International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 10 Issue 5 ǁ 2022 ǁ PP. 72-81

Temporal characterization of daily rainfall trends in Zambia from 1983 to 2019: A crop growing season perspective.

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Abstract
This study aims to provide improved knowledge and evidence on current (1983-2019) rainfall trends in Zambia using CHIRPS data with the purpose of drawing inferences of their implications on the length of crop growing season. The study adopted an explanatory sequential embedded mixed-method research design that allowed approaching the study problems from different perspective. Stratified random sampling method was utilized to select the meteorological stations and purposive sampling for secondary data. Data analysis was conducted using the Mann-Kendall (MK) test for trend analysis. The Standard Precipitation Index technique was employed in determining the characteristics of intra-annual rainfall variability. Furthermore, qualitative data analysis was performed by utilizing a rainfall-based criterion which was earlier used by the Famine and Early Warning System (FEWS). Results show that the average rain season onset dates are 19^{th}, 17^{th}, and 16^{th} of November for agro-ecological regions I, II and III, respectively. Further, with an average withdraw date of 19^{th} March; agro-ecological region III experiences the latest cessation of the rainy season. Trends in rainy season length were found to be declining across all agro-ecological regions with the steepest slope on the Sen's estimator (-0.11) being observed over agro-ecological region II, followed by region I (-0.08) and region III (-0.06), respectively. The observation that rainy seasons are getting shorter reflects the late-onset that has been found across all agro-ecological regions. In conclusion, the observed decrease in the length of the rainy season translates into shorter crop growing seasons. This is likely to affect the choice of crops to be grown in each of the three agro-ecological regions. Therefore, the study recommends farmers in AER III to have multiple harvests in any given season or could easily diversify to drought resistant crops and other types of farming that does not depend heavily on rainfall. Farmers may also change their farming systems to adapt to the reduced growing season by concentrating on early maturing varieties or low-moisture demand crops.
Keywords: *Rain season onset, rain season cessation, rain season length, CHIRPS dataset*

Date of Submission: 07-05-2022 Date of acceptance: 22-05-2022

I. INTRODUCTION

The agriculture sector in Zambia is the fourth largest contributor to national GDP (8.7%) and the largest contributor to employment (GRZ, 2007). Zambia's agricultural sector is said to be key to the development of the Zambian economy and provides livelihood for more than 60% of the population (Jain, 2007; IAPRI, 2020). The agriculture sector is critical for achieving economic growth and poverty reduction in Zambia (CSO, 2019). It covers 98% small-scale farmers whose agricultural activities are entirely dependent on rainfall (FAO, 2004; IAPRI, 2014). This makes it extremely vulnerable to rainfall variability and impacts of climate change (NAPA 2007; Phiri et al, 2013).

Rainfall is the most important limiting factor in rain-fed farming systems in Africa (Niles et al. 2015) since it determines the availability of soil moisture required for potential productivity. The amount and distribution of rainfall determine the suitability of crop varieties and related agronomic management at different locations (Muthoni et al. 2017). Low or sub-optimal rainfall contributes to agricultural droughts that retard plant growth and reduce yields (Zampieri et al., 2017; Zipper et al., 2016) while extremely high rainfall events could destroy crops.

Generally, the analysis of extreme trends and variability in annual daily rainfall and temperature has been carried out in recent years by a number of researchers in various parts of the World at varying spatial and temporal scales. However, in Zambia, few studies have characterized daily rainfall trends for purposes of understanding the effects on the length of the crop growing season for the country despite being among the main cause of decline in crop yields in Zambia (IAPRI, 2014). Induced impacts of climatic changes, such as a decrease of early-rainy season rainfall and a high number of extreme events (Christine et al., 2007; Kotir, 2011), increase the risk of low yields or even yield losses.

This study aimed at analyzing the characteristics of daily rainfall trends with the intention of drawing inferences to the length of crop growing season. The objectives were threefold; to generate annual temporal rainfall trends for Zambia, from 1983 to 2019; to determine the characteristics of annual rainfall in Zambia's AERs and to assess the implications of the rainfall trend on the crop growing season of Zambia. This is important because rain-fed agriculture is predominant in all the AERs in Zambia.

II. Materials and Methods

2.1 Study area

Zambia is divided into three agro-ecological regions (AERs) based on the rainfall quantities received in each region.

Agro-ecological region I (AER I) lies in Western and Southern Zambia accounting for 15% of the total land area of the country (Jain, 2007). It is a low rainfall region that receives an average annual rainfall in the range of 400 to 800mm and average temperatures of 30 to 36˚C. The region has diverse and slightly acidic and eroded soil types that are frequently exposed to climatic events such as droughts and flash floods (World Bank, 2003). Due to precipitation or moisture stress and short plant growing season of 60 to 90 days, the region is characterized by drought tolerant, early maturing seed varieties and subsistence mixed cropping systems (Saasa, 2003).

Agro-ecological region II consists of central Zambia extending East through Western and receives between 800 to 1000mm of rainfall annually (World Bank, 2003). It is divided into two parts; AER IIa and AER IIb (Figure 1). AER IIa extends from the eastern to the central parts of the country and is known to have highly fertile soils (Jain, 2007). Crops grown in the region include maize, groundnuts, sunflower and horticultural crops (Aregheore, 2006). AER IIb extends from the western part of the country and comprises unproductive soils for arable agriculture making it a priority for livestock rearing (Jain, 2007; Phiri et al., 2013). The region has the most fertile soils with a plant growing season of 90 to 140 days which is capable of supporting growth of a wide range of crops grown in Zambia. Much of the country's agriculture is in this region and comprises both mixed cropping subsistence to commercial farming (World Bank, 2006; Jain, 2007)

Agro-ecological region III consists of the northern part of the country and receives over 1000mm of rainfall annually (World Bank, 2006) with other features such as long crop growing season of 140-200 days, low probability of drought, and cooler temperatures during the growing season (Saasa, 2003). The amount of rainfall received results in most of soils in the region being leached and acidic (Aregheore, 2006). The main crops grown include maize, cassava, finger millet, and beans. Livestock rearing is not very common in this region (World Bank, 2006).

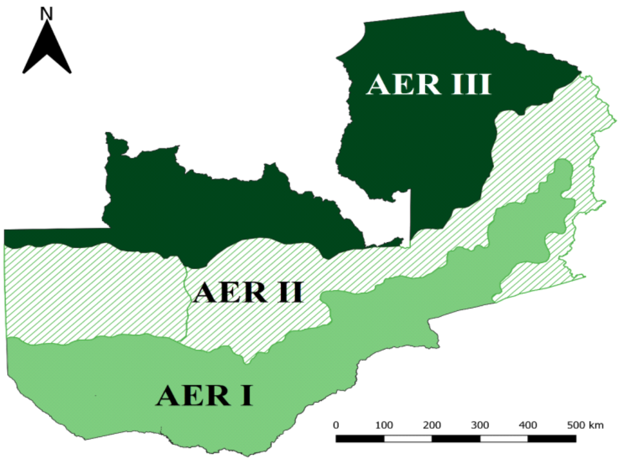


Figure1: Agro-ecological regions of Zambia.

2.2 Data collection

Given the low density and poor spatial-temporal resolution of rain gauges across the 3 agro-ecological regions for the period 1983 – 2019, the daily Climate Hazards Group InfraRed Precipitation with Station data version 2 dataset (CHIRPSv2.0: Funk et al., 2015) was used instead. CHIRPS (https://www.chc.ucsb.edu/data/chirps/) was developed by the University of California, Santa Barbara and the

United States Geological Survey (USGS) by merging observed rain gauge data with satellite images from the Globally Gridded Satellite dataset of the National Climate Centre of NOAA. The dataset has a high resolution of 0.05^0 x 0.05^0; it is of high quality and widely used in climatic and allied studies around the world (Katsanos et al., 2016; Cavalcante et al., 2020; Libanda et al., 2020).

2.3 Data analysis

This study utilized the Mann-Kendall test (Mann, 1945 and Kendall, 1975) improved by Hamed and Rao, (1998) using the 'modifiedmk' Package in R programming Language (R Core Team, 2013) to analyse trends in daily rainfall. This approach was chosen because of its robustness in accounting for autocorrelation structures in time series.

The modified Mann-Kendall test is mathematically expressed as follows:

$$Z_i = \phi^{-1}\left(\frac{R_i}{n+1}\right) \text{ for } i = 1:n, \quad [1]$$

Where: R_i is the rank of the detrended series, n is the time series' length, $i = 1:n,$ and is the inverse standard normal distribution function with a mean of 0 and a standard deviation of 1.

After computing trends, their magnitudes were quantified using the non-parametric Sen's slope estimator (Sen 1968) which is mathematically expressed as:

$$Q = \frac{Y_{i'} - Y_i}{i' - i} \quad [2]$$

Where: Q is a slope estimate. ' are the values at times I' and I, where I' is greater than I, N' is all data pairs for which I' is greater than i.

The 'pheno' package (Schaber, 2003) in R Programming Language was then used to run the sequential Mann-Kendall test (Sneyers, 1990) with the aim of detecting abrupt changes in the trend of the timeseries.

The Meteorological Drought Monitoring software (Salehnia et al., 2017) was used to calculate the standardized precipitation index (SPI) as follows:

$$g(x) = \frac{1}{\beta^{\alpha\Gamma(\alpha)}} x^{\alpha-1} e^{\frac{-x}{\beta}} (> 0) \quad [3]$$

Where: $\Gamma(\alpha)$ represents the gamma function, x is the amount of precipitation in millimeters ($x>0$); α is the shape parameter, and β is the scale parameter ($\beta>0$).

The classification of wet and dry years was subsequently done following McKee et al., (1993) and as given in Table 1. The SPI has been calculated on an annual basis.

Table 1 Classification of wet and dry years on the SPI scale

Description	Magnitude
Extremely dry	≤ -2
Severely dry	-1.5 to -1.9
Moderately dry	-1.0 to -1.4
Near Normal	-0.9 to 0.9

A number of methods for computing onset and cessation of the rainy season exist. Hachigonta et al., (2008) employed a rainfall-based criterion which was earlier used by the Famine and Early Warning System (FEWS) and documented in AGRHYMET, (1996). This approach requires the first dekad (10 days) of the rain season to accumulate a total of 25 mm followed by two dekads with a total of at least 20 mm. The onset date is then taken as the first day of the first dekad. In the work of Hachigonta et al., (2008), this method was used to calculate the onset date and rain season duration for maize cultivation in Zambia. Ryan et al. (2017) also used the same statistical approach to examine pre-rain green-up across tropical southern Africa. In their study, Ryan et al., (2017) cautioned that this approach is designed to determine rainfall that allows the start of maize cultivation. Thus, the approach should be used conservatively with respect to other requirements e.g., ecological. For this reason, a method that is generally applicable to both agricultural and ecological fields was used in this study. Specifically, an algorithm was developed in R Programming Language. To do this, each individual year was sectioned into an agrometeorological year beginning on 1st September and ending on 30th September the following year. The onset was then considered as the first day of the agrometeorological year when 8% of precipitation was recorded across each agro-ecological region and the cessation as the day when 90% of precipitation was reported. The length of the rainy season was then taken as the difference between cessation and onset. Many researchers (e.g. Ilesanmi, 1972; Laux et al., 2008; Ndomba et al., 2010; Guenang and Kamga, 2012; Amekudzi et al., 2015) have utilized a similar approach in studies around the world.

III. Results

3.1 Trends in mean annual precipitation

The trends in mean annual precipitation were increasing across all the AERs between 1983 and 2019 (Figure 2). The rate of increase in mean annual rainfall has been highest in AER 1 at 2.2 mm/year (p = 0.1), while AER 2 (1.8 mm/year; p = 0.5) and AER 3 (1.1 mm/year; p = 0.8). However, as indicated by the p-values, none of the increase was significant; implying that the overall quantity of rainfall received remained statistically the same over the study period.

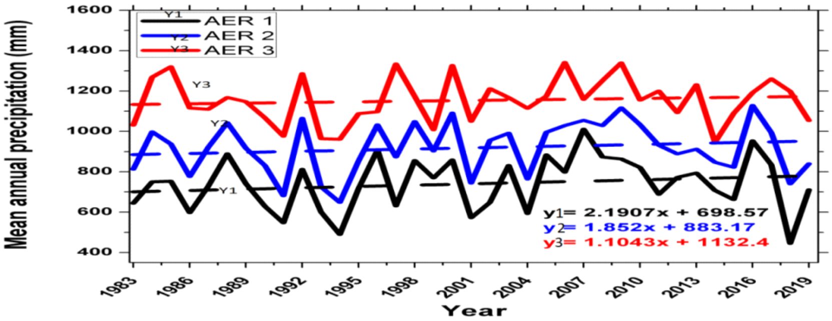


Figure 2: Trends in mean annual precipitation the period 1983 -2019 fitted using the Sen's slope estimator

The observed trends in figure 2 of mean annual precipitation were further explored for potential turning points. Results indicate that several significant abrupt changes occurred over all the three Agro-ecological Regions. AER I experienced a drought turning point in 1995, 2000, 2003, and 2010 (Figure 3a). However, the change in magnitude was different with those that occurred in 1995, 2000 and 2003. AER II experienced abrupt changes in 1992, 1993, 1995, and 2011 experiencing some form of droughts (Figure 3b). Further in 2017 and 2018, the forward and backward sequential statistics barely cross thus, these two years cannot be considered turning points although not statistically significant at the $\alpha = 0.95$ (*Onset:* Sen's slope = 0.02; P-value = 0.4; *Cessation:* Sen's slope = 0.3; P-value = 0.3). AER III experienced sudden changes in 1995, 2010, 2017, and 2019 (Figure 3c) and all changes were not significant at the $\alpha = 0.9$ (*Onset:* Sen's slope = 0.04; P-value = 0.7; *Cessation:* Sen's slope = 0.1; P-value = 0.1). Trends in rainy season length were found to be declining across all Agro-ecological regions with the steepest slope on the Sen's estimator (-0.11) being observed over AER II, followed by AER I (-0.08) and AER III (-0.06) respectively. Noteworthy, all the AERs experienced a statistically significant abrupt change in 1995 towards increased drought occurrence.

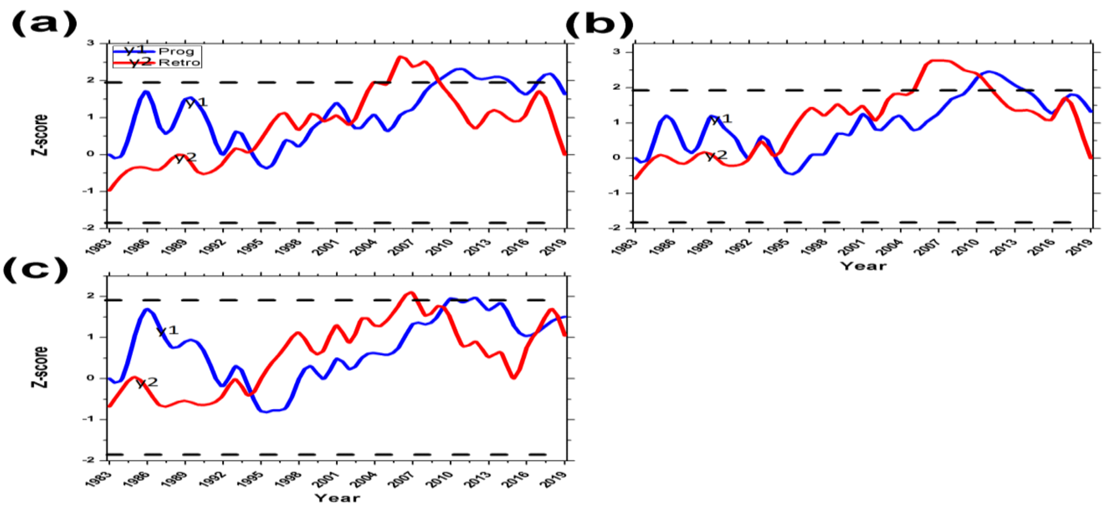


Figure 3: Turning points (abrupt charges) in precipitation trends over; a) agro-ecological region I, b) agro-ecological region II, and c) agro-ecological region III based on the sequential Mann-Kendall test statistic. Prog *is the abbreviation of* progressive *and indicates the forward sequential statistic and* retro *indicates the backward sequential statistic. The dashed lines indicate limits of statistical significance at* α = 0.95*. The period covered is 1983 – 2019.*

3.2 Variations in intra-annual rainfall characteristics

At the annual scale, SPI results indicated that the occurrence of wet and dry events coincided across all AERs for 27 of the 36-year study period 1983 – 2019 (Figure 4). Differences were observed in 1987 when AER II experienced a slight positive value of 0.02 on the SPI scale whereas AERs I and III received below normal rainfall. Further, in 1989, AER 2 experienced a dry year while AER I and III received above average rainfall. The most recent differences were in 2018 when AER I and II experienced a generally dry year while AER III was characterized by above normal rainfall.

Overall, it was found that AER III experienced the highest number of wet events (21), followed by AER I with 20 and AER II with 19.

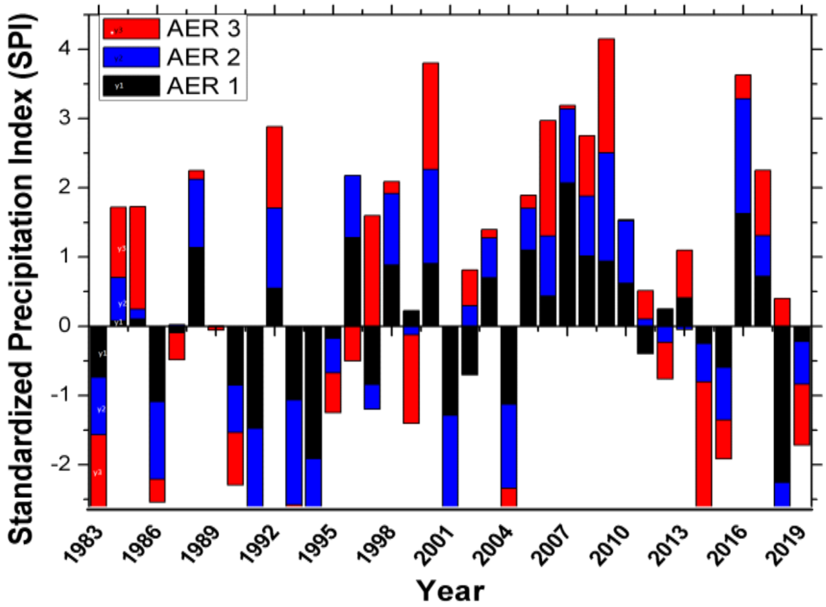
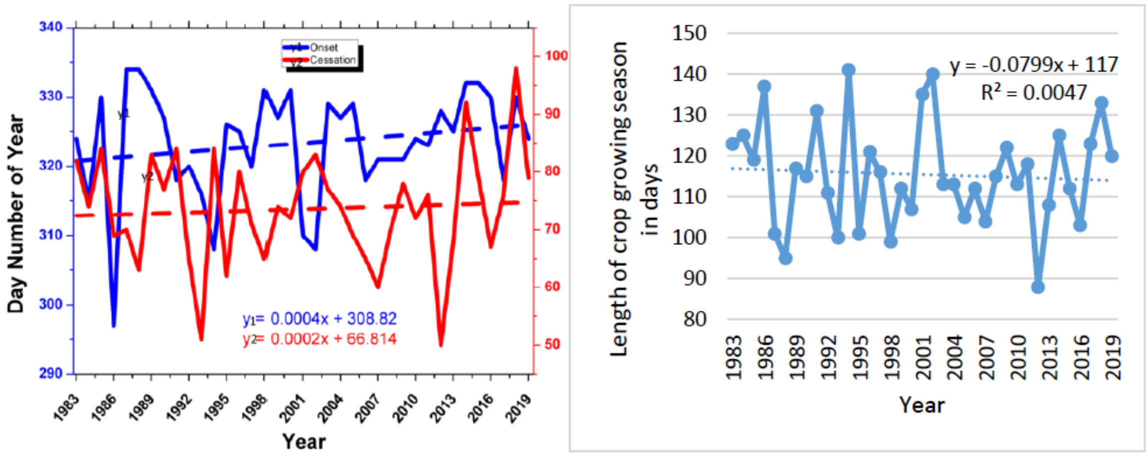


Figure 4: Standardized precipitation index (SPI) results for the period 1983 -2019

3.3 Length of crop growing season

Results indicated that the average onset date over AER I is 19th November while the cessation is on 14th March each year during the period 1983 to 2019. One other observation that emerged from the data was that the onset of the rainy season exhibits an increasing trend (*Onset:* Sen's slope = 0.07; P-value = 0.4) while the trend of cessation dates is not statistically significant (*Cessation:* Sen's slope = 0; P-value = 0.6). Therefore, these results suggest that rainy seasons across AER I are generally starting late without much difference in their withdraw dates (Figure 5).

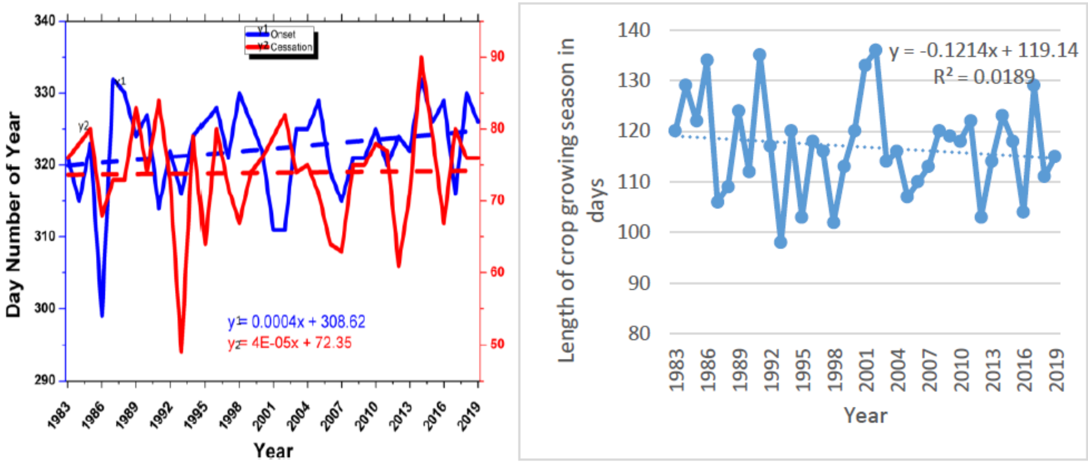


(a) ***(b)***

Figure 5: (a) Mean trend in onset and cessation of the rainy season over AER I for the period 1983 – 2019. The blue (y1) dashed line is the trend for onset while the red (y2) dashed one represents cessation fitted using the Sen's slope estimator, (b) Length of crop growing season over AER II

These findings were analyzed further to determine the length of crop growing season (Figure 6). Results indicate that useful rainfall starts on 17th November and ended around 15th March for the period 1983 to 2019. Trends in the length of crop growing season revealed that the crop growing season over the AER I begin late with no significant changes in offset dates. Length of crop growing season was longest in 1991 with 135 days with mean annual precipitation of 680.8mm, while the shortest crop growing season occurred in 1993 with 98 days with a mean annual precipitation of 725.5mm. However, the crop growing season trend in AER I have been reducing.

Across AER II, rainy seasons were found to start two days earlier than in AER1 (i.e., 17th November). The average cessation date, in comparison to AER I, was found to be a day later (15th March). Similar to AER I, trends in onset dates over AER II were found to be upwards (*Onset:* Sen's slope = 0.08; P-value = 0.04). However, unlike over AER I, the trends for AER II are statistically significant at $\alpha = 0.95$. Regarding cessation dates, the trends over AER II was found to be not statistically significant (*Cessation:* Sen's slope = 0; P-value = 0.9). Conclusively, these results indicate that the rainy season over AER II starts late but there were no significant changes in the cessation during the period 1983 – 2019 (Figure 6*a*). Figure 6*b* showed the mean length of crop growing season of 119 days respectively.



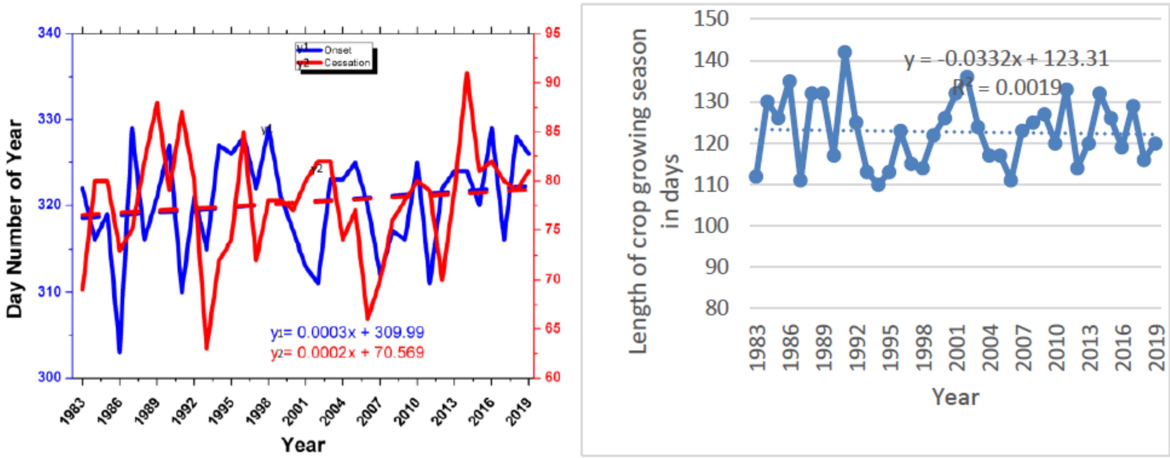
(a) *(b)*

Figure 6: (a) Trend in onset and cessation of the rainy season over AER II for the period 1983 – 2019, averaged over longitude 22.1° E – 33.2° E and latitudes 15.6° S and 13.3° S. The blue (y1) dashed line is the trend for onset while the red (y2) dashed one represents cessation fitted using the Sen's slope estimator, (b) Length of crop growing season over AER II.

Figure 7 indicates decreasing rainfall trends or shortening crop growing season. Despite this AER III experience the longest crop growing season and receives highest amounts of rainfall for the period under investigation. Generally, useful rainfall starts on 17th November and ended around 15th March for the period 1983 to 2019. Trends in the length of crop growing season showed that crop growing season over AER III begin late with no discrepancy in withdraw dates. Length of crop growing season was longest in 1991 with 142 days with a mean annual precipitation of 975.8mm, while the shortest crop growing season with the study period occurred in 1994 with 110 days with mean annual precipitation of 961.3mm. However the crop growing season shows a decreasing trend. Overall, it was found that the mean rainy season length over AER III is 121 days with annual precipitation of 1153.3mm.

When cessation and onset dates of the rainy season were analyzed over AER III, results showed that this AER experiences the earliest precipitation onset date (16th November) among the three agro-ecological regions (Figure 7). Further, with an average withdraw date of 19th March; agro-ecological region III experiences the latest cessation of the rainy season. Against this background, it was shown that AER III experience the longest rainy seasons of 123 days (Figure 7). .

Regarding trends, both onset and cessation dates were found to exhibit an upward orientation although all trends were not statistically significant at $\alpha = 0.95$ (*Onset:* Sen's slope = 0.04; P-value = 0.7; *Cessation:* Sen's slope = 0.1; P-value = 0.1).



(a) (b)

Figure 7: (a) Trend in onset and cessation of the rainy season over AER III for the period 1983 – 2019, averaged over longitude 22.1° E – 33.2° E and latitudes 15.6° S and 13.3° S. The blue (y1) dashed line is the trend for onset while the red (y2) dashed one represents cessation fitted using the Sen's slope estimator, (b) Length of crop growing seasons over AER III

Results presented in Figure 8 confirm the set hypothesis that due to the observed differences in rainy season onset and cessation dates, AER III experiences the longest rainy season. Overall, it was found that the mean rainy season length over AER 3 is 123 days while over AER II and I, its 119 and 117 days, respectively (Figures 8)

Trends in the length of the rainy season were found to be declining across all agro-ecological regions with the steepest slope on the Sen's estimator (-0.11) being observed over AER II, followed by AER I (-0.08) and AER III (-0.06) respectively (Figure 8). However, these results were found not to be statistically significant at α = 0.95. Although, they could be expressing trends of what could be expected, taken together, these findings suggest that the rainy seasons are becoming shorter across all agro-ecological regions with the magnitude being largest across agro-ecological region II. However, this should be taken to indicate a possible trend whose magnitude could become significant with time. As it is, the trends are not significant at α = 0.95. The observation that rainy seasons are potentially getting shorter reflects the late-onset that has been found across all Agro-ecological regions coupled with a near static cessation.

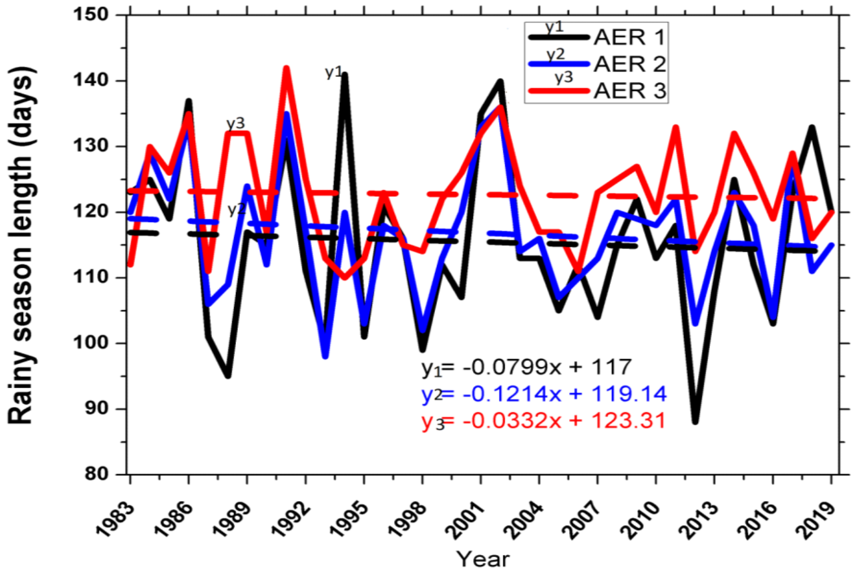


Figure 8: Trends in the length of the rainy season for the period 1983 – 2019 averaged over longitude 22.1° E – 33.2° E and latitudes 15.6° S and 13.3° S. The black (y1) linear line is the trend for AER 1, blue (y2) AER 2 and red (y3) AER 3 fitted using the Sen's slope estimation.

IV. Discussion

4.1 Trends in Mean Annual Precipitation

The mean annual precipitation was showing increased trends across all the AERs between 1983 and 2019 with annual rates of 2.1 mm/year for AER 1, while AER 2 had 1.8 mm/year; and AER 3 recorded 1.1 mm/year. . The observed increase can be explained in terms of rainfall variability, even though the observed trends should be of interest to policy makers as it could represent rainfall characteristics of the AERs in future. Further, the observation that the trend of mean annual precipitation was not significant can be attributed to the multiple abrupt changes that have been observed across all the Agro-ecological Regions resulting from general, shifts in air currents aggravated by local and synoptic scale mechanisms that are known to induce changes in the trends of mean annual precipitation (Caloiero et al., 2010).

The findings of this study were in agreement with Maidment et al. (2015) who also observed increasing rainfall trend in Southern Africa where Zambia is located at (0.04 mm per day in a year) using CHIRPS-v1 data from 1983 to 2008 that were resampled to march coarser 2.5 degrees grids (-275 km at equator). Maidment et al. (2015) correlated with this research results because it was reported that the increasing annual rainfall in Southern Africa where Zambia is positioned was driven mainly by more DJF rains that are attributed to sea surface temperature patterns particularly the Pacific Walker Circulation. However, the findings of this study have not complied with those established in different models at both local and global level. For example, the rainfall projection from CMIP5 GCMs over the Southern African context suggests a decrease in rainfall by the end of the 21st century despite the occurrences of extremes (droughts and floods). These models further reveal that the whole Southern African region will experience more drought incidences than flood (Maidment et al. 2015).

4.2 Variations in intra-annual rainfall characteristics

At the annual scale, SPI results indicated that the occurrence of wet and dry events coincided across all agro-ecological regions for 27 of the 36-year study period (1983 – 2019). Differences were observed in 1987 when AER 2 experienced a slight positive value of 0.02 on the SPI scale whereas AERs I and III received below normal rainfall. Further, in 1989, AER II experienced a dry year while AER I and III received above average rainfall. The most recent differences were in 2018 when AER I and II experienced a generally dry year while AER III was characterized by above-normal rainfall.

Overall, it was found that AER III experienced the highest number of wet events (21 years), followed by AER I with 20 and AER II with 19. This observed high number of wet compared to dry events across all agro-ecological regions, while rainy seasons were getting shorter implied that rainfall intensity was increasing across all the AERs. An increase in mean annual precipitation with reduced rainy season length translates into more intense precipitation events.

4.3 Implications on the crop growing season

The findings of this study showed that the rainy seasons are becoming shorter across all agro-ecological regions with the magnitude being largest across agro-ecological region II. However, this should be taken to indicate a possible trend whose magnitude could become significant with time. The observation that rainy seasons are potentially getting shorter reflects the late onset that has been found across all agro ecological regions coupled with a near static cessation apart from AER III.

Overall results of this study indicate that the length of crop growing season is getting shorter in the last three decades. This follows a delaying trend in suitable onset dates. The results support the notion that the rainfall patterns, which are important for rain fed agriculture have shifted despite the seasonal amount of rainfall in the three AERs of Zambia still remaining the same. An implication of this phenomenon is that farmers will have to adopt farming practices which can fit in this shortened growing season.

The results of this study compare well with previous findings of Hachigonta et al. (2008) and Mubanga and Umar (2014). It is evident from the current analysis that the crop growing season in Zambia is getting shorter and this has great consequences for food security as problems can arise due to these agro-climatic shifts (Harrison et al. 2011). Farmers have to adjust their cropping calendars and possibly change their cultivars to suit the shorter crop growing period as well as the adoption of conservation agricultural practices that help in moisture retention, improving soil fertility and reducing the period of preparing land for crops (Umar, 2011; GRZ, 2007). Further, swift changes are needed to the local farmer practices to deal with this shortening crop growing season in Zambia. One of the most widespread strategies for dealing with the increasing trend of the onset of rains is to change planting dates and staggered planting. These can take care of the false starts which occur at the start of the rainy season. This would also lessen the exposure of the young plants to early dry spells which occur during the early part of the growing season.

5.1 Conclusion

Although insignificant, the observation that mean annual precipitation is increasing across all the three AERs is not consistent with reported declining trends across Zambia (Makondo and Thomas 2020; Libanda et al., 2020) and the Southern African region (Narisma et al., 2007). However, it is notable that while mean annual precipitation was found to exhibit an increasing trend; rainy season length showed a decreasing trend. This suggests that higher amounts of rainfall are falling within short periods of time thus, higher intensity. The observed increase in high rainfall intensity is consistent with earlier studies (e.g., Libanda et al., 2016) across the whole country.

Characterization of rainfall behaviour in Zambia using 36-years SPI At the annual scale, SPI results indicated that the occurrence of wet and dry events coincided across all agro-ecological regions for 27 of the 37-year study period (1983 – 2019). Trends in rainy season length were found to be declining across all agro-ecological regions with the steepest slope on the Sen's estimator (-0.11) being observed over AER II, followed by AER I (-0.08) and AER III (-0.06), respectively. Taken together, these findings suggest that the rainy seasons are becoming shorter across all agro-ecological regions with the magnitude being largest across AER II. However, this should be taken to indicate a possible trend whose magnitude could become significant with time. As such, it was recommended that farmers adapt their farming systems and planting techniques to suit the changed rainfall patterns.

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