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Fluctuation of rainfall time series in Malawi: An analysis of selected areas

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Inter annual fluctuation of rainfall in Malawi was studied using a 31 year time series from selected rain gauge stations with the aim of analyzing the spatial and temporal characteristics of rainfall in Malawi. The study found strong inter-annual fluctuation of rainfall, with topography and location playing major roles in the annual rainfall distribution. The seasonal index and precipitation concentration index showed that rainfall is highly seasonal and highly concentrated with most stations receiving rainfall in three months, except for Nkhatabay which has seasonal rainfall. The intra annual rainfall distribution was highly variable in time and space. Cross correlations among the stations suggested two distinct zones, zone 1 composed of Karonga and Nkhatabay and zone 2 composed of Bolero, Kasungu, Salima, Dedza, Mangochi, Makoka and Ngabu. Spectral analysis of the rainfall time series revealed cycles at five to eight years, suggesting links with the El Niño Southern Oscillation and double the period of the Quasi Biennial Oscillation. Apart from the common cycles, the rainfall time series of the two zones showed periods of 13.64 and 10.06 years, respectively, which suggests links with the solar cycle. These cycles are consistent with those found in other southern Africa countries.

Keywords: bimodal rainfall, inter annual fluctuation, seasonal index, precipitation concentration index, spectral analysis

1. Introduction

An aspect of climate change that requires thorough investigation is the time distribution of rainfall and its historical changes. Rainfall is an important climatic variable that underlies both droughts and floods (Coscarelli and Caloiero, 2012). An understanding of the temporal and spatial characteristics of rainfall is central to water resources planning and management, agricultural planning, flood frequency analysis, flood hazard mapping, hydrological modeling, water resource assessments, climate change impacts and other environmental assessments (Michaelides et al., 2009).

Many studies of the temporal and spatial characteristics of rainfall have been conducted around the world (De Luís et al., 2000; González-Hildago et al., 2001; Cannarozzo et al., 2006; Zhang et al., 2008; Chu et al., 2010). Ould Cherif Ahmed et al. (2008) showed decreasing tendency of rainfall in western Africa. Fauchereau et al. (2003) reported significant variations of precipitation in southern Africa, especially in recent decades. In particular, droughts have become more intense and widespread. New et al. (2006) reported a decrease in average precipitation intensity and an increase in dry-spell length from 1961 to 2000. In addition, the Intergovernmental Panel on Climate Change reported a trend of increasing precipitation amount from 1901 to 2005 from the equator to tropical eastern Africa and a declining trend in Africa south of 20º S latitude. The panel also found that dry periods in southern Africa have become longer and more intense (Solomon et al., 2007). If these phenomena are occurring as suggested, then the precipitation amount and intensity in the wet season may have increasing trends (Morishima and Akasaka, 2010). These works suggest that rigorous studies should be carried out at global, national and local scales using different methodologies (Ngongondo et al., 2011).

Malawi has an economy based on rain-fed agriculture in which crop production and the choice of crops that can be grown are largely determined by climatic and soil factors. Therefore, a detailed knowledge of the precipitation regime in Malawi is an important prerequisite for agricultural planning and economic development (Ngongondo et al., 2011).

Studies of the characteristics of rainfall in Malawi include those by Jury and Mwafulirwa (2002), Jury and Gwazantini (2002), and Mbano et al. (2008). A positive correlation between rainfall in Malawi and Ethiopia was reported by Nkhokwe (1996) who found associations between the Southern Oscillation Index (SOI) and stratospheric Quasi-Biennial Oscillation (QBO), a change in the zonal wind in the equatorial stratosphere from easterly to westerly with a period of about 28 months (Naujokat, 1986).

This paper presents an analysis of the fluctuations in space and time of rainfall time series from nine stations in Malawi over a 31 year period.

2. Materials and methods

2.1. Location and climate

Malawi extends across latitudes 9° to 15° S in eastern southern Africa. The country's topography is highly variable, dominated by the Great Rift Valley including Lake Malawi. Malawi has a sub-tropical climate, which is relatively dry and strongly seasonal. Annual average rainfall varies from 725 to 2,500 mm. Wet season rainfalls depend on the position of the Intertropical Convergence

Zone (ITCZ), which can vary in its timing and intensity from year to year (McSweeney et al., 2012). The other main rain-bearing system for Malawi is the northwest monsoon, comprised of recurved tropical Atlantic air that reaches Malawi through the Congo basin. There are times when the country is affected by tropical cyclones from the West Indian Ocean. Depending on their position, cyclones may result in either dry or wet spells over Malawi. Easterly waves originating near Madagascar often penetrate up the Zambezi Valley during summer. Extra-tropical westerly waves are thought to be most active at the beginning and end of the rainy season (Jury and Mwafulirwa, 2002). A cool, dry winter season is evident from May to August and a hot, dry season lasts from September to October with average temperatures varying between 25 and 37 degrees Celsius. Humidity ranges from 50% to 87% for the dry (September/October) and wetter (January/February) months respectively.

2.2. Data and sources

Monthly rainfall data for the period 1981 to 2011 of nine rainfall stations in Malawi obtained from the Department of Climate Change and Meteorological Services were used in the study. The stations used in the study were Karonga, Nkhatabay Salima and Mangochi along the shores of Lake Malawi (Fig. 1.) Bo-

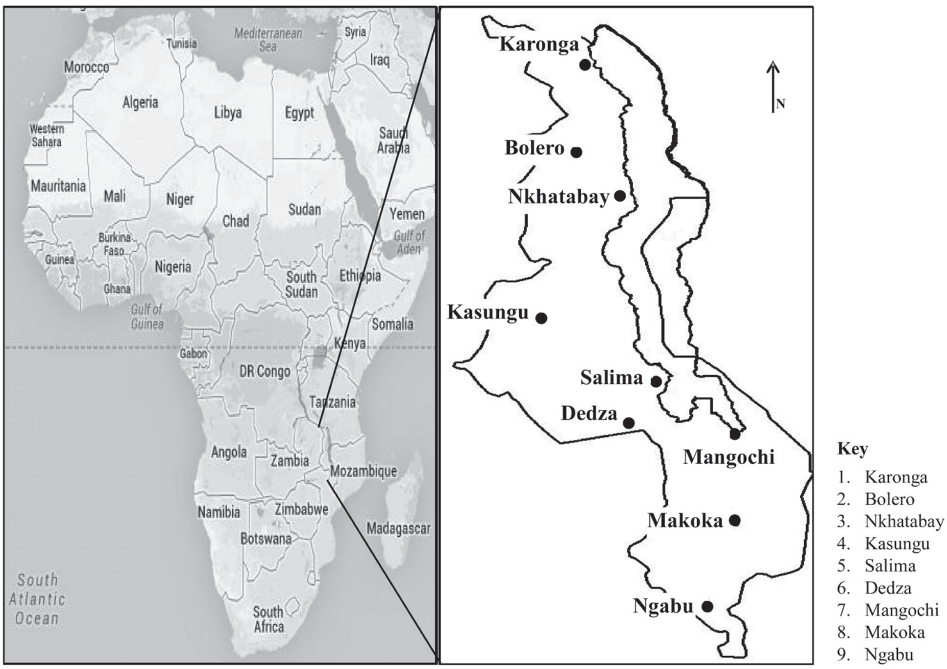

Figure 1. Map of Africa *(left)* showing the location of Malawi and map of Malawi showing study locations and some geographic features.

lero in the northern highlands; Kasungu in the central plains; Dedza in the central highlands near Lake Malawi and Ngabu located in Lower Shire River valley which has a high risk of flooding most of the time. Annual rainfall distributions for selected stations are shown in Fig. 1.

The monthly data were screened to make sure they were consistent, homogenous and stationary. Spearman rank correlation was used to test for the absence of trends; F test for stability of variance was used to test for stability of variance and mean and serial correlation coefficient was used to test for absence of persistence (Dahmen and Hall, 1990).

Mean monthly and annual values were calculated with the corresponding coefficient of variation.

2.3. Rainfall seasonality

To assess the aspect of rainfall seasonality, the Seasonal Index (*SI*) designed by Walsh and Lawler (1981) was used in this study as given by:

$$SI = \frac{1}{R} \sum_{n=1}^{12} \left| X_n - \frac{R}{12} \right| \tag{1}$$

where X_n is rainfall of month n and R is annual rainfall.

SI permits quantification of the variability of rainfall through the year, but should be complemented by a detailed analysis of monthly rainfall (Sumner et al., 2001). For this reason, we calculated the mean monthly rainfall and coefficient of variation (*CV*) for each station. The index varies from zero, if all the months have equal rainfall, to 1.83 if all the rainfall occurs in a single month. The detailed descriptions of the seasonality index are given as equal rainfall ($SI < 0.19$); equal rainfall but with definite wet season ($0.20 < SI < 0.39$); seasonal with short dry season ($0.40 < SI < 0.59$); seasonal ($0.60 < SI < 0.79$); markedly seasonal with long dry season ($0.80 < SI < 0.99$); most rain in 3 months or less ($1.00 < SI < 1.19$); and extreme seasonality with almost all rain in 1 to 2 months ($SI \geq 1.20$).

2.4. Precipitation concentration

The seasonality of rainfall regime and heterogeneity of rainfall amounts was evaluated by using the Precipitation Concentration Index (*PCI*) as described by Oliver (1980):

$$PCI = \frac{\left(\sum_{i=1}^{12} P_i^{\,2} \right)}{\left(\sum_{i=1}^{12} P_i \right)^2} \times 100 \tag{2}$$

where P_i is the rainfall amount of the month i.

Precipitation Concentration Index (*PCI*) defines the temporal aspect of rainfall distribution. It was derived by Oliver (1980) from the Index of Employment Diversification (Gibbs and Martin, 1962). *PCI* is described as uniform (*PCI* = 8.3–10), moderately seasonal (*PCI* = 10–15), seasonal (*PCI* = 15–20), highly seasonal (*PCI* = 20–50) and irregular (*PCI* = 50–100).

Elagib (2011) used *SI* and *PCI* in his study of Changing rainfall seasonality and erosivity in the hyper-arid zone of Sudan.

2.5. Spectrum analysis and Fourier fit

To evaluate the periodicity of the rainfall time series, spectral analysis was used. Spectral analysis is applied to the annual time series of rainfall. While the classical way of spectrum analysis is the Fourier transfer, the Maximum Entropy Method (MEM) which presents higher resolution of power spectrum distribution and avoids aliasing was used in this study. The MEMSI is based on the principle of entropy maximization. To extract peaks of frequencies, a Fortran code program was composed and used. We incorporated a computer subroutine by Press et al. (1992) to the code program. Obtained frequencies were applied to the Fourier series to fit to the original rainfall time series:

$$r(t) = a_0 + \sum_{i=1}^{n} \left[a_i \cos 2\pi f_i t + b_i \sin 2\pi f_i t \right] \tag{3}$$

where: a_i, b_i – the Fourier coefficients of term i, f_i – frequency of term i, t – time, n –number of terms.

On the way of the fitting process, combinations of obtained frequencies were optimized by the Akaike Information Criterion (*AIC*) given by

$$AIC = m \cdot \ln(\sigma) + 2n \tag{4}$$

where: σ – fitting error variation, m – number of rain data, n – number of coefficients of the Fourier series.

AIC has been used for model optimization (e.g., Lee and Ouarda, 2011). The minimum value of the *AIC* presents the optimal model. *AIC* deals with the tradeoff between the goodness of fit of the model and complexity of the model. The *AIC* of all combinations of frequencies was calculated for the optimization.

3. Results and discussion

3.1. Annual rainfall time series

The mean annual rainfall for all the stations is given in Tab. 1. Nkhatabay had the highest mean annual rainfall of 1570 mm and a *CV* of 0.21. Nkhatabay is located along the lake shore, which lies in the Rift valley and on the windward side of Viphya plateau such that it receives both convectional and topographic rainfall. Bolero, in the rain shadow area of Nyika plateau, had the lowest annual rainfall of 626 mm and a *CV* of 0.22. Six stations had mean annual rainfall between 600 to 1000 mm and three stations had mean annual rainfall greater than 1000 mm: Makoka (1003 mm), Salima (1207 mm), and Nkhatabay (1570 mm). Salima and Nkhatabay are located along the lake shore plains near the rift valley escarpment, giving them a tropical type of climate which favors rainfall. Makoka is in the Shire highlands within the Lake Chilwa basin.

Table 1. Mean annual rainfall and coefficient of variation (CV).

Station	Karonga	Bolero	Nkhatabay	Kasungu	Salima	Dedza	Mangochi	Makoka	Ngabu
Rainfall (mm)	942	626	1570	784	1207	947	805	1003	826
CV	0.23	0.22	0.21	0.22	0.26	0.16	0.31	0.21	0.29

3.2. Mean monthly rainfall

The mean monthly rainfall and *CV* for all stations were calculated as shown in Fig. 2. January had the highest mean monthly rainfall for seven stations with a mean value of 225 mm and *CV* of 0.4, at Karonga and Nkhatabay the highest mean monthly rainfall was recorded in March with a value of 280 mm and *CV* of 0.57. The lowest mean monthly rainfall for all stations was in September with a mean value of 2.2 mm and *CV* of 2.8. The most significant result of this analysis was that rainfall was mainly concentrated between November and April for all stations with a peak in January except for two stations, Nkhatabay and Karonga which had bimodal rainfall patterns with peaks in January and March. For Nkhatabay, the mean rainfall was 211 mm for January and 320 mm for March and for Karonga, mean rainfall was 176 mm for January and 240 mm for March.

The climate of Malawi depends on the ITCZ, the subtropical high pressure belt in the south between latitudes 25° and 35° S, and its topography (Torrance, 1972). The ITCZ enters the country from the north during its southwards movement to its southern limit in February and then moves back to the north. The other main rain bearing system for Malawi during the rainy season is the Congo Air Boundary, which marks the confluence between the Indian Ocean southeast trades and recurved South Atlantic air that reaches Malawi as north westerly air mass through the Democratic Republic of Congo. This system brings well-distributed rainfall over the country and floods may occur in some areas especially in association with ITCZ (Jury and Mwafulirwa, 2002). These two rainfall systems account for the bimodal pattern of monthly rainfall in Karonga and Nkhatabay. Most equatorial countries in east Africa (e.g., Kenya, Tanzania and Uganda) experience a bimodal seasonal distribution of rainfall, the rains from October to December being called short rains and those from March to May being called long rains (Nicholson, 1996).

3.3. Rainfall seasonality

The results of the seasonality analysis show that Nkhatabay with an annual *SI* of 0.74 was the only station with rainfall classified as seasonal (Tab. 2). Monthly rainfall at Nkhatabay (Fig. 2) which receives both convectional and topographical rainfall and has a long rainfall season is more evenly distributed than at other stations. The dry season is short, from August to October, and there is significant rainfall from May to July, when rain is rare at other stations. Topographical rains occur due to southeasterly winds particularly during cool dry months (May–July) and transitional periods. Ngabu, with an annual *SI* of 0.87, has a markedly seasonal rainfall pattern with a long dry season.

Table 2. Seasonal index (SI) of rainfall stations.

Station	Karonga	Bolero	Nkhatabay	Kasungu	Salima	Dedza	Mangochi	Makoka	Ngabu
Annual *SI*	1.03	1.08	0.74	1.13	1.15	1.06	1.04	1.03	0.87
Description	Most rain in 3 months or less		Seasonal	Most rain in 3 months or less					Markedly seasonal

Table 3. Precipitation concentration index (PCI) of rainfall stations.

Station	Karonga	Bolero	Nkhatabay	Kasungu	Salima	Dedza	Mangochi	Makoka	Ngabu
PCI	18	21	14	21	21	20	19	19	17
Description	Seasonal	Highly seasonal	Moderately seasonal	Highly seasonal		Seasonal			
Temporal *PCI*	23	24	18	25	27	23	24	23	21
Description	Highly seasonal		Seasonal	Highly seasonal					

Ngabus location at the end of the Rift valley escarpment in the rain shadow area of the lower Shire valley accounts for the long dry season. The rest of the

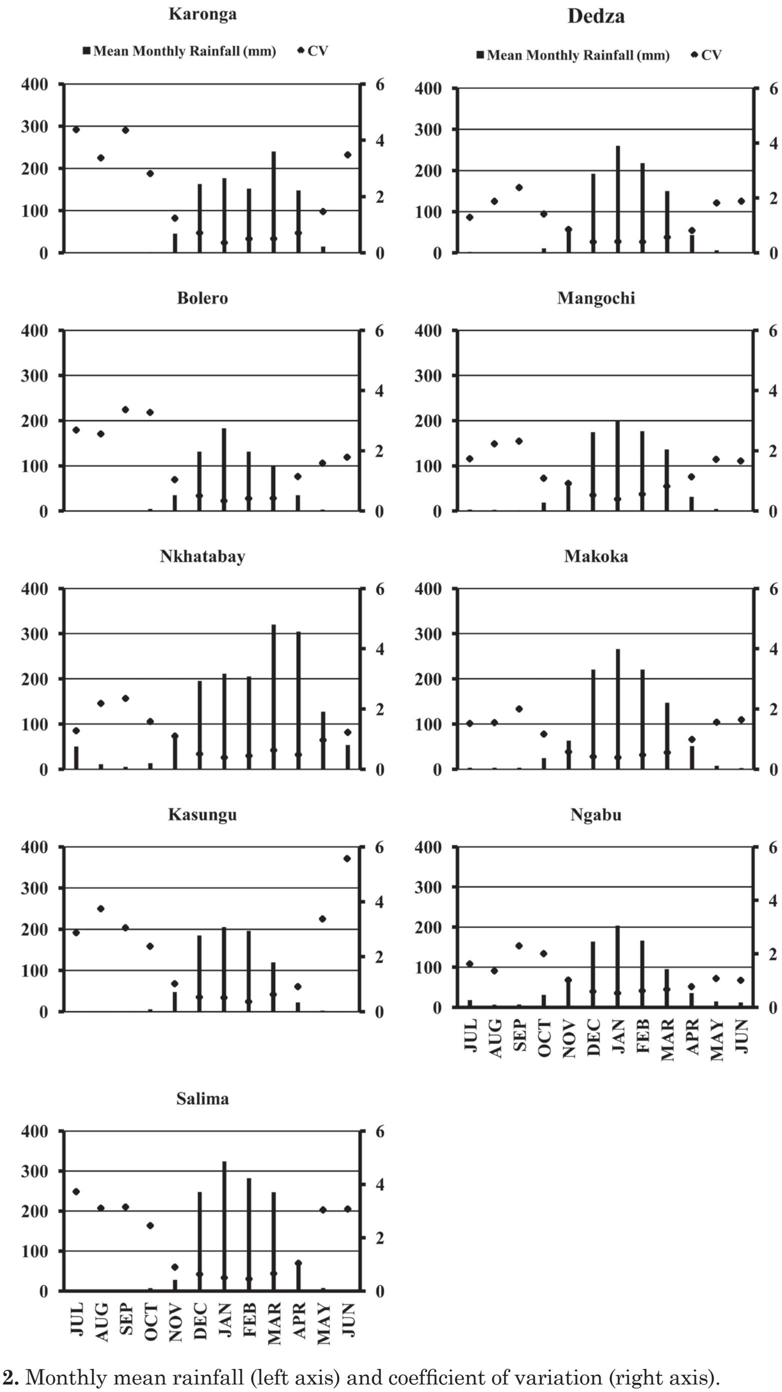

Figure 2. Monthly mean rainfall (left axis) and coefficient of variation (right axis).

stations had *SI* values ranging from 1.03 to 1.15 classifying them as receiving most rain in three months or less.

PCI of the rainfall stations varied from 14 to 21 (Tab. 3). Only Nkhatabay, with a *PCI* value of 14, had moderately seasonal rainfall concentration. Ngabu, Makoka, Mangochi and Karonga, with *PCI* values of 17 to 19, had seasonal rainfall concentration. The other four stations had *PCI* values greater than 20, or highly seasonal rainfall concentration.

The *PCI* was calculated from mean monthly rainfall data averaged over 31 years. The temporal *PCI* is calculated from the rainfall data of individual years averaged over 31 years. On this metric, Nkhatabay station had a seasonal rainfall concentration while the rest of the stations with temporal *PCI* values ranging from 21 to 27 had a highly seasonal rainfall concentration.

The results for *SI* and *PCI* both indicate that rainfall time series at all stations have pronounced seasonality. Nkhatabay showed notably less seasonality than the other stations.

3.4. Zoning of the stations

November to April rainfall was extracted from the rainfall time series of the nine stations and cross correlations among the stations were calculated as shown in Tab. 4. The stations were classified in one of two zones on the basis of the strength of the correlations. Jury and Mwafulirwa (2002) used the same approach in their analysis of climate variability in Malawi.

Table 4. Cross correlation of rainy season rainfall among the rainfall stations.

	Karonga	Bolero	Nkhatabay	Kasungu	Salima	Dedza	Mangochi	Makoka	Ngabu
Karonga	1.000								
Bolero	0.358	1.000							
Nkhatabay	0.535	0.220	1.000						
Kasungu	0.197	0.652	0.122	1.000					
Salima	0.403	0.531	0.270	0.634	1.000				
Dedza	0.290	0.613	0.137	0.675	0.728	1.000			
Mangochi	0.209	0.596	0.081	0.614	0.664	0.686	1.000		
Makoka	0.192	0.511	0.085	0.542	0.624	0.670	0.675	1.000	
Ngabu	0.153	0.491	0.071	0.558	0.535	0.588	0.616	0.630	1.000

*r = 0.36 at 0.05 level of significance and **r = 0.47 at 0.01 level of significance

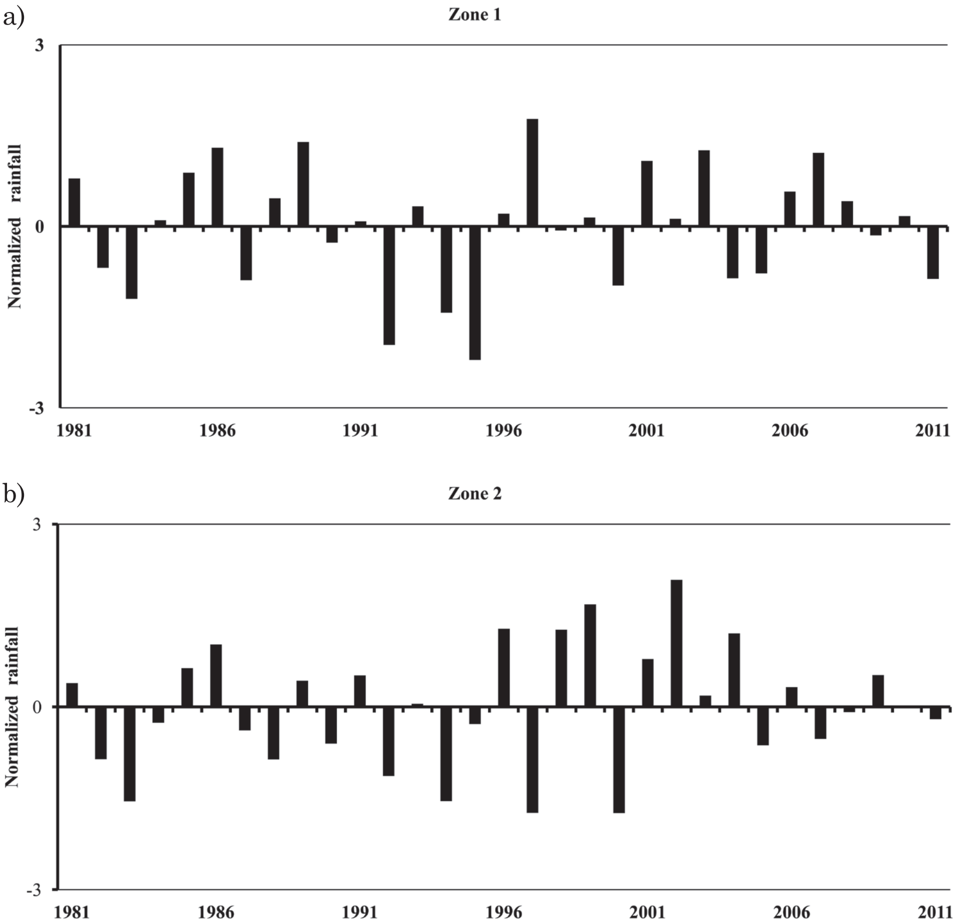

Figure 3. Normalized annual rainfall of (*a*) Zone 1 and (*b*) Zone 2.

Karonga and Nkhatabay had low correlation with the other stations. Nkhatabay had very low correlations ($r < 0.1$) with stations in the south (Mangochi, Makoka and Ngabu). The correlation between Karonga and Nkhatabay was 0.535. Monthly average rainfall of Karonga and Nkhatabay showed a bimodal distribution suggesting that these stations experienced different meteorological mechanisms from the rest of the stations. These two stations were grouped into zone one. The other seven stations showed high correlations ($r > 0.47$ significant at 0.01 level) and were grouped into zone two. Normalized (standardized) values of rainfall for the rainy season of each zone were calculated. Figures 3a and 3b show the normalized rainfall of the two zones over the study period.

Figures 3a and 3b show that the annual rainfall has a tendency for years with high rainfall to be followed by years with low rainfall.

Zone 1 had the least annual rainfall between 1992 and 1995 and Zone 2 had the least rainfall in the years 1983, 1994, 1997 and 2000. Malawi experienced drought during these years which adversely affected crop production.

3.5. Spectrum analysis and Fourier fit

Spectral analysis was carried out on the rainfall time series to determine the periods and frequencies at which climatic events like drought and floods are likely to occur at the stations

The maximum entropy spectrum (Fig. 4a) for Zone 1 rainfall shows strong peak between 0 and 0.15 and between 0.25 and 0.40 with smaller peaks at higher frequencies

The maximum entropy spectrum (Fig. 4b) for Zone 2 rainfall shows strong peak between 0 and 0.40 with smaller peaks at higher frequencies in between.

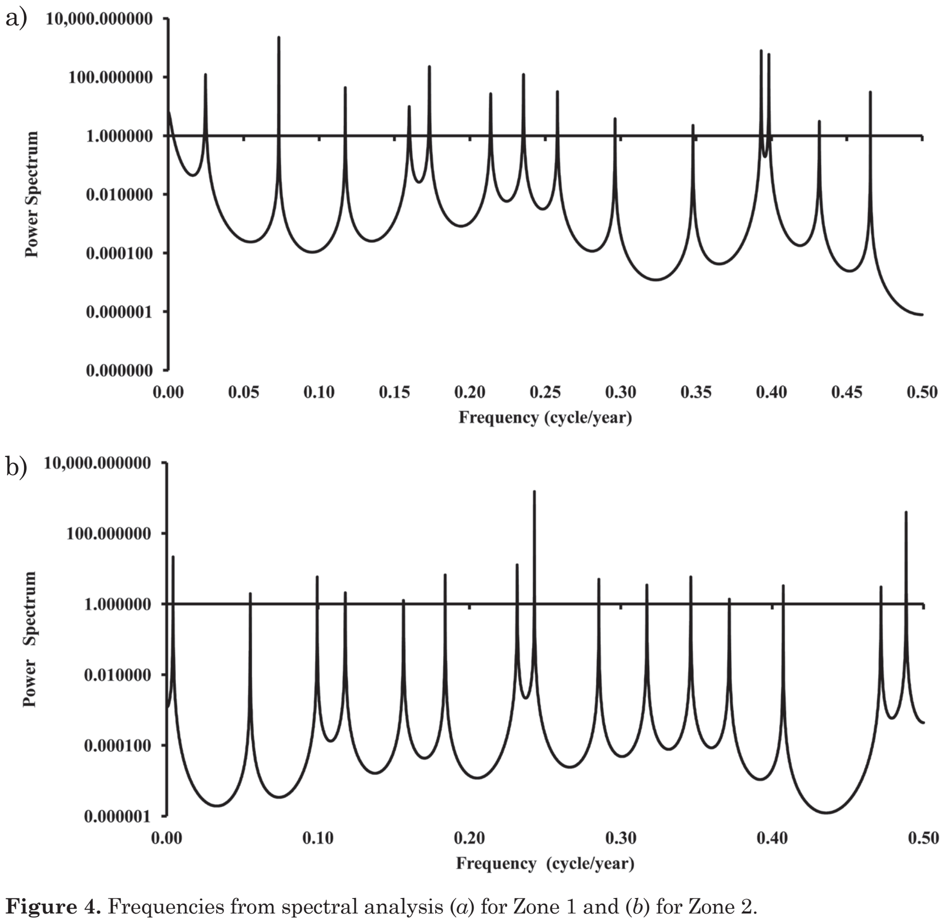

Figure 4. Frequencies from spectral analysis (*a*) for Zone 1 and (*b*) for Zone 2.

Table 5. Detected frequencies (f) and corresponding periods (T) from spectral analysis.

		Detected frequencies and corresponding periods									
Zone 1	*f* (cycle/ year):	0.4656	0.3983	0.3932	0.2581	0.2356	0.2138	0.1732	0.1174	0.0733	0.0247
	T (years):	2.15	2.51	2.54	3.87	4.24	4.68	5.77	8.52	13.64	40.49
Zone 2	*f* (cycle/ year):	0.4885	0.3462	0.2855	0.2429	0.2315	0.1840	0.0994			
	T (years):	2.05	2.89	3.50	4.12	4.32	5.43	10.06			

The detected frequencies from the initial calculation were further scrutinized to choose the optimized combination for the frequencies and periods. The model optimization was performed considering combination of frequencies and fit with observed data. A way of optimization was the *AIC*. The *AIC* was used to optimize

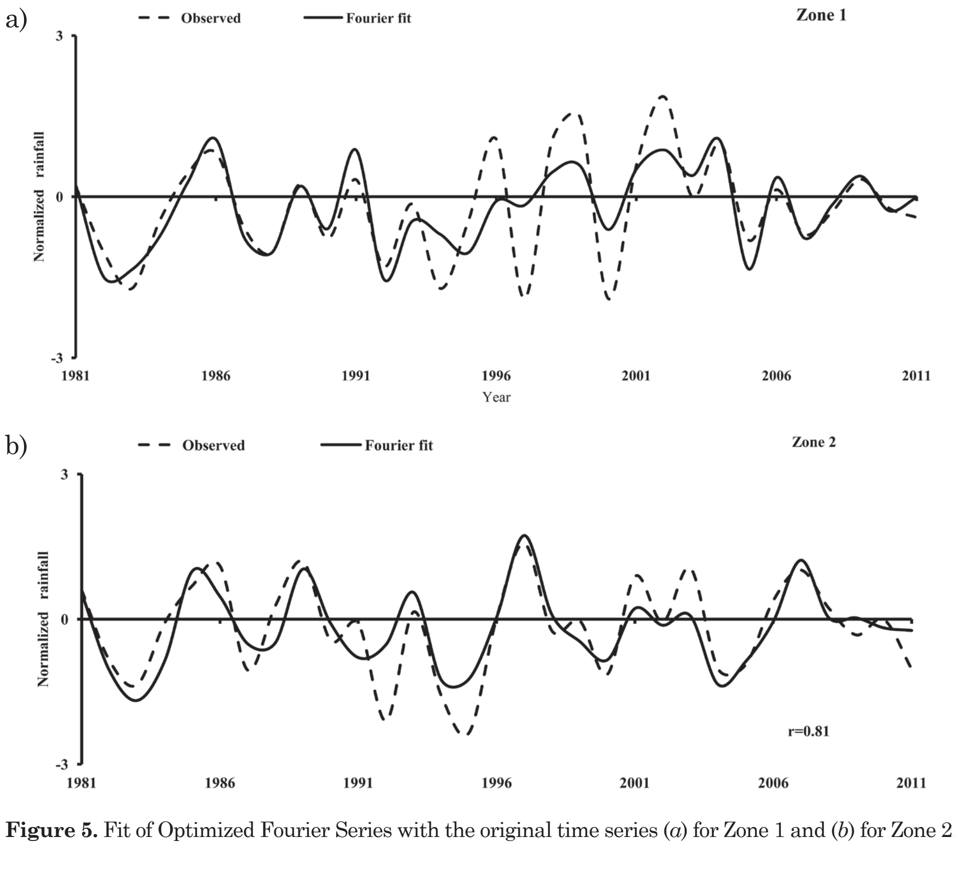

Figure 5. Fit of Optimized Fourier Series with the original time series (*a*) for Zone 1 and (*b*) for Zone 2.

the Fourier fitting with the observed values. Table 5 presents the results of the analysis.

The optimization of the spectral analysis of the rainfall time series revealed cycles between 2.15 and 40.49 years for stations in zone 1 and between 2.05 to 10.06 for stations in zone 2. There were suggested links with ENSO, QBO and solar cycle in both zones. Jury and Mwafulirwa (2002) found similar cycles in their study of climate variability in Malawi whilst Jury and Makarau (1997) also found similar cycles in rainfall records over Zimbabwe and South Africa. Jury and Mpeta (2005) reported 3–8 years as the annual cycle of climate in Africa. Figures 5a and 5b present the results of the Fourier fit. The correlations of the fit were larger than 0.78 for Zone 1 and 0.81 for Zone 2. The optimized Fourier fit follows the general tendency of the original rainfall time series.

Goddard and Graham (1999) evaluated the significance of the ENSO influence by analyzing the correlation amongst stations. The analysis showed there was high significant correlation amongst stations in the south and the correlation became weaker in the north. They suggested that the correlation was weaker in the north because the north lies near the transition zone of ENSO influence with opposing centers of action in southern and eastern Africa.

4. Conclusions

The inter-annual fluctuation of monthly rainfall over a 31 year period was studied for nine locations in Malawi. The analysis of this time series revealed the following points:

There was a high spatial variability of both monthly and annual rainfall. Rainfall was greatest from November to March with peaks in January, except for Karonga and Nkhatabay stations, which had dual peaks in January and March. The rainfall pattern in Malawi suggests that local factors like topography and location have a dominant role in the spatial distribution of rainfall.

On the basis of seasonal indices, *SI* and *PCI*, rainfall time series of all stations except Nkhatabay indicated apparent seasonality (rainfall received in 3 months or less in *SI*, seasonal to highly seasonal rainfall concentration in *PCI*). Only Nkhatabay experienced less seasonality.

Spectrum analysis of the rainfall time series revealed cycles at 2.15 to 40.49 years for zone 1 and 2.05 to 10.06 for zone 2. There were suggested links with the ENSO, QBO and solar cycle. These results are consistent with those found in other southern Africa countries.

All parts of Malawi displayed strong seasonality and interannual fluctuation in rainfall. Given the importance of rainfall to Malawi agriculture, these variations need to be applied to the planning of water resources management.

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SAŽETAK

Promjenljivost vremenskog niza oborine u Malaviju: Analiza odabranih područja

Chisomo Patrick Kumbuyo, Hiroshi Yasuda, Yoshinobu Kitamura i Katsuyuki Shimizu

U radu je promatrana međugodišnja promjenljivost oborine u Malaviju na temelju 31-godišnjeg vremenskog niza s odabranih kišomjernih postaja s ciljem analiziranja prostornih i vremenskih karakteristika oborine u Malaviju. Studija je pokazala jaku međugodišnju promjenljivost oborine, pri čemu topografija i lokacija igraju najveću ulogu u godišnjoj razdiobi oborine. Sezonski indeks (*SI*) i indeks koncentracije oborine (*PCI*) su pokazali da je na većini postaja oborina sezonska i vrlo koncentrirana u razdoblje od tri mjeseca, izuzev Nkhatabaya koji ima sezonsku oborinu. Raspodjela oborine unutar godine bila je jako promjenljiva u vremenu i prostoru. Poprečne korelacije među postajama upućuju na dvije odvojene zone: zonu 1 koju čine postaje Karonga i Nkhatabay te zonu 2 s pripadajućim postajama: Bolero, Kasungu, Salima, Dedza, Mangochi, Makoka i Ngabu. Spektralna analiza vremenskih nizova oborine otkrila je periode od pet do osam godina, nagovješćujući poveznice s El Niño Južnom oscilacijom (ENSO) i dvostrukim periodom kvazibijenalne oscilacije (QBO). Pored općih ciklusa, vremenski nizovi oborine dviju zona pokazali su periode od 13,64 (zona 1) i 10,06 (zona 2) godina, što upućuje na poveznicu sa Sunčevim ciklusom. Ovi periodi su u skladu s periodima utvrđenim za druge južnoafričke zemlje.

Ključne riječi: bimodalni oborinski režim, međugodišnja promjenljivost, sezonski indeks, indeks koncentracije oborine, spektralna analiza

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