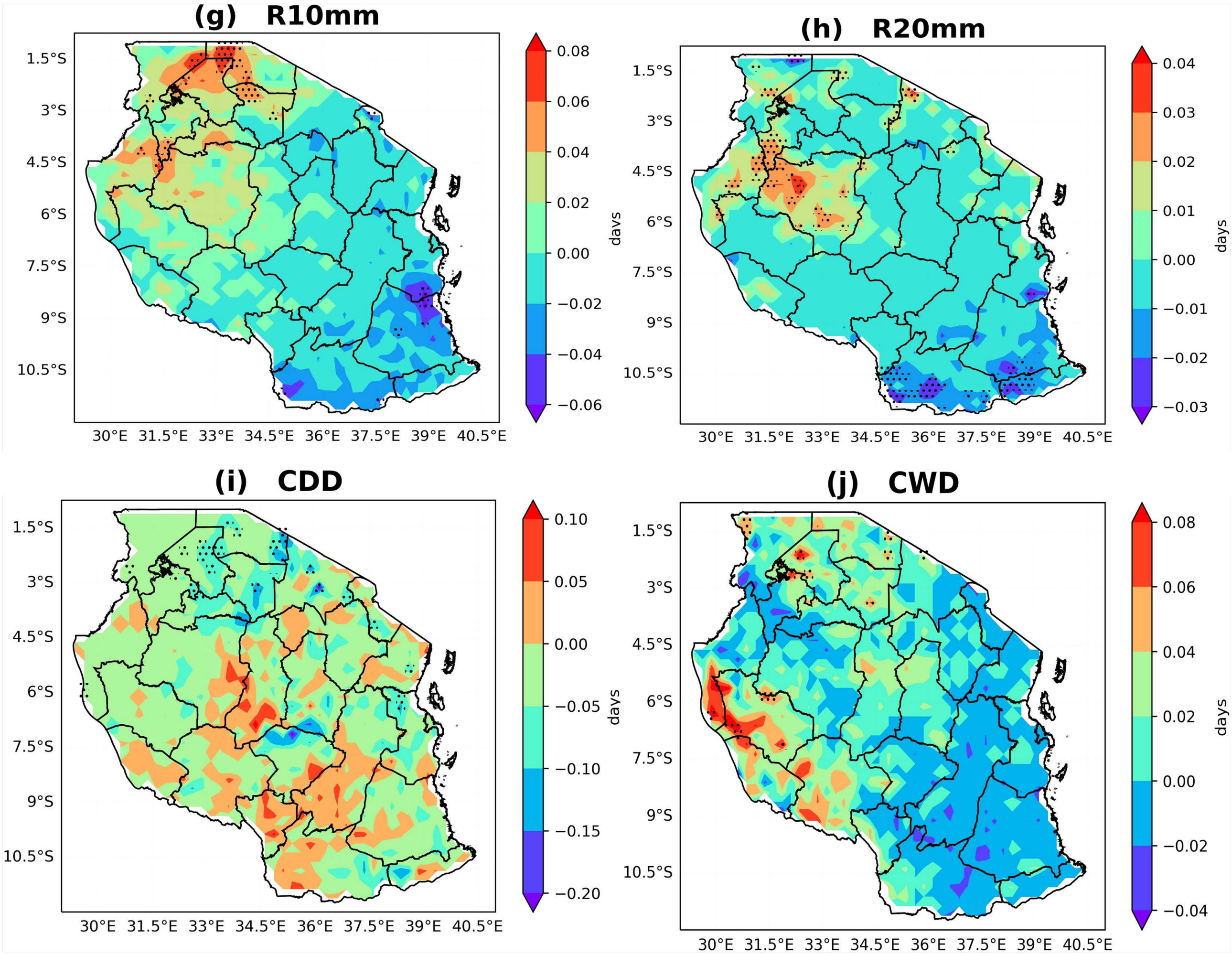
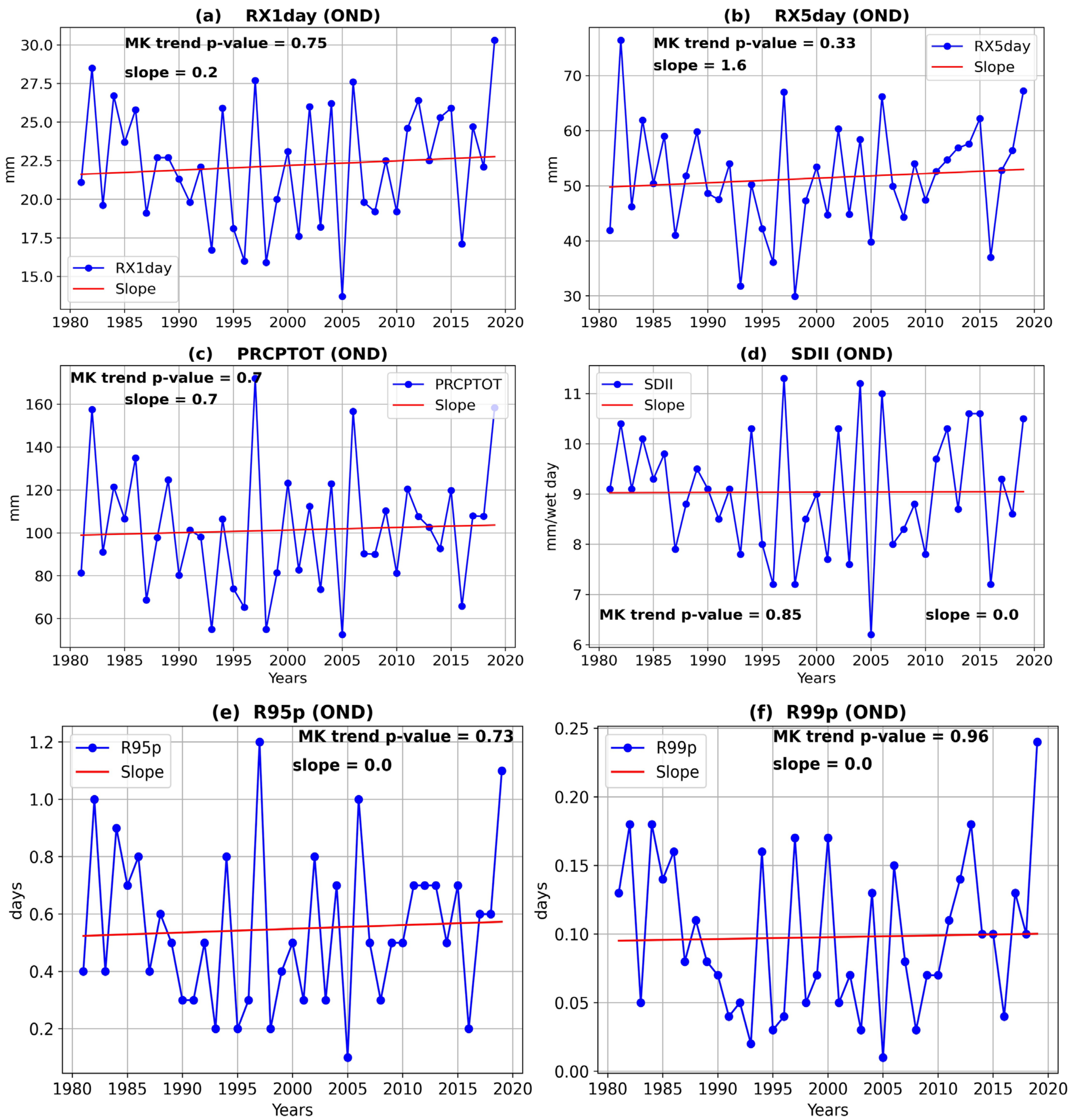


Figure 5. Spatial patterns of trends of extreme precipitation climatic indices during OND Season in Tanzania (1981-2020). The dots represent areas which have statistically significant changes at 95% confidence level during the study period.

3.2.2. Trend Analysis of Climatic Indices during MAM Season

During MAM season, Both RX1day and RX5day showed significant increasing trend over some parts of Bukoba, Arusha, Kilimanjaro, Northern Coast, some parts of Songea and Iringa at the rate 3.0 - 15.0 mm/decade with non-significant down trend over many parts of the country (Figure 7(a) and Figure 7(b)). PRCPTOT had positive significant increasing trend over Bukoba, Arusha Mara, Simiyu, Manyara, Dodoma and Mbeya (6.0 - 18.0 mm/decade) but majority parts portrayed non-significant increasing trend (Figure 7(c)). Simple Daily Intesity index (SDII) depicted the same patterns as RX1day and RX5day (Figure 7(d)). R95p showed significant increasing trend over Kigoma, some parts of Arusha, Mara and Simiyu, Northen coast, Morogoro, Mahenge and Njombe region. Most parts of the country depicted downward significant trend of R99p except for Some parts of Mahenge, Songea and Njombe which showed significant increasing trend. The trend analysis highlighted similar patterns of significant increase/decrease of R10mm/R20mm (Figure 7(g) and Figure 7(h)). The significant increase of these indices was observed few parts of west, lake Victoria basin, Northern eastern highlands and Mtwara at (0.2 - 0.6 days/decade) but majority parts depicted non-significant negative trend. More conspicuous increase of consecutive dry days (CDD) during the season was detected over some parts of Central region, Mpanda and Iringa while significant downadward trend was observed over south-western highland, Lake Victoria Basin and North-eastern highland. Significant increase in Consecutive wet days (CWD) was highlighted over most areas which had significant downward trend in CDD during MAM. Also, some parts of Mahenge and Northern coast showed negative significant decreasing trend of CWD (Figure 7(h) and Figure 7(i)).



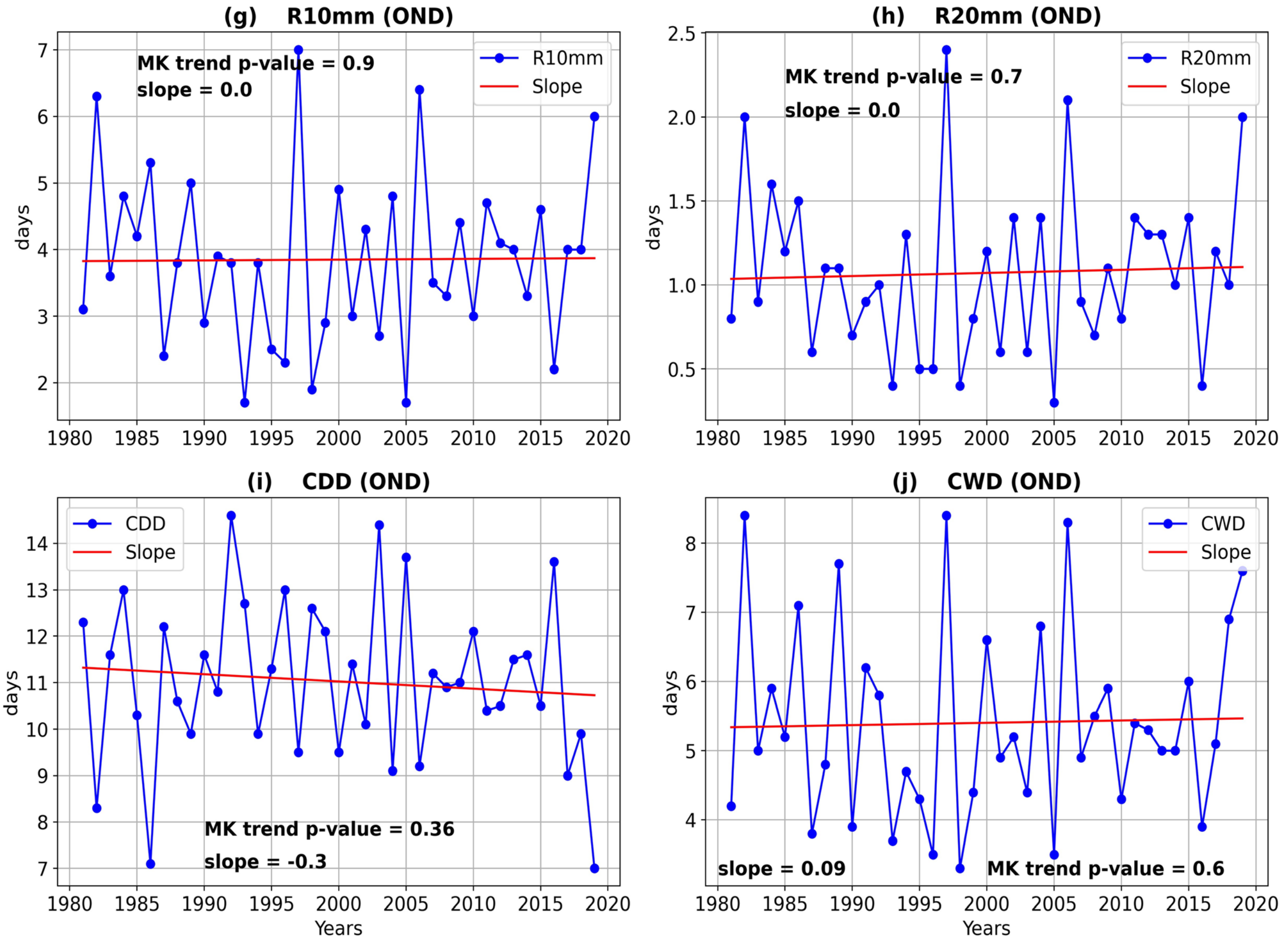
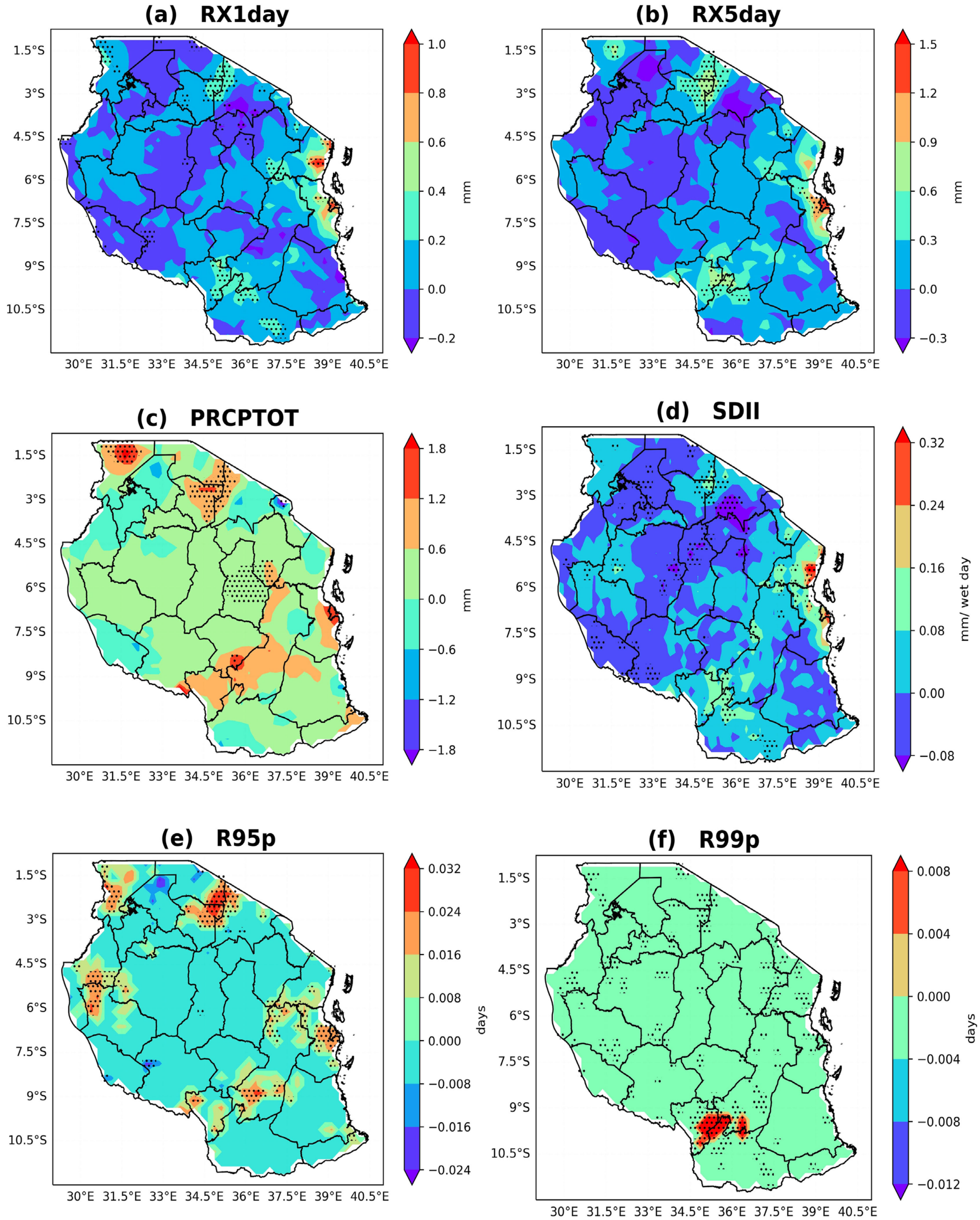


Figure 6. Seasonal average Time series of the Extreme precipitation climatic indices during OND Season in Tanzania (1981-2020).

The average changes of the seasonal time series of the indices of extreme precipitation (1981-2020) during MAM is highlighted in **Figures 8(a)-(j)**. 8 indices showed non-significant increasing trend except for CWD with downward non-significant trend and R10mm with no trend. Both RX1day and RX5day were increasing at the rate of 0.5 mm/decade. Other increase in trend was observed for PRCPTOT (1.9 mm/decade), SDII (0.2 mm/wet day per decade), R95p (0.04 days/decade), R99p (0.01 days/decade), R20mm (0.04 days/decade) and CDD (0.1 days/decade). CWD was decreasing at the rate of 0.1 days/decade for the whole time period of the analysis.

3.3. Discussion

This study used data from 28 meteorological stations over a 40-year period to give an annual, seasonal and temporal analysis of the patterns of 10 extreme precipitation indices over Tanzania. The annual climatological means of extreme indices' spatial distributions show that, compared to decreasing trend observed over the southern region, the increasing trend of the precipitation extremes over the country are typically more. The annual mean time series of the intensity related indices (RX1day, RX5day, PRCPTOT and SDII) have depicted upward increasing trend, 3 of them except PRCPTOT have increased statistically significant. Most stations of these indices are concentrated in most parts over the country except over Southern region. The dominance of the increasing trend of



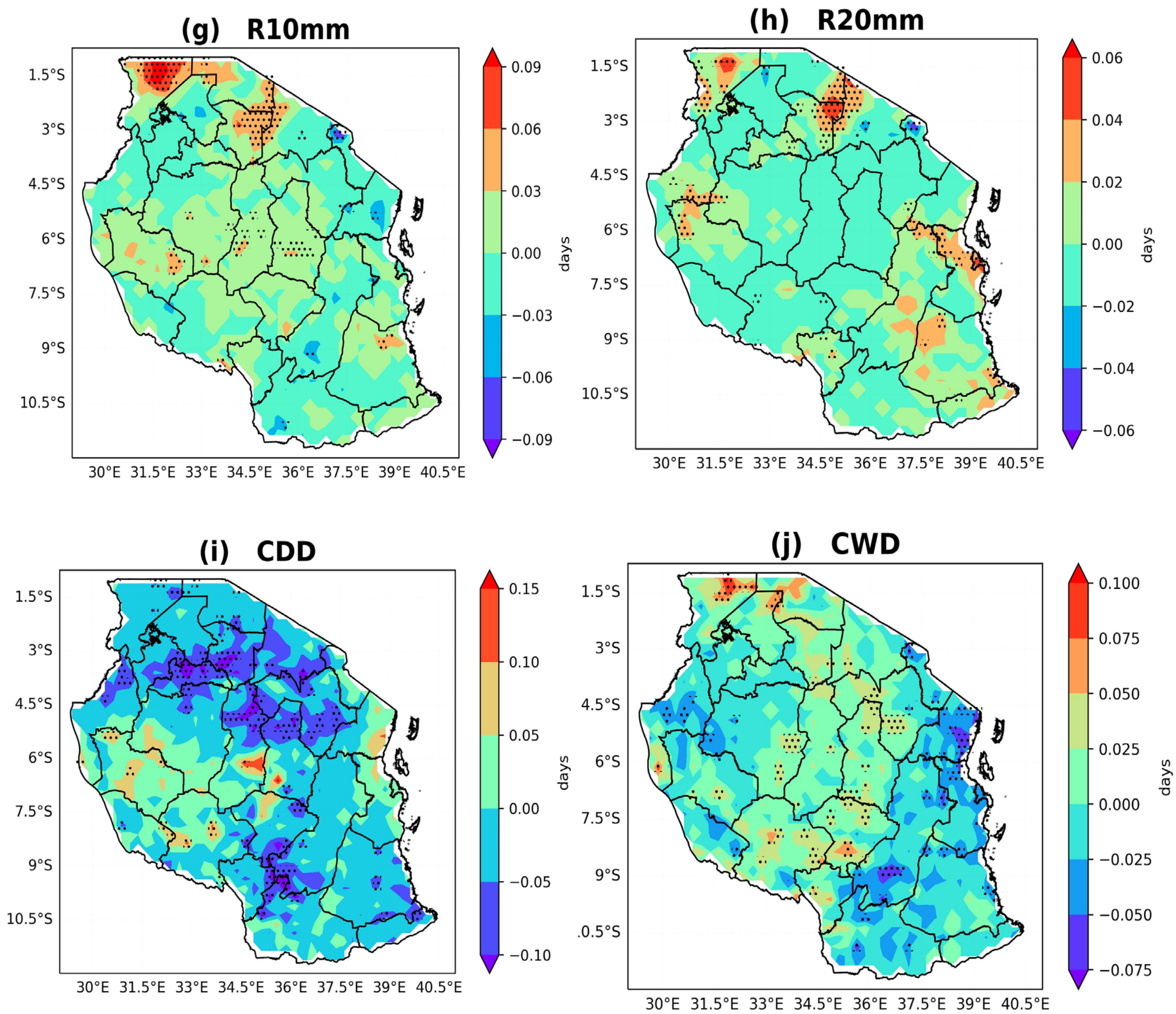
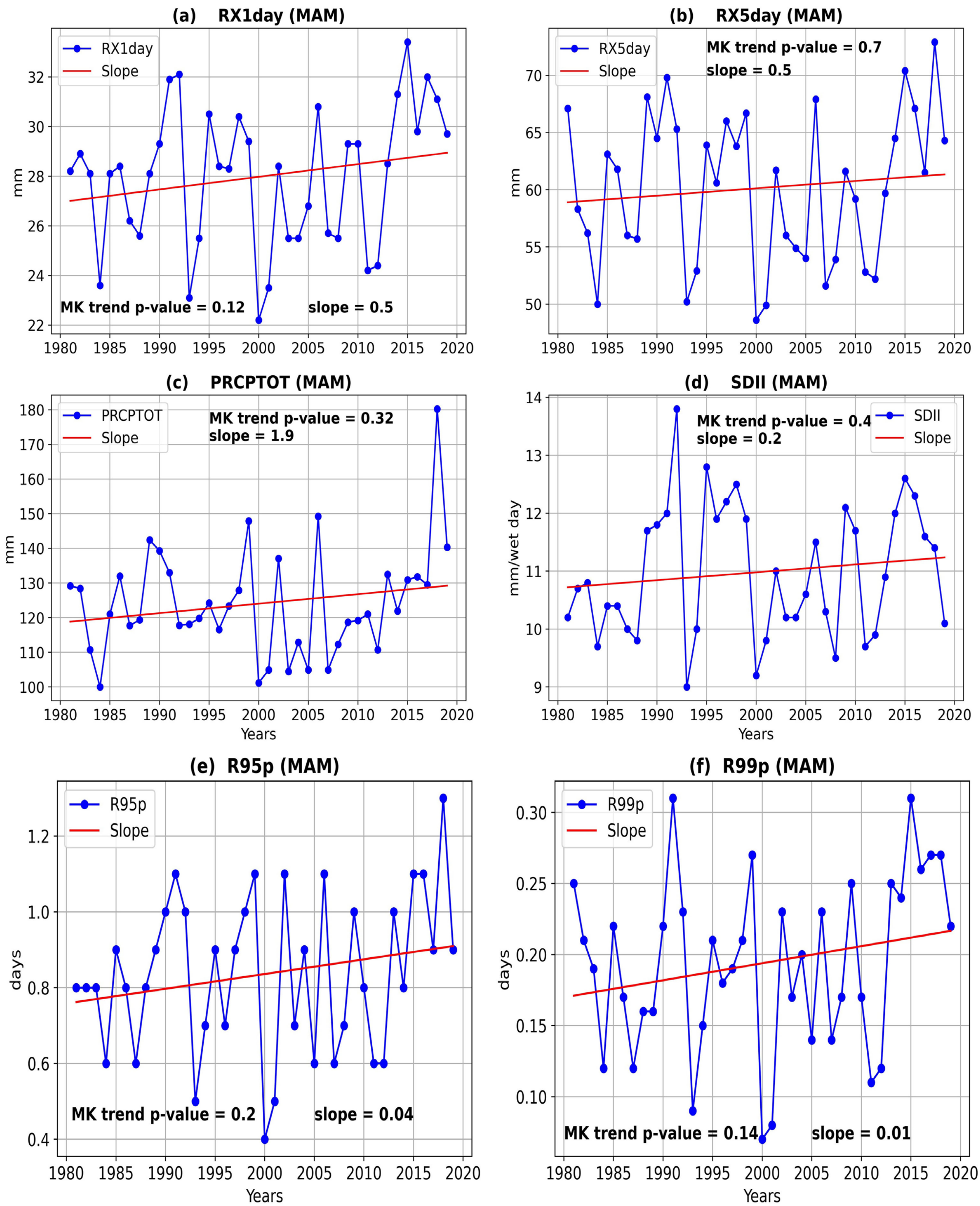


Figure 7. Spatial patterns of trends of extreme precipitation climatic indices during MAM Season in Tanzania (1981-2020). The dots represent areas which have statistically significant changes at 95% confidence level during the study period.

the ETCCDI's indices highlights that the extreme precipitation incidences in the country have increased for the time period 1981-2020. The results are consistent with other many studies and reports (IPCC, 2023; Ogega et al., 2020; *Statement on the Status of Tanzania Climate*, 2020). Reasons for the these extremes are explained by (IPCC, 2023; Ojara et al., 2021; Osima et al., 2018) to be caused by increasing global warming, Teleconnection systems (El Niño-Southern Oscillation (ENSO) and positive Indian Ocean Dipole (IOD)) and Tropical cyclones in the basin of South-Western Indian Ocean (Kai, Osima, et al., 2021b). The indices related to very wet days (R95p) and extremely wet days (R99p) have observed to increase statistically significant over the entire period of time 1981-2020 at 29 mm/decade and 13 mm/decade respectively with most stations all over the country (more than 85%) except for the southern region. This result of increasing trend depicted by these indices is similar to those found by (Luhunga, 2022) in historical period (1971-2000). For the significant decreasing trend of precipitation over the southern region, the result is consistent with (Chang'a et al., 2017). Three frequency related indices (R10mm, R20mm and CWD) have observed to



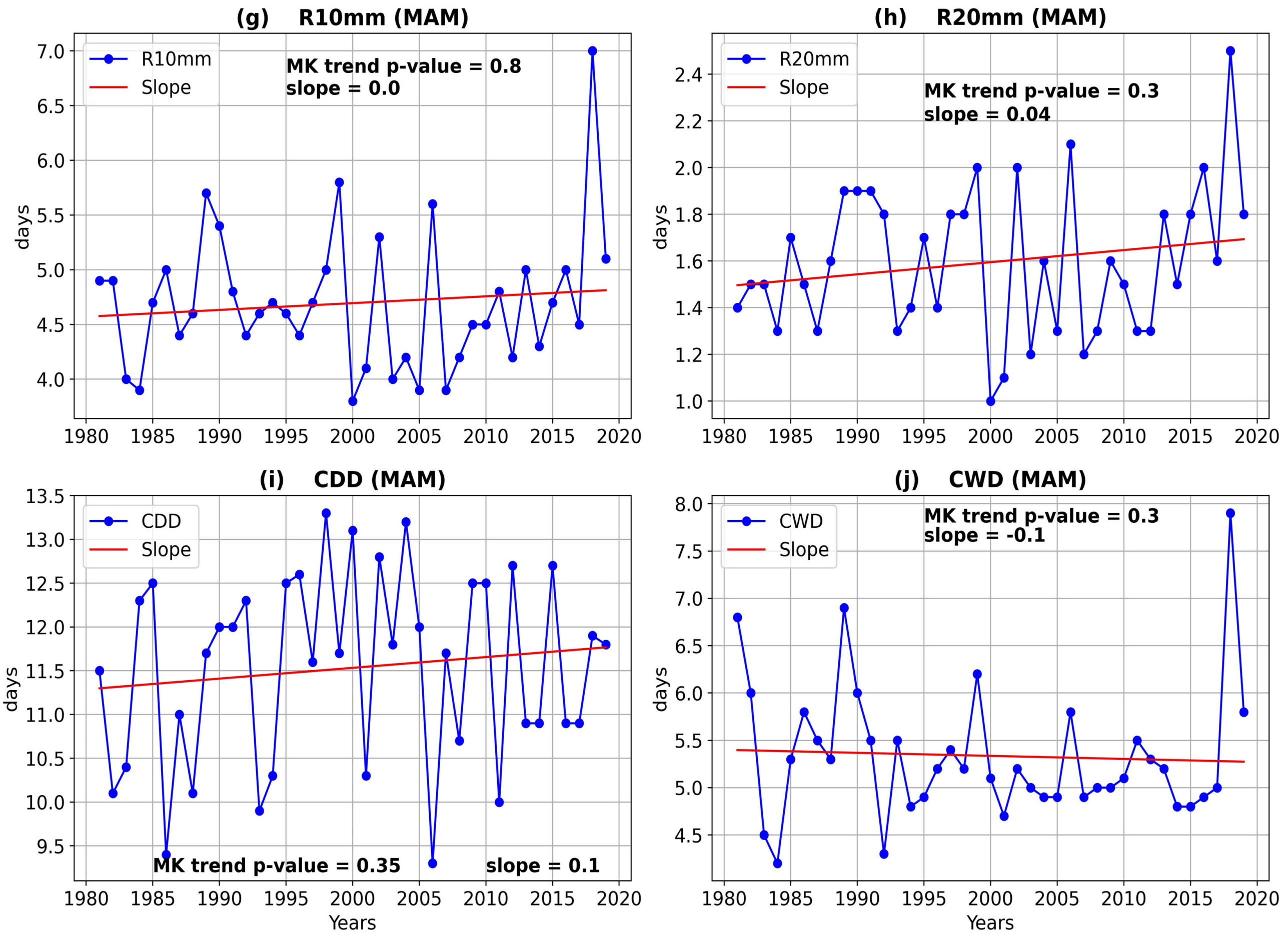


Figure 8. Seasonal average Time series of Extreme precipitation climatic indices during MAM Season in Tanzania (1981-2020).

have upward increasing trend, of which only R20mm showed significant positive trend. In terms of spatial patterns, R10mm and R20mm stations were almost similar to those found with intensity related indices, R95p and R99p. Among all extreme indices, the non-significant decrease in trend was depicted by the Consecutive dry days (CDD). The decrease in 0.7 days/decade was observed over 19 stations (67.8%) and is in agreement with a total 19 stations (67.8%) over the country. Although the annual time series have depicted slight non-significant increase in Consecutive Wet Days (CWD) at 0.3 days/decade, the spatial patterns have revealed the decrease in CWD in majority stations (64.3%). The decrease of Consecutive Wet days in many stations highlights the presence of drought events over the country for the time period 1981-2020. The results of decrease in CWD over the country is consistent to those found by (Luhunga, 2022; Osima et al., 2018) in the historical period. The decrease in trend of precipitation over southern region can be explained by the climatological wind circulations of Tropical cyclones in SWIO during November to April season. Many Tropical cyclones which form along Mozambique Channel are associated with North-west movement which sweeps away moisture from the region; this leads to decrease in the expected total Precipitaion over the region.

During OND season, all extreme precipitation climatic indices except R99p showed positive significant trend over Lake Victoria Basin and Western part of the country. This is caused by the presence of ITCZ as explained by (*Statement on the Status of Tanzania Climate*, 2020). This is opposite over the southern region where majority of the stations depicted decrease in extreme precipitation. The maximum 1-day precipitation (RX1day), Annual total wet-day precipitation (PRCPTOT) and number of heavy precipitation days (R10mm) were observed to have decreased over the Mount Kilimanjaro (**Figure 5(a)**, **Figure 5(c)** and **Figure 5(g)**) but with R10mm significantly. The seasonal average time series of the climatic indices for the whole period of study (1981-2020) did not show any trend except for CDD which showed non-significant decrease at 0.3 days/decade during OND season. But generally, spatial patterns indicate decrease of precipitation over most parts of the country. The study conducted by (Kijazi & Reason, 2009a, 2009b) during OND season (1998-2005) showed that Tanzania's low-level moisture divergence, sinking of westerly winds, and the country's eastward shift of the ascending arm of the Walker cell were all factors contributing to the extended drought spells.

For MAM season, the indices (RX1day, RX5day, R95p) have showed positive significant trend over North-eastern highlands and Northern Coast. PRCPTOT shows that most parts of the country have depicted wetness, this is due to the fact that MAM is the long rain season in the country (TMA, 2022). All the seasonal time series (**Figure 8**) showed that extreme precipitation indices have increased non-significantly during MAM season, except for CWD which showed non-significant decrease in trend. PRCPTOT, the number of heavy days (R10mm), very heavy days (R20mm) of precipitation and Consecutive Wet Days (CWD) have observed to decrease significantly over the Mount Kilimanjaro (**Figure 7(c)**, **Figure 7(g)** and **Figure 7(j)**). PRCPTOT has decreased at 12.0 - 18.0 mm/decade, R10mm at 0.6 - 0.9 days/decade, R20mm at 0.4 - 0.6 days/decade and CWD at 0.3 - 0.6 days/decade during the seasonal analysis time period (1981-2020). The result of decrease of annual total precipitation over Mount Kilimanjaro is parallel to those explained by (Agrawala et al., 2003; Thompson et al., 2009). Over the last several decades, massive savanna forests over the Mountain have been used more and more for agriculture, while logging, burning and overgrazing have devastated thousands of hectares of the mountain's forest cover hence resulting in decrease of the precipitation.

4. Conclusion

This study used daily precipitation data for the period 1981-2020 to examine annual and seasonal changes in extreme precipitation over Tanzania using 28 synoptic stations.

1) At annual scale, climatological means of extreme indices' spatial distributions have shown that, compared to decreasing trend observed over the southern region, the increasing trend of the precipitation extremes over the country is

typically more. The increasing trends had high frequency percentage than the decreasing ones, collecting about 76% in total. The decreasing trend was approximately 24%, and most of the stations with increasing trend are concentrated in Northern coast, Central, West, North-eastern highlands and Lake Victoria Basin. The spatial patterns have revealed the decrease in CWD in majority stations (64.3%).

2) Spatial patterns indicate decrease of precipitation over most parts of the country during OND. Over the Mount Kilimanjaro; RX1day, PRCPTOT and R10mm were observed to decrease at 10.0 - 12.5 mm/decade, 4 - 8 mm/decade and 0.4 - 0.6 days/decade respectively. The seasonal average time series of extreme precipitation indices (SDII, R95p, R99p, R10mm and R20mm) did not show trend, the rest except CDD showed non-significant positive trend.

3) During MAM season; spatial patterns of the days related to R95p and R99p have observed to decrease in many parts of the country. PRCPTOT, the number of heavy days (R10mm), very heavy days (R20mm) precipitation and Consecutive Wet Days (CWD) were observed to decrease significantly over the Mount Kilimanjaro. The seasonal average time series depicted non-significant increase (decrease) of CDD (CWD) for the whole study time period during MAM season.

4) The Mount Kilimanjaro is very important for tourism as well as the source of the country's income. Deliberate actions must be taken and implemented to protect this important ecology of the surrounding and the world's heritage. Furthermore, majority people in the country depend on rain-fed agriculture. Due to decrease of CWD and increase in CDD as depicted in this study, alternative ways like establishment of irrigation systems are very important in this age of climate change. This will not only help farmers not to depend on seasonal agriculture but also ensure them food security. Further studies are recommended to explore extreme precipitation relationship with weather driving systems like atmospheric circulations and Teleconnections, this will help to improve accurate forecast of extreme precipitation events.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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