INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **27**: 1467–1477 (2007)
Published online 22 May 2007 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/joc.1481

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A note on the temporal and spatial variability of rainfall in the drought-prone Amhara region of Ethiopia

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Abstract:

The aim of this study is to characterise rainfall variability and trend in the drought-prone Amhara Regional State of Ethiopia using standard rainfall statistical descriptors. A review of previous studies of Ethiopian rainfall shows different conclusions between studies about the existence of trends primarily due to their use of different periods of analysis. Various rainfall indicator series are presented and analysed for trend on annual, seasonal and daily time steps (including wet-day amounts and probabilities, percentiles and dry spell lengths). Two periods are used for analysis: 1975–2003 (12 stations) to optimise station density and 1961–2003 (five stations) to optimise record length in this relatively poorly monitored region.

A complex picture of rainfall variability emerges from the analysis, both in terms of spatial variability and temporal variability, from decadal to daily timescales. The results generally support those of the previous studies in Ethiopia with the additional findings that: (1) High levels of spatial variability exist at subregional scales in Ethiopia that are unlikely to be fully explained by large-scale climate influences; (2) Choice of study period strongly influences the results of trend analysis in this region due to the effects of decadal variability (particularly because the 1980s was the driest decade and the 1990s the wettest decade on record); (3) Annual rainfall in the region recovered during the 1990s, although 2001–2003 were average or slightly lower; and (4) There are no consistent emergent patterns or trends in daily rainfall characteristics in this part of Ethiopia. Copyright © 2007 Royal Meteorological Society

KEY WORDS rainfall variability; spatial; temporal; trend; Ethiopia

Received 15 August 2005; Revised 14 November 2006; Accepted 19 November 2006

INTRODUCTION

Agriculture is the source of livelihood to an overwhelming majority of Ethiopia's population. It employs some 80% of the labour force and accounts for 45% of the GDP and 85% of the export revenue (FDRE, 1997b) in any single year. The sector is presently given particular emphasis in the overall economic development strategy of the country, which is known as *Agriculture Development Led Industrialisation*. Ethiopian agriculture is heavily dependent on natural rainfall, with irrigation agriculture accounting for only around 1.1% of the total cultivated land in the country. The amount and temporal distribution of rainfall is thus the single most important determinant of national crop production levels from year to year, and rainfall in much of the country is often erratic and unreliable. Rainfall variability and associated droughts have historically been major causes of food shortages and famine in the country (Wood, 1977; RRC, 1985; Pankhurst and Johnson, 1988). Even though drought followed by food insecurity is not a new phenomenon in Ethiopia, its frequency of occurrence has increased during recent decades (Ezra, 1997; Tilahun, 1999).

The temporal distribution of rainfall during the growing season is an important influence on crop yields and can induce food shortages and famine. Yet, very few studies have considered in detail the relation between crop yields and rainfall characteristics in Ethiopia. At the national scale the link between drought and crop production has been widely documented, for example, von Braun (1991) reported that a 10% decrease in seasonal rainfall from the long-term average generally translates into a 4.4% decrease in the country's food production. The details of specific events at the regional and subregional levels, however, remain contested with debate about the interactions and importance of confounding factors such as the civil war, land tenure, poverty and long-term environmental change (Rahmato, 1991; de Waal, 1994). Indeed, statistical associations between rainfall and crop production at subregional scales have not been studied in any detail.

In addition to high inter-annual rainfall variability, some researchers report that rainfall has recently exhibited a downward trend in parts of the country. Seleshi and Demarée (1995) identified a declining trend in the main June–September (*kiremt*) rains,

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mainly because of reduction of July and August rainfall, for the period 1965–1984 in the northcentral Ethiopian highlands (June–September and March–May are called *kiremt* and *belg* seasons, respectively, in Ethiopia). This negative trend in seasonal rainfall was attributed to atmosphere–ocean interactions. Similarly, Osman and Sauerborn (2002) also described a downward trend for annual rainfall in the central highlands. More recently, FEWS (2003) reported a significant decreasing trend of the *kiremt* rains in the southwestern highlands of the country for the period 1961–1996. On the other hand, Conway (2000) reported absence of any long-term trend for annual rainfall in the northern and northeastern parts of the country. This was supported by Seleshi and Zanke (2004) who found no significant trend in the annual and seasonal rainfall totals in the central, northern and northwestern parts of the country over the period 1965–2002. They (*ibid.*), however, did find significant declines in the annual and *kiremt* rainfall totals in the eastern, southern and southwestern parts of Ethiopia. Seleshi and Camberlin (2006) reported absence of trends in many indices of extreme rainfall events for the *kiremt* and *belg* rainfall seasons in much of Ethiopia and absence of trend in the length of maximum dry spells (days with <1 mm rainfall) in both seasons. Conway *et al*. (2004) analysed the 104 year rainfall record at Addis Ababa in the central Ethiopian highlands and found no trend over the period (1898–2002). Meze-Hausken (2004) also reported absence of a declining trend in rainfall in the northern and northeastern parts of Ethiopia despite the local people's perceptions that the total rainfall had decreased over the past 25–30 years because of the loss of spring rains (*belg*) and shortened *kiremt*.

The main reason for the contrasting results of trend identification in annual rainfall in the central and northern highlands is the use of different periods in the analyses. In the region the 1980s were generally dry relative to preceding decades whilst rainfall recovered during the 1990s – trend analysis that ends during the late 1980s or early 1990s, therefore, shows a declining trend, however, when the period is extended this trend in annual rainfall is reduced or even removed. Seasonal and intra-seasonal trends may exist, as may more localised trends. Certainly as Meze-Hausken (2004) notes, local perceptions of change in rainfall may indicate changes in intra-seasonal distribution of rainfall and their effects on crop production and pasture availability for local people. For instance, Tessema and Lamb (2003) observed a significant inter-annual variability in the onset, cessation and length of growing period during 1965–1999 in the northeastern part of the country. Similarly, Seleshi and Zanke (2004) found no trend over the central, northern and northwestern parts, but a declining trend in the eastern and southwestern parts of the country during the period 1965–2002. More work needs to be done to reconcile meteorological observations with local people's experience and perceptions.

Most studies of long-term rainfall behaviour have been restricted by the low number of long series available for much of Ethiopia. Some studies have been based on areal averages, which may also mask spatial variability (Seleshi and Demarée, 1995; Osman and Sauerborn, 2002) while others have been based on too few stations to be fully representative of the spatial variability in the study regions (Meze-Hausken, 2004; Seleshi and Zanke, 2004). Such analyses may easily miss out localised trends in the Ethiopian highlands particularly because of the diverse topography and the role that altitude plays in the distribution of climatic elements in the country (Gamachu, 1988; Krauer, 1988). Gissila *et al*. (2004) also demonstrate spatial variation in inter-annual rainfall variability and influence of the southern oscillation index on the total *kiremt* rainfall. This implies that local scale spatial and temporal rainfall variability in much of Ethiopia is so far largely unknown and remains to be investigated.

The aim of this study is to analyse, in detail, rainfall variability and trend in the Amhara National Regional State (ANRS) (Figure 1). By using data from a relatively dense network of stations, the study examines temporal and spatial patterns in rainfall of a subregional scale. Previous studies have analysed rainfall data using only a few stations with long records in the Amhara region, which includes North and South Wello and experiences frequent crop failure and food shortages. Of the 105 *woredas* (Districts) in the region, 48 are drought-prone and, consequently, suffer from chronic (long-term) and episodic food-insecurity (USAID, 2000). The linkages between crop yields and rainfall will be explored in a companion paper (Bewket and Conway, in preparation), which also examines the theoretical and actual ability of rainwater harvesting methods to reduce vulnerability to soil moisture/rainfall deficits, on the basis of the sampling of existing programmes aimed at enhancing food security in the region. Here, we begin with a short description of the study area, the rainfall data and the methods used in the analysis. This is followed by the results sections that present, in order, seasonal and spatial patterns, seasonal and annual trends, and daily trends in rainfall in the region. The paper ends with a short discussion and the main conclusions.

THE AMHARA NATIONAL REGIONAL STATE (ANRS): BRIEF DESCRIPTION OF STUDY AREA

The ANRS is located in the northwestern and northcentral parts of Ethiopia and lies within 9° and 13°45′N and 36° and 40°30′E (Figure 1). It has a total area of $\sim$170 000 km^2, which is divided into 11 administrative zones (provinces) and 105 w*oredas*. Rugged mountains, plateaux, valleys and gorges characterise its physical landscape. Elevations range from 700 m in the eastern part to over 4600 m in the northwest. Areas lying below 1500 m are commonly classified as lowlands and those with elevations of $\geq$1500 m are classified as highlands (FDRE, 1997a). Following this classification, 69% of the total area of the ANRS is highland and the remaining 31% is lowland. Around 50% of the total area of the ANRS

DOI: 10.1002/joc

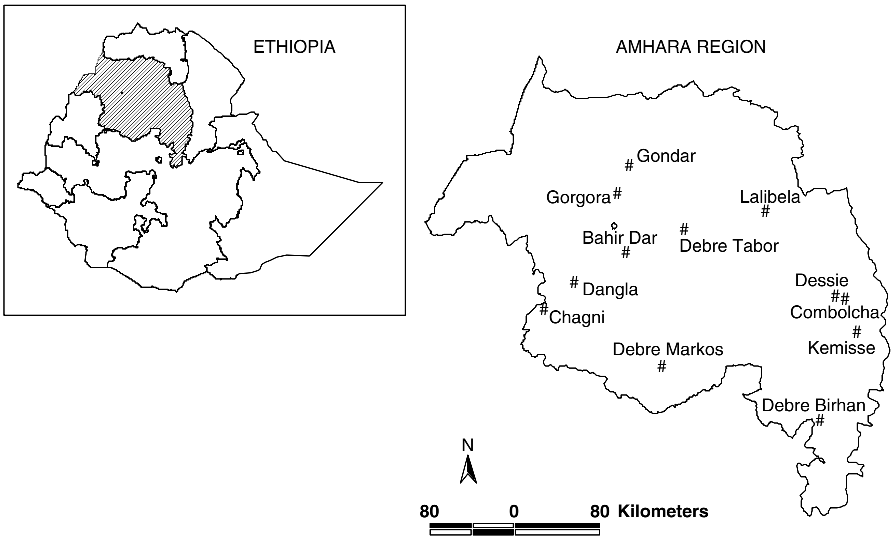

Figure 1. The ANRS and location of the 12 stations used in the study.

is considered to be arable land. Currently, 60% of the total area is used for cultivation and grazing (30% each), 17% is under forests, woodlands and shrublands, 4% is covered by water bodies, 3% is occupied by settlements and 16% is wasteland (Lakew *et al.*, 2000).

Land degradation and drought are the major physical challenges to agriculture in the ANRS. The rugged topography, expansion of cultivation into steeplands owing to increasing population pressure, intense grazing pressure, and torrential rains are linked with land degradation mainly due to soil erosion by water. According to Lakew *et al.* (2000), 10% of the total area of the ANRS suffers from annual soil loss rates of >200 t/ha, and 29% of the total area experiences soil loss of 51–200 t/ha per year. In the remaining area, annual soil loss rates are 16–50 t/ha (in 31% of total area) and <16 t/ha (in 30% of total area). These estimates are, however, based on plot scale measurements and should be interpreted with caution, as there are methodological problems associated with their scaling-up to larger areas.

Agricultural drought is the other major problem in the Amhara region. The eastern parts of the region are particularly affected by recurrent droughts. According to USAID (2000 : 3), 'there has been no single year since 1950 where there was no drought in this part of the region'. This statement is, however, not based on analysis of climatological records; it probably refers to the persistent problem of food insecurity in the area. Droughts often translate into food shortages and famines in the region because of the heavy dependence of agricultural production on natural rainfall. Irrigated agriculture is negligible in the ANRS, although 500 000 ha of land are considered to be suitable for irrigation agriculture (IWMI, 2004).

RAINFALL DATA AND DESCRIPTORS

The data used for the study were collected from the National Meteorological Services Agency of Ethiopia.

Table I. Details of rainfall stations used in the study.

Station	Altitude (m)	Years of observation	No. of years with no data[a]
Bahir Dar	1805	1961–2003	–
Chagni	1587	1973–2003	7
Combolcha	1903	1953–2002	–
Dangla	1981	1959–2003	23[b]
Debre Birhan	2640	1984–2003	–
Dessie	2402	1962–2003	1
Debre Markos	2415	1954–2003	–
Debre Tabor	2945	1975–2003	4
Gondar	2120	1953–2003	–
Gorgora	1803	1972–2003	1
Kemissie	1553	1963–2003	4
Lalibela	2240	1978–2003	4

[a] Years with complete missing records were not included in the analysis.
[b] Missing years = 1969–1991.

Relatively long rainfall records were obtained for 12 stations (Table I), with a reasonably good geographic distribution to cover the study area (Figure 1). Station records are from the early 1950s to the 1980s. Station histories are not known, but it is likely that some have incurred some changes in location and observation practices with implications for homogeneity of their records, particularly for detecting changes in the frequency of extreme events on daily timescales. All records were scanned for discontinuities, outliers and obvious errors – where possible/appropriate these were cross-checked with records from nearby locations and removed if judged erroneous (the number of years with missing data in each record is listed in Table I). The Standard Normal Homogeneity Test (SNHT) is a widely used method to determine homogeneity of records (Peterson *et al.*, 1998). Wijngaard *et al.* (2003) also used this method, along with three others, to evaluate homogeneity of the 20th century European daily temperature and precipitation series.

DOI: 10.1002/joc

We followed the approach in Wijngaard *et al*. (2003) and found that all the monthly, seasonal and annual records are homogenous.

All 12 records are analysed at annual and seasonal time steps and a subset of five records (with long series and for which daily data were available) are analysed at daily time steps. The five stations used for daily analysis were chosen on the basis of their much longer and more reliable records (few missing data, synoptic stations with good support for maintenance). We use two periods for the analysis as a trade-off between optimising for record length and station density, in this relatively poorly monitored region, as follows:

1. 1975–2003: a shorter period comprised of 12 stations located in the region designed to maximise the number of stations and hence spatial coverage,
2. 1961–2003: a longer period comprised of five stations located in the region designed to maximise the period for analysis and hence temporal coverage.

The coefficient of variation and the Precipitation Concentration Index (PCI) are used as statistical descriptors of rainfall variability. The PCI values are calculated as given by Oliver (1980);

$$\mathrm{PCI} = 100 \times [\Sigma P_i^2/(\Sigma P_i)^2]$$

Where P_i is the rainfall amount of the ith month; and Σ = summation over the 12 months.

According to Oliver (1980), PCI values of less than 10 indicate uniform monthly distribution of rainfall, values between 11 and 20 indicate high concentration, and values above 21 indicate very high concentration. Inter-annual fluctuations were evaluated by calculating standardised rainfall anomalies and graphically presenting the results. The standardised rainfall anomalies were calculated as follows:

$$\mathrm{SRA} = (P_t - P_m)/\sigma$$

Where SRA is standardised rainfall anomaly, P_t is annual rainfall in year t, P_m is long-term mean annual rainfall over a period of observation and σ is standard deviation of annual rainfall over the period of observation.

Least squares regression was used to quantify trend and the Spearman's *rho* test was used to test statistical significance of trend. For daily data we calculated the number of wet days, wet-day amounts (classifying wet days as >0.1 mm), probabilities of wet days and dry days, wet spells, and dry spell lengths. Table II presents definitions for these parameters. Dry spell lengths were assumed to finish at missing data, and missing data were ignored in the calculation of number of dry days and mean wet-day amounts. Extremes were examined using low (5th and 10th percentiles) and high (90th and 95th percentiles) wet-day amounts (Table I for definitions). Probabilities of wet days were calculated as follows:

Table II. Definitions of annual rainfall indices.

Index name	Definition
Wet day	A day with rainfall of >0.1 mm
Dry day	A day with rainfall of ≤0.1 mm or no rainfall
Wet spell	Two or more consecutive wet days
Dry spell	Two or more consecutive dry days
5th percentile	The 5th percentile of daily rainfall in a year
10th percentile	The 10th percentile of daily rainfall in a year
90th percentile	The 90th percentile of daily rainfall in a year
95th percentile	The 95th percentile of daily rainfall in a year

$$P(w) = n/N$$

Where $P(w)$ is probability of wet days, n is number of wet days and N is total number of days in a year. Similarly, probabilities of dry days were calculated as follows:

$$P(d) = n/N$$

Where $P(d)$ is probability of dry days, n is number of dry days and N is total number of days in a year.

ANALYSIS AND RESULTS

Seasonal patterns of rainfall

The annual total rainfall in the highlands of the ANRS varies from slightly over 770 mm in Lalibela to >1660 mm in Chagni (Table III). Only three stations (Debre Birhan, Gorgora and Lalibela) experience annual rainfall amounts of <1000 mm. Three stations (Chagni, Dangla and Debre Tabor) receive >1500 mm of rainfall per year. Rainfall is unimodal in most of the region; and bimodal in the Wello highlands (Figure 1). Much of the rainfall is concentrated in the 4 months of the *kiremt* season. The rainfall shows moderate inter-annual variability as shown by the coefficients of variations (Table III). Generally, the *belg* and the *bega* (dry season – October to February) rainfalls are much more variable than the *kiremt* rainfall. A similar conclusion – that *belg* and *bega* rainfalls are more variable than *kiremt* rainfall – was arrived at by Mersha (1999) in his study that analysed rainfall data from 419 stations throughout the country. Mersha (1999, 2003) also reported that rainfall variability is higher in areas of low annual rainfall.

The contribution of *kiremt* rainfall to the annual total ranges from 64% in Combolcha (in the eastern part of the ANRS) to nearly 85% in Gorgora (in the northwestern part) (Table IV). *Belg* rainfall makes a considerable contribution to the annual total in the more easterly stations of Combolcha, Dessie, Kemissie and Lalibela. These stations record rainfall during the *belg* season because of the south-easterly winds from the Indian

DOI: 10.1002/joc

Table III. Annual and seasonal rainfall (mm) and coefficient of variation, 1975–2003.

Station	Annual		*Kiremt*		*Belg*		*Bega*	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Bahr Dar	1445	0.17	1214	0.18	115	0.68	121	0.55
Chagni	1665	0.12	1252	0.11	174	0.50	252	0.34
Combolcha	1045	0.17	669	0.23	230	0.40	143	0.53
Dangla	1542	0.14	1165	0.14	183	0.50	178	0.46
Debre Birhan	893	0.13	691	0.17	139	0.35	60	0.61
Dessie	1193	0.16	787	0.23	251	0.44	163	0.50
Debre Markos	1349	0.12	978	0.12	208	0.41	162	0.55
Debre Tabor	1580	0.18	1253	0.19	156	0.54	160	0.67
Gondar	1110	0.17	876	0.22	140	0.48	109	0.49
Gorgora	959	0.21	815	0.25	93	0.60	68	1.47
Kemissie	1063	0.23	675	0.27	219	0.56	150	0.63
Lalibela	772	0.22	594	0.29	136	0.58	53	0.97

Table IV. Average contribution of the three seasons and the highest monthly rainfall contribution to the annual total (in percent) and the Precipitation Concentration Index (PCI), 1975–2003.

Station	*Kiremt* rainfall	*Belg* rainfall	*Bega* rainfall	Highest monthly rainfall	PCI (%)	Trend of PCI (corr. with time)
B-Dar	84	8	8	33	22	−0.08
Chagni	74	10	15	23	17	0.08
Combolcha	64	22	14	29	18	0.08
Dangla	76	12	11	24	17	−0.17
D-Birhan	77	16	7	36	24	0.29
Dessie	66	21	13	30	18	0.03
D-Markos	73	15	12	25	17	−0.05
D-Tabor	80	10	10	30	20	−0.15
Gondar	78	12	10	29	20	−0.02
Gorgora	85	9	6	31	22	0.03
Kemissie	65	21	15	31	20	0.35[a]
Lalibela	75	18	7	39	27	−0.08

[a] Significant at 0.05 level.

Ocean blowing towards a thermal low (cyclone) which develops over the south of Sudan during this season (Seleshi and Zanke, 2004). The extreme concentration of rainfall can also be seen from the contribution of the single largest monthly total to annual total rainfall at each of the stations (Table IV). The highest monthly totals generally account for a very high proportion of the annual totals and range from 23% in Chagni to nearly 40% in Lalibela. The PCI shows (Table IV) that rainfall in the ANRS is generally characterised by high to very high monthly concentration. Only one rainfall record, Kemissie, showed a significant trend in PCI, towards greater rainfall concentration (Table IV, last column).

Spatial patterns of rainfall

Figure 2(a–c) shows the correlation decay length between the stations for annual, *kiremt* and *belg* series. Correlation between annual series identifies two clusters of spatial coherence in the region. Combolcha, Dessie, Debre Birhan, Kemissie and Lalibela show statistically significant correlations (<0.01 level of significance) and are all located in the eastern part of the ANRS in the Wello highlands (except Debre Birhan). Likewise the correlation coefficients between Bahir Dar, Gondar and Gorgora located in the northwestern parts of the ANRS in the Gojjam and Gondar highlands are significant (<0.01 level). In Figure 2(a–c), correlations between the three stations in the west and the five stations in the east are shown by square and triangular symbols, respectively. The two spatial clusters are also visible from the correlations between *kiremt* rainfalls while they are less distinctive in terms of *belg* rainfalls (Table V).

Inter-station correlations generally decrease with increasing distance between stations. An exponential decay curve is the best fit for the annual and *kiremt* rainfall series, whilst linear fit best describes the correlation decay with distance of the *belg* series. Nevertheless, the results show wide scatter; some stations situated only 50–100 km apart show very low and slightly negative

DOI: 10.1002/joc

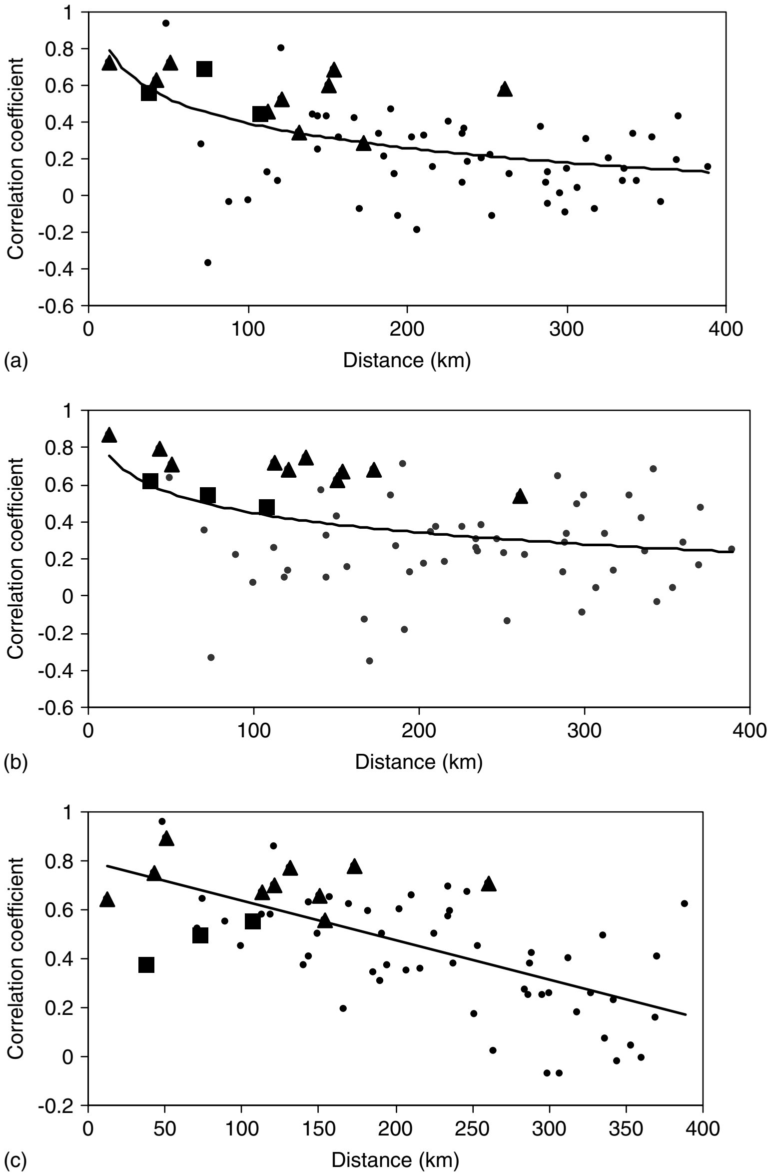

Figure 2. (a) Correlation decay length between annual rainfall series (square and triangular symbols show highly significantly correlated three and five stations in the western and eastern parts of the region, respectively). (b) Correlation decay length between *kiremt* rainfall series (square and triangular symbols show highly significantly correlated three and five stations in the western and eastern parts of the region, respectively). (c) Correlation decay length between *belg* rainfall series (square and triangular symbols show highly significantly correlated three and five stations in the western and eastern parts of the region, respectively).

(all insignificant) correlations. These correlations are generally between stations with short records located in regions with different temporal behaviour of rainfall and no obvious common influence from large-scale forcing.

Table VI lists the driest and wettest years at each of the stations over the common period 1975–2003, which includes the notable drought years in Ethiopia of 1984 and 2002–2003. The 1980s stand out as the decade with driest years in six of the stations in terms of annual rainfall and in nine stations in terms of the *kiremt* rains. The driest *belg* occurred in 1999 in five of the stations. The 1990s stand out as the wettest years in six stations in terms of both annual and *kiremt* rainfalls and nine stations in terms of *belg* rainfall. The two clusters of spatial coherence tend to show similarities more in terms of annual rainfall than the seasonal amounts. Indeed, availability of records for a specific year at a specific location influences identification of driest and wettest years. For instance, there is no data for Kemissie and Lalibela in 1984 – which might possibly have been the driest year at these stations.

Annual and seasonal trend and variability: 1975–2003 and 1961–2003

For the period 1975–2003, annual rainfall shows negative trend in 4 out of the 12 stations and positive trend in eight of the stations (Table VII). The positive trends at Dessie (128 mm/decade) and at Lalibela (101 mm/decade) are statistically significant at <0.01 and 0.05 levels, respectively. The positive trends in annual rainfall at Bahir Dar, Combolcha, Debre Birhan, Debre Markos and Kemissie

Table V. Correlation between seasonal rainfall series at the 12 stations. *Kiremt* (upper half) and *belg* (lower half), 1975–2003.

	B-Dar	Chagni	Combolcha	Dangla	D-Birhan	Dessie	D-Markos	D-Tabor	Gondar	Gorgora	Kemissie	Lalibela
B-Dar	–	0.10	0.22	0.35	0.33	0.23	0.32[a]	−0.34	0.48[b]	0.55[b]	0.12	0.27
Chagni	0.58[b]	–	0.04	0.63	0.28	−0.04	0.43[a]	−0.19	0.17	−0.13	0.16	−0.09
Combolcha	0.02	0.04	–	0.13	0.62[b]	0.87[b]	0.26	0.34	0.54[b]	0.49[a]	0.79[b]	0.75[b]
Dangla	0.52[a]	0.96[a]	0.18	–	0.68[a]	0.04	0.57[a]	0.10	0.15	0.13	0.24	−0.14
D-Birhan	0.40	−0.01	0.66[b]	0.23	–	0.67[b]	0.37	0.33	0.25	0.47	0.72[b]	0.54[a]
Dessie	0.17	−0.02	0.64[b]	−0.07	0.56[a]	–	0.37[a]	0.12	0.28	0.64[b]	0.71[b]	0.68[b]
D-Markos	0.41[b]	0.50[a]	0.57[b]	0.37	0.66[b]	0.50[b]	–	−0.36	0.30[a]	0.18	0.24	0.30
D-Tabor	0.64[b]	0.50[a]	0.35	0.63[a]	0.42	0.37	0.62[b]	–	0.07	0.22	0.38	0.26
Gondar	0.56[b]	0.60[b]	0.26	0.65[b]	0.62[b]	0.38[a]	0.67[b]	0.45[a]	–	0.62[b]	0.42[a]	0.54[a]
Gorgora	0.50[b]	0.19	0.25	0.86[a]	0.41	0.27	0.36	0.55[a]	0.38	–	0.54[a]	0.71[b]
Kemissie	0.25	0.16	0.75[b]	0.07	0.67[b]	0.89[b]	0.59[b]	0.38	0.49[b]	0.26	–	0.68[b]
Lalibela	0.34	−0.07	0.77[b]	0.45	0.71[b]	0.70[b]	0.69[b]	0.58[b]	0.59[b]	0.31	0.78[b]	–

[a] Significant at 0.05 level.
[b] Significant at 0.01 level.

are also high, though not statistically significant due to large inter-annual fluctuations. For the *kiremt* rainfall, increasing trends at Dessie and Lalibela are statistically significant. The other significant trends are the decreasing *kiremt* rainfall at Debre Tabor and the decreasing *belg* rainfall at Dangla (both to <0.1 significance level).

The lower rows of Table VII show the trend over the longer period 1961–2003 with just six stations. Annual rainfall showed declining trends at Bahir Dar and Gondar, but increasing trends at the other four stations. Of these, the increasing trend at Dessie (36 mm/decade) is statistically significant (<0.1 level of significance); much of the increase is due to higher rainfall during the 1990s. Likewise, the increasing trend in the *kiremt* rainfall at Dessie (29 mm/decade) is significant (<0.1 level of significance). At Debre Markos, annual rainfall in the strong drought year 1984 was close to normal. This confirms that the region around Debre Markos was relatively less affected than the northern, northcentral and eastern parts of the country by the devastating drought in 1984. At Gondar rainfall showed negative trends for nine months of the year, of which five are statistically significant; and Bahr Dar experienced statistically significant negative trends for 2 months of the year (monthly results not shown here). Comparison of the trend results for the stations with data in both periods shows the influence of the study period in detecting rainfall trends. For instance, at Bahir Dar annual rainfall shows an increasing trend of 45 mm/decade over the period 1975–2003, but a decreasing trend of 44 mm/decade when the period 1961–2003 is considered.

Figure 3 shows standardised anomalies of annual rainfall at the six stations. During the period 1961–2003, the proportion of negative anomalies ranged from 39% (in Debre Markos) to 53% (in Gondar) of total number of observations. Rainfall in the region shows substantial decadal variability; i.e. persistence, a year with a positive anomaly tends to be followed by another year with a positive anomaly as do years with negative anomalies.

Table VI. The three driest and wettest years and seasons by station during the period 1975–2003.

Station	Driest years			Wettest years		
	Annual	*Kiremt*	*Belg*	Annual	*Kiremt*	*Belg*
B-Dar	1982	1982	2003	1975	2003	1997
Chagni	1986	1979	1986	1988	1985	1976
Combolcha	1984	1984	1999	1998	1994	1993
Dangla	1995	1995	2003	1999	1999	1996
D-Birhan	1984	1987	1999	1986	1999	1987
Dessie	1984	1984	1999	1998	1999	1995
D-Markos	1978	1987	1988	1996	1985	1995
D-Tabor	2002	2002	1981	1977	1977	1993
Gondar	1982	1982	1986	1975	1975	1976
Gorgora	1982	1987	2003	1978	1994	1996
Kemissie	1992	1987	1999	1996	1988	1993
Lalibela	1979	1987	1999	1997	1994	1993

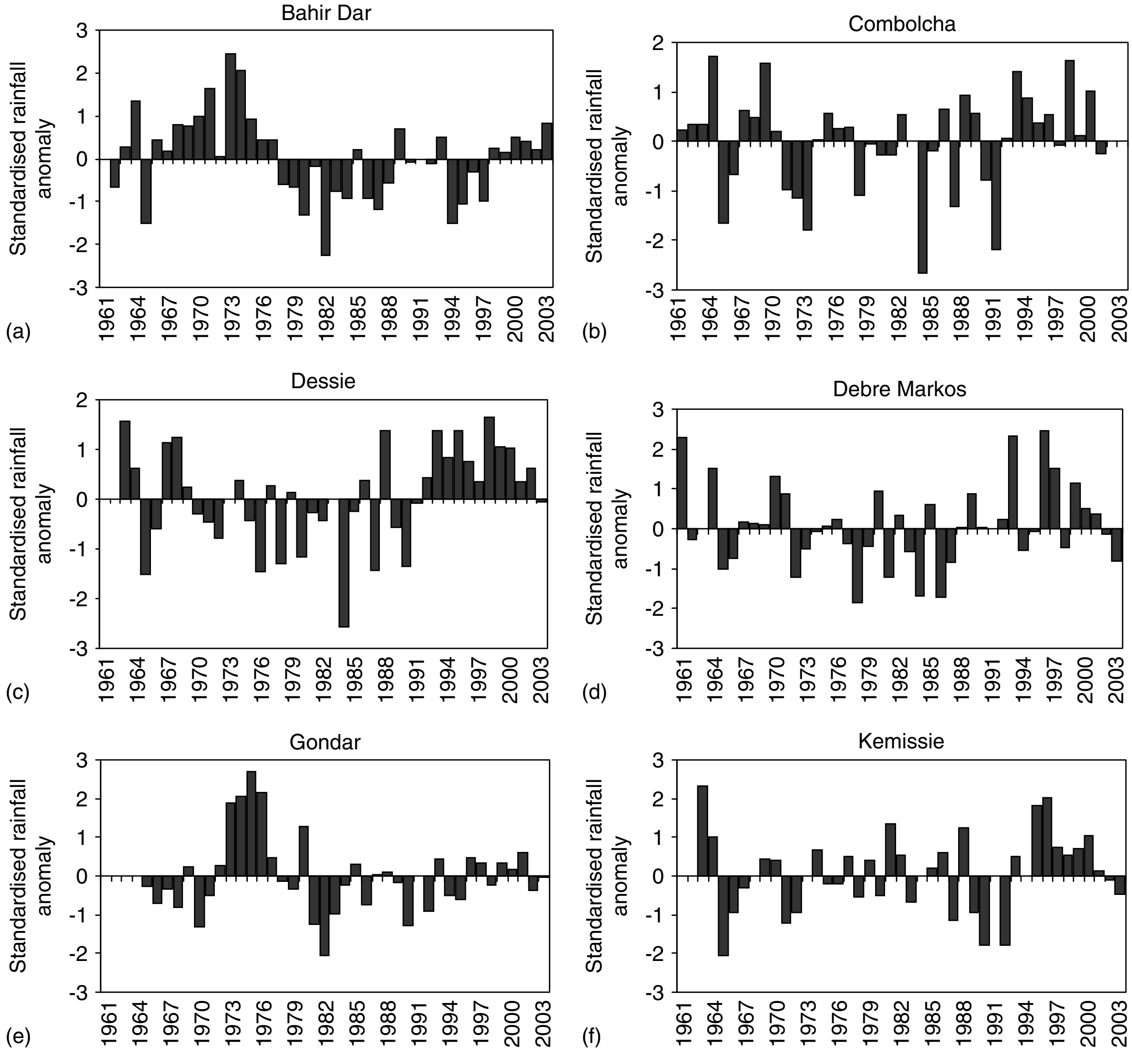

Figure 3. Standardised anomalies of annual rainfall at the six stations. (a) Standardised anomaly of annual rainfall at Bahir Dar. (b) Standardised anomaly of annual rainfall at Combolcha. (c) Standardised anomaly of annual rainfall at Dessie. (d) Standardised anomaly of annual rainfall at Debre Markos. (e) Standardised anomaly of annual rainfall at Gondar. (f) Standardised anomaly of annual rainfall at Kemissie.

At Bahir Dar, annual rainfall shows positive anomaly for the 1966–1977 decade, and negative anomaly for the 1978–1988 decade, except in 1985 when a slight positive anomaly has occurred. During the wettest and the driest years, annual rainfalls have been 2.44 and 2.24 times the standard deviation above and below the long-term (1961–2003) average, respectively. Significant positive anomalies in Gondar and Debre Markos occurred during 1973–1976 and in 1961, 1993 and 1996, respectively. At Dessie, annual rainfall has shown negative anomalies for much of the 1970s and 1980s, and positive anomalies for the decade 1992–2002. During the driest year, 1984, annual rainfall was 2.6 and 2.7 times the standard deviation below the 1961–2003 mean rainfall at Dessie and Combolcha, respectively. As at Dessie, many of the negative anomalies at Combolcha and Kemissie, the other stations in Wello, occurred during the 1970s and 1980s, while positive anomalies have occurred during the 1990s.

Trends in daily rainfall statistics: 1961–2003

Table VIII lists means and trends of daily rainfall statistics for the period 1961–2003. The mean wet-day amount ranged from 7.9 mm in Debre Markos to 12.6 mm in Kemissie; it was higher in Dessie and Kemissie than the other three stations, suggesting rainfall intensity is higher in the eastern part of the ANRS. The 90th and 95th percentile values show similar patterns (higher in Dessie and Kemissie) as do the 5th and 10th percentiles, although Bahir Dar has values closer to Dessie and Kemissie. The probability of a dry day is lowest in Debre Markos and highest (around 75% of days) in Kemissie and Dessie. Mean dry spell lengths ranged from 5.6 days in Debre Markos to 7.6 days in Bahir Dar; the inter-station differences are not large.

The trends in wet-day amount show decreasing values in four of the five stations but these are not statistically significant (except Bahir Dar). In Bahir Dar, the mean wet-day amount decreased at a rate of 0.77 mm/decade during 1961–2003. The 5th and 10th percentiles show

DOI: 10.1002/joc

Table VII. Annual and seasonal rainfall trends for two periods; 1975–2003 (12 stations) and 1961–2003 (six stations with long series).

Station	Annual		*Kiremt*		*Belg*	
	Trend (mm/10 yrs)	Spearman's *rho*	Trend (mm/10 yrs)	Spearman's *rho*	Trend (mm/10 yrs)	Spearman's *rho*
1975–2003	–	–	–	–	–	–
B-Dar	45	0.17	42	0.16	8	0.09
Chagni	−24	−0.17	−12	−0.12	−4	−0.12
Combolcha	51	0.26	60	0.27	−15	−0.16
Dangla	−22	−0.03	12	0.36	−19	−0.56[a]
D-Birhan	62	0.20	73	0.23	−23	−0.16
Dessie	128	0.62[c]	107	0.48[c]	2	−0.04
D-Markos	55	0.26	33	0.26	6	0.04
D-Tabor	−103	−0.28	−101	−0.40[a]	25	0.23
Gondar	−36	−0.02	−29	−0.04	−19	−0.28
Gorgora	29	0.12	11	0.13	−10	−0.01
Kemissie	34	0.21	30	0.11	5	0.04
Lalibela	101	0.47[b]	104	0.45[b]	−19	0.09
1961–2003	–	–	–	–	–	–
B-Dar	−44	−0.22	−30	−0.16	−8	−0.13
Combolcha	12	0.09	14	0.13	−1	−0.03
Dessie	36	0.27[a]	29	0.21[a]	−7	−0.01
D-Markos	4	0.05	8	0.07	−0.3	−0.06
Gondar	−9	0.1	−5	−0.03	−6	−0.14
Kemissie	19	0.15	26	0.15	−2	0.03

[a] Significant at 0.1 level.
[b] Significant at 0.05 level.
[c] Significant at 0.01 level.

Table VIII. Mean wet-day amounts and observed trends in rainfall statistics for five stations with long daily series, 1961–2003.

	Gondar	B-Dar	D-Markos	Dessie	Kemissie
Mean wet-day amount (mm) Trend in mean wet-day amount (mm/10 yrs)	8.3 (−0.27)	11.6 (−0.77[c])	7.9 (−0.03)	12.4 (−0.07)	12.6 (0.24)
5th percentile: Mean Trend (mm/10 yrs)	0.33 (−0.03)	0.44 (−0.15[c])	0.33 (−0.04)	1.46 (−0.25[b])	1.23 (−0.35[c])
10th percentile: Mean Trend (mm/10 yrs)	0.61 (−0.05)	0.74 (−0.24[c])	0.60 (−0.02)	2.18 (−0.42[b])	2.02 (−0.27[b])
90th percentile: Mean Trend (mm/10 yrs)	19.6 (−0.45)	28.28 (−1.50[b])	18.17 (−0.04)	26.12 (0.71)	27.19 (1.4[a])
95th percentile: Mean Trend (mm/10 yrs)	25.9 (−1.11)	37.16 (−1.05)	24.20 (−0.11)	33.18 (1.22)	34.86 (2.11[b])
Mean probability of a dry day Trend in probability of dry days	0.63 (0.00)	0.65 (−0.01[c])	0.52 (0.00)	0.73 (0.00)	0.77 (0.00)
Mean dry spell length (in days) Trend in mean dry spell length (days/10 yrs)	6.0 (−0.09)	7.6 (−0.13)	5.6 (−0.06)	6.7 (−0.05)	7.5(0.29)

[a] Significant at 0.1 level.
[b] Significant at 0.05 level.
[c] Significant at 0.01 level.

decreasing trends in all of the stations, and the trends in Bahir Dar, Dessie and Kemissie are statistically significant (in six out of ten cases). The heavy events, 90th and 95th percentiles, show less coherent patterns of change with increasing trends in Dessie and Kemissie, and moderate decreasing trends at the other stations. The increasing trends in Kemissie (for both the 90th and 95th percentiles) and the decreasing trend in the 90th percentile in Bahir Dar are significant statistically (three out of ten cases). Only Bahir Dar shows a significant decreasing trend in the probability of dry days, and the other stations show no trend. The lengths of dry spells show moderate increasing trend in Kemissie and decreasing trends in the other stations, none of which is significant in statistical terms. Analysis of daily rainfall statistics for the *kiremt* and *belg* seasons separately revealed similar, rather mixed, results (not shown here). A study that covered 14 south and west African countries also reported absence of consistent trends in many precipitation indices across the region over 1961–2000 (New *et al*., 2006).

SUMMARY AND CONCLUSIONS

This study has presented a detailed analysis of rainfall variability and trend in the drought-prone ANRS. By using two sets of station records, one with 12 stations but with shorter records and one with six stations with longer records, the study examined the temporal and spatial behaviour of rainfall on a subregional scale. The main findings of the study are summarised below.

1. Annual rainfall in the ANRS varies from about 770 mm in Lalibela (eastern part) to >1660 mm in Chagni (western part).
2. For the short period, 1975–2003 annual and *kiremt* rainfall show statistically significant increasing trends in Dessie and Lalibela (eastern part). Other significant trends are decreasing *kiremt* rainfall in Debre Tabor and decreasing *belg* rainfall in Dangla. For the longer period (six stations), the only significant trends are the increasing annual and *kiremt* rainfall at Dessie. Recovery of rainfall during the 1990s from the low values of the 1980s obscures decadal scale trends in annual and seasonal rainfall at some stations. Many stations show drier conditions in 2002 and 2003.
3. Correlation between annual series identifies two clusters of spatial coherence in the region: the eastern part and the western part. The two spatial clusters are also visible from the correlations between *kiremt* rainfalls while they are less distinctive in *belg* rainfalls.
4. The mean wet-day amount ranges from 7.9 mm in Debre Markos to 12.6 mm in Kemissie; i.e. rainfall intensity is higher in the eastern part of the ANRS. The probability of dry days is lowest in Debre Markos and highest (∼75% of days) in Kemissie and Dessie. Mean dry spell length ranges from 5.6 days in Debre Markos to 7.6 days in Bahir Dar; however, the inter-station differences are not large.
5. Trend analysis of daily rainfall indicators shows no clear emergent patterns. Bahir Dar shows a significant decreasing trend in mean wet-day amount and in the probability of dry days; the other stations show no significant trends in these indicators. There is no trend in dry spell length in any of the stations. Of the extreme daily amounts, the 5th and 10th percentiles show significant decreasing trends in Bahir Dar, Dessie and Kemissie (in six out of ten cases). The heavy events, 90th and 95th percentiles, show less coherent patterns of change with increasing trends in Dessie and Kemissie, and moderate decreasing trends at the other stations.

Significant progress has been made in recent years towards a better understanding of large-scale influences on Ethiopian rainfall (Shanko and Camberlin, 1998; Gissila *et al*., 2004; Seleshi and Zanke, 2004 and Tessema and Lamb, 2003). The focus in this study has been to describe rainfall variability as a basis for improving the understanding of crop-climate relationships in this drought-prone region. In a follow-up paper, we analyse impacts of rainfall variability on yields of staple crops and investigate the benefits of rainwater harvesting as a livelihood strategy (Bewket and Conway, in preparation). In conclusion, this study has shown that there are significant intra-regional differences in rainfall amount, variability and trend. In general, rainfall amount is higher and its variability lower, in the western part of the region than in the eastern part. Examination of trends in mean wet-day amount, probability of dry days, mean dry spell length, and the 5th, 10th, 90th and 95th percentiles of daily rainfall shows absence of any systematic patterns of change across the region. The observed trends in some of the indices are thus mainly dependent on local scale climatic controls, rather than large-scale climatic forcing.

ACKNOWLEDGEMENTS

This study was made possible by the global change SysTem for Analysis, Research and Training (START) program fellowship award given to the first author. We are grateful to the Ethiopian National Meteorological Services Agency for kindly providing us with the rainfall data.

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