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Variability of Extreme Wet Events over Malawi

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Abstract

Adverse effects of extreme wet events are well documented by several studies around the world. These effects are exacerbated in developing countries like Malawi that have insufficient risk reduction strategies and capacity to cope with extreme wet weather. Ardent monitoring of the variability of extreme wet events over Malawi is therefore imperative. The use of the Expert Team on Climate Change Detection and Indices (ETCCDI) has been recommended by many studies as an effective way of quantifying extreme wet events. In this study, ETCCDI indices were used to examine the number of heavy, very heavy, and extremely heavy rainfall days; daily and five-day maximum rainfall; very wet and extremely wet days; annual wet days and simple daily intensity. The Standard Normal Homogeneity Test (SNHT) was employed at 5% significance level before any statistical test was done. Trend analysis was done using the nonparametric Mann-Kendall statistical test. All stations were found to be homogeneous apart from Mimosa. Trend results show high temporal and spatial variability with the only significant results being: increase in daily maximum rainfall (Rx1day) over Karonga and Bvumbwe, increase in five-day maximum rainfall (Rx5day) over Bvumbwe. Mzimba and Chileka recorded a significant decrease in very wet days (R95p) while a significant increase was observed over Thyolo. Chileka was the only station which observed a significant trend (decrease) in extremely wet rainfall (R99p). Mzimba was the only station that reported a significant trend (decrease) in annual wet-day rainfall total (PRCPTOT) and Thyolo was the only station that reported a significant trend (increase) in simple daily intensity (SDII). Furthermore, the findings of this study revealed that, during wet years, Malawi is characterised by an anomalous convergence of strong south-easterly and north-easterly winds. This convergence is the main rain bringing mechanism to Malawi.

Key Words: Extreme wet events, frequency, rainfall intensity, Malawi, Africa

Introduction

In recent years, there is *generally* a consensus on the fact that the climate is changing (Intergovernmental Panel on Climate Change, IPCC 2014) in part due to human influences (Kaser, et al., 2010). Contributing to the IPCC's Fifth Assessment Report, Working Group II (WGII AR5), documents that human-induced climate change expedites and worsens climate variations and change that would otherwise occur naturally (IPCC, 2014; Bouwer, et al., 2011). Evidences of the changing climate have been shown by observations of the atmosphere, land, oceans and cryosphere (IPCC, 2013; Bouwer, et al., 2011). In previous studies, the IPCC has shown that the atmospheric global mean temperatures over land and oceans have increased by 0.85°C over the last hundred years (IPCC, 2001). This temperature change in the long-run affects the global water cycle, altering the inten-

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sity, frequency and amount of precipitation (Sylla, et al., 2012).

Climate change will increase uncertainty and exert adverse effects on water security, agricultural planning, analysis of flood intensity and frequency, climatological and hydrological modelling, mapping of floods and flood risk in developing countries (IPCC, 2012). This is because developing countries have little ability to *'bounce back'* from hostile impacts of climate change. A study published in Nature by Vorosmarty et al. (2010), showed that estimated future impacts of climate change would be worse in some developed regions than developing ones. However, this was reversed when the ability of a country to *'bounce back'* was taken into consideration. In a study of the challenge of feeding a world population of more than eight billion people, Loomis et al. argues that developing countries will be affected more by the impacts of climate change owing to their heavy reliance on weather and climate sensitive sectors such as rain-fed agriculture (Loomis, et al., 1999). This sector is affected by both negative and positive extreme weather events; understanding the variability of extremes is thus, the primary protection against climate change-induced disasters (Westra, et al., 2014). Most Global Circulation Models (GCMs) ensembles' predictions indicate a more wet than dry trend over much of the north-eastern parts of southern Africa including Malawi and a more dry than wet trend over the southern parts of Malawi; most of these simulations agree on the trend direction but not magnitude (Christensen, et al., 2007).

Extreme wet events are common in Malawi (Karl, et al., 2010a). For example, in January 2015, 150 people were feared dead after a heavy downpour of rainfall and 100, 000 more were displaced after the same wet event and many people were reported as having crossed to neighbouring Mozambique to seek refuge (BBC, 2015). In April 2016, low-lying areas of Malawi were again flooded leaving 12 people dead and 9000 displaced in Ngosi, Karonga and Mzuzu. This was after a heavy downpour of 143 mm in 24 hours (Juma, 2017) which is an equivalent of the rainfall amount received in some months. More recently (4th April 2017), flood-prone Karonga was again hit by extreme wet weather leaving 5,520 households adversely affected and about 1075 hectares of crops fields, including rice, maize and cassava, severely damaged (Davies, 2017). Many other studies have shown detailed evidence that the impacts of extremes are exacerbated due to Malawi's over-dependence on rain-fed agriculture just like many other southern African countries such as Zambia (Libanda, et al. 2017). In fact, half of Malawi's gross domestic products (GDP) are directly or indirectly from agriculture (Benin, et al., 2008). Ngongondo et al. described Malawi as an *agro-based economy* with the majority of its agricultural produce being rain-fed (Ngongondo, et al., 2011). In a discussion paper on the economic effects of droughts and floods in Malawi, Karl et al. estimated that Malawi loses US$22 million of its GDP annually due to extreme weather events (Karl, et al., 2010). Thus, the World Bank classifies Malawi and the whole of sub-Saharan Africa as highly vulnerable to climate change (Benson, et al., 1998). A project (ND-GAIN) by the University of Notre Dame which investigates a country's vulnerability to climate change and its readiness to improve resilience ranks Malawi as the thirty ninth most vulnerable country and the twenty-first least ready country (ND-GAIN, 2017).

While understanding changes in mean rainfall climatology is necessary (Libanda, et al., 2015a), this study focuses on extremes due to their detrimental effects on socio-economic activities of Malawi (Karl, et al., 2013b). An understanding of extremes also strengthens the ability to predict them. Studies (e.g. Nicholas, et al., 2017) have also shown that that many professions, *inter alia* water resource engineers, hydrologists, civil and structural engineers are keen to understand projections of extremes because future designs e.g. flood detention facilities, hydroelectricity supply, bridges etc are highly dependent on reliable understanding of extremes. Mokrech, et al. documents that extremes distort the natural balance of ecosystems, structural designs are meant to be able to withstand floods, a good understanding of these extremes offsets uncertainties inherent in socio-economic activities and play a central role in strategizing mitigating approaches (Mokrech, et al., 2014). Therefore, investigating extremes underpins development. The goal of this study was to investigate extreme wet events for the period 1982 – 2012 using ETCCDI Indices. Particularly, the indices were grouped to represent intensity (number of heavy rainfall days, very heavy rainfall days and extremely heavy rainfall days) and frequency (daily maximum rainfall, 5-day maximum rainfall, annual-wet day rainfall total, simple daily intensity index, very wet days and extremely wet days). Extremes considered in this study are with respect to the amount of precipitation over a given area and exceeding a given daily rainfall amount, daily maxima and/or percentile. Detailed definitions of the extreme indices used herein are discussed by (Karl, et al., 1999).

Data and Methodology

Sources of data

The daily rainfall data used in this study is courtesy of the Malawi Department of Climate Change and Meteorological Services (MDCCMS). The data covers a period of thirty years from 1982 – 2012 and is

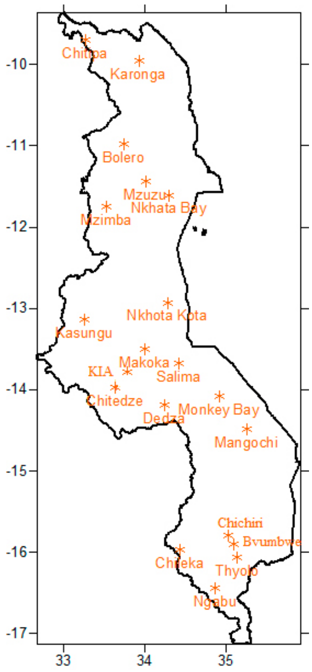

Figure 1. Meteorological Stations used in this study

sourced from 21 Meteorological Stations (i.e. synoptic, agro and aviation meteorological stations) widely spread over the whole country. However, the datasets for Thyolo Meteorological Stations only spans over a period of 27 years from 1982 – 2009 (Table 1). Figure 1 shows the geographical spread of the Meteorological stations used in this study.

Methodology

Extreme rainfall indices

Previous studies have analysed daily extreme rainfall by using indices as proposed by the Expert Team on Climate Change Detection and Indices (ETCCDI), a joint team of the World Meteorological Organization (WMO), Climate Change Initiative (CCl), Climate Variability and Predictability (CLIVAR) and the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM). This joint task force was formed following the CLIVAR/GCOS/WMO workshop on indices and indicators for climate extremes. A summary of the CLIVAR/GCOS/WMO workshop on ETCCDI indices is documented by (Karl, et al., 1999).

This study utilized nine (Table 2) of the ETCCDI indices to understand the behaviour of extreme wet events over Malawi during the period 1982 – 2012.

Table 1. Period of rainfall data used and climatology for each station. Mimosa was not included in the analysis for being inhomogeneous.

Meteorological Station	Period of Data	Mean (mm)	Max (mm)	Min (mm)	Standard Deviation
Bolero	1982 - 2012	629.6	924.7	370.7	139.9
Bvumbwe	1982 - 2012	1153.5	1887.9	745.8	265.6
Chichiri	1982 - 2012	1117.7	1678.1	674	272.6
Chileka	1982 - 2012	857.6	1290.9	506.8	205.6
Chitedze	1982 - 2012	858.8	1201.4	281.9	205.8
Chitipa	1982 - 2012	928.2	1369.2	696.8	162.9
Dedza	1982 - 2012	933.1	1504.1	568.7	208.9
Karonga	1982 - 2012	946.7	1514.4	638.8	238.9
Kasungu	1982 - 2012	770.6	1309.9	456.2	181.3
KIA	1982 - 2012	825	1306.7	546.3	173.1
Makoka	1982 - 2012	1001.5	1516	417.2	251.5
Mangonchi	1982 - 2012	726	1240.5	246.5	231.2
Monkey BAY	1982 - 2012	835.4	1358.6	387.5	247.5
Mzimba	1982 - 2012	833.7	1339.4	572.1	161.3
Mzuzu	1982 - 2012	928.2	1369.2	696.8	162.9
Ngabu	1982 - 2012	782.8	1261.7	414.1	251
Nkhata Bay	1982 - 2012	1521.4	2465.6	862.9	381.4
Nkhota Kota	1982 - 2012	1330	1961.4	860.2	287.3
Salima	1982 - 2012	1192.3	2018.7	409.3	370.1
Thyolo	1982 - 2009	1226.1	1808.4	746.6	298.4
Mimosa	1982 - 2012				

Table 2. Indices used in this study.

Indices	Name	Indices Calculation	Definition	Unit
R10mm	Number of heavy rainfall days	$RRij \geq 10\text{mm}$	Annual count of days when days rainfall ≥ 10 mm	Days
R20mm	Number of very heavy rainfall days	$RRij \geq 20\text{mm}$	Annual count of days when days rainfall ≥ 20 mm	Days
R25mm	Number of extremely heavy rainfall days	$RRij \geq 25\text{mm}$	Annual count of days when days rainfall ≥ 25 mm	Days
RX1day	Daily maximum rainfall	$Rx1day\ j = \max\ (RRij)$	Monthly maximum 1-day rainfall	mm
RX5day	5-day maximum rainfall	$Rx5day\ j = \max\ (RRij)$	Monthly maximum 5-day rainfall	mm
PRCPTOT	Annual wet-day rainfall total	$PRCPTOTj = \sum_{i=1}^{i} RRij$	Annual total rainfall in wet day (RR > 1 mm)	mm
SDII	Simple daily intensity index	$SDII_j = \frac{\sum_{W=1}^{W} RR_j}{W}$	Annual mean rainfall when PRCP ≥ 1 mm	mm/day
R95p	Very wet day	$R95p_j = \sum_{W=1}^{W} RR_{wj}$	Annual total rainfall when RR > 95 percentile	mm
R99p	Extremely wet day	$R99p_j = \sum_{W=1}^{W} RR_{wj}$	Annual total rainfall when RR > 99 percentile	mm

RR = *Rainfall on consecutive days.*

Homogeneity test

Over the years, many approaches used for checking the homogeneity of rainfall data have been developed; in this study, following (Alexandersson, et al., 1977), Standard Normal Homogeneity Test (SNHT) was used to check the homogeneity of the daily rainfall series. The equations for computing the SNHT is shown below:

$$T_y = y\overline{z_1} + (n-y)\overline{z_2}, y = 1,2,...n \qquad (1)$$

Where:

$$\overline{z_1} = \frac{1}{y}\sum_{i=1}^{n}\frac{(Yi-\overline{Y})}{S} \text{ and } \overline{z_2} = \frac{1}{n-y}\sum_{i=y+1}^{n}\frac{(Yi-\overline{Y})}{S} \qquad (2)$$

If the value of T is maximum, the year of y would be considered as having a break. The null hypothesis is rejected if the test

$$T_0 = \max_{1\leq y\leq n} T_y \qquad (3)$$

is greater than the critical value, which is dependent on the size of the sample under consideration. Many studies (e.g. Javari, 2016; Kang, et al., 2012) have recommended SNHT as a robust method of checking homogeneity of daily rainfall.

Trend analysis

To investigate trends in the observed daily rainfall over Malawi, a non-parametric Mann-Kendall test statistic was employed after (Mann, 1945) and (Kendall, 1975). The Mann-Kendall test does not need the data to be normally distributed. Furthermore, the Mann-Kendall test has a low sensitivity to missing data. A number of approaches have been developed to detect trends in timeseries. However, the Mann-Kendall test statistic is widely used by climatologists and Hydrologists. Mathematically, the Mann-Kendall test statistic is given as shown below:

$$s = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} sig(X_i - X_j) \qquad (4)$$

Where:

n is the sample size X_i and X_j are sequential values of X. The p-value after the Z-test has been used herein in comparison to the alpha 5% confidence level; if the p-value is lower (higher) than alpha then it is taken to be significant (insignificant). The hypothesis employed was:

1. Null hypothesis (H_0) there is no trend in the series
2. Alternative hypothesis (H_1) There is a trend in the series

Following (Sen, 1968), the slope estimator gives the magnitude of trends. Sen's slope estimator is a non-parametric approach, which assumes that the trend is linear. Multiple estimates (N') of the slope can be determined using Sen's slope which is mathematically given as:

$$Q = \frac{Y_{i'} - Y_i}{i' - i} \tag{5}$$

Where:

- Q is a slope estimate.
- Y_{i}' are Y_i 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 correlation coefficient (r)

Pearson's correlation (r) was used to scrutinize the strength of the linear relationship (if any) between Mean December – February (DJF) wind anomaly vectors (m^{-1}) at 850 hpa and mean rainfall over Malawi. The Pearson correlation is obtained by dividing the covariance of the two variables by the product of their standard deviations and is thus given as:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x}) \cdot (y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \cdot \sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{6}$$

1 is given if there is a perfect upward linear relationship, and -1 if there is a downward linear relationship, and the values in between indicate the magnitude of relationship between Mean DJF wind anomaly vectors (m^{-1}) at 850 hpa and mean rainfall over Malawi. A correlation coefficient of 0 means the no linear relationship exists (Yang, et al., 2005)

Results and Discussion

Distribution and variability of rainfall over Malawi

Malawi is located within the confines of latitudes 9° and 15°S and longitudes 32 – 36° E and is completely surrounded by three countries: Zambia and Tanzania to the North and Mozambique to the south (figure 2). The topography of Malawi is mainly characterized by the Great Lift Valley. High points include Mount Mulanje at 3,048 meters and Mount Zomba at 2,133 meters. The lowest areas are mainly in the south of the country over the Shire and are in the range of 609 to 914 meters (Kumbuyo, et al., 2011).

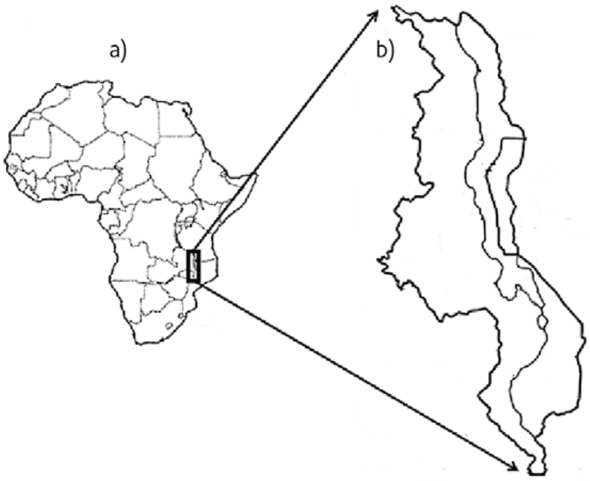

Figure 2. a) Location of Malawi (rectangle) on map of Africa **b)** map of Malawi

The country experiences a sub-tropical climate (Ngwira, et al., 2014). The core wet months over all the stations in Malawi have been observed to be November to April (figure 3) with over 90% of annual precipitation received during these months. The rain season is thus, clearly defined.

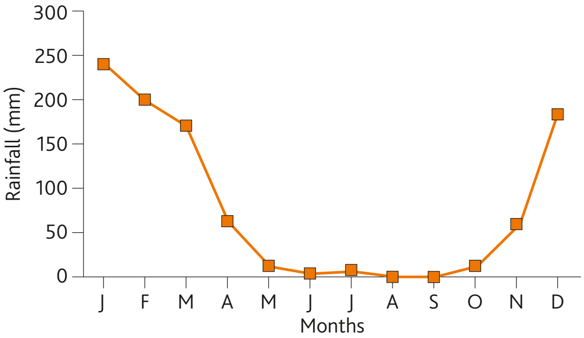

Figure 3. 1982 – 2012 annual rainfall cycle over Malawi

In a study on determining the onset and cessation of seasonal rains in Malawi, Kazembe et al. documents that the fluctuations of the Inter Tropical Convergence Zone (ITCZ) triggers the onset and offset of the rainy season in Malawi (Kazembe, et al., 2014). The ITCZ is a zone of convergence between the moist Congo air mass, the north-eastern trade winds and the meridional south-eastern trade winds (Libanda, et al., 2015b). The ITCZ oscillates over the country during the transition month of October to give Malawi it's first rains. it traverses southwards reaching Thyolo, Mulanje, Bvumbwe and surrounding areas at the end (beginning) of November (December) before retreating northwards at the end (beginning) of March (April) and thus, bringing the rainy season to a close and ushering in the cool dry season. Thus, the behaviour of the ITCZ gives Malawi a clear bimodal climatic pattern with three distinct seasons: cool dry (May to August), hot (August to November) and wet (November to April). Jury and Mwafulirwa have also attributed the variations of Malawi's wet and dry seasons to tropical cyclones originating from the west of the India Ocean (Jury, et al., 2012). These cyclones have been found to cause spells of dryness or wetness depending on their location. Jury et al. also shows in a study on the variability in the tropical southwest Indian Ocean and influence on southern African climate that these systems bring widespread extreme rainfall and subsequent flooding over the Limpopo region in Malawi (Jury, et al., 2013). The bimodal climate pattern of Malawi has also been attributed to the teleconnections especially the El Nino Southern Oscillation (ENSO). Studies (e.g. Hoell, et al., 2014) have found that generally the Northern parts of the country, together with eastern African countries, experience extreme wetness during El Nino years while the southern parts experience extreme dryness. During La Nina years however, the southern half of the country together with southern African countries (e.g. Zambia) experience extreme wetness while the northern parts and eastern African countries experience extreme dryness (Ngongondo, et al., 2006). This observation will be key for agricultural tactical purposes especially considering that most models project wetness on the northern half of the country and dryness on the southern half. The choice of crops grown in each part of the country will have to be dependent not only on the soil type but on climatic conditions. Strategic planning will also have to be employed in the supply of electricity as over 90% of the country's electricity is hydro and powered from the river Shire in the southern part of the country (Benin, et al., 2008).

During the study period (1982 to 2012), more precipitation was received during December – February (DJF) than March to May (MAM) over Malawi. Off-peak (May to October) rains were observed to be highest over Nkhata Bay while the lowest was observed over Mzuzu. During the peak season (November to March), the highest rains were again recorded over Nkhata Bay, with a mean of 1521.4 mm, received more rainfall than any other station in the country while the lowest (629.6 mm) was reported over Bolero in the north of the country (Table 1). Nkhata Bay meteorological station also reported the highest maxima of 2018.7 mm. These results are in agreement with rainfall patterns documented by the Malawi Department of Climate Change and Meteorological Services (Metmalawi, 2017).

While a definite uniform precipitation pattern (800 – 1000 mm) has been observed in the central parts of the country from the north to the south (figure 4), the north-eastern parts of the country especially towards lake Malawi received more rainfall (above 1000 mm) than the north-western parts (below 800 mm) during the study period.

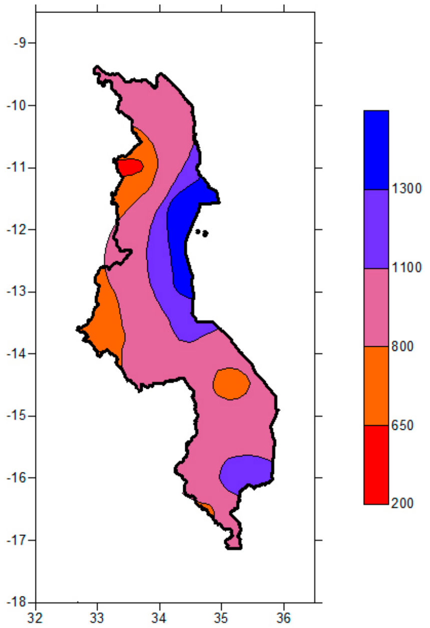

Figure 4. Distribution of annual mean rainfall (mm) over Malawi for the period 1982 – 2012

The more rainfall received over the eastern parts of the country have been, in part, linked to the contribution that Lake Malawi makes over areas near it. Jury and Gwazantini also hinted that the variations in moisture transport from Lake Malawi have an impact on the rainfall pattern (Jury, et al., 2002). In a study on the evaluation of spatial and temporal characteristics of rainfall in Malawi, Ngongondo et al. classified the lake as a *dominant water resources feature* given it's large surface area of 2.8×104i.e. two thirds of the country's total area (Ngongondo et al. 2012). Studies (e.g. Nicholson, et al., 2000) have shown that localised rainfall can be enhanced by the presence of major water bodies e.g. lakes. This is because evaporation is to a great extent dependent on the amount of available water (Majidi, et al. 2015). This is why evaporation is higher in tropical rainforests than in arid and semiarid regions. Studies (e.g. Lee, 2015) have also shown a direct link between evaporation and cloud formation which in turn leads to localized precipitation. Nicholson et al. also found that Lake Malawi exerts significant influence on the variations of precipitation (Nicholson, et al., 2013); in a similar study over Lakes Victoria and Tanganyika, Nicholson and Yin found that the two lakes boosted rainfall by 35 (Victoria) and 11% (Lake Tanganyika) (Nicholson, et al., 2002). Further analysis showed that during wet years, Malawi is characterised by a convergence of strong south-easterly and north-easterly winds at 850 hpa. Convergence at low level boosts ascending motion which in turn enhances rainfall, hence wet years (e.g. 1989). However, during periods of extreme dryness, this convergence completely disappears. In this study, extreme wet year

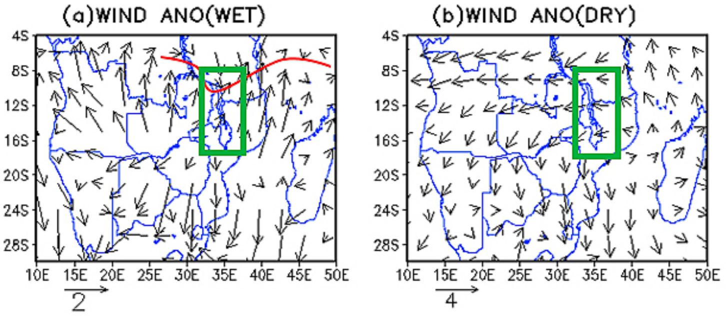

Figure 5. Mean DJF wind anomaly vectors (m^{-1}) at 850 hpa **a** wet year (1989) and **b** dry year (2005), based on ERA-interim reanalysis data. Red curve on figure 5a shows the anomalous convergence zone. The green rectangles show the geographical location of the study area

1989 (figure 5a) and extreme dry year 2005 (figure 5b) have been used to show this anomalous convergence during wet year and lack thereof during the dry year.

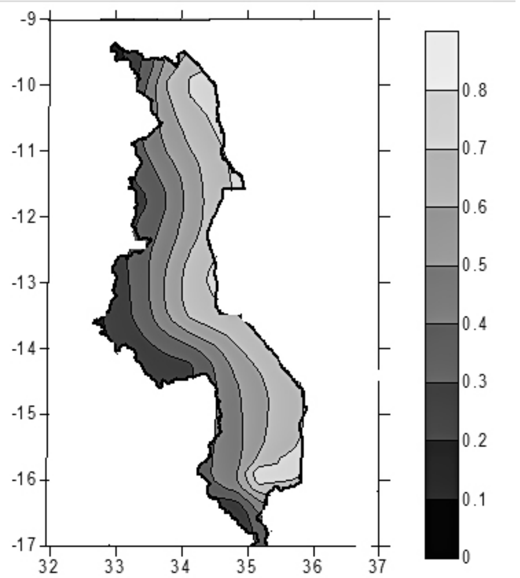

Figure 6. Spatial correlation between mean DJF wind anomaly vectors (m^{-1}) at 850 hpa and mean rainfall over Malawi

Results of Pearson's correlation (figure 6) between mean DJF wind anomaly vectors (m^{-1}) at 850 hpa and mean rainfall over Malawi show stronger correlation along the eastern parts of the country and weakens west-wards hence contributing to more precipitation on the eastern than on the western parts of the country.

Having removed influences of dispersion, the magnitude of rainfall anomalies during the period of study (1982 – 2012) is given in figure 7 below. These results show that Malawi received more extreme negative years (exceeding -1) than positive ones (exceeding 1) with the most intense wet year being recorded in 1989 which was however followed by four years of below normal rainfall (1992 to 1995). With the exception of 1998 and 2005, from 1996 to 2010, precipitation was generally above normal over most of the stations in Malawi. While antecedent conditions of a given region play a role in triggering floods, above normal rainfall is regarded by many studies (e.g. Zaroug, et al. 2014) as a key driver of floods. In a similar study on extreme events over Uganda, Ogwang et al. shows that standardized anomaly can be used as a measure of how intense an extreme event was with showing extreme wetness while ≤-1 showing extreme

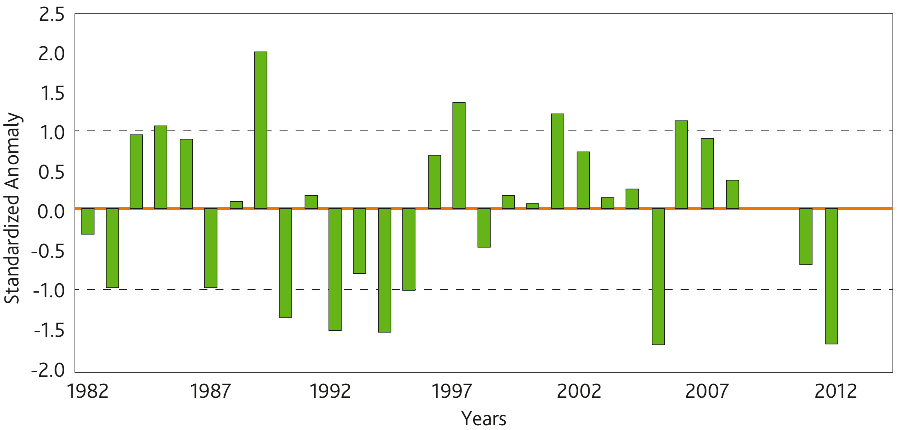

Figure 7. Standardized rainfall anomalies over Malawi for the period 1982 – 2012

dryness (Ogwang, et al., 2012). Ongoma et al. has also used this methodology to classify precipitation intensity (Ongoma, et al., 2016).

ETCCDI Indices over Malawi

Frequency indices

The first part of the extreme indices experiments was to determine the frequency of extreme rainfall over Malawi. Understanding the frequency of extreme rainfall is cardinal as it can give an understanding of the return period of a given event i.e. the probability of a given event of equal to or greater magnitude occurring in any given time frame (Bradshaw, et al. 2007). Results (figure 8a) show that apart from Karonga, Bolero, Nkhata Bay, Nkhota Kota, Monkey Bay, and Mangochi all the other stations observed a decreasing trend in the frequency of heavy rainfall days (RRij ≥ 10mm). One interesting find is that all the stations that experienced an increasing trend are located on the eastern part of Malawi (figure 1) towards Lake Malawi. Changes in very heavy rainfall days (figure 8b) and extremely heavy rainfall days (figure 8c) were not concentrated on any given location; wide variations have been observed from station to station. All these rainfall frequency results are insignificant at 5% significance level.

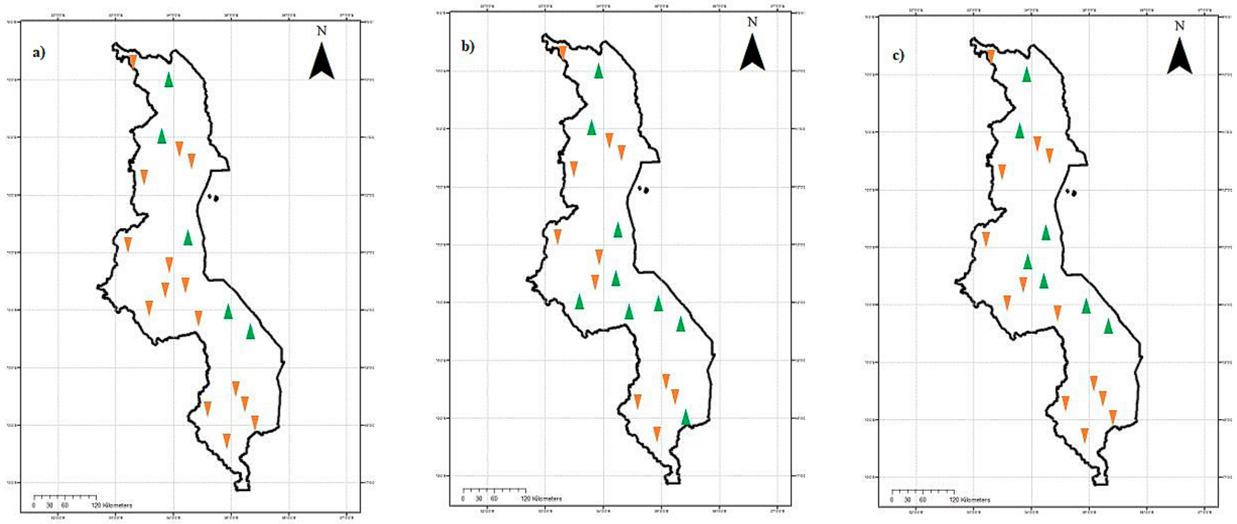

Figure 8. shows Trend of **a)** heavy rainfall days (RRij ≥ 10mm); **b)** very heavy rainfall days (RRij ≥ 20mm) and **c)** extremely heavy rainfall days (RRij ≥ 25mm). The green up right triangles signify insignificant upward trend while the upside-down orange triangles signify a downward trend

Intensity indices

Another significant part that was considered and is documented herein is the intensity of rainfall. Many studies have described the intensity of a given wet event by considering the effects of the accompanying winds, lighting and flooding. For instance, in a study on evidence that deforestation amplifies flood risk and severity in the developing world, Bradshaw et al. (2007) used the duration of a flood, the number of lives lost, the number of people displaced and estimated total damage to describe the intensity of a flood.

In this study, a significant increasing trend of daily maximum rainfall (Rx1day j = max (RRij) has been observed over Karonga in the north and Bvumbwe in the south. Six other stations i.e. Ngangu, Chichiri, Mangochi, Dedza, Kamuzu International Airport (KIA), and Salima exhibited an increasing insignificant trend while all the other stations showed that daily maximum rainfall is reducing insignificantly (figure 9a).

Figure 9b shows 5-day maximum rainfall (Rx5day j = max (RRij); again Bvumbwe experienced a significant positive trend but a complete reversal was seen over Karonga which experienced an insignificant negative trend.

Three stations showed significant trends in very wet days (R95p). Chileka and Mzimba, on the western parts of the country experienced a significant decreasing trend while Thyolo had a significant increasing trend (figure 9c).

Figure 8d shows that Chileka was the only station in the country that received a significant trend (decreasing) in very wet days (R99p)

Results of simple daily intensity are given in figure 10a. Thyolo was the only station that received a significant increasing trend in the annual mean rainfall when PRCP ≥ 1 mm (SDII). All the other results were insignificant at the 5% confidence level. Notably, the eastern parts of the country received an increas-

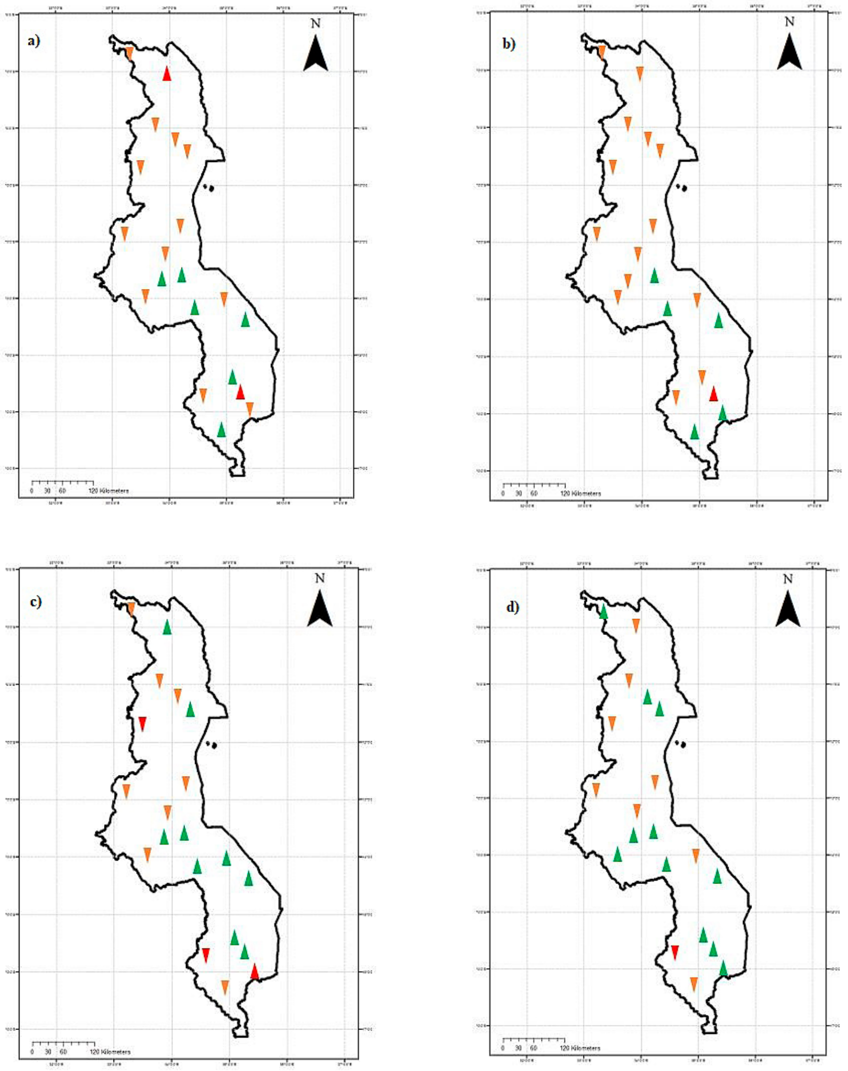

Figure 9. shows Trend of **a)** daily maximum rainfall (Rx1day); **b)** 5-day maximum rainfall; **c)** very wet days (R95p) and **d)** extremely wet days (R99p). The green up right triangles signify insignificant upward trend while the upside-down orange triangles signify an insignificant downward trend. Red triangles signify significant trends

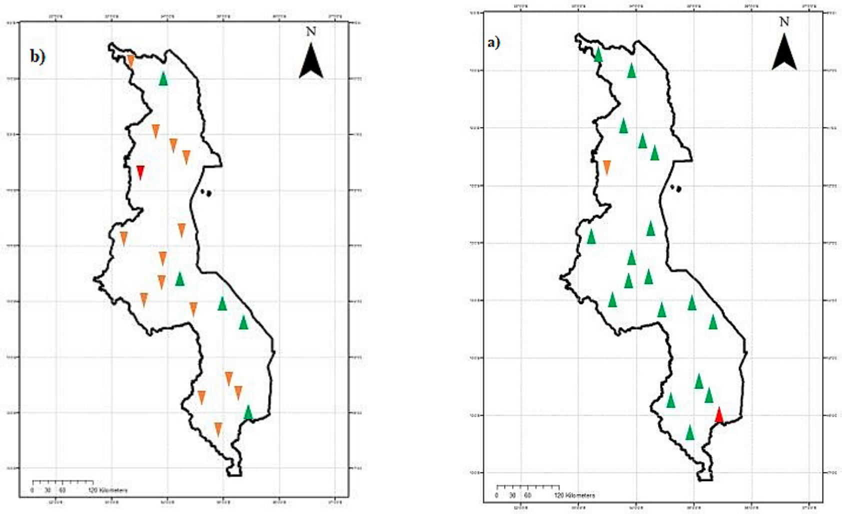

Figure 10. shows Trend of **a)** Simple daily intensity (SDII) and **b)** Total rainfall in wet days (PRCPTOT). The green up right triangles signify insignificant upward trend while the upside-down orange triangles signify an insignificant downward trend. Red triangles signify significant trends

ing trend whereas the western parts of the country observed a decreasing trend. Figure 10b shows annual total rainfall in wet days (RR > 1 mm). A significant decreasing trend was observed over Mzimba while insignificant increasing and decreasing changes, different from station to station were observed over the rest of the country.

Conclusion and Recommendations

The variability of extreme wet events over Malawi was analysed using indices of the Expert Team on Climate Change Detection and Indices (ETCCDI), a joint team of the World Meteorological Organization (WMO), Climate Change Initiative (CCl), Climate Variability and Predictability (CLIVAR) and the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM). The daily rainfall data used was kindly provided by Malawi Department of Climate Change and Meteorological Services. The data covers a period of thirty years from 1982 – 2012 and is sourced from 21 Meteorological Stations widely spread over the whole country. However, the datasets for Thyolo Meteorological Station only spans over a period of 27 years from 1982 – 2009. Mimosa was not included in further analysis as the homogeneity tests showed that it was inhomogeneous. It has been observed that generally the northern parts of the country, together with eastern African countries, experience extreme wetness during El Nino years while the southern parts experience extreme dryness. During La Nina years however, the southern half of the country together with southern African countries (e.g. Zambia) experience extreme wetness while the northern parts and eastern African countries experience extreme dryness (Ngongondo, et al., 2006). This observation will be key for agricultural tactical purposes especially considering that most models project wetness on the northern half of the country and dryness on the southern half. Indices results indicate large temporal and spatial variability in trends. Notably, only five stations have observed significant trends – all increasing significant trends were observed over Thyolo (SDII and R95p), Bvumbwe (Rx1day and Rx5day) and Karonga (Rx1day) while significant decreasing trends were observed over Chileka (R95p and R99p) and Mzimba (PRCPTOT and R95p). The more rainfall received over the eastern parts of the country has been linked to the contribution that Lake Malawi makes over areas near it. More evaporation from lake Malawi as compared to land surface enhances cloud formation and rainfall over the eastern areas of the country. During wet years, Malawi is characterised by an anomalous convergence of strong south-easterly and north-easterly winds. This convergence is the main rain bringing mechanism to Malawi. Results of Pearson's correlation between Mean DJF wind anomaly vectors () at 850 hpa and mean rainfall over Malawi show stronger correlation along the eastern parts of the country and weakens west-wards hence contributing to more precipitation on the eastern than on the western parts of the country. This paper recommends that longer datasets (with more stations) be used to investigate if this trend will still be prevalent. It is further recommended that projections be employed and studied to check if this eastern-western trend will still be noticeable; these studies can aid in water resources management planning and flood risk strategies.

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