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Investigating possible changes of extreme annual rainfall in Zimbabwe

D. Mazvimavi

Harry Oppenheimer Okavango Research Centre, University of Botswana, P Bag 285,
Maun, Botswana

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Correspondence to: D. Mazvimavi (dmazvimavi@orc.ub.bw)

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Abstract

There is increasing concern about the perceived decline in rainfall which is sometimes attributed to global warming. Some studies have concluded that average rainfall in Zimbabwe has declined by 10% or 100 mm/yr during the last 100 yrs. This paper investigates the validity of the assumption that rainfall is declining in Zimbabwe. Time series of annual rainfall, and total rainfall for a) the early party of the rainy season, October-November-December (OND), and b) the mid to end of the rainy season, January-February-March (JFM) are analysed for the presence of trends using the Mann-Kendall test, and changes in extreme rainfall using quantile regression analysis. The analysis has been done for 40 rainfall stations with records starting during the 1892–1940 period and ending in 2000, and representative of the major rainfall regions.

The Mann-Kendal test did not identify a significant trend at all the 40 stations, and therefore there is no proof that the average rainfall at each of these stations has changed. Quantile regression analysis revealed a decline in annual rainfall less than the tenth percentile at only one station, and increasing rainfall for rainfall greater than the ninetieth percentile at another station. All the other stations revealed no changes over time in both the extreme low and high rainfall at the annual interval. Therefore, there is no evidence that the frequency and severity of droughts has changed during the 1892 to 2000 period. The general perception about declining rainfall is likely shaped by a comparison of the recent drought years (1980's–1990's) to recent wet periods (1970's). There have however been periods with similar dry years beyond the recallable memory, e.g. 1926–1936, 1940's. Crop failures and livestock losses attributed to declining rainfall are most likely due to poor agricultural practices such as production of crops in unsuitable climatic regions, degradation of rangelands partly due to increasing livestock populations. Rainfall in Zimbabwe has high inter-annual variability, and currently any change due to global warming is not yet statistically detectable. The annual renewal rate of water resources from rainfall has therefore not changed, and an adaptive water resources management approach is called to overcome problems

arising from increasing water demand, and variability of available water resources.

1 Introduction

There are more and more instances when the occurrence of disasters associated with floods or droughts are considered as evidence of increasing climate variability due to global warming. Some studies have concluded that rainfall is decreasing in Zimbabwe due to global warming. Unganai (1996) fitted a linear regression model to annual areal average rainfall of Zimbabwe and concluded that rainfall had declined by 10% between 1900 and 1994; Makarau (1995) made a similar conclusion. Mason and Jury (1997) suggested that there was some evidence of desiccation and increased rainfall variability. Chamaille-Jammes et al. (2007) carried out quantile regression of rainfall at three stations in north-western Zimbabwe and concluded that rainfall during extreme dry years was declining at two stations. This decline in rainfall was attributed to global warming. Van Wageningen and du Plessis (2007) made a similar conclusion regarding the 1961–2003 rainfall at a station in Cape Town, South Africa. If these conclusions are valid, then planning, designing and management of water resources systems have to adapt to non-stationary behaviour arising from declining rainfall.

The decline in rainfall over the years as concluded by Makarau (1995), Unganai (1996), and Chamaille-Jammes et al. (2007) has however not been established in other studies carried out in Zimbabwe and other parts of Africa. An analysis of annual rainfall at 20 stations in Zimbabwe did not reveal the presence of trends (Mazvimavi, 1989). Nicholson (2000) noted that decadal variations of rainfall during the 1950–1989 period were similar to variations that occurred during the nineteenth century. Hulme et al. (2001) and Faucherean et al. (2003) did not find evidence of progressive desiccation in Africa. The presence of cyclic behaviour in southern African rainfall (Tyson, 1986), and linkages between rainfall and El Nino events (Mason and Jury, 1997; Nicholson, 2000; Nash and Endfield, 2008) are considered to partly explain the occurrence of droughts. What is uncertain is whether the general perception about the progressive desiccation in Zimbabwe is valid. Nash and Endfield (2002) noted that perceptions about increasing severity of droughts are affected by the tendency for humans to compare recent drought years to wet periods during recallable memory. Thus perceptions about droughts increasing in their frequencies and severity in Zimbabwe may be due to a comparison of the dry 1980's and 1990's to the wet 1970's. Decline in agricultural output in Zimbabe during the 2000's has also been given as evidence for increasing frequency and severity of droughts, but Richardson (2007) was of the view that this decline was mainly due to inappropriate government policies.

Previous studies (Makarau, 1994; Unganai, 1995) investigating the possible decline of rainfall in Zimbabwe have used techniques capable of detecting changes in mean responses. But, climate change effects may manifest in changes in other parts of the probability distribution of rainfall such as changes of extreme high and low rainfall, and not measures of central tendency. A study that examines possible changes of annual rainfall in other parts of the probability distribution is therefore warranted. This paper aims to investigate if extreme high and low rainfall during a) the early part of the wet season, b) mid to end of the season, and c) at the annual level has changed over time. The outputs of this study will assist agricultural and water resources planners and managers to determine whether current problems of water availability are due to effects of natural climate variability, effects of enhanced greenhouse effects, or poor water resources management practices. Southern Africa has since the 1980's experienced disasters associated with extreme hydrological events such as droughts and floods. Effective management of these events requires information about the cause of the increasing vulnerability to these events.

2 Material and methods

The selected time series for analysis are for each year (a) total rainfall during the early part of the rainy season, October-November-December (OND), (b) total rainfall during the middle to end of the rainy season, January-February-March (JFM), and (c) annual rainfall. Annual and monthly rainfall data for 40 stations with records starting during the 1892 to 1941 period, and ending in 2000 have been used in this study (Fig. 1). The stations were selected so that they are representative of spatial variation of rainfall throughout Zimbabwe. In this regard, the selection of rainfall stations was done so that the full range of average annual rainfall in Zimbabwe was covered, i.e. from areas receiving the lowest to the highest rainfall.

Changes in extreme rainfall at the annual interval have the potential to change the median rainfall or introduce a trend. Therefore, statistical tests for determining a change in the median rainfall and presence of a trend were used in this study. The Pettitt test for detecting changes in the median was used for this purpose. A description of this test is given in several references (Pettitt, 1979; Nechval and Nechval, 2000; Kundzewicz and Robson, 2004; Mazvimavi and Wolski, 2006) and is not repeated in this paper. Nechval and Nechval (2000) modified this test so that the location within a time series of the change point is identifiable. The Mann-Kendall test which is capable of detecting both linear and non-linear trend (Kendall, 1976; Kundzewicz, 2004; Kundzewicz and Robson 2004) has been used in this study.

Highly variable time series like rainfall in Zimbabwe present a problem in detecting changes over time of extreme high or low rainfall since these changes can be masked by the inter-annual variability. Changes of extreme rainfall may not manifest themselves as changes of the median or mean. Quantile regression which was developed by Koenker and Basset (1978) is capable of identifying changes for different parts of a distribution such as changes of extreme values of a dependent variable (rainfall) associated with an independent variable (year when rainfall was observed). Very few studies have made use of this technique for hydrological analysis (Chamaille-Jammes et al., 2007). A full description of the quantile regression technique was given in Koenker and Basset (1978), Buchinsky (1998), Koenker and Hallock (2001), Cade and Noon (2003), and Yu et al. (2003). Let Y be a random variable such as the time series of annual rainfall, and θ whose values are in the $0 \le \theta \le 1$ range, is the probability of Y being less than or equal to τ. Therefore τ is the θth quantile or percentile of Y. Suppose X is a covariate of Y, and τ or $Y(\theta|\mathrm{x})$ is now the θth conditional quantile of Y given that $X=x$. The first order quantile regression model relating Y to X has the following form;

$$Y\left(\theta|\times\right) = \beta\left(\theta\right)_0 + \beta\left(\theta\right)_1 X + F^{-1}\left(\theta\right) \tag{1}$$

where $\beta(\theta)_0$ is the intercept, $\beta(\theta)_1$ is the slope coefficient both of which vary depending on the value of θth quantile or percentile being considered. F is the distribution function of the error, whose expectation is zero. The θth quantile regression estimate is obtained by minimizing the following function (Koenker and Basset, 1978; Buchinsky, 1998);

$$\text{minimize}\ \frac{1}{n}\left\{\sum_{i:y\geq x_i\beta}\theta\left|y_i - x_i\ \beta\right| + \sum_{i:y_i\langle x_i\beta}(1-\theta)\left|y_i - x_i\ \beta\right|\right\} \tag{2}$$

where n=sample size or number of years of rainfall record, $i=1,2,..,n$, y_i=value of random variable Y, x_i=value of random variable X. Koenker (2006) developed the software, "quantreg", written in R language for undertaking quantile regression and is available for downloading from http://www.r-project.org/. R is an integrated free software for statistical and graphical applications. Parameters of the quantile regression model, the intercept and slope coefficients in Eq. (1) are estimated using the rank inverse method. Standard errors, confidence intervals, t-statistics, and p-values for these coefficients are also estimated in this software package.

For the purpose of detecting possible trends of quantiles of OND, JFM, and annual rainfall over time, X is the year of record. A $\beta(\theta)_1$ that is negative (positive) and significantly different from zero is an indication that the θth quantile of rainfall is decreasing (increasing). Quantile regression has the desirable attribute of being able to describe responses of both homoscedastic and heteroscedastic variables. The slope parameter, $\beta(\theta)_1$, is constant for all quantiles when the dependent variable is homoscedastic (Fig. 2). For a heteroscedastic dependent variable the slope parameter, $\beta(\theta)_1$, differs for different quantiles (θ) (Fig. 2).

For each rainfall station, the 0.1, 0.2 and 0.3 quantiles or 10th, 20th, and 30th percentiles were considered to be indicators of extremely low rainfall, while the 0.7, 0.8 and 0.9 quantiles (70th, 80th, and 90th percentiles) were regarded as indicators of extremely high rainfall. The magnitude of quantile values varies from station to station. When the quantile regression model (Eq. 1) was fitted to each of the selected quantiles at each station, if the slope coefficient was found to be significantly different from zero at the 5.0% significance level, this was considered as evidence of the decline or increase of extreme rainfall. The quantreg software can derive intercepts and slope coefficients for any valid θ value at each station.

The 5% level of significance has been used for all the statistical tests in this study.

3 Results and discussion

Average annual rainfall at the selected stations varies from 337 mm/yr in the extreme southern part of the country to 1110 mm/yr on the Eastern Highlands located along the eastern border of Zimbabwe and Mozambique (Fig. 1). Over 86% of the selected stations have rainfall data longer than 61 yrs, while 40% of the stations have over 100 yrs of data (Table 1). Tyson (1986) identified an 18–20 yr cycle in time series of annual rainfall for parts of southern Africa including Zimbabwe. This means years with generally above average rainfall tend to occur together over a 9–10 yr period, such as during the 1970's, followed by years with generally below average rainfall for about 9–10 yrs, e.g. 1980's. The presence of such cycles in short time series can therefore be mistaken for a trend. Trend analysis and other analyses were therefore conducted on rainfall time series longer than 50 yrs to minimize the risk of any cyclic behaviour being identified as a trend.

Annual rainfall at all the 40 stations did not have any significant autocorrelation for lags up to 20 yrs which is an indication of lack of persistency in the occurrences of wet and dry years. The Pettitt test only identified significant change points or change of the median of the OND rainfall at three out of the 40 stations (Fig. 3). These change points were identified for the 1946/47 season at two stations (Plumtree, Kezi) located on the extreme south-western part, and in 1986/87 for a northern station (Banket). Plumtree and Kezi experienced the worst drought during the 1946/47 season which is likely to be a cause of the occurrence of the change in the median. Significant change points for the JFM rainfall were identified at six stations with four of these being located on the eastern part of the country (Fig. 3). These change points have been identified for different years with the exception of two stations, which suggests that change points identified have no physical cause. If the change points had a physical cause, it would be expected that the changes would have occurred at several stations almost at the same time.

No significant change points in annual rainfall were identified except for three stations for the following periods 1926/27, 1980/81, 1994/95 (Fig. 3). Stations for which change points have been identified in the OND, JFM, and in annual rainfall time series, are not located in geographically contiguous areas, while neighbouring stations do not have similar changes in the median. Furthermore, change points have been identified at a small number of stations, 7 to 14% of the total number of stations. These observations again suggest that the change points identified have no physical cause. They could be due to sampling errors, changes over time in the exposure of rain gauges, or change of rainfall measurement procedures.

The Mann-Kendall test did not identify any trend at all the stations for the OND, and annual time series. A significant trend was identified in the JFM time series at two out of 40 stations. The lack of trends in rainfall time series does not support the conclusion made by Unganai (1994) and Makarau (1995) that annual rainfall in Zimbabwe was declining. Possible changes in extreme rainfall have therefore not induced either a positive or negative trend in rainfall during the early, and mid-to-end rainy season, or for the annual rainfall.

Quantile regression results show that the tenth percentile of the OND rainfall increased over time at two stations, Hwange and Plumtree, while the 20th percentile decreased at one station, Wedza (Figs. 4 and 5, Table 2). A decline in the 80th and

90th percentiles of OND rainfall was detected at one station (Guruve). Some declines of 10th to 30th percentiles of JFM rainfall were identified at five stations (Figs. 4 and 6), and a change in extremely high JFM rainfall at one station, Buhera. The 70th and 80th percentiles of the annual rainfall were identified as decreasing at one station (Guruve) on the extreme northern part. An increasing trend of the 80th and 90th percentiles for annual rainfall at Harare was detected. (Fig. 7, Table 2).

The decline of extreme low or 0.2 quantile of OND rainfall was detected at one station, and four stations for the JFM rainfall (0.1, 0.2, 0.3 quantiles). Extreme high rainfall (0.8, 0.9 quantiles) was detected to have declined at one station for the OND rainfall, one station for the JFM (0.9 quantile), and one station for the annual total rainfall (0.7, 0.8 quantiles). The decline in these quantiles could in reality be a case of committing a Type I error in that the null hypothesis of no change in quantile values is being rejected when it is correct. The total number of stations examined is 40, and therefore these few stations showing some declines in some of the low quantiles do not provide convincing evidence that extreme low rainfall in Zimbabwe is declining due to global warming. Similarly, the evidence that extreme high rainfall has declined is very weak, only at one station for OND and JFM. The results of this study do not support the conclusion made by Chamaille-Jammes et al. (2007) that rainfall was declining in Zimbabwe due to global warming on the basis of quantile regression results at one station in Hwange National Park.

4 Conclusions

Rainfall records for the 1892 to 2000 period at 40 stations selected for study in Zimbabwe do not demonstrate evidence of changes in the median, and extreme high or low rainfall during the beginning (October to December), mid-to-end (January to March) of the rainy season, and for the whole year. The very few stations which had evidence of changes of the median and some quantile values were located in different parts of the country, which is an indication that the changes identified have no physical meaning and are due to sampling errors. Effects of global warming on rainfall that may have occurred are not yet statistically identifiable within the available rainfall time series. This does not imply that global warming will not cause changes of rainfall in Zimbabwe, but the effects are not yet statistically significant within the available rainfall record. Appropriate adaptations strategies for changes of rainfall that will occur have to be developed.

The results of this study show that the long-term average input of rainfall into the land phase of the hydrological system has not changed. Thus the long-term renewal rate of water resources from the atmosphere has not changed. However, anthropogenic changes of land use and land cover, accelerated soil erosion resulting in increased siltation rates have in some cases adversely affected the available water resources (Schulze, 2000). These adverse effects are sometimes erroneously attributed to increasing frequency and severity of droughts. Human and livestock populations in southern Africa increased tremendously during the twentieth century, but with no commensurate increase in resilience against droughts and floods. Consequently, the numbers of people and livestock adversely affected by droughts and floods have been increasing which is again perceived as evidence for increasing frequency and severity of droughts and floods. The perception about gradual desiccation can also be a symptom of an environmental nostalgia resulting in the past being considered to have been wetter than the current period.

Most parts of southern Africa are semi-arid to arid with high inter-annual variability of rainfall and the available water resources. Policy makers, planners and managers of water resources systems have to accept this as a fact of this region. The challenge is to develop hydrological monitoring systems, water supply systems, and investing in the development and retention of human resources with skills for managing highly variable water resources, and therefore reduce vulnerability towards droughts and floods (Kundzewicz and Kaczmarek, 2000; Kunzewicz, et al., 2002). Reducing vulnerability towards the current high variability will increase the capacity to respond to uncertainty arising from climate change.

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Table 1. Record lengths for stations selected with continuous data and records beginning during the 1892 to 1941 period and ending in 2000.

Record Length (Years)	No. of Stations
60–70	1
71–80	7
81–90	11
91–100	15
101–109	6
Total	40

Table 2. Values of the slope coefficient $(\beta)(\theta)_1$ t-statistic, and p-values for quantile regression of OND, JFM, and annual rainfall against year of record for stations where trends were significant.

Station	θ	$\beta(\theta)_1$	t-statistic	p-value
		OND (Oct-Nov-Dec)		
Hwange	0.10	0.56	2.00	0.048
Plumtree	0.10	0.86	3.11	0.003
Wedza	0.20	−1.63	−2.32	0.023
Guruve	0.80	−1.10	−2.14	0.035
Guruve	0.90	−2.30	−3.16	0.002
		JFM (Jan-Feb-Mar)		
Mutare	0.10	−1.21	−2.03	0.045
Gutu	0.20	−2.03	−2.83	0.006
Gutu	0.30	−1.71	−2.11	0.037
Kadoma	0.30	−2.27	−2.34	0.022
Thuli	0.30	−1.19	−2.66	0.009
Mt Darwin	0.30	1.72	2.08	0.041
Buhera	0.90	−4.55	−2.67	0.009
		Annual		
Guruve	0.70	−2.74	−2.22	0.029
Guruve	0.80	−3.41	−2.50	0.014
Harare	0.80	2.04	2.37	0.020
Harare	0.90	2.06	2.41	0.018
Middle Save	0.80	3.69	2.17	0.033

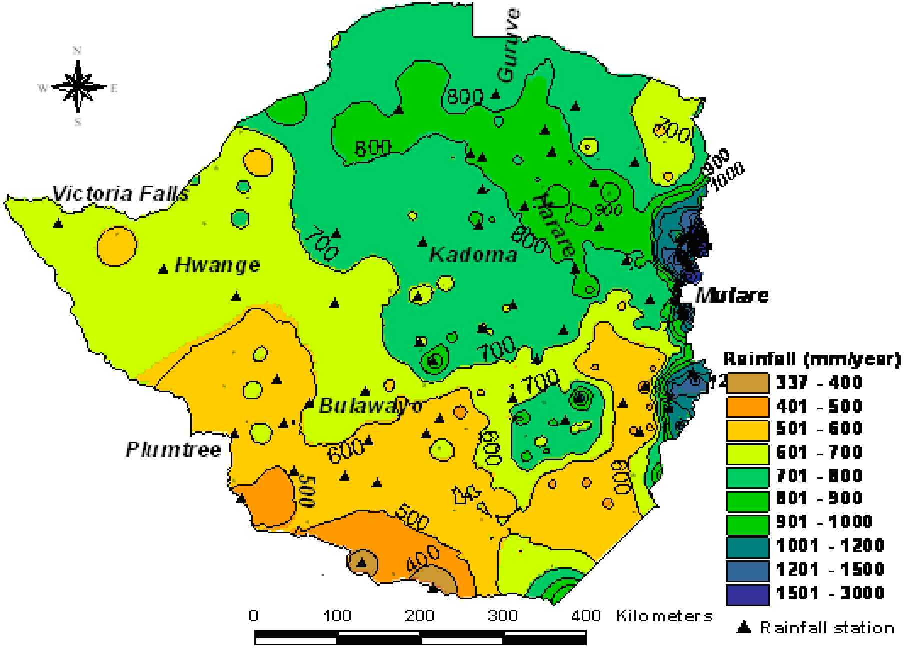

Fig. 1. Location of the 40 stations selected for analysis and the variation of average annual rainfall in Zimbabwe.

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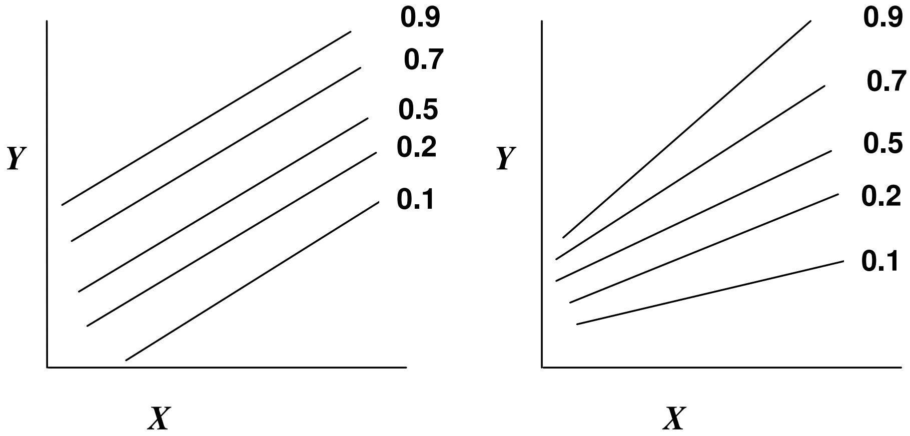

Fig. 2. Quantile regression is capable of modelling a homoscedastic relationship (left graph) with constant slope coefficient, $\beta(\theta)_1$, for all quantile values, and a heteroscedastic relationship which has different values of the slope coefficient for different quantile values. The plotted lines show relationships for the 0.1, 0.2, 0.5, 0.7, and 0.9 quantiles.

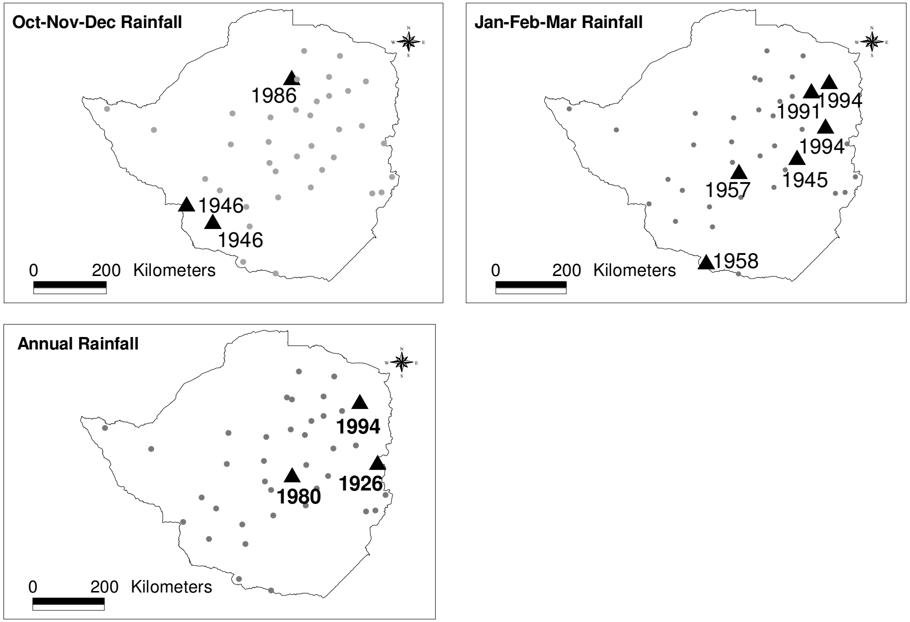

Fig. 3. Location of stations (triangles) where change points were identified and the year for which this change occurred is shown adjacent to the station.

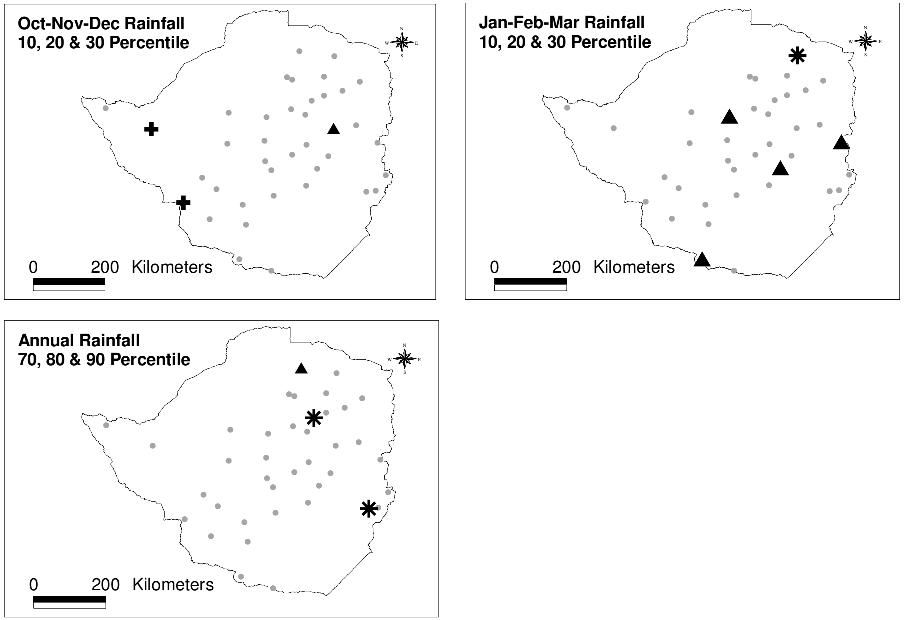

Fig. 4. Location of stations for which quantile regression identified a decreasing (triangle) or increasing (cross or star) trend for extreme low (10%, 20% and 30% percentile) and high (70%, 80% and 90% percentile) rainfall.

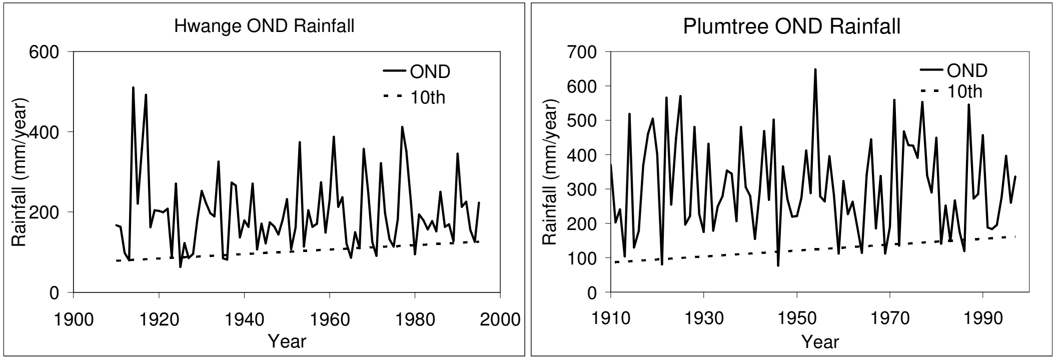

Fig. 5. An increasing trend detected for the 10th percentile of OND rainfall at Hwange, and Plumtree.

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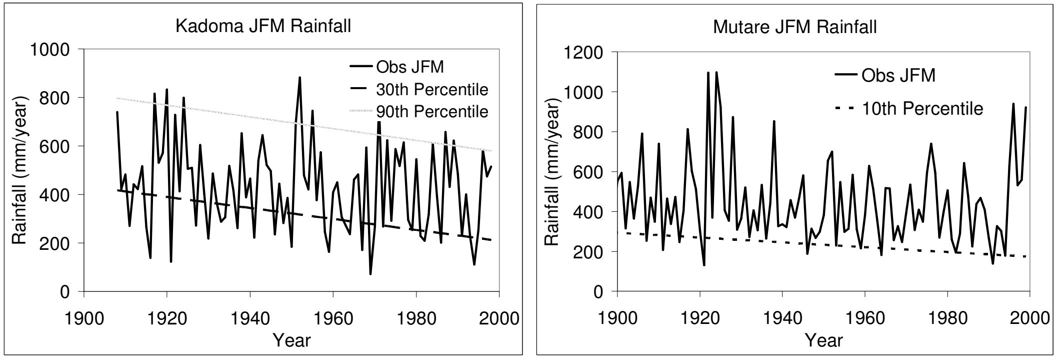

Fig. 6. A decreasing trend in the 30th and 90th percentiles at Kadoma, and 10th percentile at Mutare for the JFM rainfall.

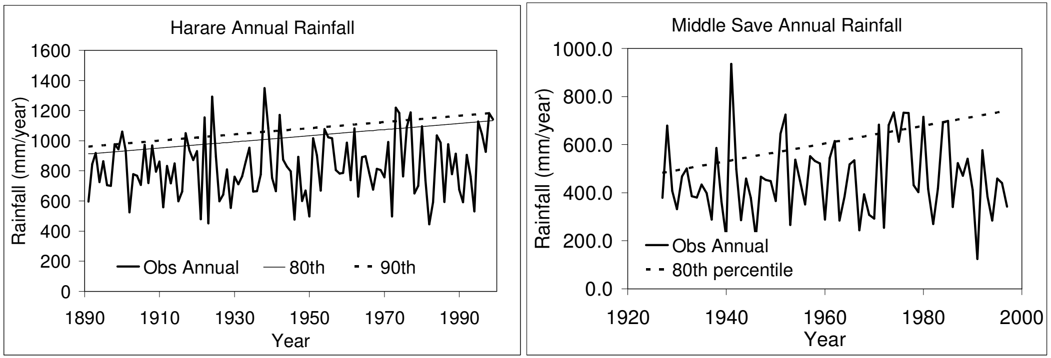

Fig. 7. An increasing trend for the 80th and 90th percentiles of annual rainfall at Harare and 80th percentile of annual rainfall at Middle Save.