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Growing season length and rainfall extremes analysis in Malawi

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Abstract Malawi's agro-based economy, based largely on rain fed agriculture production, renders the country highly vulnerable to impacts of climate change and variability. Changes in the seasonal rainfall distribution can be used to predict the impacts of climate change and variability on agricultural productivity. In this study, extreme rainfall indices were analysed at 43 stations and a methodology was proposed for detecting rainfall onset, cessation and length of the growing season at 26 stations in Malawi. These indices were derived from daily rainfall records from 1961 to 2009. Geostatistical techniques and parametric and non-parametric statistics were applied to understand the levels of change in these indices and their distribution functions. The results show a countrywide shift in rainfall onset and cessation, but without significant changes in the length of the growing season; a decrease in total annual rainfall, annual maximum 1-day and 5-day rainfall amount, number of heavy and extreme rainfall days. However, there was an increase in the consecutive number of wet and dry days. Most indices analysed did not show any regionally consistent pattern and were not statistically significant at $\alpha = 0.05$ level.

Key words rainfall extremes; rainfall indices; seasonal rainfall; trends; Malawi

INTRODUCTION

An understanding and knowledge of seasonal rainfall distribution, e.g. length of the growing season and rainfall extremes, is very important in agro-based economies like Malawi, where 95% of the farmers depend on rain fed agricultural production (Simelton *et al.*, 2013). Changing frequency and intensity of rainfall events have been highlighted among the major impacts of climate change globally (IPCC, 2007). Such rainfall extremes are normally associated with floods and droughts, often resulting in widespread famine due to crop failure or destruction. A widespread perception among vulnerable rural communities in southern Africa and Malawi is that of significant changes in the rainfall onset and cessation, and consequently the growing season length (Simelton *et al.*, 2013). In addition, many perceive that there have been notable changes in the rainfall distribution pattern and frequency, marked by increased intensity and frequency of extreme rainfall events (Magrath, 2010). Such extremes include: those that refer to counts of days crossing a specified absolute value (e.g. the number of days per year with precipitation exceeding 20 mm); and those based on statistical quantities such as percentiles, implying that the tails of the statistical distribution are examined and days exceeding (or not exceeding) a given high (low) percentile are counted (Costa & Soares, 2009). Indices based on percentile thresholds have a clear advantage for climate change detection studies as they compare changes in the same parts of the precipitation distributions and thus can be used in regional studies (Haylock & Nicholls, 2000; Klein Tank & Konnen, 2003). However, indices based on the count of days crossing certain fixed (absolute) thresholds are beneficial for impact studies as they can be related with extreme events that affect human society and the natural environment (Klein Tank & Konnen, 2003). Rainfall indices such as those identified above are crucial for the agriculture sector as their changing patterns can inform the crop selection process in these communities. There is therefore a need for validating such perceptions of change with empirical evidence. This study analysed changes in onset, cessation and length of growing season, and rainfall extremes over Malawi during 1961–2009 for evidence of climate change.

DATA AND METHODS

All climate data (daily rainfall 1961–2009), pan evaporation (1971 to 2000) and mean temperature (1971–2007) were supplied by the Malawi Department of Climate Change and Meteorological Services (Fig. 1).

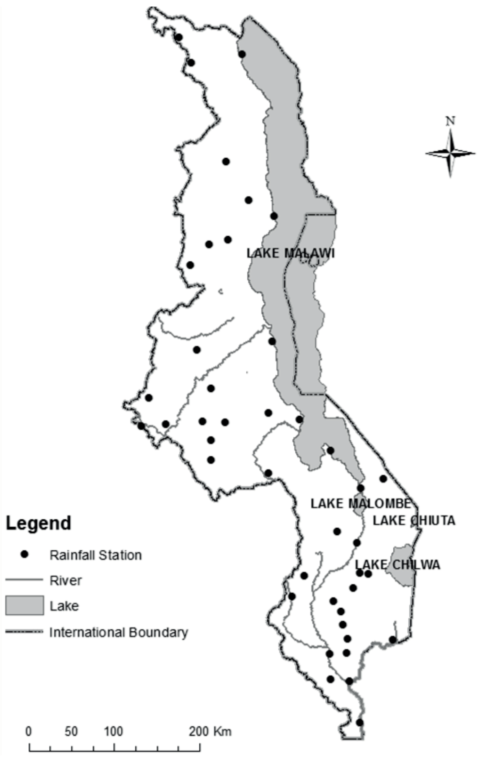

Fig. 1 Map of Malawi showing the location of rainfall stations.

Table 1 List of rain season indices and extremes

Index	Description	Units
OS	Onset date of rainy season	date
CS	Cessation date of rainy season	date
GS	Growing season length	days
PRCPTOT	Total wet day annual precipitation when PRCP>1mm	mm
CDD	Maximum number of consecutive days with RR<1mm	days
CDDwet	Wet season maximum number of consecutive days with RR <1mm	days
CWD	Annual maximum number of consecutive days with RR>=1mm	days
CWDwet	Wet season maximum number of consecutive days with RR>1mm	days
CWDdry	Dry season maximum number of consecutive days with RR<1mm	days
SDII	Annual total precipitation divided by the number of wet days when PRCP≥1.0mm	mm/day
SDIIwet	Wet season total precipitation divided by the number of wet days when PRCP≥1.0mm	mm/day
SDIIdry	Dry season total precipitation divided by the number of wet days when PRCP≥1.0mm	mm/day
R10mm	Annual count of days when PRCP>10mm	days
R20mm	Annual count of days when PRCP>20mm	days
R25mm	Annual count of days when PRCP>25mm	days
Rx1day	Annual Maximum 1-day Precipitation	mm
Rx5day	Annual Maximum 5-day Precipitation	mm
R95p	Annual total precipitation when RR>95th percentile	mm
R99p	Annual total precipitation when RR>99th percentile	mm

The study analysed the seasonal and extreme rainfall variables shown in Table 1. Rainfall data were available for 43 stations. However, rainfall onset (OS), cessation (CS) and length of growing season (LGS) were derived using observed daily rainfall at 26 stations, which had either pan evaporation or temperature data available for the period 1961–2009. For eight stations without pan measurements, daily pan evaporation (P_E) was estimated as:

$$P_E = P_n * T_E / T_n \tag{1}$$

where T_E is the station's daily mean temperature, and T_n and P_n are the daily mean temperature and evaporation, respectively, at the nearest neighboring station. The rainfall onset and cessation dates were defined using a modified version of the Food and Agricultural Organisation (FAO, 1986) method. Instead of using the monthly threshold for rainfall onset, where rainfall (R) is defined to be greater than half the potential evapotranspiration (PET) $(\mathrm{R} > \mathrm{PET}/2)$, a cumulative daily threshold was used based on the hydrological year (1 October–30 September). The rainfall onset was defined as the day *n* after 1 October (*i*) when:

$$\sum_{i=1}^{n} \mathrm{R} > \sum_{i=1}^{n} \mathrm{PET}/2 \tag{2}$$

Rainfall cessation was defined as the period when this relationship no longer holds.The length of the growing season is simply defined as the number of days between the onset and cessation. Daily average pan evaporation during 1971–2000 was used assuming no changes in the evaporation climatology. This definition (growing season) is different from Nicholson *et al.* (2013) who defined onset once 25 mm of rainfall has accumulated within 10 days, without 10 consecutive dry days (<2 mm) occurring afterward and cessation as three consecutive periods (after 1 February) of <20 mm each. Our cumulative approach builds on the threshold method as it was more robust in avoiding false starts and ends to the rainy season.

Extreme rainfall indices that were analysed annually (and seasonally for selected indices as described below) for all 43 stations (Table 1) were those recommended by the World Meteorological Organization–Commission for Climatology (WMO–CCL) and the Research Programme on Climate Variability and Predictability (CLIVAR). Five additional indices were introduced in this study, i.e. the CDD for the wet season (CDDwet), the seasonal CWD (CWDwet and CWDdry) and the seasonal SDII (SDIIwet and SDIIdry). To capture the temporal variability across Malawi, all station-based indices were standardised by subtracting the station long-term mean from each annual (seasonal) value and dividing by the standard deviation and then regionally averaging over Malawi at an annual timescale. This approach also tends to avoid bias towards stations with very high or low values (Kruger, 2006). The extreme rainfall indices were derived using the RClimdex package of R software (Zhang & Yang, 2004, http://www.r-project.org). RClimdex also checks for outliers and consistency of the data. Significance of trends was investigated using the Mann-Kendall test (Mann, 1945; Kendall, 1975) and slopes were quantified by linear regression.

RESULTS AND DISCUSSIONS

On average, the earliest rainfall onset date of 11 November was recorded in the predominantly high rainfall area to the southeast of Malawi at Mimosa Station. This station also experienced the longest growing season of 204 days, with late cessation at the end of May. Most other areas experienced rainfall onset between 15 December and 1 January with the earliest cessation recorded at the end of April. This cessation may not coincide with the meteorological definition of the normal growing season in Malawi from November to April. The shortest growing season lengths were recorded in the Lower Shire area where most of the stations experienced an average length of 85 days, with Nchalo having the shortest growing season length of 62 days on average. Ngabu and Makhanga further South of Nchalo had longer growing seasons of 115 and 103 days, respectively. In the North, the growing season was shortest at Bolero with 88 days and this was marked by late onset in mid-January and early cessation in April. The rainfall onset dates agree with Nicholson *et al.* (2013), whereas the cessation dates and consequently the length of the growing season deviate mainly due to different definitions employed.

The Mann-Kendall statistics over Malawi (Fig. 2) did not show any consistent regional trend patterns and most of the seasonal rainfall trends were not statistically significant at $\alpha = 0.05$. A positive trend in onset (OS) means a later start of the rainy season, whereas a positive trend in cessation (CS) implies a later end of the rainfall season. Countrywide rainfall onset dates were dominated by positive trends suggesting a later onset date (18 stations), with two stations in Central Malawi showing significant positive trends. The positive trend pattern was also evident for the end dates, with 21 stations suggesting later cessation. The changes in OS and CS affected the length of the growing season (LGS), which increased at 15 stations and decreased at 10 stations. However, only one station in Central Malawi showed a significant negative trend in LGS. These results suggest that the later onset of rainfall was in most cases compensated by later cessation.

Changes in rainfall extremes are small in most indices, with no clear regional patterns (Fig. 2). The annual total wet day precipitation (PRCPTOT) decreased at 28 stations with two stations, in the Centre and North, showing a significant decrease, whereas 15 stations had positive trends, none of which were statistically significant. The standardised regionally derived anomalies of PRCPTOT showed an overall countywide mean annual rainfall of 1002.2 mm and a negative trend that was not statistically significant. This agrees with New *et al*. (2006) who found that regionally averaged total precipitation had decreased over Malawi, but not statistically significant at the 5% level. The annual number of consecutive dry days (CDD) increased at almost all stations, but only nine stations had significant increasing trends (Fig. 3(a)). The wet season CDD (CDDwet) also increased countrywide although the number of stations with increasing trends (1 significant) is lower (29 stations) as compared to the annual CDD (39 stations). It was also observed that some stations experienced a decrease (14 stations) in the CDDwet (3 significant). The regionally averaged annual CDD trend (increasing) was statistically significant at $\alpha = 0.05$. An increase in annual CDD coupled with a stationary trend in PRCPTOT and late rainfall onset suggests higher daily totals in the rainy. The CDD trend pattern is consistent with a regional pattern for Southern Africa (New *et al.*, 2006; Donat *et al.*, 2013).

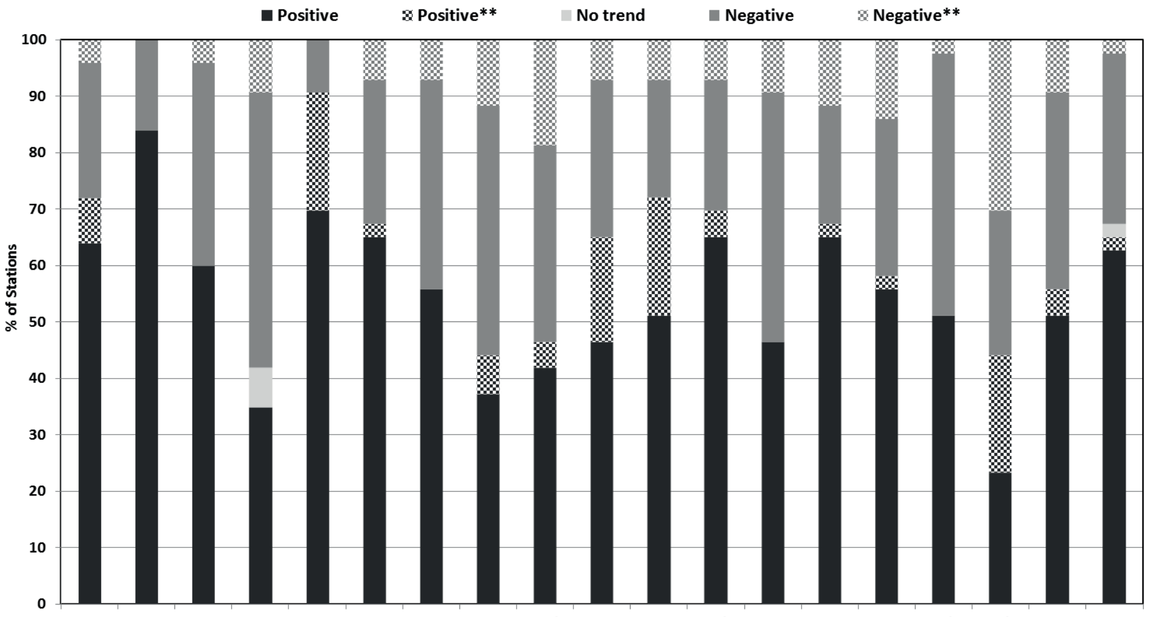

Fig. 2 Summary of Mann-Kendall trends as percentage of stations (26 stations for OS, CS and GS and 43 for the rest of the indices) with or without trends in rainfall over Malawi (1961–2009).

There was no obvious regional pattern in the annual cumulative wet days (CWD) trends; almost half the stations showed increasing trends (none significant) and the other half decreasing trends (three significant). However, significant negative trends in the CWD wet and CWD dry dominate most of the southern region. However, significant positive trends in the CWDwet and CWDdry season are found in the Centre and North. Dry season rains locally called *Chiperone*, are normally experienced in the south during the winter period (between May and July). The negative trend in the CWDdry in the South could therefore be an indication of the *Chiperon*e becoming less intense. Regionally, the CWD slightly decreased over Malawi, although not significantly. In agreement with New *et al.* (2006), a countrywide statistically significant positive trend dominates for the SDII (Fig. 3(b)). The annual, wet and dry season SDII trends in northern Malawi are largely negative (three significant) for the annual and wet season SDII. A systematic decrease in the annual and wet season SDII is also evident at stations along Lake Malawi. In contrast, the annual and wet season SDII increased at most stations in the South and Centre with eight and nine stations having significant increases, respectively. With the countrywide lack of trend in PRCPTOT, this pattern suggests a concentration of rainfall days within the rainy season.

The R10mm, R20mm and R25mm (Table 1) decreased in the northern parts and along Lake Malawi with R10mm having statistical significance. However, the R10 mm, increased in most parts of Central and southern Malawi, largely without statistical significance. However, all three had a consistent pattern of significant decreases in northern Malawi, as also reported by New *et al.* (2006). The regionally averaged values of these indices showed a predominance of negative trends without statistical significance.

Most stations had Rx1day trends that were not statistically significant (Fig. 2). However, positive trends dominate in southern Malawi, whereas the North and Centre show predominately negative trends. The same spatial pattern is found for Rx5day. However, here 30% of the stations, mainly in central and northern Malawi, had statistically significant negative Rx5day trends, whereas 20%, mostly stations in southern Malawi, have significant positive trends (Fig. 3(c)). Both regionally averaged Rx1day and Rx5day indices over Malawi showed positive trends that were not statistically significant.

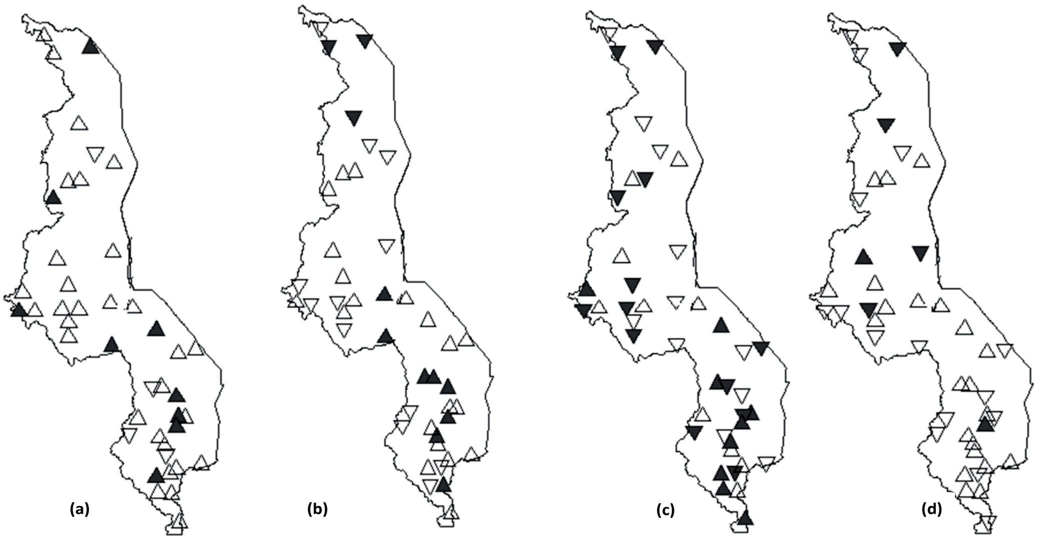

Fig. 3 Mann-Kendall trends in (a) CDD; (b)SDII; (c) Rx5day; and (d) R95p. Positive trends = upward triangle; negative trends = downwards triangles. Statistically significant trend at $\alpha = 0.05$ level are shaded.

Overall, R95p and R99p increased over Malawi with more stations having significant positive trends for R95p, although a larger number of stations showed overall positive trends for R99p (Figs 2 and 3(d)). Spatially, both southern and Central Malawi experienced increasing trends in these extremes, with decreases dominating the northern parts. An index derived as the ratio between R95p (or R99p) to the PRCPTOT was further analysed, which describes the fractional contribution of the upper tail events (very wet days and extremely wet days) to the total annual rainfall. The North was however largely dominated by negative trends, whereas positive trends dominated the centre and the southern parts, mostly not significant. The results of regionally weighted means over Malawi showed positive trends with significant trends for the R95p only. Aguilar *et al.* (2005) and Klein Tank *et al.* (2006), respectively, found statistically significant increases in the contribution of very wet days to rainfall as well as the ratio R95p/PRCPTOT in central and northern South America (1961–2003) and central and south Asia (1960–2000). Such increasing trends could therefore be an indication of disproportionately large changes in the extremes, as Klein Tank *et al*. (2006) suggested.

CONCLUSION

Between 1961 and 2009, rainfall onset and cessation over Malawi shifted to later dates, but without major changes in the length of the growing season. Based on the modified version of the FAO method, the results suggest that the growing season in most parts of Malawi starts in the middle or late December, although some stations experience an earlier start in November. It was traced that rainfall cessation at most stations changed to the end of April or early May. Statistically, these changes were not significant; however, some indices and stations indicate changes in accordance with people's perceptions of modifications of the growing season. It was also noted that trends in extreme rainfall indices over Malawi were largely without statistical significance, with the exception of: R95p and R99p whose increases, coupled with decreases in R10 mm, R20 mm, R25 mm and PRCPTOT, and increases in SDII and CDD, suggest disproportionate contributions of the very wet days to the PRCPTOT. This means that the increased average intensity detected is mainly concentrated on extreme precipitation days. It was observed that an increase in CWD is correlated with an increase in Rx5days. The differences in seasonal changes in some of the indices also demonstrates the value of looking at rainfall indices separately for the dry and the wet season as a means to increased understanding of changes in seasonal precipitation. There is a further need to establish how these changes are correlated with regional and larger scale climate forcing.

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