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Research paper

Temporal rainfall trend analysis in different agro-ecological regions of southern Africa

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Rainfall is a major driver of food production in rainfed smallholder farming systems. This study was conducted to assess linear trends in (i) different daily rainfall amounts (<5, 5–10, 11–20, 21–40 and >40 mm·day^{-1}), and (ii) monthly and seasonal rainfall amounts. Drought was determined using the rainfall variability index. Daily rainfall data were derived from 18 meteorological stations in southern Africa. Daily rainfall was dominated by <5 mm·day^{-1} followed by 5–10 mm·day^{-1}. Three locations experienced increasing linear trends of <5 mm·day^{-1} amounts and two others in sub-humid region had increases in the >40 mm day^{-1} category. Semi-arid location experienced increasing trends in <5 and 5–10 mm·day^{-1} events. A significant linear trend in seasonal rainfall occurred at two locations with decreasing rainfall (1.24 and 3 mm·season^{-1}). A 3 mm·season^{-1} decrease in seasonal rainfall was experienced under semi-arid conditions. There were no apparent linear trends in monthly and seasonal rainfall at 15 of the 18 locations studied. Drought frequencies varied with location and were 50% or higher during the November–March growing season. Rainfall trends were location and agro-ecology specific, but most of the locations studied did not experience significant changes between the 1900s and 2000s.

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INTRODUCTION

Smallholder farming systems in sub-Saharan Africa (SSA) are threatened by climate change and variability and face a huge challenge of producing enough food for close to a billion people in the region (Sonwa et al., 2017). The situation is critical in southern Africa because the region is one of the climate-change hotspots as indicated by recent projections (Lobell et al., 2008; Maure et al., 2018). Rainfall projections indicate mixed trends where some parts of the region will experience no significant changes while rainfall decrease is expected in others (Shongwe et al., 2009; Nicholson et al., 2014; Conway et al., 2015). Approximately 41 million people are already food insecure in southern Africa, the majority of whom are in rural communities that depend on rainfed agriculture (SADC, 2016). The food availability situation is further exacerbated by the continued decline in yields of major cereals and pulses due to a plethora of reasons, including high variability in the start and end of growing seasons, intra-seasonal dry spells, deteriorating soil health and limited use of mineral fertilizers, among others (Cooper et al., 2008; Sileshi et al., 2009; Van Ittersum et al., 2013). Production of major food crops has also been constrained by inappropriate policy environments that do not promote conducive input–output markets and producer prices for the smallholder farmers (Smale et al., 2011).

Rainfall is a major driver of crop and livestock production in SSA, with the majority of smallholder agriculture relying on its seasonal amount and distribution (Zinyengere et al., 2011; Mamombe et al., 2017). Smallholder agriculture is dependent on seasonal rainfall because irrigation is generally limited due to poor infrastructure and dwindling water sources (Fanadzo and Ncube, 2018). Major droughts have intensified over time and the current trends show increased frequency in southern Africa (Manatsa et al., 2008; Masih et al., 2014). Compared to seasonal totals, rainfall distribution during the growing season currently has a greater impact on crop and livestock productivity on smallholder farms of southern Africa (Twomlow et al., 2006). The start and the end of the growing season is highly variable (Usman and Reason, 2004; Tadross et al., 2005), making selection of crop types and varieties, and crop establishment methods in the field, difficult for smallholder farmers (Mupangwa et al., 2011; Nyagumbo et al., 2017). Intra-seasonal dry spells are a common feature in the region and often coincide with flowering and early reproductive growth stages of major cereal crops (Usman and Reason, 2004; Cooper et al., 2008). These dry spells significantly reduce yield of the major food security crops and limit biomass production for livestock feed (Ogenga et al., 2018). The high variability in the start and end of rains not only affects food and forage crop productivity on the smallholder farms, but also for communal grazing lands which are critical for livestock production (Manyawu et al., 2016).

Studies from SSA have reported daily rainfall dominated by amounts of less than 10 mm·day^{-1} and these have limited impact on crop growth and development (Dixit et al., 2011; Goenster et al., 2015). In Sudan, Goenster et al. (2015) observed that daily rainfall amounts of less than 3 mm have increased, while 10–20 mm events have declined, since 1970. In southern Africa where daily pan evaporation averages 5–10 mm·day^{-1} (Woltering, 2005) and atmospheric evaporative demand is 1.5–10 times the annual total rainfall (Barron, 2004), rainfall amounts of less than 5 mm·day^{-1} have limited impact on crop productivity on smallholder farms where soil water conservation techniques are rarely part of the cropping systems. Clay and sandy soils often require 20–25 mm and 30–50 mm of rainfall, respectively, to fully wet the top 30 cm of the soil profile (Twomlow, 1994; Twomlow and Bruneau, 2000). During the growing season, high intensity storms (>40 mm·day^{-1}) with high erosivity occur frequently in some parts of southern Africa (Love et al., 2010), leading to reduced water infiltration due to capping and surface sealing in certain soil types and widespread soil erosion on farmlands (Elwell and Stocking, 1988; Twomlow et al., 2006). Additionally, rainfall conditions in southern Africa are already conducive for emerging pests such as the fall armyworm (*Spodoptera frugiperda* (Smith)) and further variability might worsen pest and disease pressure on smallholder farms (Prasanna et al., 2018). Consequently, household food security in southern Africa remains under threat in the coming decades.

Information on the trends in elements of the weather that drive rainfed farming is critical for decision making by smallholder farmers, agricultural extension agents and research practitioners, rural development agents, the private sector involved in agriculture insurance, and national policy makers. This study was undertaken to assess the trends in daily, monthly and seasonal rainfall over the past decades in selected locations of southern Africa. It was hypothesized that (i) daily rainfall amounts are dominated by light showers (<5 mm·day^{-1}), (ii) there are linear trends in daily rainfall amounts, and monthly and seasonal rainfall totals, and (iii) seasonal rainfall variability leading to droughts exists in most parts of southern Africa. The specific objectives were to determine: (i) the frequency and assess linear trends in different rainfall classes (<5, 5–10, 11–20, 21–40, >40 mm·day^{-1}), (ii) trends in monthly and seasonal total rainfall, and (iii) drought occurrences in selected locations under different agro-ecological conditions of southern Africa.

MATERIALS AND METHODS

Data source and quality

Initial daily rainfall data were collected from 23 meteorological stations spread to cover different agro-ecological conditions of the selected southern African countries (Malawi, Mozambique, South Africa and Zimbabwe). The final daily rainfall data used in the analyses were derived from 18 meteorological stations located in the 4 countries (Appendix, Table A1; Fig. 1). The choice of these stations was based on availability of complete long-term measured/observed daily rainfall data. Any meteorological station that had missing measured daily rainfall data and needed data infilling at daily, monthly or seasonal timesteps considered in this study, was not included in the analyses, hence reducing the number from 23 to 18 locations. For the final 18 stations, only periods with at least 30 years of data without any missing data were considered, and are summarized in Table A1. The choice of these criteria was based on the availability of data which is considered to be long-term enough for valid trend results in climate change research (Burn and Elnur, 2002). The length of available rainfall datasets varied from country to country and station to station.

Analyses were conducted at daily, monthly and seasonal time-steps in order to answer the research questions selected for the study. Acquired data were converted to the standard June–July calendar (agriculture year in southern Africa) and underwent data quality control routines to identify missing data, errors and suspect data, as well as to ensure that data were consistent and met the data quality objectives. The quality checks were performed using the computer program RClimDex 1.1 and its software package RHtestV3 (Wang and Feng, 2013), that can be accessed at: http://etccdi.pacificclimate.org.

Data analyses

Time series of daily, monthly and seasonal rainfall data were used to identify trends at different temporal resolutions. Seasonal rainfall totals were used to assess drought occurrences at locations in different agro-ecological regions of Malawi, Mozambique, South Africa and Zimbabwe. Daily rainfall amounts were divided into classes of <5, 5–10, 11–20, 21–40 and >40 mm·day^{-1}.

Mann–Kendall (MK) test

Non-parametric statistical methods were used to detect temporal linear trends in the daily, monthly and seasonal rainfall data. The main advantages of non-parametric methods are that datasets with missing values are allowed and the data need not conform to any particular distribution (Da Silva at al., 2015). The Mann-Kendall test analysis was performed in R version 3.5.2 (R Core Team, 2018) using the Kendall package to detect the existence of monotonic trends for daily, monthly and seasonal rainfall during the summer season (November–March). The test compares a data value (x_i and y_i) to its subsequent values (x_j and y_j) and adds an

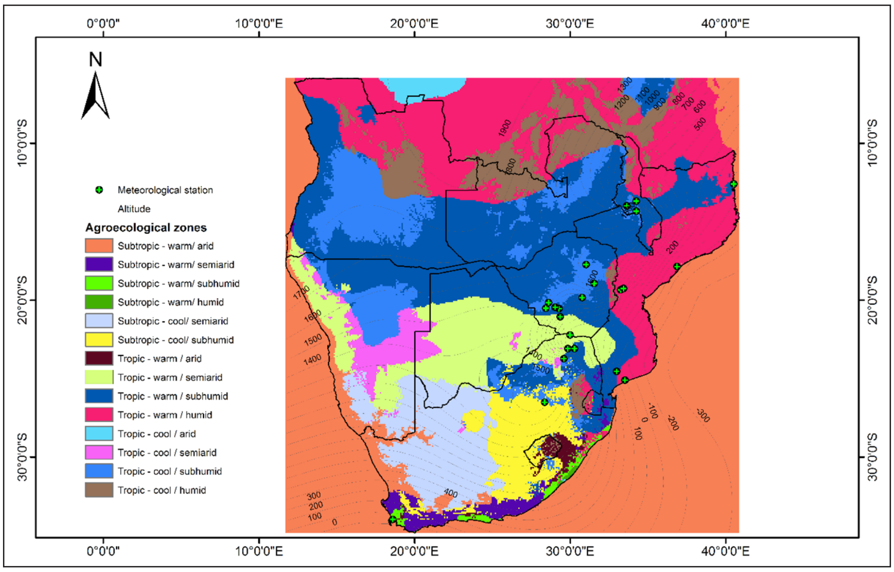

Figure 1. Location of selected meteorological stations in Malawi, Mozambique, South Africa and Zimbabwe used in the study. Different agro-ecological regions of southern Africa are indicated by different colour codes.

increment or decrement of 1 to the MK test statistic (S) when the subsequent data values were higher or lower, respectively (Karmeshu, 2012), as illustrated in Eq: 1 below. Any missing values were automatically removed during analysis.

$$S=\sum_{i<j}(\text{sign}(x_j-x_i)\ x\ \text{sign}(y_j-y_i)) \tag{1}$$

When there were no ties between the x and y variables, the strength of monotonic association was given by Kendall`s rank correlation, tau (τ) (Eq. 2) and subsequent p-value of tau for the null hypothesis of no association was calculated (Best and Gipps, 1974).

$$\tau = S/D \quad \text{where} \quad D=n(n-1)/2 \tag{2}$$

In the presence of less extensive ties, a normal approximation of S with subsequent continuity correction was made with mean zero, and variance var(S) where var(S) was given by Kendall (1975, Eq. 4.4, p. 55).

The Theil–Sen slope estimator

Since a monotonic trend was demonstrated from the Mann-Kendall test which appeared linear in some stations, the Theil-Sen slope test was further performed to examine the magnitude of the slope for daily, monthly and seasonal rainfall. The test was performed in R version 3.5.2 (R Core Team, 2018) using the Trend package (Pohlert, 2018). The test computes slope using Sen's method, which calculates a set of linear slopes, followed by a median of the slopes, as follows:

$$d_k=\frac{X_j-X_i}{j-i} \tag{3}$$

for ($1 \le i < j \le n$), where d is the slope, X denotes the variable, n is the number of data points, and i, j are indices. As a result, the Sen slope (b_{Sen}) is given by b_{Sen} = median d_k

Rainfall variability index

Rainfall variability index (δ) is calculated as:

$$\delta_i=\left(P_i-\mu\right)/\sigma \tag{4}$$

where δ_i = rainfall variability index for year i, P_i = seasonal rainfall for year i, μ and σ are the mean seasonal rainfall and standard deviation for the period under consideration.

In this study P_i represented the November–March seasonal rainfall; consequently, μ and σ were the mean and standard deviation of the total seasonal rainfall. A drought year occurs if the δ is negative and, according to WMO (1975), rainfall time-series can be classified into different climatic regimes (Table 1). All calculations for the different rainfall ranges were performed in Microsoft Excel.

RESULTS

Frequency and trends of different daily rainfall amounts

Daily rainfall events occurring in southern Africa were dominated by amounts of <5 mm at all locations (Table 2). Generally, the chances of getting higher daily rainfall amounts decreased consistently across the rainfall classes, regardless of agro-ecological conditions. In Zimbabwe, 5–10 mm·day^{-1}, and 11–20 mm·day^{-1} amounts occurred more frequently in sub-humid locations than semi-arid sites. Beitbridge had the least chance (1.4%) of getting more than 40 mm·day^{-1} during the growing season. In Malawi, 21–40 mm·day^{-1} amounts occurred more frequently along Lake Malawi than at further inland locations. Chitedze and Dedza had better chances of getting 11–20 mm·day^{-1} than 5–10 mm·day^{-1} during the growing season. In Mozambique, rainfall amounts of <5 mm·day^{-1} occurred more frequently at Chimoio compared to the other locations. In South Africa 5–10 mm·day^{-1} events occurred more frequently than <5 mm·day^{-1} at Harmony.

Table 1. Rainfall ranges and corresponding climatic regimes based on WMO classification (Source: WMO, 1975)

Rainfall range	Climatic regime
$P < \mu - 2{\cdot}\sigma$	Extremely dry
$\mu - 2{\cdot}\sigma < P < \mu - \sigma$	Dry
$\mu - \sigma < P < \mu + \sigma$	Normal
$P > \mu + \sigma$	Wet

Table 2. The frequency (%) of receiving different amount during the November-March growing season at different weather stations in Zimbabwe, Malawi, Mozambique and South Africa.

Country	Station	Rainfall amount (mm·day^{-1})				
		<5	5-10	11–20	21–40	>40
		Probability (%)				
Zimbabwe	Harare	22.5	11.8	12.7	8.0	2.9
	Marondera	20.5	12.0	11.9	8.5	3.3
	Matopos	13.2	7.5	8.0	6.3	1.9
	Bulawayo	16.1	8.8	8.6	6.1	2.0
	W. Nich.	16.5	6.5	5.8	4.4	1.8
	Beitbridge	13.1	5.3	4.7	3.1	1.3
Malawi	Chitala	17.4	12.5	12.3	10.4	4.0
	Chitedze	23.1	13.3	14.6	8.9	3.8
	Dedza	26.1	14.8	15.5	9.7	3.3
Mozambique	Chimoio	21.3	11.2	11.2	8.6	5.4
	Chokwe	14.7	6.5	5.0	3.9	2.1
	Pemba	17.8	9.1	9.3	6.7	3.6
	Quelimane	17.9	9.2	9.8	8.6	6.6
	Xai Xai	19.4	7.2	6.3	5.0	3.4
South Africa	Harmony	10.8	12.5	6.8	4.0	1.8
	Levubu	22.0	8.3	7.7	6.3	5.0
	Mertz	10.5	10.3	7.1	3.8	1.8
	Polokwane	15.1	7.3	6.2	4.1	1.4

Trends of the different rainfall classes varied with location (Tables 3 and 4). Significant increases in the >40 mm·day^{-1} class were detected at one of the 6 locations in Zimbabwe. Beitbridge experienced an increasing trajectory in <5 and 5–10 mm·day^{-1} amounts. A significantly decreasing trajectory of <5 day^{-1} amounts was detected at one of the 6 Zimbabwean locations. Chitala and Chitedze experienced decreases in <5 and 5–10 mm·day^{-1}, and increases in <5 mm·day^{-1} rainfall amounts, respectively. Significant decreases in <5 and 11–20 mm·day^{-1}, and 5–10 mm·day^{-1} amounts were detected at Chimoio and Chokwe, respectively (Table 5). The >40 and 11–20 mm·day^{-1} amounts decreased over time at Harmony and Mertz, respectively (Table 6).

Table 3. Mann-Kendall trend and Sen slope for different rainfall classes at weather stations in Zimbabwe

Station	Rainfall class	Kendall's tau	*P*-value	Sen slope	*P*-value
Harare	<5	0.0247	0.8367	0.0000	0.8367
	5–10	0.0125	0.9226	0.0000	0.9226
	11–20	0.0961	0.4084	0.0625	0.4084
	21–40	−0.0310	0.7979	0.0000	0.7979
	>40	0.2287	0.0577	0.0400	0.0557
Marondera	<5	−0.2937	0.0036	−0.200	0.0036
	5–10	−0.1770	0.0807	−0.1026	0.0807
	11–20	−0.1302	0.2004	−0.0659	0.2004
	21–40	0.1053	0.3061	0.0345	0.3061
	>40	−0.0792	0.4557	0.0000	0.4557
Matopos	<5	−0.0956	0.2335	−0.0396	0.2335
	5–10	−0.1720	0.0344	−0.0367	0.0344
	11–20	−0.1717	0.0335	−0.0440	0.0335
	21–40	−0.0978	0.2327	0.0000	0.2327
	>40	−0.0111	0.9007	0.0000	0.9007
Bulawayo	<5	0.0698	0.4030	0.0222	0.4030
	5–10	−0.1417	0.0941	−0.0263	0.0941
	11–20	0.0462	0.5834	0.0000	0.5834
	21–40	−0.0183	0.8333	0.0000	0.8333
	>40	0.0169	0.8509	0.0000	0.8509
West Nich	<5	0.1022	0.3756	0.0800	0.3756
	5–10	−0.0700	0.9612	0.0000	0.9612
	11–20	−0.0958	0.4140	−0.0345	0.4140
	21–40	0.0904	0.4473	0.0000	0.4473
	>40	0.0699	0.5684	0.0000	0.5684
Beitbridge	<5	0.2396	0.0181	0.1429	0.0181
	5–10	0.0238	0.0212	0.0667	0.0212
	11–20	0.1902	0.0643	0.0606	0.0643
	21–40	0.1770	0.0954	0.0000	0.0954
	>40	−0.0558	0.6175	0.0000	0.6175

Table 4. Mann-Kendall trend and Sen slope for different rainfall classes at weather stations in Malawi

Station	Rainfall class	Kendall's tau	*P*-value	Sen slope	*P*-value
Chitala	<5	−0.0882	0.3745	−0.0278	0.3745
	5–10	−0.3657	0.0002	−0.1567	0.0002
	11–20	−0.0976	0.3303	0.0000	0.3303
	21–40	0.0755	0.4506	0.0000	0.4506
	>40	0.0489	0.6353	0.0000	0.6353
Chitedze	<5	0.2864	0.0230	0.0262	0.0230
	5–10	−0.0176	0.9008	0.0000	0.9008
	11–20	0.0938	0.4638	0.0625	0.4638
	21–40	0.0885	0.5194	0.0000	0.5194
	>40	−0.1816	0.1655	−0.0465	0.1655
Dedza	<5	−0.1556	0.1575	−0.1053	0.1575
	5–10	−0.1325	0.2313	−0.0690	0.2313
	11–20	0.0598	0.9653	0.0000	0.9653
	21–40	0.1649	0.1406	0.0625	0.1406
	>40	−0.1742	0.1389	0.0000	0.1389

Table 5. Mann-Kendall trend test of different rainfall classes at weather stations in Mozambique

Country	Station	Rainfall class	Kendall's tau	*P*-value	Sen slope	*P*-value
Mozambique	Chimoio	<5	−0.1609	0.0722	−0.0714	0.0722
		5–10	−0.1062	0.2388	−0.0357	0.2388
		11–20	−0.1950	0.0295	−0.0769	0.0295
		21–40	−0.0055	0.9562	0.0000	0.9562
		>40	−0.0269	0.7732	0.0000	0.7732
	Chokwe	<5	−0.0104	0.9431	0.0000	0.9431
		5–10	−0.2707	0.0292	−0.0952	0.0292
		11–20	0.2403	0.0567	0.0606	0.0567
		21–40	0.0432	0.7401	0.0000	0.7401
		>40	−0.2177	0.0889	−0.0370	0.0889
	Quelimane	<5	−0.0671	0.5155	0.0000	0.5155
		5–10	−0.0798	0.4401	0.0000	0.4401
		11–20	0.0505	0.6270	0.0000	0.6270
		21–40	−0.0142	0.8965	0.0000	0.8965
		>40	−0.0876	0.3990	0.0000	0.3990
	Pemba	<5	−0.0700	0.4661	−0.0256	0.4661
		5–10	−0.0237	0.8098	0.0000	0.8098
		11–20	0.1865	0.0529	0.0513	0.0529
		21–40	0.0204	0.8378	0.0000	0.8378
		>40	0.0836	0.4052	0.0000	0.4052
	Xai Xai	<5	−0.0570	0.6315	−0.0370	0.6315
		5–10	−0.0707	0.5586	0.0000	0.5586
		11–20	−0.0431	0.7227	0.0000	0.7227
		21–40	0.0597	0.6261	0.0000	0.6261
		>40	−0.1438	0.2315	−0.0333	0.2315

Table 6. Mann-Kendall trend test of different rainfall classes at weather stations in South Africa

Country	Station	Rainfall class	Kendall's tau	*P*-value	Sen slope	*P*-value
SA	Harmony	<5	0.2667	0.0002	0.1053	0.0002
		5–10	0.0351	0.6210	0.0000	0.6210
		11–20	−0.0887	0.2220	0.0000	0.2220
		21–40	−0.0720	0.3237	0.0000	0.3237
		>40	−0.2698	0.0004	−0.0141	0.0004
	Levubu	<5	−0.0497	0.6709	−0.0313	0.6709
		5–10	0.0535	0.6521	0.0000	0.6521
		11–20	−0.0324	0.7884	0.0000	0.7884
		21–40	0.0423	0.7234	0.0000	0.7234
		>40	−0.0084	0.9515	0.0000	0.9515
	Mertz	<5	−0.1591	0.0244	−0.0606	0.0244
		5–10	−0.3836	$6.65e^{-8}$	−0.1092	$6.65e^{-8}$
		11–20	−0.1756	0.0146	−0.0323	0.0146
		21–40	−0.0401	0.5864	0.0000	0.5864
		>40	0.2840	0.0002	0.0156	0.0002
	Polokwane	<5	−0.1454	0.1681	−0.0588	0.1681
		5–10	0.0440	0.6876	0.0000	0.6876
		11–20	−0.0446	0.6815	0.0000	0.6815
		21–40	0.0186	0.8704	0.0000	0.8704
		>40	0.2001	0.0803	0.0000	0.0803

Trends of monthly and seasonal rainfall

The presence of linear trends in monthly and seasonal (November–March) rainfall varied between locations. The November–March period had significant increasing (0.09 mm·season^{-1}) and decreasing rainfall trajectories at Matopos and Beitbridge, respectively (Table 7). January rainfall decreased by 1.8 mm·season^{-1} while seasonal total declined by 0.3 mm·season^{-1} at Beitbridge. The January and March rainfall significantly increased at 3.3 and 1.8 mm·season^{-1} at Harare. March and November–March rainfall increased (P < 0.05) by 0.6 and 2.1 mm·season^{-1}, respectively, at Bulawayo. There was a general decrease in February and March rainfall at Malawian locations (Table 8). February rainfall significantly (P = 0.0132) decreased by 2.5 mm·season^{-1} at Chitala. Rainfall decreased by 0.15–3.7 mm·season^{-1} during the November–March period at 3 of the 5 locations in Mozambique (Table 9). February rainfall decreased (P = 0.0111) by 3.3 mm·season^{-1} at Xai Xai. In South Africa, February rainfall decreased at three locations (Table 10). During the November–March period, rainfall decreased (P = 0.0421) by 1.24 mm·season^{-1} at Harmony.

Table 7. Mann-Kendall trend and Sen slope tests of monthly and seasonal (November–March) rainfall at weather stations in Zimbabwe

Station	Month(s)	*N*	Kendall's tau	*P*-value	Sen slope	*P*-value
Harare	Nov	38	−0.053	0.651	−0.5429	0.6418
	Dec	38	−0.027	0.821	−0.2462	0.8210
	Jan	38	0.260	0.022	3.2550	0.0221
	Feb	38	−0.018	0.022	−0.2320	0.8801
	Mar	38	0.240	0.035	1.7889	0.0347
	Nov–Mar	38	0.073	0.530	2.2273	0.5296
Marondera	Nov	50	−0.034	0.737	0.2292	0.3234
	Dec	50	−0.160	0.107	0.2727	0.2767
	Jan	50	−0.075	0.453	−0.0370	0.9067
	Feb	50	−0.095	0.339	0.2286	0.4413
	Mar	50	0.153	0.123	0.1600	0.5347
	Nov–Mar	50	−0.095	0.339	0.8929	0.3194
Matopos	Nov	76	−0.105	0.184	0.000	0.2884
	Dec	76	−0.056	0.476	−0.0910	0.8365
	Jan	76	−0.094	0.231	0.0498	0.8894
	Feb	76	−0.110	0.163	0.2388	0.5068
	Mar	76	−0.168	0.033	0.4493	0.0817
	Nov–Mar	76	−0.176	0.025	0.0941	0.0517
Bulawayo	Nov	71	0.084	0.302	0.5887	0.0685
	Dec	71	−0.046	0.571	−0.4550	0.2770
	Jan	71	−0.038	0.641	0.2866	0.5715
	Feb	71	0.002	0.984	0.7154	0.1056
	Mar	71	0.008	0.925	0.6000	0.0110
	Nov–Mar	71	0.012	0.889	2.0817	0.0418
West Nich	Nov	39	−0.004	0.981	−0.0333	0.9807
	Dec	39	−0.112	0.321	−0.7214	0.3212
	Jan	39	0.093	0.411	0.9182	0.4107
	Feb	39	−0.007	0.961	−0.0250	0.9614
	Mar	39	0.119	0.293	0.6000	0.2926
	Nov–Mar	39	0.026	0.828	0.4677	0.8276
Beitbridge	Nov	50	0.138	0.160	−0.1875	0.5582
	Dec	50	−0.026	0.795	−0.0681	0.8474
	Jan	50	0.156	0.112	−1.7727	0.0052
	Feb	50	0.105	0.284	−0.6429	0.2553
	Mar	50	0.180	0.035	−0.2826	0.2880
	Nov–Mar	50	0.176	0.043	−0.3000	0.0139

Table 8. Mann-Kendall trend test of monthly and seasonal rainfall at weather stations in Malawi

Station	Month	*N*	Kendall's tau	*P*-value	Sen slope	*P*-value
Chitala	Nov	52	−0.0630	0.5173	−0.1467	0.5173
	Dec	52	0.1028	0.2866	0.8475	0.2866
	Jan	52	0.1086	0.2590	0.8967	0.2591
	Feb	52	−0.2382	0.0132	−2.5286	0.0132
	Mar	52	−0.0045	0.9685	−0.0063	0.9685
	Nov–Mar	52	−0.0166	0.8684	−0.3896	0.8684
Chitedze	Nov	33	0.0000	1.0000	0.0110	1.0000
	Dec	33	−0.0057	0.9753	−0.0577	0.9753
	Jan	33	0.16330	0.1930	1.9912	0.1930
	Feb	33	−0.0909	0.4665	−1.1479	0.4665
	Mar	33	−0.0719	0.5664	−0.9393	0.5664
	Nov–Mar	33	0.0000	1.0000	0.0110	1.0000
Dedza	Nov	41	0.1049	0.3397	0.5476	0.3397
	Dec	41	0.0317	0.7789	0.2730	0.7797
	Jan	41	−0.0952	0.3871	−1.2443	0.3871
	Feb	41	−0.0647	0.5592	−0.6125	0.5592
	Mar	41	−0.0354	0.7531	−0.3711	0.7531
	Nov–Mar	41	−0.0195	0.8662	−0.5900	0.8662

Table 9. Mann-Kendall trend test of monthly and seasonal rainfall at weather stations in Mozambique

Station	Month	*N*	Kendall's tau	*P*-value	Sen slope	*P*-value
Chimoio	Nov	62	0.0952	0.2769	0.5000	0.2769
	Dec	62	−0.0407	0.6443	−0.4357	0.6443
	Jan	62	0.0085	0.9274	0.1333	0.9274
	Feb	62	0.0619	0.4811	0.7103	0.4811
	Mar	62	0.0709	0.4192	0.4864	0.4192
	Nov–Mar	62	0.0423	0.6313	1.1143	0.6313
Chokwe	Nov	35	0.0151	0.9095	0.0944	0.9095
	Dec	35	0.0723	0.5509	0.5125	0.5509
	Jan	35	−0.1899	0.1117	−2.1200	0.1117
	Feb	35	0.0151	0.9095	0.1000	0.9095
	Mar	35	−0.0538	0.6597	−0.2286	0.6597
	Nov–Mar	35	−0.1261	0.2933	−3.2917	0.2933
Quelimane	Nov	49	0.1192	0.2308	0.5489	0.2308
	Dec	49	−0.0459	0.6478	−0.4681	0.6478
	Jan	49	−0.0799	0.4228	−1.1542	0.4228
	Feb	49	0.0204	0.8428	0.2133	0.8428
	Mar	49	0.1225	0.2177	1.9106	0.2177
	Nov–Mar	49	0.0136	0.8971	−0.5482	0.8971
Pemba	Nov	55	−0.0866	0.3563	−0.1469	0.3563
	Dec	55	0.1447	0.1203	0.9424	0.1203
	Jan	55	−0.0842	0.3680	−0.5927	0.3680
	Feb	55	−0.0074	0.9421	−0.0500	0.9421
	Mar	55	0.0303	0.7494	0.2910	0.7494
	Nov–Mar	55	0.0222	0.8163	0.3333	0.8163
Xai Xai	Nov	38	−0.1480	0.1953	−0.7895	0.1953
	Dec	38	0.0655	0.5715	0.5000	0.5715
	Jan	38	0.0370	0.7533	0.3054	0.7533
	Feb	38	−0.2888	0.0111	−3.3167	0.0111
	Mar	38	0.0213	0.8603	0.1333	0.8603
	Nov–Mar	38	−0.1607	0.1591	−3.7250	0.1591

Table 10. Mann-Kendall trend test of monthly and seasonal rainfall at weather stations in South Africa

Station	Month	*N*	Kendall's tau	*P*-value	Sen slope	*P*-value
Harmony	Nov	96	−0.0715	0.3036	−0.1562	0.3036
	Dec	96	−0.1562	0.0244	−0.4119	0.0244
	Jan	96	−0.0959	0.1676	−0.2490	0.1676
	Feb	96	−0.0748	0.2818	−0.2846	0.2818
	Mar	96	−0.0242	0.7301	−0.0552	0.7301
	Nov–Mar	96	−0.1410	0.0421	−1.2397	0.0421
Levubu	Nov	39	0.0202	0.8655	0.1629	0.8655
	Dec	39	0.0418	0.7167	0.3044	0.7167
	Jan	39	−0.0065	0.9614	−0.1106	0.9614
	Feb	39	−0.0958	0.3971	−1.1417	0.3971
	Mar	39	−0.0445	0.6987	−0.3950	0.6987
	Nov–Mar	39	0.0122	0.9229	0.6000	0.9229
Mertz	Nov	96	0.0466	0.5041	0.1043	0.5041
	Dec	96	−0.0147	0.8345	−0.0417	0.8345
	Jan	96	0.0029	0.9697	0.0072	0.9697
	Feb	96	−0.0411	0.5560	−0.1321	0.5560
	Mar	96	0.0176	0.8025	0.0427	0.8025
	Nov–Mar	96	−0.0075	0.9167	0.0000	0.9167
Polokwane	Nov	45	0.0657	0.5313	0.3114	0.5313
	Dec	45	0.0172	0.8756	0.0599	0.8756
	Jan	45	0.0000	1.0000	−0.0063	1.0000
	Feb	45	0.0424	0.6884	0.1289	0.6884
	Mar	45	0.0788	0.4513	0.3285	0.4513
	Nov–Mar	45	0.1051	0.3137	1.2479	0.3137

Seasonal rainfall variability

The number of drought years varied with location and the period considered for each station. Harare experienced 20 droughts, with 12 being very dry, and 3 wet years during the 38-year period (Fig. 2). The worst droughts occurred during 1964, 1968 and 1995. Marondera experienced one extreme drought (1992) and 7 wet years over a 49-year period; 41 droughts were experienced between 1940 and 2015, and most wet years occurred before 1975 at Matopos. The number of wet years decreased between 1980 to 2015. At Bulawayo, 39 droughts and 13 wet years were experienced. West Nicholson experienced 21 droughts and just 6 wet years in 39 years; 29 droughts in 50 years were experienced at Beitbridge and the 1960 and 1980s were the driest decades with 5 severe droughts occurring. Only 4 wet years were experienced between 1952 and 2001 and this included the El Niño year.

At Chitala, 26 droughts were experienced, evenly distributed over the 52 years, with the majority occurring during the 1980s and 1990s (Fig. 3); 6 wet years were recorded between 1976 and 1986. At Chitedze, 18 droughts were experienced and 6 of them were very dry; 7 dry and 4 wet seasons were experienced at Dedza where a total of 21 droughts were recorded in 33 years.

Chimoio experienced an extremely dry 1972 and the extreme drought of 1972 was immediately followed by 3 consecutive wet years (Fig. 4). A total of 34 droughts occurred at Chimoio in 62 years. At Chokwe, 18 droughts occurred and most of the droughts occurred in the 1980s; 5 wet years, evenly distributed over the 35 years, occurred at Chokwe; and 29 droughts with 1 extreme and 5 wet years were experienced at Pemba in 54 years. The droughts were concentrated in the 1960s and 1970s. Quelimane had 28 droughts, one of them being extreme and 5 wet years were experienced in the 1960s and 1980s. A very dry year followed by a relatively wet one occurred once at Quelimane during the 1960s. At Xai Xai, 24 droughts and 7 wet years were recorded in 38 years.

The Mertz location experienced 58 droughts and 15 wet years over a 96-year period. Most of the droughts occurred in the 1940s, 1980s and 1990s (Fig. 5). At Harmony, 56 droughts, with 8 being very dry, and 9 wet years occurred in 96 years. Most of the droughts occurred between the 1920s and 1940s. Over a 39-year period, 22 droughts and 5 wet years occurred at Levubu. Most of the droughts occurred between 1982 and 2004. In 45 years, 26 droughts and 5 wet years were experienced at Polokwane.

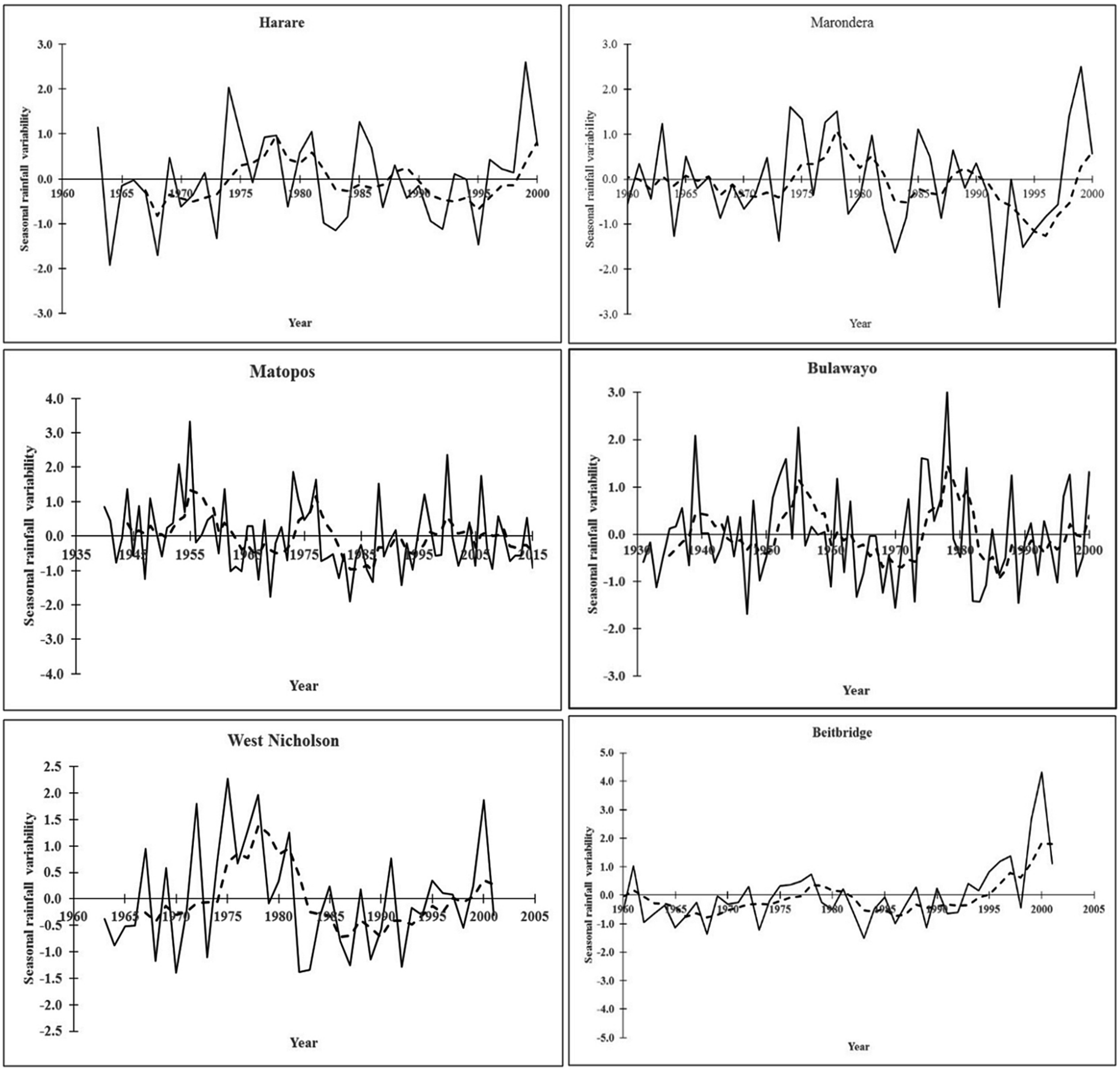

Figure 2. Seasonal rainfall variation at different locations in Zimbabwe. Dotted line represents 5-year moving average.

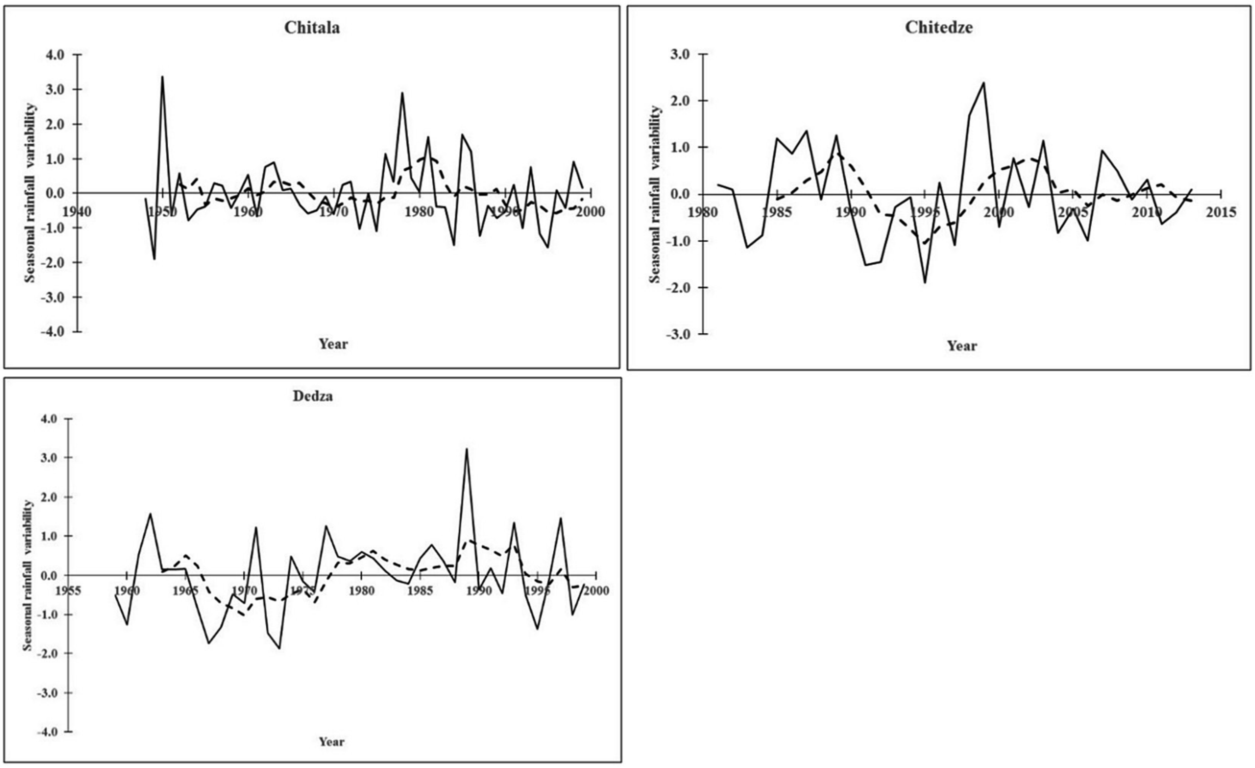

Figure 3. Seasonal rainfall variation at different locations in Malawi. Dotted line represents 5-year moving average.

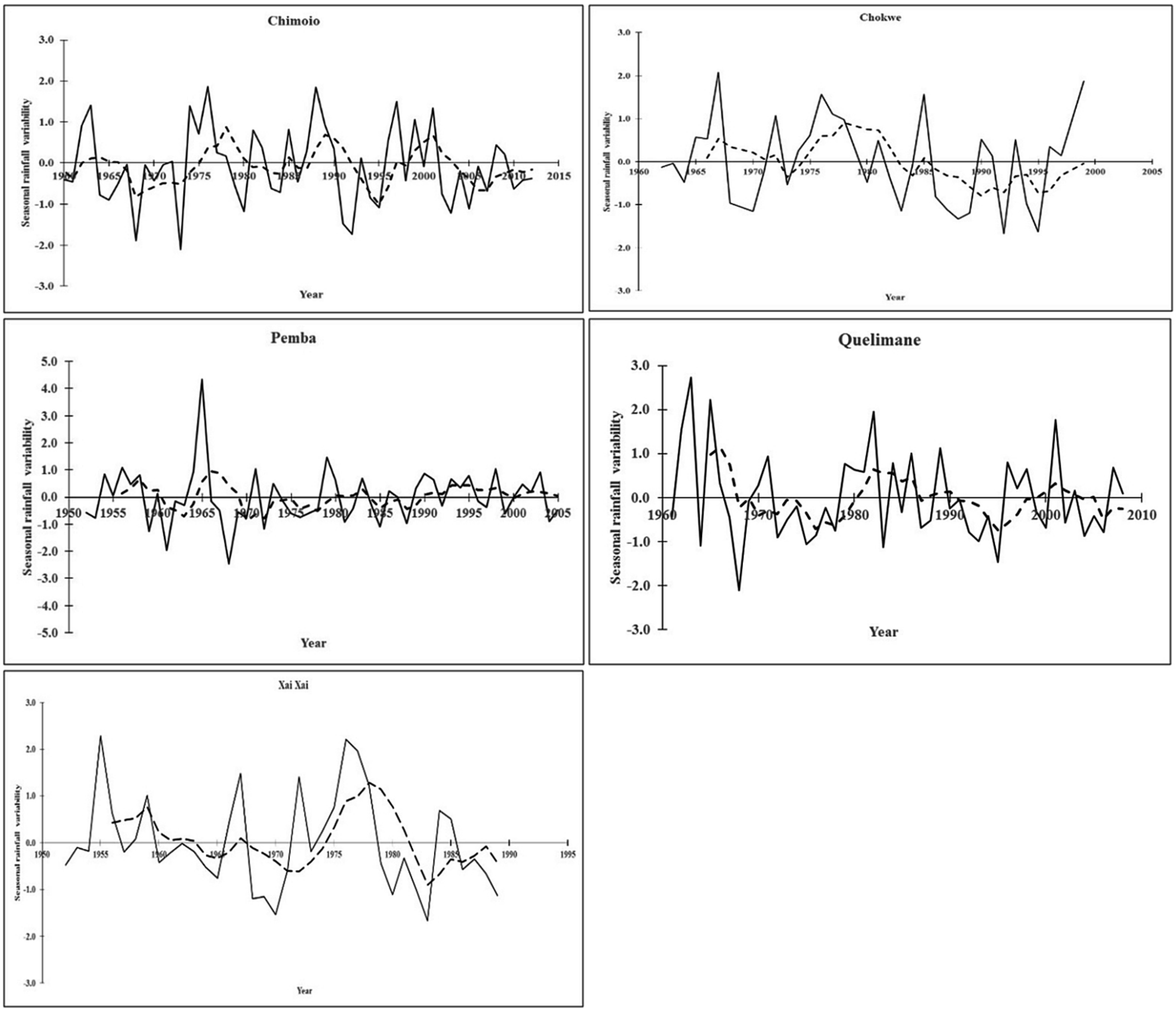

Figure 4. Seasonal rainfall variation at different locations in Mozambique. Dotted line represents 5-year moving average.

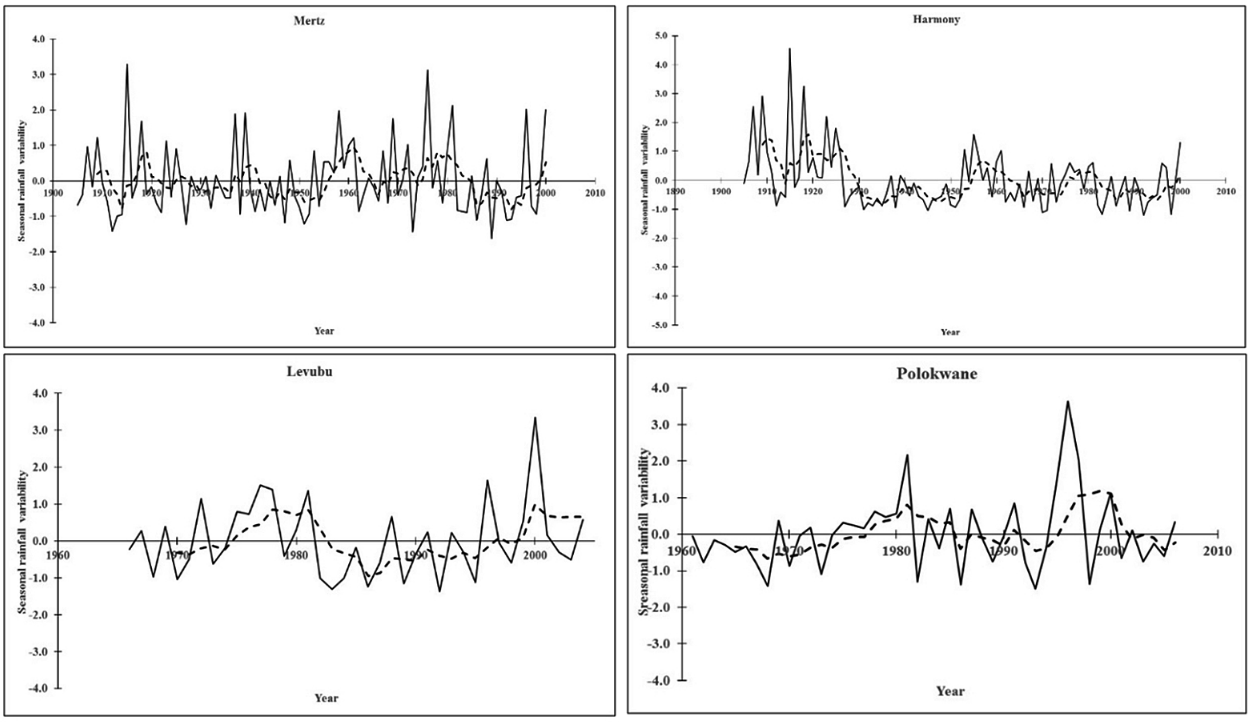

Figure 5. Seasonal rainfall variation at different locations in South Africa. Dotted line represents 5-year moving average.

DISCUSSION

Frequency and trends of different daily rainfall amounts

Daily rainfall was dominated by <5 mm events under semi-arid and sub-humid conditions of the selected locations of southern Africa. These rainfall quantities have a negligible effect on recharging soil moisture in soil types of southern Africa. Previous studies have shown that 20–25 and 30–50 mm of rainfall are required to fully charge the top 30 cm of sandy and clay soils, respectively (Twomlow 1994; Twomlow and Bruneau, 2000). Most of the rainwater from such light showers can be lost through evaporation because of the high atmospheric evaporative demand (Barron, 2004). Some semi-arid areas experience 5–8 mm·day^{-1} evaporative water losses (Woltering, 2005) and less than 5 mm·day^{-1} showers are therefore insignificant for crop production. Under sub-humid conditions of southern Africa, atmospheric evaporative demand can reach 5 mm·day^{-1} during summer months (Trambauer et al. 2014), thereby making the light showers insignificant for cropping under such conditions.

Decreasing trajectories of 5–10 and, 11–20 mm·day^{-1} were detected at some locations in southern Africa. Rainfall amounts of 5–10 and, 11–20 mm·day^{-1} can have significant influence on crop growth, depending on soil and crop type, atmospheric evaporative demand and water management practices implemented in the cropping systems. When these rainfall amounts are received for 2 or 3 days, the soil profiles can be recharged with moisture, thereby facilitating crop growth. With the current trend of poor seasonal rainfall distribution and frequent in-crop dry spells (Ngetich et al., 2014), it is critical to capture this rainwater in order to prolong soil moisture availability in cropping systems. There were no linear trends in >40 mm·day^{-1} at most of the selected locations. It is critical that rainwater from the few 40 mm·day^{-1} events be conserved through in-situ water capture practices (Mupangwa et al., 2007) or ex-situ storage for later use as supplementary irrigation (Rockström et al., 2003).

Despite the increased moisture stress associated with low rainfall of less than 5 mm·day^{-1}, such amounts have sustained crop production across the region, though the yield gap is high. Farmers have adapted to this through use of alternate cropping systems such as intercrops as well as shifting planting time. There is, however, still greater value from low rainfall events compared to the high rainfall events. Most farmers do not use in-situ moisture conservation; hence such amounts would not be very useful to the farmer given the fact that they occur at low frequencies. In addition, heavy rains are associated with challenges such as nutrient leaching, which increases fertilizer costs and ultimately reduces productivity (Geneti et al., 2019).

Trends of monthly and seasonal rainfall

Linear trends in monthly and seasonal rainfall varied with location, as some increasing and decreasing rainfall trajectories were indicated in the analyses conducted. This result is consistent with previous findings from studies conducted in southern Africa (Bellpart et al., 2015; Muthoni et al., 2019). Mitigation and adaptive measures to climate variability need to be informed by these local trends as blanket recommendations will not be effective. Significant seasonal rainfall increase occurred at semi-arid Matopos station, and this is consistent with results from Muthoni et al. (2019), which revealed a 3–15 mm·year^{-1} increase in rainfall at some locations in south-western Zambia. Future rainfall projections have also indicated increases in rainfall in some parts of SSA (Shongwe et al., 2011).

Decreasing rainfall trends in some parts of southern Africa have been reported previously (Mason, 2001; Shi et al., 2007; Bellpart et al., 2015). These decreases in rainfall have been attributed to the influence of El Niño and shifts in atmospheric circulation processes (Nicholson et al., 2014; Gaughan et al., 2016). Smallholder farmers in parts of the region have generally observed declining rainfall over the years and acknowledge the importance of increasing adaptive measures in their farming systems (Zuma-Netshiukwi et al., 2013; Mkuhlani et al., 2019). Significant rainfall decrease (up to 3.3 mm·year^{-1}) in February rainfall occurred at a few of the locations. Differences in atmospheric drivers of rainfall patterns exist over short distances in southern Africa (Hachigonta and Reason, 2006; Manatsa and Matarira, 2009), and this could explain the variability between locations within the same agro-ecology. Additionally, Nicholson et al. (2014) reported that most of the inter-annual rainfall variability is generated during the March–April period of the growing season. The second half of the peak rainfall period is therefore at risk in southern Africa and cropping systems will continue experiencing soil moisture deficits at critical crop growth stages. The major food security cereals in southern Africa are sensitive to soil moisture deficits at reproductive growth stage which often occurs around December to February (Zaman-Allah, 2016), and this leads to significant yield reduction. Smallholder farming families would therefore be exposed to food deficits which are already prevalent in some parts of the region (FAO and ECA, 2018). Another related study, analysing optimum planting dates at Chitala and Chitedze in Malawi, confirmed a significant delay ($P < 0.05$) of 0.28 and 0.39 days·yr^{-1} in optimum planting dates at Chitala and Chitedze in Malawi, respectively, within the last 30 years, thereby making the length of the growing season increasingly shorter at these locations (Nyagumbo et al., 2017). Such changes in rainfall patterns over time corroborate findings from this study that the southern Africa region increasingly faces more difficult weather patterns for rainfed crop production.

Linear trends in monthly rainfall were location specific, a result that has been reported elsewhere in the region and for other SSA countries (Gummadi et al., 2017; Muthoni et al., 2019). Local factors such as topography or the presence of an inland water body can have a significant influence on spatial and temporal rainfall patterns (Goenster et al., 2015; Muthoni et al., 2019). The proximity of Chitala to Lake Malawi influenced the rainfall pattern and the location had greater chances of getting more rainfall than Chitedze and Dedza, which are located further inland in a relatively wetter agro-ecology. Muthoni et al. (2019) also reported the effects of local physical features such as mountains on spatio-temporal rainfall patterns in Tanzania. Adaptation strategies on smallholder farms in such areas with natural drivers of local rainfall patterns need to be tailor-made accordingly and cannot be generalized for the region.

Seasonal rainfall variability

The rainfall variability index (WMO, 1975) indicated the occurrence of drought conditions at the selected locations under different agro-ecological conditions. Droughts of varying degrees of severity occurred in 50% or more of the time periods considered in this study. Such drought frequency has been reported and is now a common phenomenon in southern Africa (Cooper et al., 2008; Nicholson et al., 2014; Bellprat et al., 2015). A drought frequency of every 3 to 4 years has been reported in some parts of southern Africa (World Bank, 2017). With such high frequencies, drought mitigation measures adapted to different biophysical and socio-economic smallholder farmer circumstances ought to be implemented to buffer cropping systems. Various adaptation and mitigation options have been developed and tested for smallholder conditions, and these include crop diversification (Twomlow et al., 2006), adapted crop types and varieties (Setimela et al., 2018), improving soil fertility (Zougmore et al., 2014), conservation agriculture–based practices (Thierfelder et al., 2017; Steward et al., 2018), and in-situ or ex-situ rainwater harvesting (Motsi et al., 2004; Mupangwa et al., 2007). Traditionally, droughts have been more severe in semi-arid areas (Graef and Haigis, 2001) and this is consistent with results from the low rainfall agro-ecologies of the current study, particularly Beitbridge in southern Zimbabwe. The importance of designing and implementing drought mitigation strategies cannot be over-emphasized in order to buffer rainfed farming systems. Climate-smart crop and livestock production practices are core for semi-arid areas and some adapted options are available for southern Africa (Chakoma et al., 2016; Thierfelder et al., 2017; Setimela et al., 2018).

Chitala location illustrated the influence of existing water bodies on local rainfall patterns in some parts of southern Africa. Despite this localized influence on rainfall, the threat of severe droughts was evident at Chitala and this highlights the importance of developing adaptation and mitigation interventions suited to local climatic conditions. All locations experienced incidences of either wet seasons followed immediately by mild to strong drought or the reverse trend. This has been occurring in southern Africa and is one of the major causes of chronic food shortages (Bell et al., 2003). Generally, the frequency of dry years increased between 1980 and 2007 compared to past years of 1950–1975 (Gaughan et al., 2016). This shift in southern Africa rainfall patterns and other climatic forcings has been reported previously (Manatsa and Behera, 2013; Nicholson et al., 2014; Bellprat et al., 2015), and emphasizes the need for climate-smart agricultural practices to buffer smallholder farming systems. The inter-seasonal rainfall variability has made planning and decision making on selection of crop species and cropping systems, and investments in agricultural inputs, difficult on smallholder farms.

CONCLUSION

Rainfall in southern Africa was dominated by <5 mm·day^{-1} events in both semi-arid and sub-humid agro-ecological conditions. The frequency of 5–10 and 11–20 mm·day^{-1} varied with location, even where a large water body influenced the rainfall pattern. There were no apparent linear trends in monthly and seasonal rainfall at 15 of the 18 selected locations from southern Africa. Where trends were significant, a decreasing trajectory in February rainfall was detected at two locations. Increasing March and seasonal rainfall trajectories were apparent at a semi-arid location in south-western Zimbabwe. Moderate and strong drought conditions were detected, and these also varied with location. Drought frequency was higher than 50%, and a location close to a large water body also experienced strong drought conditions during the November–March growing season. All locations experienced incidences of a wet season followed immediately by very dry conditions, or vice versa, regardless of agro-ecological conditions.

Results of this study emphasize the need for policy to take due consideration of the prevailing climatic patterns in programming appropriate climate-smart adaptation measures that can help farmers to cope with the increasing frequency of droughts and ineffective rainfall events that make rainfed cropping riskier to farmers than it has been in the past 3 to 4 decades. It is also clear that policy makers need to invest more in reliable weather monitoring instruments so as to provide a higher density of measured weather patterns that help in informing the need for appropriate technological investments to cope with emerging weather patterns.

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APPENDIX

Table A1. Locations and years considered for different meteorological stations used in the rainfall analyses

Country	Station	Years	Latitude	Longitude	Altitude (m)
Zimbabwe	Harare	1963–2001	−17.72	31.02	1 475
	Marondera	1952–2000	−18.93	31.54	1 658
	Bulawayo	1931–2001	−20.16	28.61	1 356
	Matopos	1940–2015	−20.51	28.44	1 347
	West Nich.	1963–2001	−21.06	29.36	864
	Beitbridge	1952–2001	−22.21	29.99	462
Malawi	Chitala	1948–1999	−13.68	34.25	606
	Chitedze	1981–2013	−13.98	33.64	1 100
	Dedza	1959–1999	−14.32	34.25	1 632
Mozambique	Chimoio	1952–2012	−19.25	33.43	693
	Chokwe	1962–1999	−24.53	32.98	33
	Pemba	1952–2005	−12.59	40.52	70
	Quelimane	1961–2008	−17.86	36.87	5
	Xai Xai	1952–1989	−25.09	33.53	2
South Africa	Harmony	1905–2000	−23.08	29.85	517
	Levubu	1966–2004	−23.08	30.28	706
	Mertz	1905–2000	−26.50	28.36	1 521
	Polokwane	1961–2006	−23.73	29.59	1 194