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Trends of Extreme Events in Precipitation and Temperature during the 1963 - 2012 Period at Mt Makulu, Zambia

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

The Expert Team on Sector-specific Climate Indices (ET-SCI) for daily temperature and precipitation were analyzed for Mt Makulu (Latitude: 15.550° S, Longitude: 28.250° E, Elevation: 1200 meter) in Zambia. The study objective was to evaluate the ET-SCI climate indices for extreme weather conditions on temperature and precipitation from 1963 to 2012. Quality and homogeneity of the time series data were checked using RHtestsV4 and RHtests_dlyPrcp while ClimPACT2 software package was used to compute the ET-SCI indices. The Mann-Kendall for annual maximum and mean temperature were statistically significant with a positive linear trend ($p<0.05$). Additionally, results showed a significant increase in absolute indices as a function of temperature. The maximum warmest daily temperature (TXx) index showed a predominant increase in the monthly and annual maximum value of daily maximum temperature at Mt Makulu. The minimum warmest daily temperature (TXn) showed a similar trend for the annual value. Results also showed that the daily mean temperature (TMm) and mean daily maximum temperature (TXm) had increased from 1963 - 2012. The Daily Temperature Range (DTR) significantly increased annually and monthly resulting in a linear slope of 0.031 and 0.003, respectively. SU (Number of days when

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TX > 25℃) for both monthly and annual trend had in creased significantly with a slope of 1.204 and 0.009, respectively. There were much higher heat spell events during DJF and SON with probability occurrence of 0.78 and 0.98 at $p<0.05$, respectively. Precipitation extreme indices (PRCPTOT, R30 mm, RX5 day, and R95p) had a non-significant positive trend at $p<0.05$.

Keywords: ClimPACT2; climate indices; RHtest, climate change; climate extremes; heatwaves; RClimDex.

1. INTRODUCTION

Climate extremes associated with droughts, floods, frosts, and heatwaves are substantially significant to societal, ecological, and economic impacts across most regions of the world. Observations of extreme events provide a key foundation and understanding of long-term climate change and variability and provide underpinning climate model evaluations and projections [1]. The Intergovernmental Panel on Climate Change (IPCC) first attempt at global assessment of long-term changes in temperature and precipitation extremes appears in its Third Assessment Report (AR3) of 2001 [1]. The report highlights increased heavy precipitation events, decreased the frequency of extremely low temperature and increased the frequency of extremely high temperature. There is a consensus within the climate community that any change in the frequency or severity of extreme weather events would have profound impacts on nature and society [2–4] and it is thus imperative to analyze extreme events. The monitoring, detection, and attribution of changes in climate extremes usually require daily time series data [3]. The IPCC AR4 (2007) report observed that climate change was likely to affect precipitation across the world as reflected in the precipitation mean and variability estimates [5,6]. The Zambian climate has a historical record of droughts and floods occurrence [7]. Many studies have investigated climate change and extreme weather events on a large scale or either at regional or national scale [8], but few of these are undertaken in Zambia at the local level.

The Expert Team on Climate Change Detection and Indices (ETCCDI) started its work in 1999. It is co-sponsored by the World Climate Research Programme (WCRP) and Joint WMO-Intergovernmental Oceanographic Commission of the United National Educational, Scientific and Cultural Organization (UNESCO) Technical Commission for Oceanography and Marine Meteorology (JCOMM) [9]. This team has developed an internationally coordinated set of core climate indices consisting of 27 descriptive indices for moderate weather extremes [10–12]. These indices were drawn up with the detection and attribution of the research community in mind [10]. To detect changes in climate extremes, the set of indices should be statistically robust, cover a broad range of climatic zones, and possess a high signal-to-noise ratio. Also, these internationally agreed indices derived from daily temperature and precipitation allow for results to be compared consistently across different climatic zones and also have the advantage of overcoming most of the restrictions on the dissemination of daily data that are applied in many countries [9]. The ETCCDI has organized regional workshops and developed climate-extreme indices based on daily temperature and precipitation, both of which aim to document change in climate extremes over poorly studied areas [9,10,13] and thereby enhance global analysis [12]. The Expert Team on Climate Risk and Sector-specific Indices (ET CRSCI) commissioned the development of the software called ClimPACT, with the aim of producing an easy and consistent way of calculating these climatic indices [9].

The ClimPACT2 is an R software package that was written in r-code to calculate Sector-specific Climate Indices (ET-SCI) and other additional climate extreme indices from data stored in text and netCDF files. ET-SCI indices represent a set of over 60 climate extremes indices together with ETCCDI indices. ClimPACT2 provides useful indices for application in Health, Agriculture and Food Security, and Water Resources and Hydrology Sectors. ClimPACT2 is based on the computations in RClimDEX software developed by the World Meteorological Organization (WMO) Commission for Climatology (CCl)/World Climate Research Programme (WCRP) on Climate Variability and Predictability (CLIVAR)/JCOMM. It also directly incorporates the R packages climdex.pcic and climdex.pcic.ncdf developed by the Pacific Climate Impacts Consortium (PCIC). The software provides three methods for computing indices using text files containing station data: (i) Graphical User Interface; (ii) to batch process multiple station text files in parallel;

and (iii) calculating indices from netCDF data [10]. The development and analyses of these ClimPACT2 sector specific indices have made a significant contribution to climate change discussions in the IPCC Assessment Reports [1].

Before indices are computed, daily input data are checked for quality and homogeneity. This is done to detect artificial change-points in climate data series and to minimize bias in climate trends, variability, and extreme analysis [8,14]. The ETCCDI recommend the use of the RHTest software for checking data homogeneities. It is common to find: typos, missing data, outliers and trends in time series data, which may then require a detailed process of quality assessment and control, and estimation of missing data. The literature reviewed indicated that there is insufficient information on trends in climate extremes especially in developing countries at local-scale due to inadequate resources and limited access to data, Zambia is no exception. Therefore, the objective of this study was to investigate the changes in selected ET-SCI climate indices in temperature and precipitation extremes at Mt Makuku.

2. MATERIALS AND METHODS

2.1 Study Area and Data

The study used weather data from Mt Makulu Agromet (Latitude: 15.550° S, Longitude: 28.250° E, Elevation: 1213 meter above sea level) located within the perimeters of the Zambia Agriculture Research Institute (ZARI) Central Research Station. ZARI Central Research Station is also the headquarters of the Zambia Agriculture Research Institute (ZARI) and the largest Agricultural research entity in the country. The weather station is located in Agro-ecological Region II (AERII) of Zambia as shown in Fig. 1 and was characterized by an annual rainfall of 800 to 1,000 mm and area coverage, 42% of the country. The climate of Zambia is described as a wet and dry tropical and sub-tropical modified by altitude [15]. On the basis of rainfall and temperature patterns, the year is divided into four seasons, namely: the Hot Season (September to October), the Rainy Season (November to March), the Post Rainy Season (April and May), and the Cool and Dry Season (June to August) [15]. The annual precipitation is strongly influenced by the shifting of the Pacific Ocean's El Nino Southern Oscillation (ENSO), the Inter-Tropical Convergence Zone (ITCZ) and the Congo Air Boundary. The multi-decadal trends in these phenomena contribute to annual variations in rainfall patterns and temperature. Historical climate data (1963-2012) for daily rainfall, minimum and maximum air temperature was obtained from the Zambia Meteorological Department (ZMD) and is shown in Fig. 2.

2.2 Trends in Time Series Data

The Mann-Kendall test is a commonly-used nonparametric test for time trend [16–18] analysis. The annual time series data for Mt Makulu was tested for annual trends and slopes using the Mann–Kendall test in R Programming software [18,19]. Before applying the Mann-Kendall test to the time series data of annual precipitation and temperature levels, the data were assessed for serial correlation. This is an important test before applying the Mann-Kendall test in conjunction with block bootstrapping to account for serial correlation. More details on testing for trends in precipitation and temperature are provided by [16–18]. The Mann-Kendall test statistic was calculated according to the equations below:

$$s = \sum_{k-1}^{n-1} \sum_{k=k+1}^{n} sgn(x_j - x_k) \tag{1}$$

Where n is the length of the time series x_i . x_n, and sgn (.) is a sign function, x_j and x_k are values in years j and k, respectively. The expected value of S equals zero for series without trend and the variance was computed as:

$$\sigma^2(S) = \frac{1}{18}\left[n(n-1)(2n-4) - \sum_{p=1}^{q} t_p(t_p - 1)(2tp+5)\right. \tag{2}$$

and q is the number of tied groups; t_p is the number of data values in Pth group. The test statistic Z was then given as below:

$$Z = \begin{cases} \frac{s-1}{\sqrt{\sigma^2(s)}} \; if\; S > 0 \\ 0 \quad if\; S = 0 \\ \frac{s+1}{\sqrt{\sigma^2(s)}} \; if\; S < 0 \end{cases} \tag{3}$$

The Z statistic was used to test the null hypothesis, H_0, that the data were randomly ordered in time, against the alternative hypothesis, H_1, where there is an increasing or decreasing monotonic trend [16–18].

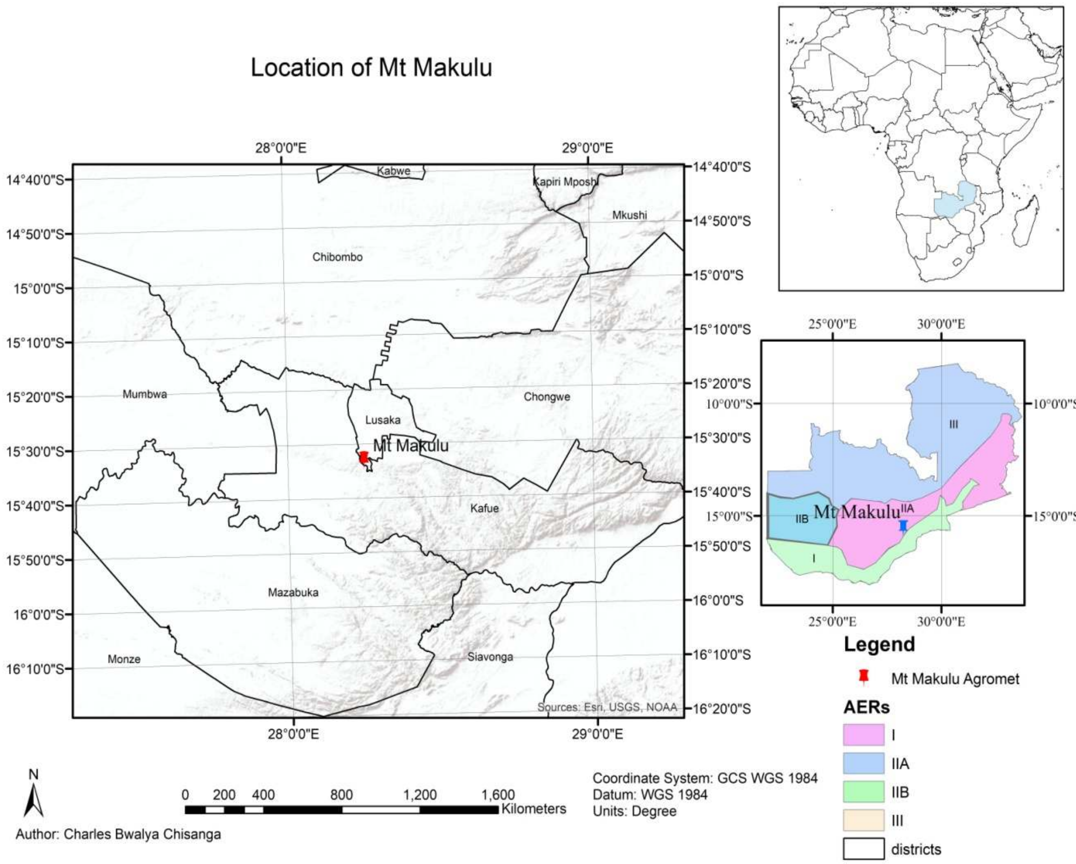

Fig. 1. Location of Mt Makulu

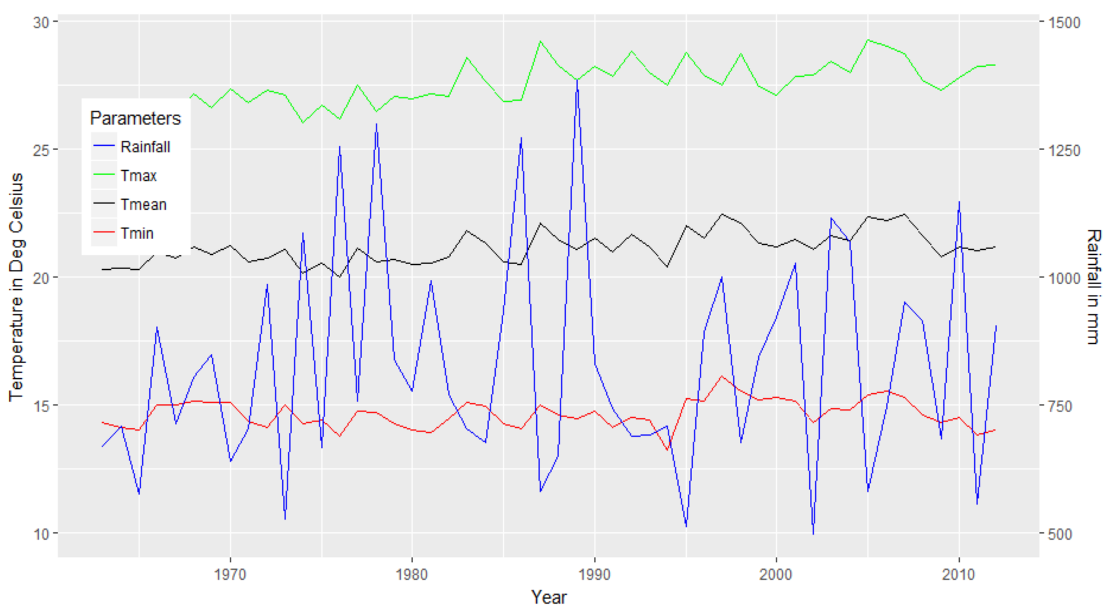

Fig. 2. Annual precipitation and temperature for Mt Makulu – 1963-2012

2.3 Seasonal and Annual Changes

The seas version 0.4-3 package [20] for the R programming environment was used to compute seasonal and annual changes between two dates. Absolute and relative for precipitation and temperature were computed from T1 (1963-1973:1974-1984), T2 (1974-1984:1985-1995) and T3 (1985-1995:1996-2006) for Mt Makulu. The seasonal sums are calculated independently from the annual sums in the seas version 0.4-3 package. The relative and absolute changes were computed between the central tendency and spread of each seasonal state.

2.4 Climate Indices

The Expert Team on Sector-specific Climate Indices (ET-SCI) indices related to daily temperature and precipitation characteristics were analyzed. A full descriptive list of the indices is found in [1,9]. ET-SCI extreme temperature and precipitation indices were used to answers questions concerning aspects of the climate system that affect many human and natural systems with particular emphasis on extremes. The temperature indices describe cold and warm extremes while the precipitation indices describe wet extremes. The studied indices were divided into 5 categories as adapted from [12] and [21] and are presented in Tables 1 and 2.

2.4.1 Percentile-based indices

The percentile-based indices are defined as days over the warmest/coldest long-term percentiles. The temperature percentile-based indices included the occurrence of hot days (TX90p), warm nights (TN90p), cold days (TX10p), very warm day (TX95t), cold nights (TN10p) and Fraction of days with above average temperature (TXGT50p). According to [12], the temperature percentile-based indices sample the coldest and warmest deciles for both maximum and minimum temperatures which enable evaluating the extent to which extremes are changing. Precipitation percentile-based indices were: very wet days (R95pTOT) and extremely wet days (R99pTOT) and these indices represent the amount of rainfall falling above the 95th (R95pTOT) and 99th (R99pTOT) percentiles;

2.4.2 Absolute indices

Absolute indices represented maximum or minimum values of weather parameters within a season or year. The temperature absolute indices included: maximum warmest daily temperature (TXx), minimum coldest daily temperature (TNn), maximum daily minimum temperature (TNx), minimum daily maximum temperature (TXn), Number of days when TX >= 30℃ (TXGE30) and Number of days when TX >= 35℃ (TXGE35). The absolute precipitation indices are maximum 1-day precipitation amount (RX1day), maximum 5-day precipitation amount (RX5day). Extreme precipitation regimes are defined as monthly maximum 1-day precipitation amount (Rx1day) and monthly maximum consecutive 5-day precipitation amount (Rx5day) [22];

2.4.3 Threshold indices

These are defined as the number of days at which temperature or precipitation value falls above or below a fixed threshold, including annual occurrence of frost days (FD), annual occurrence of ice days (ID), summer days (SU), annual occurrence of tropical nights (TR) and number of very heavy precipitation days > 20 mm (R20 mm);

2.4.4 Duration indices

Duration indices define periods of excessive warmth, cold, wetness or dryness or in the case of growing season length - periods of mildness. Temperature duration indices include excessive warmth (WSDI), cold spell duration indicator (CSDI), Growing Degree Days (GDDgrow), warm spell duration indicator (WSDI), diurnal temperature range (DTR) and extreme temperature range (ETR). The DTR and ETR indices are computed from TXx and TNn [21]. The GSL index is meaningful in the Northern Hemisphere extra-tropics [12]. Precipitation duration indices are growing season length (GSL), consecutive dry days (CDD) and consecutive wet days (CWD). The CDD index is the length of the longest dry spell in a year while the CWD index is defined as the longest wet spell in a year; and;

2.4.5 Other indices

Included indices of annual precipitation total (PRCPTOT), Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI) and simple daily intensity index (SDII).

Table 1. Core ET-SCI extreme temperature and precipitation indices

	Indices	Definition	Units	Time scale	Sector(s)
1	SU	No. of days when TX > 25℃	days	Mon/Ann	H
2	**TR**	**No. of days when TN > 20℃**	**days**	**Mon/Ann**	**H, AFS**
3	GSL	Annual No. of days between the first occurrence of 6 consecutive days with TM > 5 ℃ and the fir st occurrence of 6 consecutive days with TM < 5℃	days	Ann	AFS
4	**TXx**	**Warmest daily TX**	**℃**	**Mon/Ann**	**AFS**
5	**TNn**	**Coldest daily TN**	**℃**	**Mon/Ann**	**AFS**
6	WSDI	Annual No. of days contributing to events where 6 or more consecutive days experience TX > 90th percentile	days	Ann	H, AFS, WRH
7	CSDI	Annual No. of days contributing to events where 6 or more consecutive days experience TN < 10th percentile	days	Ann	H, AFS
8	CSDId	Annual No. of days contributing to events where d or more consecutive days experience TN < 10th percentile	days	Ann	H, AFS, WRH
9	TXgt50p	Percentage of days where TX > 50th percentile	%	Mon/Ann	H, AFS, WRH
10	TX95t	Value of 95th percentile of TX	℃	Daily	H, AFS
11	TXge30	No. of days when TX >= 30℃	days	Mon/Ann	H, AFS
12	TXge35	No. of days when TX >= 35℃	days	Mon/Ann	H, AFS
13	CDDcoldn	Annual sum of TM - n (where n is a user-defined location-specific base temperature and TM > n)	degree-days	Ann	H
14	GDDgrown	Annual sum of TM - n (where n is a user-defined location-specific base temperature and TM > n)	degree-days	Ann	H, AFS
15	**CDD**	**Maximum No. of consecutive dry days (when PR < 1.0 mm)**	**days**	**Mon/Ann**	**H, AFS, WRH**
16	R20mm	No. of days when PR >= 20 mm	days	Mon/Ann	AFS, WRH
17	PRCPTOT	Sum of daily PR >= 1.0 mm	mm	Mon/Ann	AFS, WRH
18	R95pTOT	100*r95p / PRCPTOT	%	Ann	AFS, WRH
19	R99pTOT	100*r99p / PRCPTOT	%	Ann	AFS, WRH
20	RXdday	Maximum d-day PR total	mm	Mon/Ann	H, AFS, WRH
21	SPEI	Measure of “drought” using the Standardized Precipitation Evapotranspiration Index on time scales of 3, 6 and 12 months	unit less	Custom	H, AFS, WRH

Note: *H: Health, AFS: Agriculture and Food security and WRH: Water Resources and Hydrology; Indices in bold are those used in the IPCC Fifth Assessment Report* [23]
Source: [10], [24]

Table 2. Non-core ET-SCI extreme temperature and precipitation indices

	Short name	Definition	Units	Time scale	Sector(s)
1	DTR	Mean difference between daily TX and daily TN	℃	Mon/Ann	
2	**TNx**	**Warmest daily TN**	**℃**	**Mon/Ann**	
3	**TXn**	**Coldest daily TX**	**℃**	**Mon/Ann**	
4	TMm	Mean daily mean temperature	℃	Mon/Ann	
5	TXm	Mean daily maximum temperature	℃	Mon/Ann	
6	TNm	Mean daily minimum temperature	℃	Mon/Ann	
7	**TX10p**	**Percentage of days when TX < 10th percentile**	**%**	**Ann**	
8	**TX90p**	**Percentage of days when TX > 90th percentile**	**%**	**Ann**	
9	**TN10p**	**Percentage of days when TN < 10th percentile**	**%**	**Ann**	
10	**TN90p**	**Percentage of days when TN > 90th percentile**	**%**	**Ann**	
11	CWD	Maximum annual number of consecutive wet days (when PR >= 1.0 mm)	days	Ann	
12	R10mm	Number of days when PR >= 10 mm	days	Mon/Ann	
13	Rnnmm	Number of days when PR >= nn	days	Mon/Ann	
14	**SDII**	**Annual total PR divided by the number of wet days (when total PR >= 1.0 mm)**	**mm/day**	**Ann**	
15	**R95p**	**Annual sum of daily PR > 95th percentile**	**mm**	**Ann**	
16	R99p	Annual sum of daily PR > 99th percentile	mm	Ann	
17	**Rx1day**	**Maximum 1-day PR total**	**mm**	**Mon/Ann**	
18	**Rx5day**	**Maximum 5-day PR total**	**mm**	**Mon/Ann**	
19	HWN(EHF/Tx90/Tn90)	The number of individual heatwaves that occur each summer. A heatwave is defined as 3 or more days where either the EHF is positive, TX > 90th percentile of TX or where TN > 90th percentile of TN.	events	Ann	H, AFS, WRH
20	HWF(EHF/Tx90/Tn90)	The number of days that contribute to heatwaves as identified by HWN.	days	Ann	H, AFS, WRH
21	HWD(EHF/Tx90/Tn90)	The length of the longest heatwave identified by HWN.	days	Ann	H, AFS, WRH
22	HWM(EHF/Tx90/Tn90)	The mean temperature of all heatwaves identified by HWN.	℃ (C2 for EHF)	Ann	H, AFS, WRH
23	HWA(EHF/Tx90/Tn90)	The peak daily value in the hottest heatwave (defined as the heatwave with highest HWM).	℃ (℃2 for EHF)	Ann	H, AFS, WRH
24	CWN_ECF	The number of individual 'cold waves' that occur each year.	events	Ann	H, AFS, WRH
25	CWA_ECF	The minimum daily value in the coldest 'coldwave' (defined as the coldwave with lowest ECF_HWM).	C2	Ann	H, AFS, WRH
26	CWF_ECF	The number of days that contribute to 'cold waves' as identified by ECF_HWN.	days	Ann	H, AFS, WRH

Note: H: Health, AFS: Agriculture and Food security and WRH: Water Resources and Hydrology; Indices in bold are those used in the IPCC Fifth Assessment Report [23]
Source: [10,24]

2.5 Quality Control and Homogenization

The RHTests (RHtestsV4 and RHtests_dlyPrcp) software packages by ETCCDI [9,12,25] were used to check for data quality and homogeneity. The RHtests V4 and RHtests_dly Prcp provided a free option for checking in-homogeneities in temperature and precipitation, respectively. The homogenization procedure was divided into two main steps, namely: (i) the detection of inhomogeneities; and (ii) the calculation of data adjustment parameters as described by [26]. RHtestsV4 software package was used to detect and adjust for multiple change-points (shifts) that existed in data series (temperature) that had first order autoregressive errors as described by [27]–[29]. Conversely, the RHtests_dlyPrcp software package was designed to handle homogeneity of daily precipitation data time series, which is noncontinuous, non-negative, non-Gaussian and non-normally distributed [30,31]. Details on quality control and data homogenization are well documented by [28–31]. The penalized maximal T-test and penalized maximal F-test [14,29,32] were used to check for homogeneity of the historical data series.

2.6 Computation and Analysis of Climate Indices

ClimPACT2 [9,10] was used to calculate the core and non-core ET-SCI indices presented in Tables 1 and 2, respectively. It directly incorporates the R packages climdex.pcic and climdex.pcic.ncdf developed by the Pacific Climate Impacts Consortium (PCIC). Time-series of daily minimum temperature (TN), daily maximum temperature (TX) and daily precipitation (PR) were used as inputs into the ClimPACT2. Diurnal temperature range (DTR) was calculated as the difference between the maximum and minimum temperature during a 24-hour period [33]. Many of the indices were calculated at both annual and monthly time scales.

Clim PACT2 also uses the SPEI R package which incorporates a set of functions for computing potential evapotranspiration and several widely-used drought indices. The SPEI package was developed to compute SPEI time series under various data scenarios [34,35]. Furthermore, the package contains several auxiliary functions (spei and spi) for analyzing SPEI data. The SPEI package has the advantage of combining multi-scalar character with the capacity to include the effects of temperature variability on drought assessment [36]. The procedure to calculate the index involves a climatic water balance, the accumulation of deficit/surplus at different time scales, and adjustment to a log-logistic probability distribution. Because the SPEI is based on a water balance, it can be compared to the self-calibrated Palmer Drought Severity Index (sc-PDSI) [37].

The heatwave (HW) computations used in ClimPACT2 are based on [38] with some slight modifications to the Excess Heat Factor (EHF). Three HW definitions are used in ClimPACT2, and these definitions are based on the 90th percentile of TN (minimum daily temperature) designated Tn90, the 90th percentile of TX (maximum daily temperature) designated Tx90 and the EHF. The EHF combines a measure of the temperature of a particular day relative to the baseline period, with a measure of the potential acclimatization that occurred in the preceding 30 days. The two measures are represented by excess heat indices (EHI) of significance (sig) and acclimatization (acc), respectively (see equations 4-6 below). According to the three HW definitions (Tn90, Tx90, and EHF) an HW event is defined as any length of three or more days where one of the following conditions is met[1]: (i) TN > 90th percentile of TN; (ii) TX > 90th percentile of TX; and (iii) the EHF is positive. The percentiles for Tn90 and Tx90 were calculated from the baseline specified by the user and for each calendar day using a 15-day running window [1,9].

$$\mathrm{EHI_{sig}} = \frac{(\mathrm{T_i}+\mathrm{T_{i-1}}+\mathrm{T_{i-2}})}{3} - \mathrm{T_{95}} \tag{4}$$

$$\mathrm{EHI_{acc}} = (\mathrm{T_i} + \mathrm{T_{i-1}} + \mathrm{T_{i-2}}) - (\mathrm{T_{i-1}} + \cdots + \mathrm{T_{i-30}})/30 \tag{5}$$

Where Ti represents the mean daily temperature, (TXi + TNi)/2, of day i and T95 represent the 90th percentile of T over the baseline period 1963 - 2012.

The EHF is a combination of the above two excess heat indices.

$$\mathrm{EHF} = \mathrm{EHI_{sig}} \mathrm{x} \max\,(1, \mathrm{EHI_{acc}}) \tag{6}$$

[1] *https://semc.wa.gov.au/Documents/The%20Hub/natural%20hazard%20factsheets/Heatwave%20Hazard%20Factsheet.pdf; Accessed on 10th January 2017*

All HW definitions in ClimPACT2 are calculated over the extended summer period with the exceptions of the EHF and Excess Cold Factor (ECF) as defined by [39,40]. In the southern hemisphere, the extended summer season includes November to March [1]. More details on computing indices using ClimPACT2 software package are found in [1,9,10,38]. The core and non-core ET-SCI sector specific indices were tested for significance at 95% level ($p<0.05$). Each slope (positive or negative) was categorized into four classes indicating highly significant, significant, negative non-significant or positive non-significant.

3. RESULTS AND DISCUSSION

3.1 Precipitation and Temperature Anomalies and Trends for Mt Makulu

The annual time series and trends for precipitation and temperature are presented in Fig. 4. The tau and p-value associated with the Mann-Kendall test for precipitation (tau = 0.0743, 2-sided p-value = 0.45155, Sen's Slope = 1.25) and minimum temperature (tau = 0.128, 2-sided p-value =0.19192, Sen's slope = 0.01) were statistically non-significant (see Fig. 3a and b). In contrast, the p-value associated with the Mann-Kendall test was statistically significant for annual mean (tau = 0.402, 2-sided p-value =3.8624e-05) and maximum (tau = 0.504, 2-sided p-value =2.3842e-07) temperature, respectively. This suggested that the mean and maximum temperature exhibited the presence of a statistically significant upward trend (Fig. 3c and d) with Sen's slopes of 0.025 and 0.037, respectively. The mean temperature anomaly also shows an increasing trend and is statistically significant (tau = 0.402, 2-sided p-value =3.8624e-05, Sen's slope = 0.03) at $p<0.05$.

Fig. 4 presents the annual anomalies while Fig. 5 shows seasonal precipitation and temperature for Mt Makulu. On the other hand, absolute changes in maximum and minimum temperature and relative changes and standard deviation of total precipitation are presented in Fig. 6. The relative and absolute changes in the central tendency and spread of each seasonal state are also shown in Fig. 6. The annual absolute change for the minimum temperature at T1, T2 and T3 were -0.24, 0.025, and 0.774. On the other hand, the annual absolute change for the maximum temperature at T1, T2, and T3 were 0.209, 0.979, and 0.055. Relative changes in total precipitation at T1, T2, and T3 were 1.22, 0.917 and 0.093. The relative changes in standard deviation for total precipitation were 1.65 (T1), 1.21 (T2) and 0.734 (T3).

In the recent past, Mt Makulu had experienced droughts in the seasons 1964/65, 1983/84, 1987/88, 1991/92, 1994/95 and 1997/98 and a high intensity of floods in 2007/08, 2009/2010 (see Fig. 4). This pattern has also been reported by [41,42]. In the past 30 years, rainfall variability and droughts have been observed in Zambia especially in the southern and central parts of the country resulting in reduced maize yields [43]. The analysis of rainfall data from 32 meteorological stations in Zambia by CEEPA (2006) indicated that there had been annual rainfall anomalies from 1970-2000. The data showed that of the 14 years from 1990/1991 to 2003/2004, at least ten years in each AER had below normal rainfall [44]. On the other hand, AERI has experienced more severe dry seasons than AERII in the last 20 years. However, the threat of climate change is characterized mostly by floods and droughts, and these have caused serious damage to crops and infrastructure [42]. Droughts, floods, and extreme temperatures have affected both humans, and the ecosystems and these have caused damage to crops, energy infrastructure, and affected water and its quality. Maize yield has reduced by 40% in AERs I and II within the past 20 years due to persistent dry spells and shorter rainfall seasons [45].

3.2 Trend Analysis of Temperature and Precipitation Using Climpact2

The results of the trend analysis of temperature and precipitation using the Clim PACT2 software are presented in Table 3. The results on Agriculture and Food Security, Water Resources, and Hydrology and Health sector indices showed significant trends at $p<0.05$ and exhibited significant changes on percentile based indices, absolute indices of annual maximum and minimum values, duration indices and Standardized Precipitation-Evapotranspiration Index (SPEI). The SPI index was non-significant with positive trends at all levels. Sectors affected by climate changes include agriculture, water resources, health, energy, transportation, forests, and wildlife. While much progress has been made in recent decades, the lack of high-quality analyses and credible data has been a major obstacle to assessing changes in extremes as documented by [46].

3.2.1 Percentile-based indices

Percentile-based climate extreme indices were calculated using the baseline reference period of 1963–2012 to make results easily comparable with other studies and the results are presented in Table 3. It was shown that the percentile-based thresholds were sensitive to the method of computation. The fraction of days with above average temperature (TXGT50p) or the percentage of days where TX > 50th percentile significantly increased for both annual and monthly analysis from 1963 - 2012. The monthly and annual TX10p (amount of cool days) had been decreasing significantly with a negative trend. On the other hand, the monthly and annual TX90p (amount of hot days) and TN90p (amount of warm nights [annual]) had increased at the 90th percentile. The daily very warm days (TX95t) had also increased significantly. The analysis indicated that TX10p, TX90p, TN90p, and TX95t had increased in magnitude. In contrast, the TN10p (annual and monthly) was non-significant and negatively correlated. These percentile-based temperature indices are part of the suite of indices developed by the WMO CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices [24,25]. They have been used to analyze changes in temperature extremes for Mt Makulu Station. Percentile based temperature indices are calculated by counting the number of days in a year, or season, for which daily values exceed a time-of-year-dependent threshold. According to [47], such a threshold is usually defined as a percentile of daily observations in a fixed base period that fall within a few Julian days of the day of interest. Indirectly, extreme temperatures increase plant water stress, which if not addressed results in cessation of photosynthesis and possibly death [48]. For wheat, maize, and barley, there is a clear negative response of global yields due to increased temperatures as reported by [48].

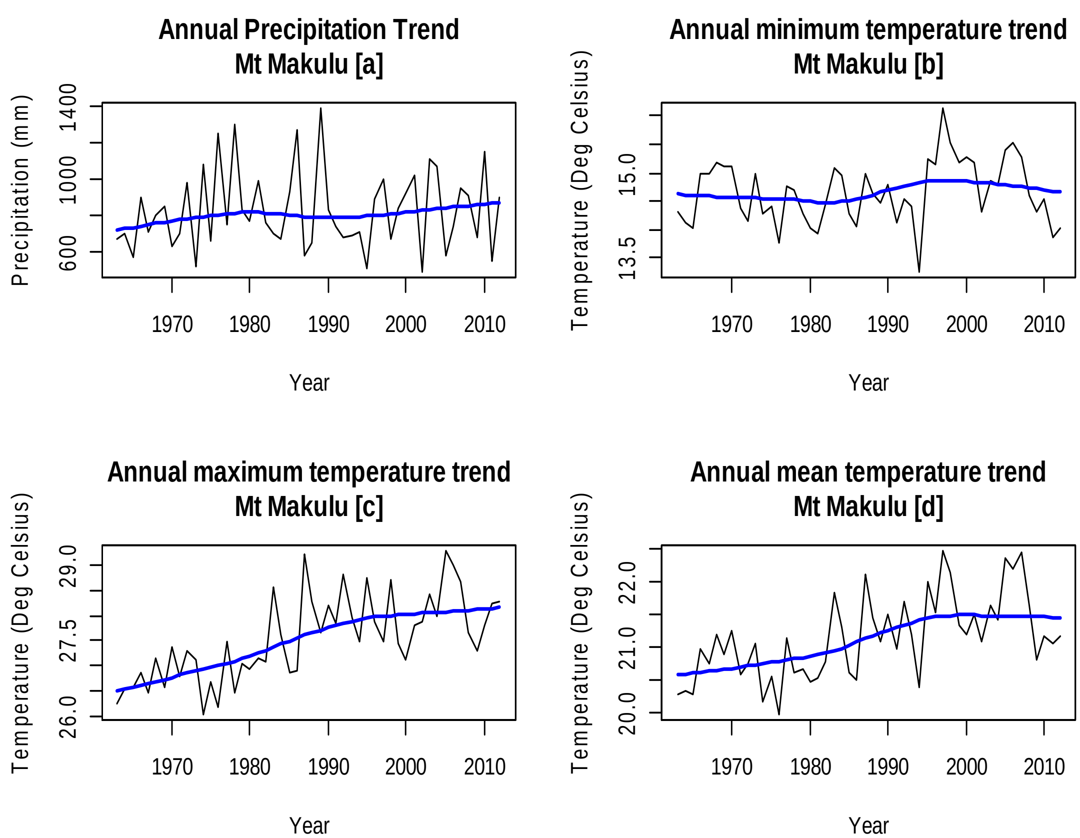

Fig. 3. Annual precipitation and temperature trends for Mt Makulu

Table 3. Annual trends of the extreme indices of daily temperature and precipitation for Mt Makulu Station

	Indices	StartYr	EndYr	Slope	Slope STD	P	Sign		Indices	StartYr	EndYr	Slope	slope STD	P	Sign
1	cdd (A)	1963	2012	0.403	0.302	0.188	+	46	rx5day (A)	1963	2012	-0.256	0.447	0.570	+
2	cdd (M)	1963	2012	0.007	0.18	0.7	+	47	rx5day (M)	1963	2012	0.005	0.044	0.665	+
3	**cddcold22 (A)**	**1963**	**2012**	**3.789**	**0.931**	0.000	***	48	sdii (A)	1963	2012	0.036	0.024	0.135	+
4	csdi (A)	1963	2012	-0.029	0.041	0.478	-	49	**spei.12.month**	**1963**	**2012**	**-0.001**	**0.000**	**0.000**	***
5	csdi5	1963	2012	-0.01	0.049	0.833	-	50	**spei.3.month**	**1963**	**2012**	**-0.002**	**0.000**	**0.000**	***
6	CWA-ECF	1963	2012	0.082	0.049	0.104	+	51	**spei.6.month**	**1963**	**2012**	**-0.001**	**0.000**	**0.000**	***
7	cwd (A)	1963	2012	-0.01	0.03	0.73	-	52	spi.12.month	1963	2012	0.001	0.000	0.048	+
8	**CWF-ECF**	**1963**	**2012**	**-0.205**	**0.093**	**0.032**	**	53	spi.3.month	1963	2012	0.000	0.000	0.826	+
9	CWM-ECF	1963	2012	0.005	0.019	0.802	+	54	spi.6.month	1963	2012	0.000	0.000	0.262	+
10	**CWN-ECF**	**1963**	**2012**	**-0.031**	**0.014**	**0.037**	**	55	**su (A)**	**1963**	**2012**	**0.009**	**0.002**	**0.000**	***
11	**dtr (A)**	**1963**	**2012**	**0.03**	**0.007**	**0.000**	***	56	**su (M)**	**1963**	**2012**	**1.141**	**0.246**	**0.000**	***
12	**dtr (M)**	**1963**	**2012**	**0.003**	**0.001**	**0.000**	***	57	**tmm (A)**	**1963**	**2012**	**0.023**	**0.005**	**0.000**	***
13	**gddgrow22 (A)**	**1963**	**2012**	**3.789**	**0.931**	**0.000**	***	58	**tmm (M)**	**1963**	**2012**	**0.002**	**0.001**	**0.003**	***
14	gsl (A)	1963	2012	0.003	0.006	0.646	+	59	tn10p (A)	1963	2012	-0.049	0.051	0.336	-
15	hddheat15	1963	2012	-0.453	0.207	0.036	-	60	tn10p (M)	1963	2012	-0.001	0.002	0.583	-
16	HWA-EHF	1963	2012	0.127	0.081	0.127	+	61	**tn90p (A)**	**1963**	**2012**	**0.150**	**0.56**	**0.011**	***
17	HWA-Tn90	1963	2012	0.044	0.028	0.133	+	62	**tn90p (M)**	**1963**	**2012**	**0.010**	**0.002**	**0.000**	***
18	HWA-Tn90	1963	2012	0.008	0.018	0.676	+	63	tnm (A)	1963	2012	0.008	0.005	0.165	+
19	**HWA-Tx90**	**1963**	**2012**	**0.066**	**0.03**	**0.037**	**	64	tnm (M)	1963	2012	0.001	0.001	0.470	+
20	HWD-EHF	1963	2012	0.072	0.041	0.087	+	65	tnn (A)	1963	2012	0.013	0.017	0.440	+
21	HWD-Tx90	1963	2012	0.036	0.024	0.144	+	66	tnn (M)	1963	2012	0.001	0.001	0.635	+
22	HWD-Tn90	1963	2012	0.008	0.018	0.676	+	67	tnx (A)	1963	2012	0.016	0.01.	0.128	+
23	**HWF-EHF**	**1963**	**2012**	**0.164**	**0.071**	**0.025**	**	68	**tnx (M)**	**1963**	**2012**	**0.001**	**0.001**	**0.026**	**
24	HWF-Tn90	1963	2012	-0.002	0.049	0.970	-	69	tr (A)	1963	2012	0.000	0.001	0.620	+
25	**HWF-Tx90**	**1963**	**2012**	**0.245**	**0.07**	**0.001**	***	70	tr (M)	1963	2012	0.052	0.066	0.430	+
26	HWM-EHF	1963	2012	0.029	0.028	0.319	+	71	**tx10p (A)**	**1963**	**2012**	**-0.236**	**0.045**	**0.000**	***
27	HWM-Tn90	1963	2012	0.014	0.019	0.465	+	72	**tx10p (M)**	**1963**	**2012**	**-0.020**	**0.002**	**0.000**	***
28	HWM-Tx90	1963	2012	0.032	0.021	0.144	+	73	**tx90p (A)**	**1963**	**2012**	**0.210**	**0.079**	**0.012**	***
29	HWN-EHF	1963	2012	0.025	0.012	0.052	+	74	**tx90p (M)**	**1963**	**2012**	**0.022**	**0.003**	**0.003**	***
30	HWN-Tn90	1963	2012	-0.002	0.012	0.882	-	75	**tx95t**	**1963**	**2012**	**0.011**	**0.001**	**0.000**	***
31	**HWN-Tx90**	**1963**	**2012**	**0.056**	**0.016**	**0.001**	***	76	**txge30 (A)**	**1963**	**2012**	**1.041**	**0.273**	**0.000**	***
32	prcptot (A)	1963	2012	1.706	2.362	0.474	+	77	**txge30 (M)**	**1963**	**2012**	**0.009**	**0.002**	**0.000**	***
33	prcptot (M)	1963	2012	0.013	0.023	0.555	+	78	**txge35 (A)**	**1963**	**2012**	**0.266**	**0.056**	**0.000**	***
34	r10mm (A)	1963	2012	0.000	0.001	0.695	+	79	**txge35 (M)**	**1963**	**2012**	**0.002**	**0.000**	**0.000**	***
35	r10mm (M)	1963	2012	0.049	0.07	0.494	+	80	**txgt50p (A)**	**1963**	**2012**	**0.652**	**0.126**	**0.000**	***
36	r20mm (A)	1963	2012	0.000	0	0.491	+	81	**txgt50p (M)**	**1963**	**2012**	**0.054**	**0.004**	**0.000**	***

	Indices	StartYr	EndYr	Slope	Slope STD	P	Sign		Indices	StartYr	EndYr	Slope	slope STD	P	Sign
37	r20mm (M)	1963	2012	0.036	0.048	0.455	+	82	**txm (A)**	**1963**	**2012**	**0.037**	**0.007**	**0.000**	***
38	r30mm (A)	1963	2012	0.000	0	0.129	+	83	**txm (M)**	**1963**	**2012**	**0.003**	**0.001**	**0.000**	***
39	r30mm (M)	1963	2012	0.042	0.033	0.207	+	84	txn (A)	1963	2012	0.030	0.019	0.111	+
40	r95p (M)	1963	2012	1.928	1.398	0.175	+	85	**txn (M)**	**1963**	**2012**	**0.003**	**0.001**	**0.000**	***
41	r95ptot (M)	1963	2012	0.178	0.118	0.138	+	86	**txx (A)**	**1963**	**2012**	**0.053**	**0.014**	**0.001**	***
42	r99p (A)	1963	2012	0.106	0.898	0.907	+	87	**txx (M)**	**1963**	**2012**	**0.004**	**0.001**	**0.000**	***
43	r99ptot	1963	2012	0.010	0.083	0.900	+	88	wsdi (A)	1963	2012	0.113	0.110	0.309	+
44	rx1day (A)	1963	2012	-0.102	0.423	0.844	-	89	wsdi7 (A)	1963	2012	0.102	0.083	0.227	+
45	rx1day (M)	1963	2012	0.004	0.006	0.513	+								

Note: A: annual; M: monthly; P: p-value; sign: significant; indices in bold were significant

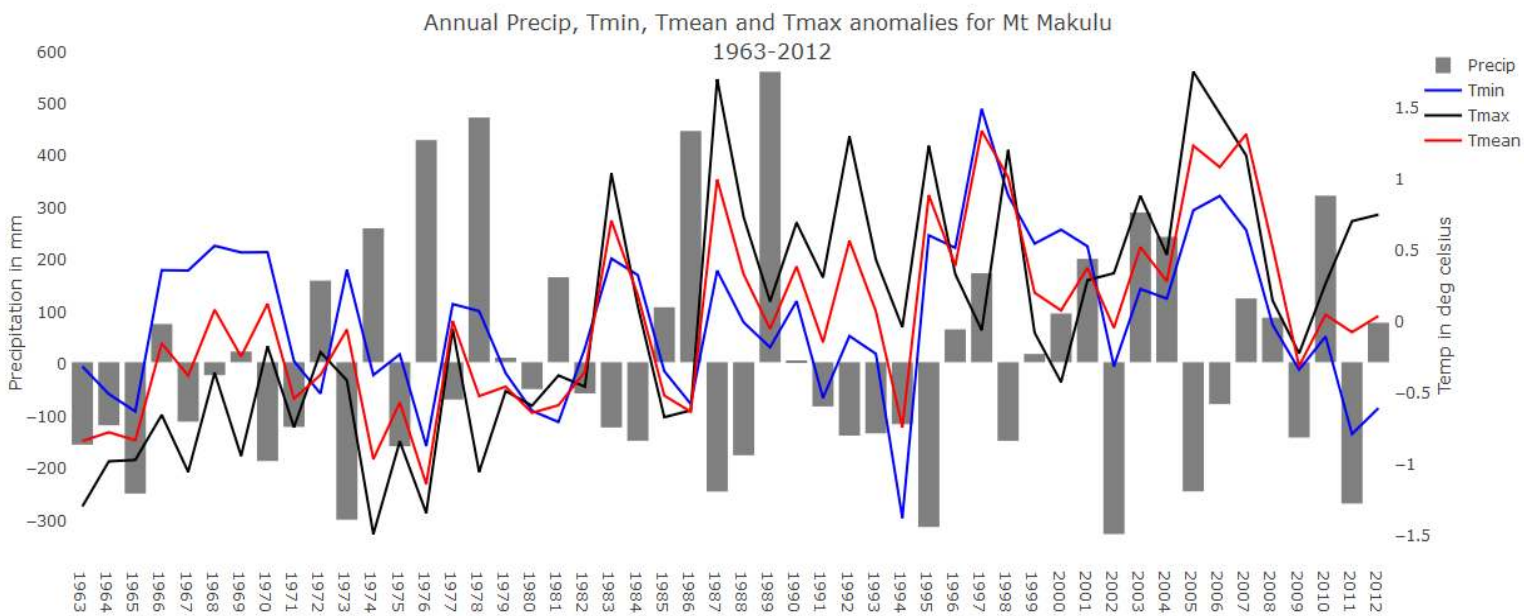

Fig. 4. Annual precipitation and temperature anomalies for Mt Makulu

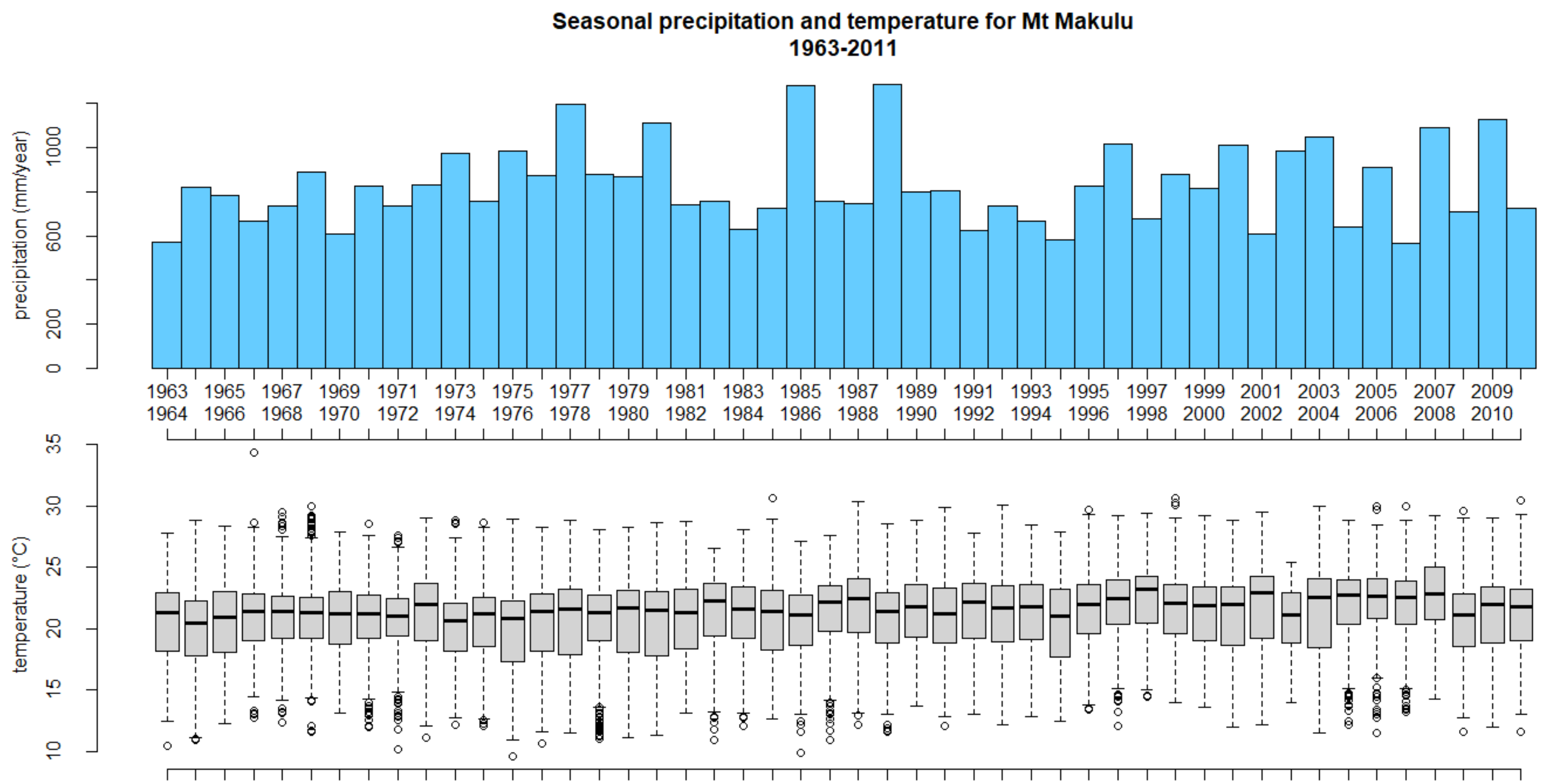

Fig. 5. Seasonal precipitation and mean temperature for Mt Makulu – 1963-2011

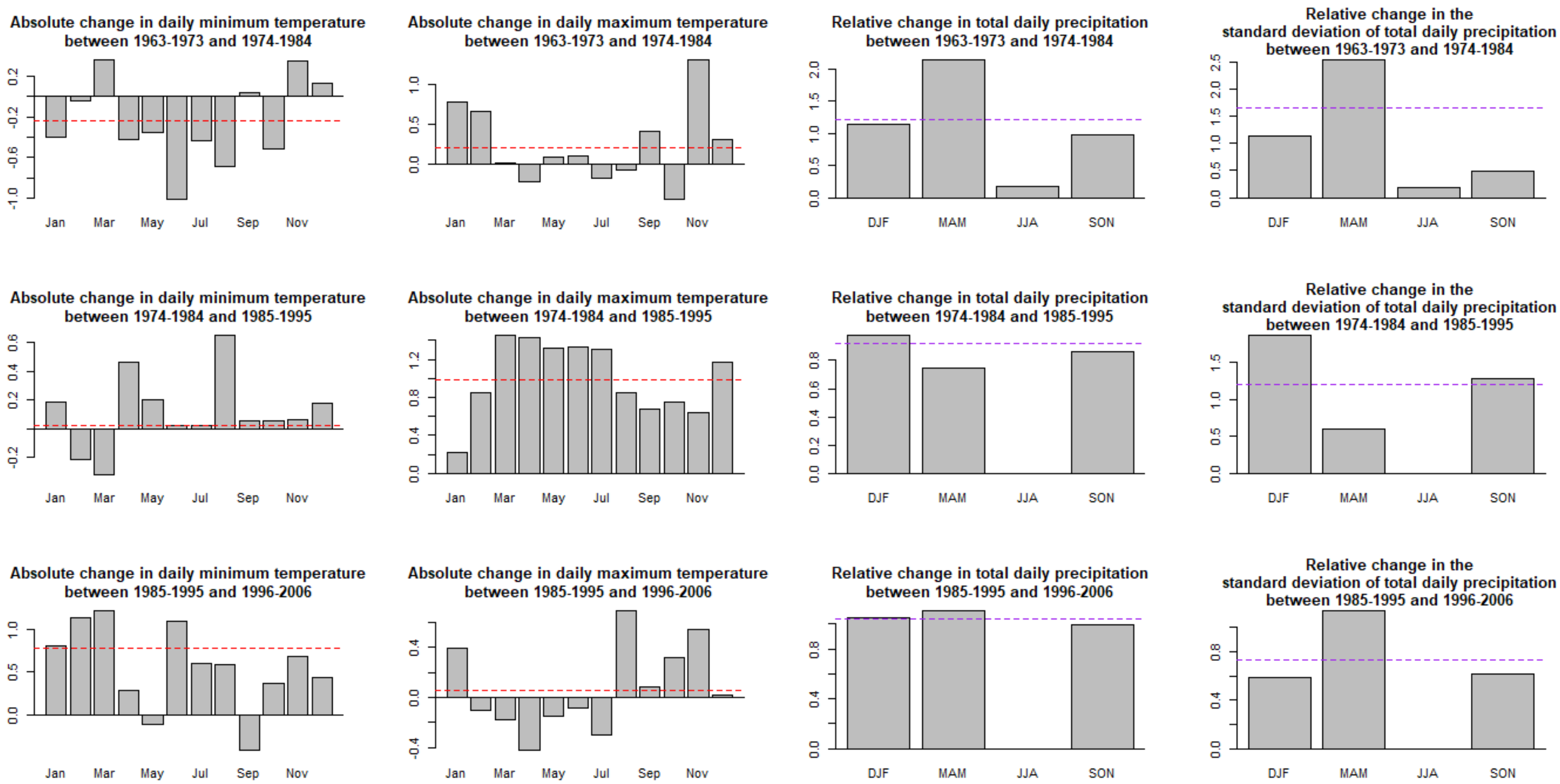

Fig. 6. Absolute and relative changes in precipitation and temperature for Mt Makulu

The R95pTOT (monthly and annual) and R99pTOT (monthly and annual) were non-significant with a positive trend. The lack of trend in precipitation time series data does not support the conclusion that annual rainfall in Zambia has decreased by 1.9 mm per month (2.3% per decade) since 1960 particularly in the months of December, January and February [15,48]. The authors did not state the statistical significance level they used when concluding. [17] also found non-significant trend in several rainfall indices derived from daily precipitation using meteorological stations in Zimbabwe.

Heatwave amplitude (HWA) as defined by either the EHF, 90th percentile of TX or the 90th percentile of TN increased significantly ($p = 0.035$). This signified that the peak daily value in the hottest heatwave (defined as the heatwave with highest HWM) increased from 1963 to 2012. Heatwave number (HWN) as defined by the Excess Heat Factor (EHF), the 90th percentile of TX or the 90th percentile of TN also increased, the mean annual temperature being 17.30℃. This indicated that the number of individual heatwaves that occurred at Mt Makulu during summer (November – March in the southern hemisphere) increased. Heatwave frequency (HWF-EHF) defined by Excess Heat Factor (EHF) and heatwave frequency (HWF-Tx90) defined by the 90th percentile of TX had increased significantly at $p<0.05$. This meant that the number of days contributing to heatwave events had increased significantly. The results showed that the number of days (frequency) that contributed to heatwaves as identified by HWN had also increased. Heatwave number (HWN-Tx90) defined by the number of discrete heatwave events had increased significantly at $p<0.05$. The cold-wave number (CWN-ECF) and cold-wave frequency (CWF-ECF) had reduced significantly with negative trends. [49] reported that heat is the leading weather-related killer in the United States of America.

Evidence based studies indicate that the human induced climate change had already doubled the probability of extreme heat events [49] and these agree with the findings of this study. On the other hand, Mt Makulu experienced heat stress during DJF, MAM, JJA and SON with probability occurrence of 0.783, 0.001, 0.060 and 0.976 at $p<0.05$. There were a much higher heat spell events during DJF and SON. [50] argued that the warming of the climate can have consequences corresponding to percentage changes in the occurrence of climate extremes that include increased probability of observed heat extremes. [47] acknowledged that heatwave impacts are widespread and severe, human damage health, infrastructure, and natural ecosystems and decrease workplace performance and agricultural productivity. Additionally, the direct effect of excessive heat is through damaging the reproductive parts of crops responsible for producing grain and thus, reducing grain yield.

3.2.2 Absolute indices represented by maximum or minimum values within a season or year

The maximum warmest daily temperature (TXx) index showed a predominant increase in the monthly and annual maximum value of daily maximum temperature at Mt Makulu (see Table 3). The minimum warmest daily temperature (TXn) showed a similar trend for the annual value. The annual warmest daily TN and coldest daily TX had increased significantly at $p<0.05$. The annual warmest TX increased significantly ($p<0.05$) for both monthly and annual analyses during the period 1963-2012. The annual number of days when the maximum temperature was at least 30℃ or 35℃ also increased significantly during the period 1963-2012. The monthly coldest daily TX (coldest day) increased significantly ($p<0.05$) resulting in a linear slope of 0.003. The monthly warmest daily TN (hottest night) significantly increased during 1963-2012 ($p<0.05$). As expected in a warming climate, researchers such as [49] agree with the findings of this study. [49] reported that recent climate change trends show that extreme heat is becoming more common, while extreme cold is becoming less common.

The mean annual and monthly difference between daily TX and daily TN (DTR) significantly increased at $p<0.05$ resulting in a linear slope of 0.031 and 0.003, respectively. This is indicative that the monthly mean difference between the maximum and the minimum temperature had increased at Mt Makulu. Similarly, the mean daily temperature (TMm) and mean daily maximum temperature (TXm) had increased from 1963-2012 as presented in Table 3. There is a significant increase in absolute indices represented for the maximum and minimum temperature. The past, present and future climate impacts as reported by [51] could be documented and adaptation and mitigation options adopted by policy-and-decision makers.

The RX1day and RX5day had a non-significant positive trend at $p<0.05$. Contrary to the study results, increasingly frequent of extreme precipitation and associated flooding can lead to injuries and increases in waterborne diseases [52]. Some extreme weather and climate events have increased in recent decades, and new and stronger evidence confirms that some of these increases are related to human activities [49].

3.2.3 Threshold indices

The number of days when TX > 25℃ (SU) for both annual and monthly trend had increased significantly at $p<0.05$ with a slope of 0.009 and 1.204, respectively as shown in Table 3. This indicated an increase in the month and an annual number of days when the maximum air temperature was higher than 25℃. The annual occurrence of tropical nights (TR) was non-significant with positive trends. Mt Makulu did not experience any seasonal frost (FD) and ice days (ID) from 1963-2012. The R20mm was non-significant with positive trends. Climate extreme indices assist in describing the past, present, and the future climate change scenarios [51]. They have been used for a long time by assessing days with temperature or precipitation observations are above or below specific physically-based thresholds [44]. They are closely related to possible impacts and are, therefore, more illustrative to planners, researchers and policy makers than simple climate means. Climate indices are widely used across sectors, and they have become important impact parameters in climate change studies and impact assessment.

3.2.4 Duration indices

Cooling Degree Days (CDDcoldn) [a measure of the energy demand needed to cool a building] and Growing Degree Days (GDDgrow) [a measure of heat accumulation to predict plant and animal developmental rates] had increased significantly ($p<0.05$) during the year 1963 to 1995 and decreased onward from 1995 to 2012 with a linear slope of 3.789 and 3.789, respectively. GSL, WSDI, CDD, and CWD were not significant at $p<0.05$. Changes in extreme weather events are the primary way that most people experience climate change. Human-induced climate change has already increased the number and strength of some of these extreme events [49].

3.2.5 Other indices

Meteorological, agricultural, and hydrological drought incidences are often presented as drought indices. Drought occurrence as measured by the Standardized Precipitation Evapotranspiration Index on time scales of 3, 6 and 12 months are presented in Table 3. The results indicated significant ($p<0.05$) changes in annual trends with linear slopes of -0.002, -0.001 and -0.001 for time-scales of 3, 6 and 12 months, respectively. Drought monitoring trends indices are usually applied at seasonal (6 months), annual (12 months) or even inter-annual (24 or 48 months) time-scales as reported by [53]. The mean temperature increased at Mt Makulu from 1963 - 2012 and this increased water evaporative demand of the atmosphere during 1990 and 2012 as the SPEI use precipitation and temperature normalized for simplified water balance. Changes in frequency and intensity of weather events often result in more frequent and intensive disasters such as flash floods and persistent droughts [52].

4. CONCLUSION

The Mann-Kendall test did not identify any trend in the precipitation and minimum temperature for Mt Makulu. However, the Mann-Kendall tests for the maximum and mean temperature were statistically significant. Climate indices provide valuable information contained in daily time series data, without the need to transmit the data itself. This study analyzed changes in ET-SCI indices at Mt Makulu based on daily minimum, and maximum temperature and precipitation time series from 1963–2012. Climate extreme indices are widely used across some disciplines and have become a significant impact parameter in climate change impact assessment studies. Climate indices computed based on temperature and precipitation can be used as a means of communicating climate change impact on agricultural production systems and hydrological risk such as exposure time, threshold levels of event intensity, etc. The TXx, TNx, TXn, DTR, GDDGrowing, TMm, TXGT50p, TX90p, TN90p, TXGE30, TXGE35, TX95t, TX90.HWA, TX90.HWN, TX90.HWF, EHF.HWD and EHF.HWF indices showed non-significant positive trends for 1963-2012. On the other hand, TX10p and SPEI indices showed a negative linear trend for the same period. The highest value for the Growing Degree Days, TMm, TX90.HWN, TX90.HWF and TX90.HWA was observed between 1995 and 2000. Four indices

(PRCPTOT, R30 mm, RX5day, and R95p) of extreme precipitation were non-significant with the positive linear trend. The extreme climate indices could be used for forecasting outbreaks of tropical diseases under the present and future climate scenarios. To have a better appreciation of the extreme climate indices, another study should focus on gridded datasets.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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