INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. (2008)

DOI: 10.1002/joc.1623

Trends and spatial distribution of annual and seasonal rainfall in Ethiopia

Wing H. Cheung,[a]* Gabriel B. Senay[b]* and Ashbindu Singh[a]

[a] *UNEP Division of Early Warning and Assessment-North America, National Centre for Earth Resources Observation and Science, Sioux Falls, SD 57198, USA*

[b] *SAIC, contractor to US Geological Survey (USGS) Center for Earth Resources Observation and Science, Sioux Falls, SD. Work performed under USGS contract 03CRCN0001, USA*

ABSTRACT: As a country whose economy is heavily dependent on low-productivity rainfed agriculture, rainfall trends are often cited as one of the more important factors in explaining various socio-economic problems such as food insecurity. Therefore, in order to help policymakers and developers make more informed decisions, this study investigated the temporal dynamics of rainfall and its spatial distribution within Ethiopia. Changes in rainfall were examined using data from 134 stations in 13 watersheds between 1960 and 2002. The variability and trends in seasonal and annual rainfall were analysed at the watershed scale with data (1) from all available years, and (2) excluding years that lacked observations from at least 25% of the gauges. Similar analyses were also performed at the gauge, regional, and national levels. By regressing annual watershed rainfall on time, results from the one-sample t-test show no significant changes in rainfall for any of the watersheds examined. However, in our regressions of seasonal rainfall averages against time, we found a significant decline in June to September rainfall (i.e. Kiremt) for the Baro-Akobo, Omo-Ghibe, Rift Valley, and Southern Blue Nile watersheds located in the southwestern and central parts of Ethiopia. While the gauge level analysis showed that certain gauge stations experienced recent changes in rainfall, these trends are not necessarily reflected at the watershed or regional levels. Copyright © 2008 Royal Meteorological Society

KEY WORDS Ethiopia; climate; trend analysis; hydrology; precipitation; rainfall distribution

Received 28 December 2006; Revised 11 August 2007; Accepted 11 August 2007

1. Introduction

Ethiopia relies on low-productivity rainfed agriculture for a majority of its national income; consequently, the importance of the timing and amount of rainfall that occurs in Ethiopia cannot be overstated. In 1997, it was reported that smallholder agriculture 'employed 89% of the labour force and contributed 56% of GDP and 67% of export earnings' (Devereux, 2000, p. 4). The reliance on agriculture is even more acute in rural areas, where small farmers reportedly accounted for over 90% of agricultural output (Bollinger *et al.*, 1999). Given such a heavy dependence on rainfall, it should be no surprise that climate extremes such as drought or flood can pose significant health and economic threats to the entire nation. The threat posed by these extremes is compounded by the fact that 'few Ethiopian farmers irrigate, (hence) when rainfall fails, so does their harvest' (The Economist Group, 2002, p. 41). In particular, negative rainfall trends often signify higher probabilities of droughts that have historically affected 'millions of rural poor farmers, pastoralists, domestic and wild animals,' and have grave ramifications for the environment and social instruments such as drought insurance programmes (Poverty-Environment Partnership, 2003; Seleshi and Zanke, 2004, p. 9). Recognizing the association between rainfall and food insecurity, the Famine Early Warning Systems Network (FEWS NET) has developed a crop water balance model that has continuously monitored agricultural performance for most of Africa since 2000 (Senay and Verdin, 2003). In one of its latest reports, FEWS NET warned that long-term negative rainfall trends coupled with increasing food requirements not only point toward chronic food shortages in the near future, but also put the number of people who will meet none of their food needs at over 17.3 million (IRIN, 2003). By studying the trends and changes in the rainfall of Ethiopia with a simple yet direct approach, we hope to show how policymakers and citizens can better prepare for natural extremes and reduce the loss of life and property in the absence of extensive expertise.

Previous time-series studies of rainfall patterns in Ethiopia have been carried out at various spatial (e.g. regional, national) and temporal (e.g. annual, seasonal, monthly) scales. Osman and Sauerborn (2002) determined that summer rainfall (known as Kiremt) in the

---

* Correspondence to: Gabriel B. Senay, SAIC, contractor to US Geological Survey (USGS) Centre for Earth Resources Observation and Science, Sioux Falls, SD. Work performed under USGS contract 03CRCN0001, USA. E-mail: senay@usgs.gov
Wing H. Cheung, UNEP Division of Early Warning and Assessment-North America, National Centre for Earth Resources Observation and Science, Sioux Falls, SD 57198, USA.

central highlands of Ethiopia declined in the second half of the 20th century, while Seleshi and Zanke (2004) failed to find such a trend over central, northern, and northwestern Ethiopia. Instead, they found a decline of annual and Kiremt rainfall in eastern, southern, and southwestern Ethiopia since 1982. Verdin *et al.* (2005) confirmed the Seleshi and Zanke (2004) findings of annual rainfall decline in southwestern and eastern Ethiopia, but argued that while rainfall has been declining in the Northeast since 1996, Kiremt rain has been consistent (i.e. no trends) for the entire nation since the 1960s. In contrast to Verdin *et al.* (2005), Conway (2000) reported that there are no recent trends in rainfall over the northeastern Ethiopian highlands.

Many of the contradictions in previous findings on rainfall trends and climate extremes in Ethiopia may be explained by the arbitrary division of the study area as well as the quality of the available data (Easterling *et al.*, 2000; Seleshi and Zanke, 2004). For example, in the study by Seleshi and Zanke (2004), the authors noted that 11 gauging stations investigated were 'grouped into five zones,' but failed to elaborate or justify the delineation of those zones (Seleshi and Zanke, 2004, p. 976). Instead of allowing the locations of gauge data, political boundaries, or other arbitrary schemes dictate our division of study units, it is imperative to define the study area in a geographically meaningful manner that conforms to the physical characteristics of the study unit. This will not only help us relate better the physical processes of the study area with our observations, but will also enable us to avoid statistical errors that may be introduced by the modifiable areal unit problem (Marceau, 1999).

2. Materials

2.1. Study area

Ethiopia is located in the Horn of Africa (Figure 1) with an area of 1 127 127 sq km, of which, 7444 sq km is water (CIA World Factbook, 2006). The topography of Ethiopia is highly diverse, with elevation ranging from −125 m at the Denakil Depression to 4620 m at Ras Dejen. More than 45% of the country is dominated by a high plateau

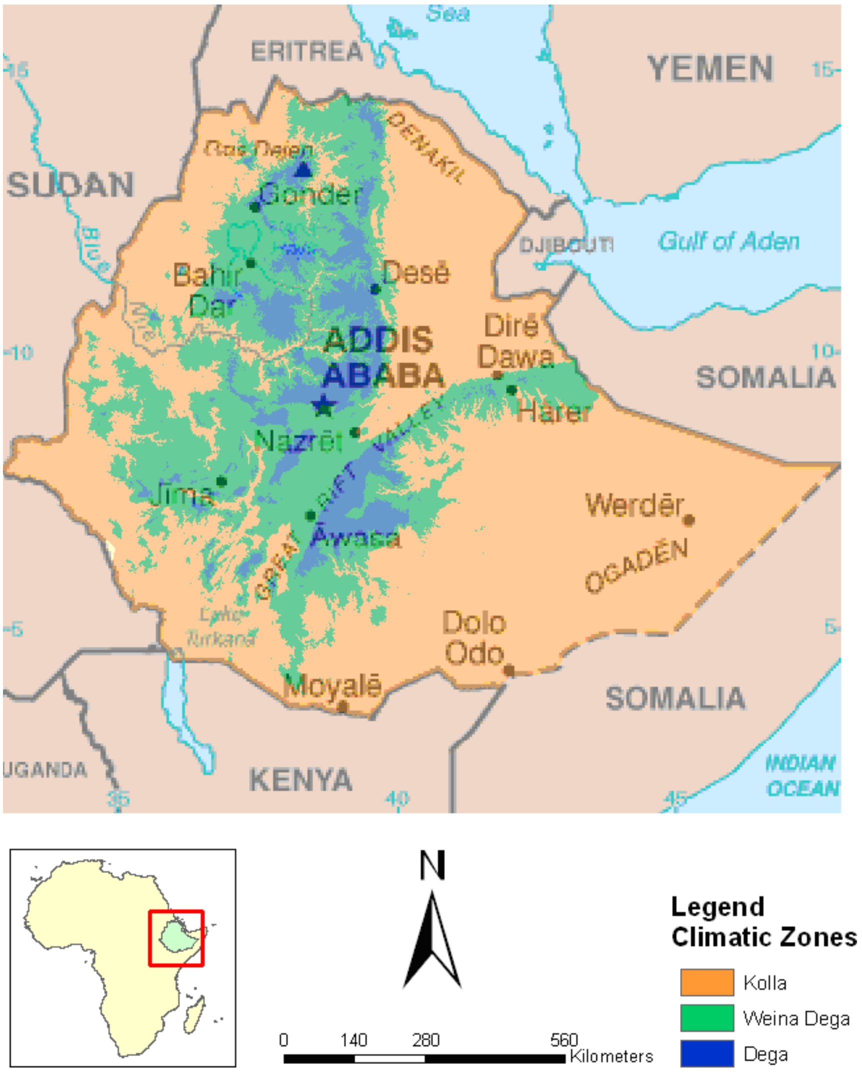

Figure 1. Geography of Ethiopia showing the country's major water features and climatic zones. (CIA World Fact Book, USGS). This figure is available in colour online at www.interscience.wiley.com/ijoc

with a chain of mountain ranges that is divided by the East African Rift Valley. This region with elevations greater than 1500 m is known as the highlands where almost 90% of the nation's population resides, perhaps to take advantage of its relatively disease-free environment (Devereux, 2000). Surrounding the highlands are regions known as the lowlands (<1500 m), where most of the remaining population (mostly pastoralists) lives (Devereux, 2000). Elevation differences can greatly influence local microclimate (Seleshi and Zanke, 2004), while these differences may be partially influencing the variability and trends in regional rainfall.

Ethiopia's varied topography has created three climatic zones (Figure 1), which have been known since antiquity as the dega, the weina dega, and the kolla (US Library of Congress, 2005). The dega (also known as the cool zone) occupies the central sections of the western and eastern parts of the northwestern plateau. The elevation of this region is mostly above 2400 m, and daily temperatures range from near freezing to 16 °C (US Library of Congress, 2005). The weina dega or the temperate zone ranges between 1500 m and 2400 m in elevation, and consists of parts of the central plateau. It has daily highs between 16 and 30 °C (US Library of Congress, 2005). The kolla or hot zone generally comprises areas lower than 1500 m in elevation, the Denakil Depression, and the tropical valleys of the Blue Nile (US Library of Congress, 2005).

Within each climatic zone, seasonal variations and atmospheric pressure systems contribute to the creation of three seasons, which are known as the Kiremt, Belg, and Bega. The Kiremt season is the main rainy season and usually lasts from June to September, covering all of Ethiopia except the southern and southeastern parts (Seleshi and Zanke, 2004). The Belg season is the light rainy season and usually lasts from March to May; it is the main source of rainfall for the water-deficient southern and southeastern parts of Ethiopia (Seleshi and Zanke, 2004). The Bega season is the dry season and usually lasts from October to February, during which the entire country is dry, with the exception of occasional rainfall that is received in the central sections (Seleshi and Zanke, 2004).

The timing, variability, and quantity of seasonal and annual rainfall are important factors in the relationship between climate and cultivation. If there is an unexpected break in rainfall early in the growing season, farmers may be able to recover and resume production despite the loss of some of their crops (Hulme, 1990). However, if such a break occurs in the middle or latter part of the growing season, all of the crops sown may suffer irreparable damage, with dire economic consequences for farmers (Hulme, 1990). Short cycle crops (e.g. wheat, teff, barley) that are cultivated during the Belg and Kiremt seasons constitute 5–10% and 40–45% of national crop production, respectively (Verdin *et al.*, 2005). Long cycle crops, such as maize and sorghum, are grown during the entire Belg and Kiremt seasons, and are responsible for 50% of national production (Verdin *et al.*, 2005).

2.2. Data

Dekadal rainfall records for 134 rain gauge stations that cover the entire country were obtained from the Ethiopian National Meteorological Agency (NMA), the Global Historical Climatology Network (GHCN), and the United Nations Food and Agricultural Organization (FAO). A dekad is about a third of a month as defined by World Meteorological Organization (WMO) (1992), where a month is divided into three parts, the first two of which are 10 days long and the third dekad is comprised of the remaining days of the given month.

Data were missing or limited for some gauge stations for certain months and/or years within a watershed. Annual observations for a gauge station with any missing dekadal or monthly rainfall records were omitted from the study to minimize errors or biases in our analysis. In order to ensure high quality of input data, data used in this study have not only been checked and previously published in Verdin *et al.* (2005), but were also subjected to repeated examinations by members of the United Nations Environment Programme/Division of Early Warning and Assessment (UNEP/DEWA) office.

The locations of the 134 gauge stations used in this study can be seen in Figure 2. The stations are scattered over 13 watersheds which were delineated on the basis of drainage pattern and flow direction. As Figure 2 shows, the 13 watersheds do not cover all of Ethiopia because of the scarcity of rain gauge data in some regions. However, the watersheds outside of our study area are sparsely populated and relatively unproductive. We concentrated our attention on areas where rainfall variability and deficiency have the most adverse consequences for agriculture. The watershed, stream, elevation, and sub-watershed data were acquired from the US Geological Survey Hydro1k Elevation Derivative Database (USGS Hydro1k, 2006).

3. Methods

3.1. Interstation and watershed correlation analyses

In the watershed-level analysis of this study, we considered the use of watershed units to be more geographically meaningful because rainfall patterns were likely to be homogeneous over a particular watershed, and hydrologic responses associated with storm events would be confined to the watershed.

In order to ensure that watersheds were homogeneous units that were suitable for our study, we first used the pairwise correlation procedure to discern the relationship between the average monthly rainfalls for different stations on each watershed. Secondly, we averaged the pairwise correlation coefficients in order to derive the mean watershed correlation coefficient. This process of averaging correlation coefficient over study regions has been used by Gissila *et al.* (2004) to derive the mean correlation coefficient for rainfall clusters.

Since the drainage of excess rainfall, or runoff, is confined to a watershed, analyses of rainfall trends based

DOI: 10.1002/joc

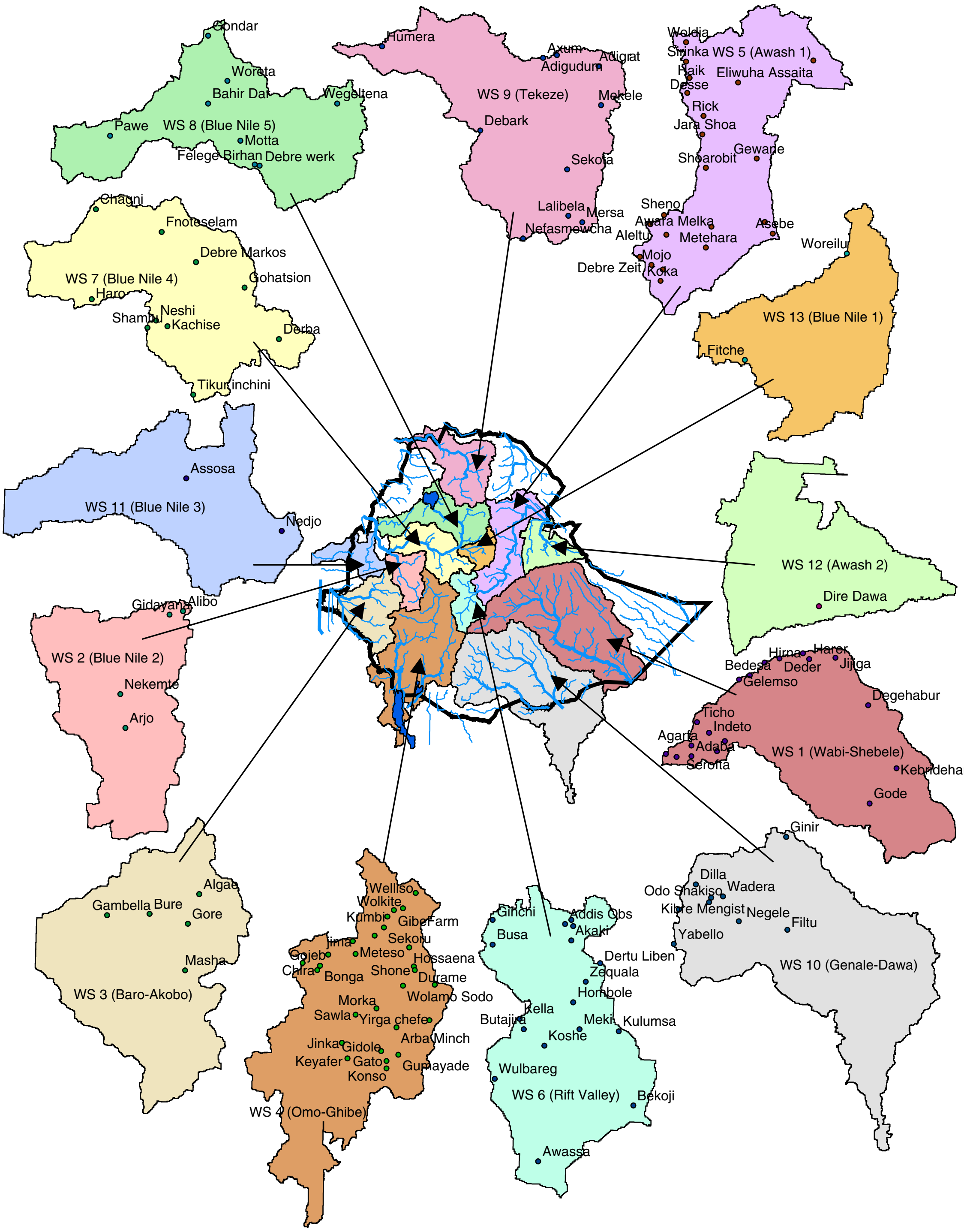

Figure 2. Names and locations of the 13 watersheds included in this study along with their respective gauge stations. *Figure not to scale; WS = Watershed. This figure is available in colour online at www.interscience.wiley.com/ijoc

on the watershed as the unit of aggregation provide an approximation of the amount of rainfall and associated runoff that is actually accumulated in a particular unit. Therefore, it is clear that the watershed units will provide researchers with a systematic means of dividing the country into relatively homogeneous study units, and will also simplify future food balance studies by allowing for an integrated analysis of rainfall and other critical determinants of livelihood (e.g. population density, runoff depth, and vegetative cover) at a common aggregation level.

In order to display probable areas that might be experiencing rainfall trends recorded by various rain gauges, Thiessen polygons were used to identify these areas at a finer spatial scale. It is important to note that unlike other rainfall studies (Goovaerts, 2000), we did not experiment with Thiessen polygons as a method of interpolating rainfall depths over the study area. Instead, we used Thiessen polygons to roughly estimate areas that were experiencing trends recorded by the gauges. We acknowledge that since Thiessen polygons merely group areas closest to a gauge into one polygon, some polygons may be committing or omitting areas that are not truly within the representative ranges of the gauges. However, Theissen polygons are, nonetheless, preliminary tools that can be used to identify small areas with interesting rainfall trends that may deserve further analyses.

3.2. Watershed and national level analysis

Annual rainfall received by each gauge was calculated from the sum of the dekadal records. Subsequently, the annual watershed rainfall magnitude from 1960 to 2002 was calculated by spatially averaging the available annual gauge rainfall records for each year. Because the averaging process is designed to reduce the bias created by spurious observations, we omitted yearly data for any watershed that failed to record observations from at least 25% of its gauge stations. The value of 25% was arbitrarily chosen as a compromise between getting nearly no data (in the case of requiring all stations to record observations before including the yearly average) and biased averages (in the case where one suspicious gauge reading may misrepresent the yearly rainfall for the watershed). A demonstration of the '25% rule' can be seen in watershed 8, where the year's data for 1960 was omitted because only one station reported an annual rainfall figure while observations from a minimum of at least two stations (8 stations × 0.25 = 2 stations) are needed in order to establish a credible watershed average. The 25% rule had little impact on watersheds with consistent gauge rainfall information (complete time-series observations), but its effect was obvious in some watersheds such as watershed 1. The importance of the '25% rule' is demonstrated in Figure 3, where the suspiciously low mean rainfall observation averaged from one gauge for the year 1962 (most probably a result of instrument error) was excluded from our analysis because a minimum of four gauge measurements were required to establish a credible average for watershed 1.

In order to detect statistically significant changes in rainfall at the watershed level, a time-series study was undertaken where annual watershed rainfall (the dependent variable) was regressed on time (the independent variable). The parameter estimate of the slope was then tested for statistical significance using the one-sample t-test at a 0.05 level of significance. In addition, the variability of annual rainfall in each watershed over the study period was examined by calculating the watershed's coefficient of variability (CV). The watershed CV was calculated by averaging the CV (standard deviation of annual rainfall divided by the mean of annual rainfall received at each gauge) of all the gauges located in that watershed. The CV calculation and regression analysis were also implemented with all of the observations at the watershed level in a single regression in order to discern whether rainfall significantly changed at the national level.

3.3. Seasonal rainfall analysis

Mean seasonal rainfall was obtained by summing the corresponding mean monthly rainfall, which was originally derived from the dekadal rainfall dataset. For example, the Belg rainfall for 1990 was obtained by summing the mean monthly rainfall records for March, April, and May of 1990. Mean seasonal rainfall was calculated for the Belg and Kiremt seasons for all 13 watersheds individually. Similar to the watershed-level analysis, the '25%

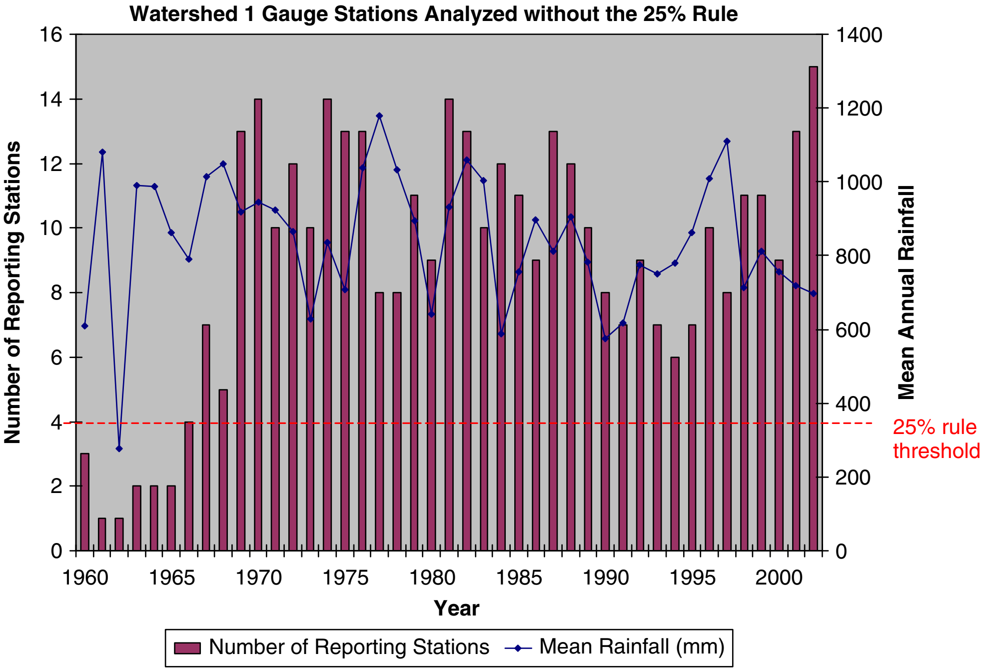

Figure 3. A summary graphic of the number of reporting gauge stations and the mean rainfall for each year in watershed 1. Years with number of reporting stations below the 25% rule threshold (red dashed line) are omitted from the study in order to minimize the influence of biased observations and instrument errors. This figure is available in colour online at www.interscience.wiley.com/ijoc

rule' was applied, whereby seasonal averages from years with less than 25% of reporting of the watershed's gauges were excluded from the regression. As a result of the 25% rule, the most dramatic drop in the number of seasonal observations to be included was in watershed 4, where the number of years analysed dropped from 43 to 35 during the Belg, and from 43 to 36 during the Kiremt seasons. Linear regression analysis was then performed for each season in order to detect significant changes or trends in seasonal rainfall.

3.4. Comparison with previous rainfall studies

To demonstrate how data processing and level of aggregation issues may have influenced findings in previous studies, we expanded our rainfall trend analysis to the gauge, watershed, and regional scales. In addition, all of the available annual rainfall observations for each gauge station were used regardless of the '25% rule,' in order to demonstrate the dangers associated with the inclusion of irregularities in rainfall trend analysis. Moreover, we also compared rainfall trends computed from observations with and without the 25% rule in order to highlight the implications of including unrepresentative observations.

In accordance with the approaches taken in previous studies (Conway, 2000; Seleshi and Zanke, 2004), the annual rainfall of individual gauges on two selected watersheds (1 and 4) were regressed on time (years). The two watersheds were selected because Seleshi and Zanke (2004) reported significant declines in rainfall for these two regions. Using the allocation function in ArcGIS 9 (ESRI, 2004), Thiessen polygons were created from a gauge station shapefile. The Thiessen polygons of gauges showing significant changes were retained and overlaid on a sub-watershed dataset of Ethiopia in order to assess areas that were affected. The procedures previously carried out in the watershed-level analysis (Section 3.2) were repeated here without the 25% rule to see if the changes at the gauge level were reflected at the watershed level, and to highlight the importance of excluding irregular observations.

To compare results, watershed units were combined to approximate the extent of regional units which showed significant trends in rainfall in previous studies, such as Verdin *et al.* (2005) and Seleshi and Zanke (2004). Regional annual rainfall at these units was then regressed on years to see if the results from our study concurred with those from prior studies.

4. Results and discussion

4.1. Interstation and watershed correlation analyses

Overall, we found high watershed correlation coefficients ($r > 0.9$) for most of the watersheds, which indicate that most watersheds in our study are relatively homogenous units influenced by similar rainfall patterns (Table I). The exceptions to this rule were observed within watersheds 1 and 4, which respectively reported correlation coefficients of 0.70 and 0.61, and contained pairwise correlation coefficients with values as low as 0.001. This information suggests that the current level of aggregation is perhaps too general to capture the dynamic rainfall patterns in watersheds 1 and 4, and implies the need to examine those areas at a finer spatial scale (e.g. sub-watershed units).

4.2. Watershed and national level analysis

Despite the constraints created by data scarcity, the general observations from the study coincide with the series of events that have occurred in Ethiopia. One of the most notable observations is that the driest year for watersheds 5, 6, 7, 8, 9, 11, and 12 occurred during the well-known drought period that lasted from 1978 to 1986. Although the driest year for other watersheds may have occurred at other time periods, gauge data from those watersheds also recorded near-minimum precipitation from late 1970 to mid-1980, confirming the unusually low rainfall received by Ethiopia during those years.

Given the implications that rainfall variability has on a country whose economy and citizens are heavily dependent on rainfed agriculture, we have examined the annual rainfall variability in each watershed. Of the 13 watersheds examined in our study, only watersheds 2 and 11 do not have any stations that show a CV greater than 0.20 (data not shown). Their low watershed CVs of 0.14 and 0.15, respectively, confirm that watersheds 2 and 11 have relatively low variability in rainfall amounts. Conversely, watershed 1 has two stations, Kebridehar and Gode, that show very high variability (CV > 0.5), and the watershed's high rainfall variability is confirmed by its relatively high watershed CV of 0.26. Given that watershed 1 is not only a watershed with highly variable

Table I. Correlation analysis showing the average watershed correlation coefficient (Correlation coefficient), standard deviation of pairwise correlation (Std deviation), absolute minimum of pairwise correlation (Min of I r I), and absolute maximum of pairwise correlation (Max of I r I) within each watershed.

Watershed	Number of stations	Correlation coefficient	Std deviation	Min of I r I	Max of I r I
1	18	0.70	0.323	0.039	0.992
2	4	0.98	0.006	0.976	0.990
3	5	0.97	0.020	0.918	0.995
4	27	0.61	0.349	0.001	0.993
5	21	0.92	0.076	0.709	0.998
6	17	0.94	0.062	0.748	0.997
7	10	0.94	0.045	0.796	0.992
8	8	0.95	0.052	0.759	0.997
9	10	0.94	0.049	0.804	0.995
10	9	0.92	0.075	0.699	0.995
11	2	0.98	N/A	N/A	N/A
12	1	N/A	N/A	N/A	N/A
13	2	0.98	N/A	N/A	N/A

(Note: N/A denotes the inability to denote the target parameter due to the scarcity of data).

rainfall but also one with relatively low mean rainfall, our results concur with observations made by Illius and O'Connor (1999), who noted that low rainfall sites tend to experience high rainfall variability.

In the national and watershed-level analysis, neither the watersheds nor the nation was found to be experiencing any significant changes in annual rainfall for the time period covered by this study (Figure 4). Although the rainfall decline in watershed 1 and the rainfall increase in watershed 11 are significant at the 0.10 level (a level more relaxed than the 0.05 level used in other parts of the study), the trends observed in most of the other watersheds (8 of 13) are insignificant ($p > 0.60$). Therefore, while no significant changes in rainfall at the watershed level were found at the 0.05 level of significance (a level used in similar studies), we can conclude that rainfall has been significantly decreasing in watershed 1 and increasing in watershed 11, if there is a justification for preferring the less strict level of significance of 0.10.

Overall, relative rainfall variability proved to be high ($CV > 0.20$) throughout Ethiopia with the exception of watersheds 2, 3, 7, 8, and 11. However, since we failed to see any significant changes in inter-annual rainfall at the watershed or national level, it is unclear whether climate change is driving any systematic trends in Ethiopia's rainfall.

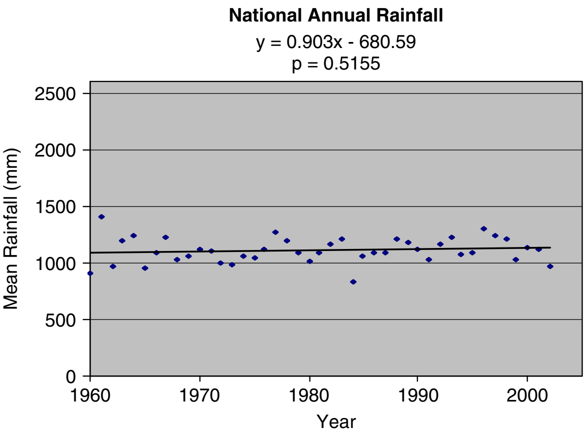

Figure 4. National Level Analysis shows no significant changes in rainfall for Ethiopia over the study period at the 0.05 level of significance. This figure is available in colour online at www.interscience.wiley.com/ijoc

4.3. Seasonal rainfall analysis

For 12 of the 13 watersheds, the Kiremt rainfall constituted a majority of the study area's annual rainfall (Table II). The only exception was watershed 10, which reported that 48.8% of its annual rainfall came during the Belg, and only 20.5% during the Kiremt season. Although

Table II. Variability, quantity, and changes in seasonal rainfall across all thirteen watersheds.

Watershed	Season	Number of Years analysed	Change in rainfall (mm/year)	*p*-value	Total watershed rainfall (mm)	Percentage of total rainfall (%)	CV
1	Belg	38	−0.7	0.5110	863	32.6	0.25
	Kiremt	39	−0.6	0.6119		42.5	0.21
2	Belg	37	0.5	0.7245	1742	19.2	0.28
	Kiremt	36	−7.0[a]	0.0015		70.5	0.12
3	Belg	43	0.1	0.9534	1735	21.9	0.23
	Kiremt	43	−5.2[a]	0.0044		60.6	0.13
4	Belg	35	0.3	0.8046	1251	31.4	0.16
	Kiremt	36	−2.6[a]	0.0331		48.1	0.14
5	Belg	42	−0.1	0.9606	858	22.2	0.38
	Kiremt	42	0.4	0.7684		63.0	0.18
6	Belg	40	0.9	0.4059	1058	23.0	0.32
	Kiremt	40	−2.9[a]	0.0130		65.8	0.13
7	Belg	38	1.8	0.0904	1496	16.5	0.29
	Kiremt	40	−0.6	0.6270		71.8	0.09
8	Belg	40	0.9	0.1601	1188	11.8	0.35
	Kiremt	42	−0.5	0.8007		68.1	0.17
9	Belg	39	0.2	0.7937	771	16.4	0.48
	Kiremt	37	3.4	0.0659		70.8	0.44
10	Belg	42	0.7	0.6519	905	48.8	0.25
	Kiremt	41	−1.2	0.0933		20.5	0.29
11	Belg	39	1.8	0.1141	1364	17.8	0.36
	Kiremt	40	1.3	0.5827		72.3	0.18
12	Belg	41	2.1	0.1312	615	36.0	0.49
	Kiremt	42	−0.6	0.6940		47.2	0.38
13	Belg	38	0.6	0.7245	1085	16.1	0.66
	Kiremt	38	−2.6	0.5275		78.4	0.32

[a] Statistically significant at the 0.05 level.

this discrepancy may initially seem unusual, such a deviation is expected given that we have already cited the Belg as the main source of rainfall for the South and Southeast. In particular, the Belg rainfall was characterized by higher variability than the Kiremt rainfall in 12 of the 13 watersheds. The higher variability of Belg rainfall was especially pronounced in the North and the Northeast (watersheds 5, 9, 12, and 13), while Kiremt rainfall variability was less dramatic in magnitude and less defined geographically.

In our examination of Belg rainfall, linear regression analyses for each of the 13 watersheds show that there were no significant changes in Belg rainfall for the years analysed. With the exceptions of watersheds 1, 6, 7, 8, 11, and 12, the changes in Belg rainfall were highly insignificant ($p > 0.60$) in 7 of the 13 watersheds. In contrast, our analyses at the individual watershed level indicate that there were significant declines in Kiremt rainfall in watersheds 2, 3, 4, and 6 (Figure 5(b), (d), (f), and (h)).

We have noted some discrepancies between seasonal rainfall analysis and annual rainfall analysis. Although the annaul analysis showed that none of the watersheds experienced a significant decline in annual rainfall between 1960 and 2002, the seasonal rainfall analysis found a significant decrease in Kiremt rainfall for watersheds 2, 3, 4, and 6 in the same time period (Table II). Because all of the watersheds that revealed significant declines in Kiremt rainfall also displayed Belg rainfall with positive (albeit insignificant) changes (Figure 5(a), (c), (e), and (g)), it is probable that the increase in Belg rainfall compensated for the decline in Kiremt rainfall. This 'compensation effect' has been alluded to in previous climatological and early warning system studies, which claim that as El Nino and Southern Oscillation events are made more active by global warming, Belg rains are heavy and Kiremt rains are of a below average level (Seleshi and Zanke, 2004; UNCT, 2006; Wolde-Georgis *et al.*, 2007). While other works have also attributed changes in African rainfall to Indian Ocean processes and atmospheric features such as the intertropical convergence zone (ITCZ) and anticyclones, it is beyond the scope of this article to examine the validation of these hypotheses (Bekele, 2000; Gissila *et al.*, 2004). However, it is worth noting that since the 'compensation effect' is only observed in time-series data collected from watersheds 2, 3, 4, and 6, it is probable that the impacts of climate forcing is most persistent and pronounced in that region. Shanko and Camberlin (1998) concluded that cyclonic activities over the Southwest Indian Ocean is correlated with Belg rainfall magnitudes, and usually affect west and Southwest before reaching the Southeast. Therefore, given that Webster *et al.* (2005) observed a large increase in the number of intense tropical cyclones in the Indian Ocean within the past 35 years, such a phenomenon may explain the increase in Belg rainfall in the Southwest. Further research is needed to test this hypothesis.

A comparison of our findings with previous studies shows that some of our results seem to differ with conclusions from Seleshi and Zanke (2004), which reported that Kiremt rainfall has not only declined in the southwest but has also dropped in the eastern (Jijiga) and southern (Negele) parts of the country since 1982. In addition, our results also appear to differ with findings from Verdin *et al.* (2005), which concluded that Kiremt rain has been consistent since the 1960s despite a reduction in Belg rain since 1996. However, because both studies defined their study units using different criteria than we did (by 'zones' and administrative regions, respectively), any attempt to compare the conclusions from the two studies is filled with uncertainties, further highlighting the importance of defining the study regions in an objective and geographically meaningful manner.

4.4. Comparison with previous rainfall studies

To show how unrepresentative observations and level of aggregation can produce dramatically different results and conclusions, we not only examined rainfall trends at the gauge level but also analysed all of our available data without the 25% rule at the watershed level as well as the regional level that was commonly used in previous studies. Furthermore, we also wish to emphasize the importance of the 25% rule in minimizing the influence of unrepresentative observations by comparing rainfall trends constructed with and without applying the 25% rule.

In the gauge level analysis, areas that are potentially affected by the change of rainfall reported at the gauges are represented by Thiessen polygons, as mentioned in the previous section (Figure 6). A visual inspection reveals that many sub-watersheds do not intersect Thiessen polygons that indicate significant declines in rainfalls. Therefore, it is evident that in spite of significant annual rainfall trends observed at individual gauge stations, these changes may only be applicable to the limited area surrounding the gauges (as roughly represented by their respective Thiessen Polygons), and tend to affect different sub-watersheds disproportionately.

Our results from analyzing gauge observations (Jijiga) used in previous studies reproduced the significant decline in rainfall that was reported by Seleshi and Zanke (2004). However, in our analysis of rainfall trends for all of the individual gauge stations in watershed 1 (in the eastern region that was reported to be experiencing a decline in rainfall), 3 additional stations (Robe Goba, Kebridehar, and Alemaya) showed significant declines in rainfall; 2 other stations (Hirna, Bedesa) reported significant increases in rainfall; and 12 other gauge stations experienced no significant changes in rainfall. By regressing annual watershed rainfall on time, we failed to discern a significant decrease in rainfall for watershed 1. This demonstrates that although one or more stations on a watershed may show a significant decline in rainfall, such results cannot be generalized from the gauge scale to the watershed or regional scale.

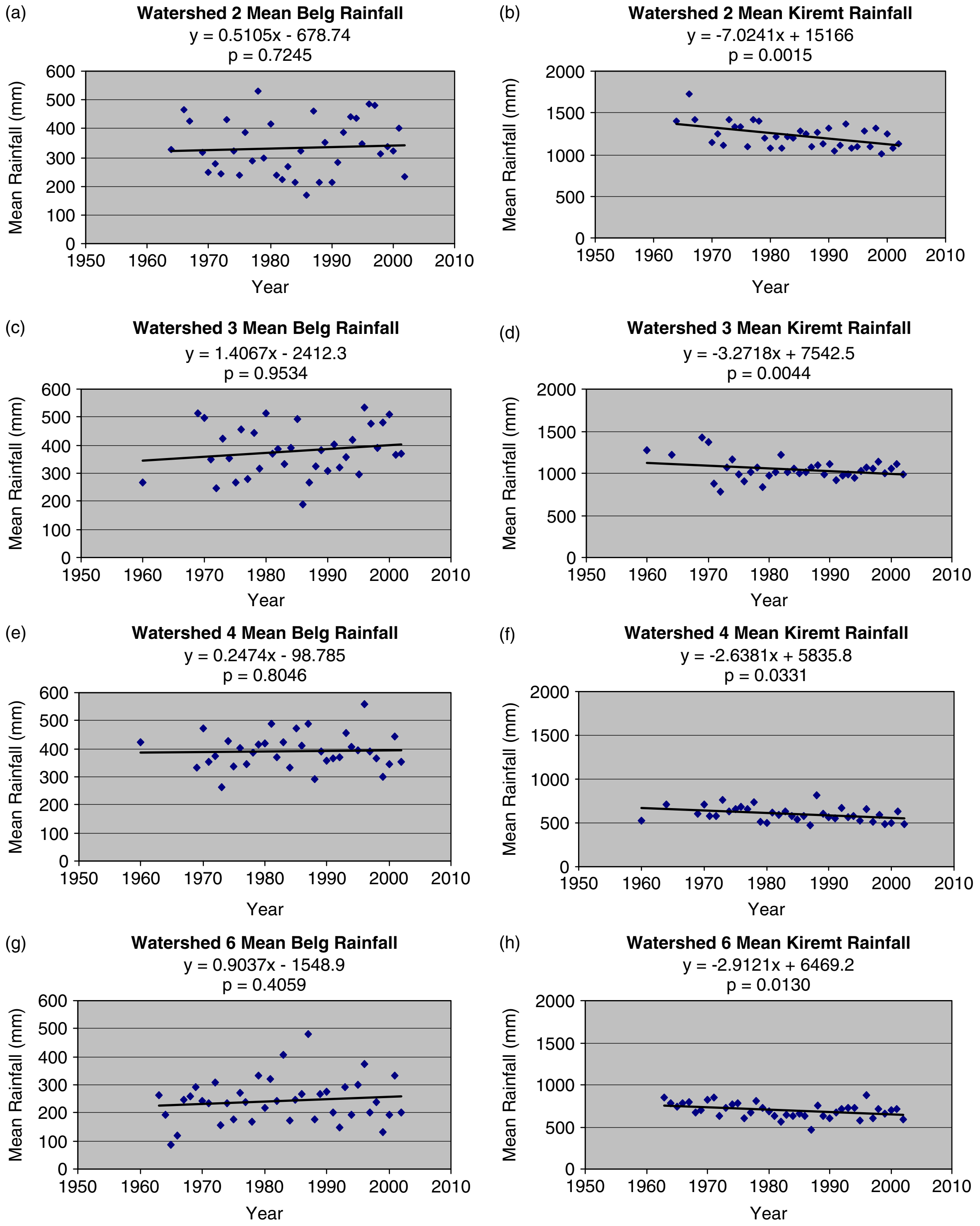

Figure 5. Watersheds that show a significant decline in Kiremt rainfall (b), (d), (f), and (h) are accompanied by positive changes in rainfall during the Belg season (a), (c), (e), and (g). *Scales for the Belg and Kiremt are different due to the different ranges of rainfall received during the seasons. This figure is available in colour online at www.interscience.wiley.com/ijoc

Because a significant decline in annual rainfall in the Southwest has been documented in Verdin *et al.* (2005) as well as Seleshi and Zanke (2004), we analysed rainfall trends at individual gauges in watershed 4 in the southwestern region. Our results indicate that 2 gauges (Meteso, Yirga chefe) have experienced significant declines in annual rainfall (Figure 6(a), (b)), 3 gauges had significant increases in rainfall (Figure 6(c), (d), and (e)), while 22 other gauges did not show any significant trends. The results from regressing annual watershed rainfall on time show that the watershed experienced a significant rainfall decline of 5.0 mm/year ($p = 0.0159$) (Table III). However, when we omitted years that lack observations from at least 25% of the watershed's

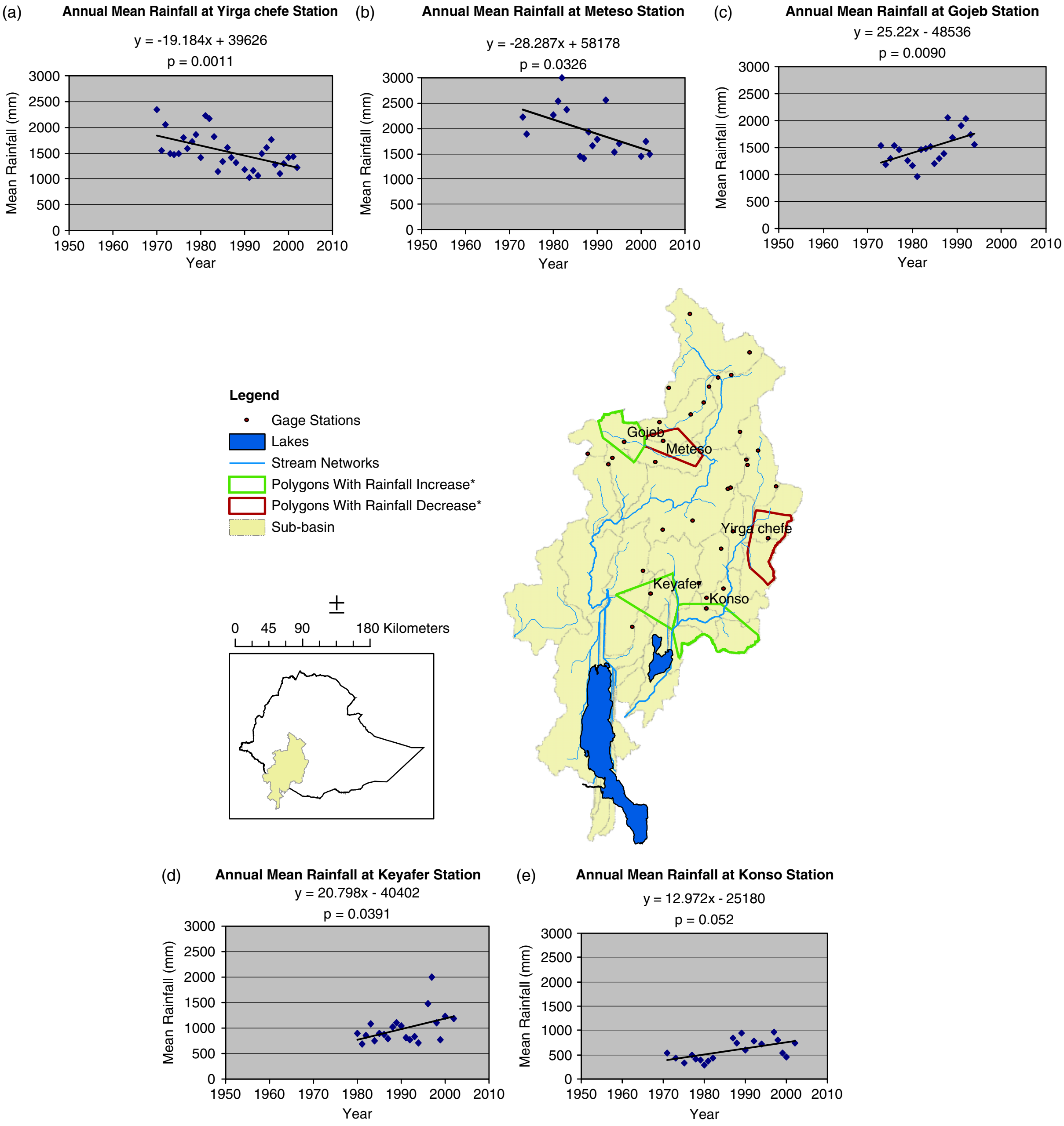

Figure 6. Gauge level analysis at watershed 4 (Omo-Ghibe) shows two Thiessen polygons (a–b) with significant decreases in rainfall and three (c–e) with significant increases in rainfall. *Significant at 0.05 level. This figure is available in colour online at www.interscience.wiley.com/ijoc

gauge stations, the formerly significant decline in rainfall became insignificant ($p = 0.2980$), thereby demonstrating the danger of including unrepresentative averages or annual watershed rainfall that may be calculated from averaging an insufficient number of gauge observations (Table III). This danger is magnified in large watersheds with highly inconsistent gauge observations. In such watersheds, the annual watershed rainfall for certain years may depend on the observation of a single station, thereby reflecting the rainfall changes at one station and not the trend experienced by the watershed as a whole.

Given our uncertainties about the definition of the southwestern region, as mentioned in Seleshi and Zanke (2004), we combined watersheds 3 and 4 in order to approximate the area of the southwestern/western region

Table III. Comparison of watershed and regional regressions with and without the 25% rule for selective watersheds.

Watershed	Method	Number of years analysed	Change in rainfall (mm/year)	*p*-value
1	Without 25% rule	43	−1.9	0.3825
	With 25% rule	37	−4.5	0.0588
3	Without 25% rule	N/A[b]	N/A[b]	N/A[b]
	With 25% rule	43	−1.5	0.6670
4	Without 25% rule	43	−5.0[a]	0.0159
	With 25% rule	33	2.7	0.2980
3 and 4	Without 25% rule	43	−9.9[a]	0.0003
	With 25% rule	31	0.6	0.9260

[a] Statistically significant at the 0.05 level.

[b] All observations satisfied the 25% rule requirement.

that was reported to be experiencing an overall decline in annual rainfall since the 1960s (Verdin *et al.*, 2005). By including all of the annual rainfall observations (including all available data regardless of the 25% rule) from both watersheds in a single regression, we found a significant decline of 9.9 mm/year ($p = 0.0003$) in rainfall for the combined regional unit (Table III). While our regional results agree with previous findings which documented a significant decline in rainfall in southwestern Ethiopia (Seleshi and Zanke, 2004; Verdin *et al.*, 2005), when the two watersheds were analysed independent of each other, only watershed 4 showed a significant decline in rainfall (Table III). Thus, by comparing our results from the regional analysis with those from the watershed-level analysis, it is clear that the choice of aggregation scheme can produce dramatically different and potentially misleading results.

In order to fully grasp the importance of the 25% rule in eliminating unrepresentative observations, we compared the rainfall trends of watershed 4 constructed using observations, with the 25% rule and without applying the 25% rule. In addition, the watershed 4 rainfall trends were compared with rainfall trend in neighbouring watershed (watershed 3) constructed using observations which fulfilled the 25% rule. Our result shows that when watershed 4 was analysed without applying the 25% rule, there was a significant decline in rainfall (Table III). However, when the same watershed (watershed 4) was analysed after applying the 25% rule, there was no significant decline in rainfall, which was consistent with the trend observed in the neighbouring watershed 3 (Table III). This shows that the 25% rule can remove unrepresentative observations that may be driving trends that are not reflective of reality.

4.5. Other considerations

We acknowledge that rainfall is a continuous geographical phenomenon that undergoes gradual changes over space and time, and realize that the use of artificial units of spatial aggregation, such as Thiessen polygons, does not truly represent reality. Because Thiessen polygons are calculated merely as a function of distance without any contextual information (e.g. topography of the area or windspeed), they ignore crucial information that may affect a rain gauge's representative range. However, in the absence of extensive information on variables such as intensity of individual storm events, or the quality of gauges, we think that the relatively large sample sizes (>30 years) should not only satisfy the normality assumption but should also minimize errors created by irregular observations. In addition, compared to the simple inclusion method, the Thiessen polygon technique is more precise in the sense that it is less likely to classify a sub-watershed as one experiencing changes in rainfall simply because its periphery contains a single gauge that recorded significant changes. While other procedures such as Cokriging and Kriging can improve the accuracy of rainfall interpolation, we feel that Thiessen polygons are sufficient for our study given our desire to approximate preliminary areas of interest rather than to interpolate rainfall information over large distances.

5. Conclusion

Although the problem of data inconsistencies has undoubtedly interfered with this study, such a problem is common in the real world and has been acknowledged by previous studies of rainfall trends in Ethiopia (Devereux, 2000; Easterling *et al.*, 2000; Seleshi and Zanke, 2004). Given our desire to devise a robust and geographically meaningful method that will enable government and development agencies to discern the spatio-temporal dynamics of rainfall without extensive expertise, we have demonstrated how simple statistical analyses and historical rain gauge data can be used to characterize rainfall.

Overall, this study showed that there are no significant changes or trends in annual rainfall at the national or watershed level in Ethiopia. Our analysis of trends in seasonal rainfall for different parts of the country found that while the highly variable Belg rain did not display any significant changes over the study period, the Kiremt rain was decreasing in watersheds 2, 3, 4, and 6. In our analysis of previous studies, we have demonstrated that the inclusion of non-representative observations and the use of arbitrary levels of aggregation can potentially lead to imprecise and contradictory findings. Therefore, in implementing rainfall trend studies, it is imperative to define the study area in a geographically meaningful manner. This will not only simplify inter-study comparison, but will also increase the precision of development efforts.

Acknowledgements

This study was carried out with the generous technical and financial support provided by the UNEP/DEWA, South Dakota State University-Geographic Information Science Center of Excellence (GIScCE), and US Geological Survey/Earth Resources Observation and Science (USGS/EROS). The Ethiopian NMA is acknowledged for providing most of the dekadal rainfall information for the study. The support and suggestions provided by Seyoum Asamenaw, Henok Alemu, Norman Bliss, Carol Deering, Arvind Pasula, Smita Shrivastav, and other members of USGS EROS as well as UNEP/DEWA are also gratefully recognized.

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the US Government.

References

Bekele F. 2000. *Ethiopian Use of ENSO Information in its Seasonal Forecasts*. National Meterological Services Agency: Addis Ababa.

Bollinger L, Stover J, Seyoum E. 1999. *The Economic Impacts of AIDS in Ethiopia*. Futures Group International: Washington, DC.

Central Intelligence Agency (CIA). 2006. Ethiopia, *The World Factbook*, Retrieved July 17, 2006, from https://www.cia.gov/cia/publications/factbook/geos/et.html.

Conway D. 2000. Some aspects of climate variability in the Northeast Ethiopian Highlands – Wollo and Tigray. *SINET – Ethiopian Journal of Science* **23**: 139–161.

Devereux S. 2000. *Food Security in Ethiopia: A Discussion Paper for Department of International Development*. Institute of Development Studies: Sussex.

Easterling DR, Evans JL, Groisman PY, Karl TR, Kunkel KE, Ambenje P. 2000. Observed variability and trends in extreme climate events: a brief review. *Bulletin of the American Meteorological Society* **81**: 417–425.

ESRI. 2004. *ArcGIS 9*. Environmental Systems Research Institute (ESRI): Redlands, CA.

Gissila T, Black E, Grimes D, Slingo J. 2004. Seasonal forecasting of the Ethiopian summer rains. *International Journal of Climatology* **24**: 1345–1358, DOI: 10.1002/joc.1078.

Goovaerts P. 2000. Geostatistical approaches for incorporating elevation into the Spatial interpolation of rainfall. *Journal of Hydrology* **228**: 1–2.

Hulme M. 1990. The changing rainfall resources of Sudan. *Transactions of the Institute of British Geographers* **15**: 21–34.

Illius AW, O'Connor TG. 1999. On the relevance of nonequilibrium concepts to arid and semiarid grazing systems. *Ecological Applications* **9**: 798–813.

Integrated Regional Information Networks-United Nations Office for the Coordination of Humanitarian Affairs (IRIN). 2003. Ethiopia: Warning of huge food needs by 2007, Addis Ababa, 14 October.

Marceau D. 1999. The scale issue in social and natural sciences. *Canadian Journal of Remote Sensing* **25**: 347–356.

Osman M, Sauerborn P. 2002. A Preliminary Assessment of Characteristics and Long Term Variability of Rainfall in Ethiopia – Basis for Sustainable Land Use and Resource Management. In Challenges to Organic Farming and Sustainable Land Use in the Tropics and Subtropics, Deutscher Tropentag 2002: Witzenhausen.

Seleshi Y, Zanke U. 2004. Recent changes in rainfall and rainy days in Ethiopia. *International Journal of Climatology* **24**: 973–983, DOI: 10.1002/joc.1052.

Senay G, Verdin J. 2003. Characterization of yield reduction in Ethiopia using a GIS-based crop water balance model. *Canadian Journal of Remote Sensing* **29**: 687–692.

Shanko D, Camberlin P. 1998. The effects of the Southwest Indian Ocean tropical cyclones on Ethiopian drought. *International Journal of Climatology* **18**: 1373–1388.

The Economist Group. 2002. Africa's horn of famine. *Economist* **365**: 16–22.

United Nations Country Team (UNCT). 2006. *Focus on Ethiopia-Oct 2006*. Retrieved March 1, 2007 from http://www.reliefweb.int/rw/RWB.NSF/db900SID/STED-6V7TET?OpenDocument.

U.S. Library of Congress. 2005. Ethiopia, *Country Studies Handbook*, Retrieved July 17, 2006, from http://countrystudies.us/ethiopia/.

USGS. 2006. HYDRO 1k Basins data set for Africa, *HYDRO 1k Elevation Derivative Database*, Retrieved July 17, 2006 from http://edc.usgs.gov/products/elevation/gtopo30/hydro/africa.html.

Verdin J, Funk C, Senay G, Choularton R. 2005. Climate science and famine early warning. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences* **360**: 2155–2168.

Webster PJ, Holland GJ, Curry JA, Chang HR. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* **309**: 1844–1846, DOI: 10.1126/science.1116448.

WMO. 1992. *International Meteorological Vocabulary*, 2nd edn. World Meteorological Organization (WMO): WMO Publication 182: Geneva.

Wolde-Georgis T, Aweke D, Hagos Y. 2007. Ethiopia country case study: impacts and responses to the 1997–98 El-Nino event, Retrieved March 1, 2007 from http://www.ccb.ucar.edu/un/ethiopia.html.

Poverty-Environment Partnership 2003. *Poverty and Climate Change: Reducing the Vulnerability of the Poor Through Adaptation*. World Bank: Washington, DC. http://lnweb18.worldbank.org/ESSD/envext.nsf/46ByDocName/PovertyandClimateChangeReducingtheVulnerabilityofthePoorthroughAdaptation/$FILE/PovertyAndClimateChangeReportPart12003.pdf.