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# SOME ASPECTS OF CLIMATE VARIABILITY IN THE NORTH EAST ETHIOPIAN HIGHLANDS - WOLLO AND TIGRAY

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**ABSTRACT:** This paper presents a review of climate variability in the northeast Ethiopian Highlands, particularly Wollo and Tigray, during the last 10000 years (the Holocene) and an analysis of rainfall variability during the historical period. To date little work has been done on climate reconstruction in Tigray and Wollo, however, a number of ongoing studies in the area using palaeosoil analysis, archaeological techniques and lake level reconstruction will help reveal the magnitude of past climate variability in the region. On recent time scales, rainfall over Wollo is characterised by a distinctive bi-modal pattern with *Belg* rains in April-May preceding the main wet season *Krempt*, July to September, which is typical of the study region along much of the eastern escarpment. Further north over Tigray the *Belg* rains are less marked and the main *Krempt* rains dominate the seasonal pattern. Only three stations in the region, Dessie, Combolcha and Mekele, possess relatively unbroken records back to the 1950s. In all three, 1984 stands out as the driest year on record due to very low rainfall during the *Krempt* season, whilst 1999's *Belg* season was the driest on record. Although the succession of dry years between the late 1970s and late 1980s produced the driest decade in the Ethiopian Highlands this century there is no evidence for a long-term trend or change in the region's annual rainfall regime. Rainfall during the 1990s has seen a return to more humid conditions since the dry 1980s. The paper ends with a discussion of the major influences on rainfall variability over the Ethiopian Highlands: the El Niño-Southern Oscillation - El Niño events tend to be associated with lower than average rainfall; Atlantic, Indian and Pacific Ocean sea surface temperatures play a varying role in different seasons; the strength of the Indian Summer Monsoon; and the frequency of several tropical depressions over the Southwest Indian Ocean.

**Key words/phrases: Climate, El Niño, Ethiopian Highlands, Holocene, rainfall variability**

## INTRODUCTION

This paper presents a review of climate variability in the north-east Ethiopian Highlands with particular emphasis on Wollo and Tigray. The fundamental questions regarding climate in Ethiopia concern the nature of the droughts of the 1970s and 1980s – were they extreme events (or sequences of events) within the normal range of natural climatic variability or were they so extreme as to be unprecedented in history and part of some secular change or trend in the climate experienced in the Ethiopian Highlands? This paper will attempt to answer these questions and put the droughts of recent decades into climatic perspective over longer time scales. First, by reviewing research that has been undertaken in the region into climate reconstruction in the period before historical observations, which begins roughly at the turn of the century. This is then put into context with an assessment of the climate and rainfall variability during the last century using the few long duration rainfall records that exist for the region. These rainfall fluctuations are then discussed in the light of current understanding of the causes of climate variability in the region, particularly influences from El Niño-Southern Oscillation events, the strength of the Indian Monsoon and fluctuations in sea surface temperatures and atmospheric circulation patterns in the Atlantic, Indian and Pacific Oceans.

## CLIMATE VARIABILITY DURING THE HOLOCENE

There are only a few studies dealing specifically with Holocene climate in Ethiopia most of which deal with lake level fluctuations in the Ethiopian Rift Valley Lakes. Street-Perrott and Perrott (1993) reviewed the research on changes in Holocene vegetation in Africa and changes in level of many African lakes as indicators of climate change. They conclude that the findings, together with results from numerical simulations based on astronomical theory of climate change (which are in agreement with the proxy data), suggest that an insolation maximum in the northern summer (9000 yr BP) led to stronger monsoon rains across northern Africa. By 6000 yr BP the Northern Hemisphere summer monsoon was still stronger than today, although its northern limit had retreated southward due to decay in the insolation anomalies. Their review does not consider climatic variations on shorter timescales ($10^2$–$10^3$ yr) superimposed on trends due to orbital forcing. However, they emphasise the importance of understanding the causes of such short-term variations in order to achieve a full understanding of Holocene climate in Africa. Nicholson and Flohn (1980) studied environmental and climatic changes in Africa in the late Pleistocene and Holocene, and Nicholson (1978; 1996) reviewed climatic variations in the Sahel and other regions of Africa over the last five centuries. Williams and Faure (1980) and Williams and Adamson (1981) edited two major books on quaternary environments in the Nile region. Both volumes concentrate on work undertaken in Sudan and Egypt, although there is some work dealing specifically with conditions in the Ethiopian highlands (Messerli and Winiger, 1980).

Gasse and Street (1978) found an early to mid-Holocene period of high lake levels in the Lake Ziway-Shala Basin followed by a well-defined regression between 6000 and 4000 yr BP. Gillespie *et al.* (1983) used various types of geomorphological and stratigraphical evidence to reconstruct Ziway-Shala Basin lake levels back to 14,000 yr BP. They found the post-glacial wet phase in tropical Africa (12500 to 5000 yr BP) was interrupted by several severe dry episodes (11000–10000, 8500–6500 and 6200–5800 yr BP) that were possibly drier than present day conditions. A major recession occurred around 5000 yr BP and since then dry conditions have prevailed. Gasse *et al.* (1980) discuss fluctuations in the Ziway-Shala Basin and also Lake Abbé, the terminal lake of the Awash river. Bonnefille and Mohammed Umer (1994) produced a 3000-yr high resolution pollen record from the Awash Mountain (just east of the Ziway-Shala Basin). Changes in species composition suggested a cooling of 2° C occurred at 560 + 120 yr BP and recent regrowth of the forest was indicative of a recent warming trend. Indeed, the development of forest above 3600 m in Ethiopia suggested that the warmest temperatures in the last 3000 years have occurred during the most recent decades.

There has been much less work undertaken further north and east in Wollo or Tigray. Hurni (1982) reconstructed snow line migrations during the Holocene in the Simen Mountains when altitudinal belts reached 800 m lower than present day (roughly 7° C cooler, between 20000–12000 yr BP). Williams *et al.* (1978) identified fossil periglacial deposits in the Simen Mountains. Messerli and Winiger (1980) estimated the lower limits for glaciation in the Simen Mountains at 4250 m and Gasse *et al.* (1980) put the maximum glaciation at between 27000 and 21000 BP. Ogbaghebriel Berakhi *et al.* (1998) undertook a geomorphological and stratigraphical analysis of a sedimentary sequence in the upper valley of the Mai Maikden river, about 10 km north of Mekele (Fig. 1).

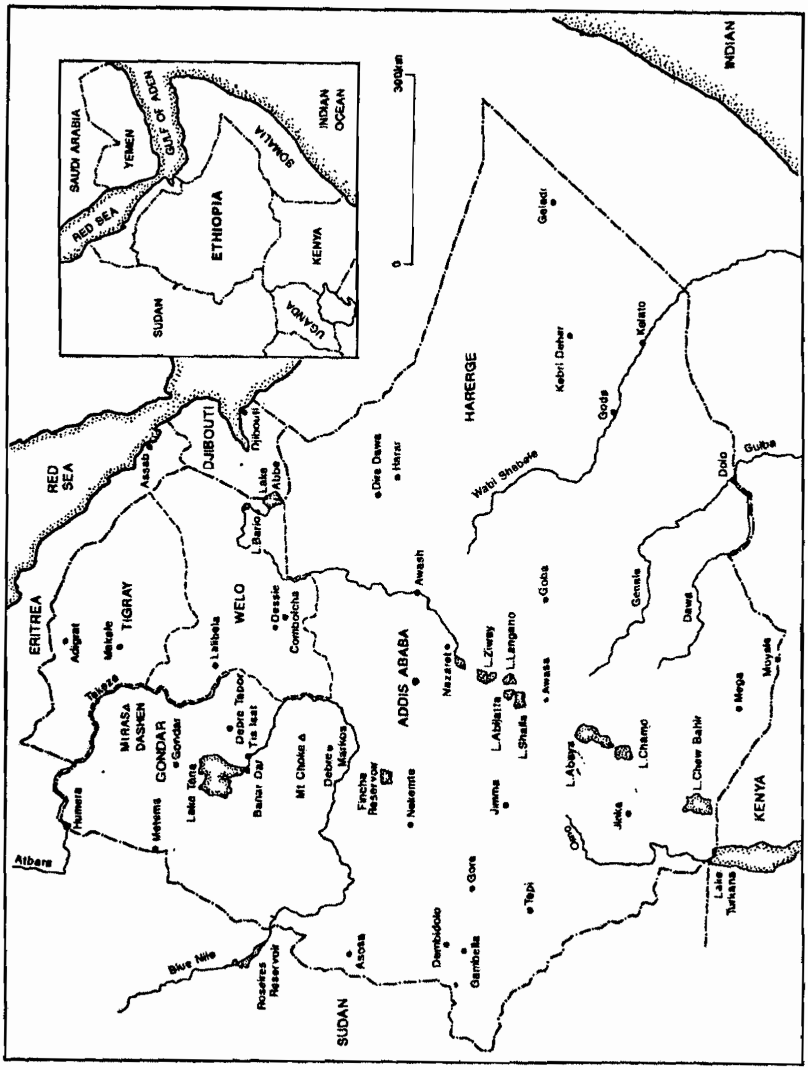


**Fig. 1.** Ethiopia and Eritrea and location of rain gauges used in this study (see Table 1 for list of rain gauges).

**Table 1. Characteristics of key rain gauge series within or close to the study region with long duration records.**

| Rain gauge | Lat. (°N) | Lon. (°E) | Ele. (m) | Period of record | MAR[1] (mm) | St Dev.[1] | CV[1] % | Trend[1] |
|---|---|---|---|---|---|---|---|---|
| **Gonder** | 12.50 | 37.40 | 1966 | 1924 - 31 | 1264 | 176 | 14 | 0.04 |
| | | | | 1953 - 59 | 1287 | | | |
| | | | | 1937 - 40 | 1209 | 201 | 17 | -0.68 |
| | | | | 1964 - 90 | 1077 | 206 | 19 | -0.14 |
| | | | | 1924 - 97 | 1140 | 202 | 18 | -0.46 |
| **Dessie** | 11.08 | 39.67 | 2460 | 1962 - 97 | 1154 | 191 | 17 | 0.15 |
| | | | | 1962 - 90 | 1129 | 191 | 17 | -0.26 |
| **Mekele** | 13.50 | 39.50 | 2212 | 1964 - 96 | 609 | 155 | 26 | 0.22 |
| | | | | 1964 - 90 | 603 | 169 | 28 | 0.25 |
| **Combolcha** | 11.08 | 39.72 | 1916 | 1909 - 14 | 1195 | - | - | - |
| | | | | 1937 - 40 | 919 | - | 17 | - |
| | | | | 1953 - 96 | 1036 | 176 | 17 | -0.17 |
| | | | | 1961 - 90 | 1011 | 172 | | -0.17 |
| **Addis Ababa** | 9.03 | 38.75 | 2324 | 1898 - 97 | 1202 | 200 | 17 | -0.10 |
| | | | | 1961 - 90 | 1186 | 142 | 12 | 0.24 |
| **Adigrat** | 14.03 | 39.45 | 2280 | 1937 - 40[2] | 615 | - | - | - |
| | | | | 1970 - 96[3] | 606 | 180 | 28 | 0.55 |
| | | | | 1970 - 90 | 563 | 159 | | 0.22 |
| **Dire Dawa** | 9.60 | 41.85 | 1260 | 1952 - 96 | 620 | 145 | 23 | -0.12 |
| | | | | 1961 - 90 | 597 | 153 | 26 | -0.02 |

[1], Calculated over whole length of record; [2], 1937, 1938 incomplete; [3], 1982–1993 missing/incomplete; MAR, Mean annual rainfall. CV, Coefficient of variation (St Dev. divided by the mean) in per cent. Trend is expressed as correlation with time.

The river has cut travertine (concretionary deposits of calcium carbonate deposited by rainfall from impregnated groundwater around a hot spring) formed in the past in connection with waterfalls separated by lacustrine basins and swamps. Peaty layers in the lacustrine-swampy deposits in the sequence were found to contain wood fragments and charcoal deposits. Radiocarbon dates from one of the peat layers from the lower part of the channel were 7130 ± 90 yr BP. Other datings of 5550 ± 80 yr BP and 5160 ± 80 yr BP were obtained from peat underlying upper alluvial sediments. They interpreted the sequence as follows. Deposition of travertine began prior to 9130 ± 90 yr BP probably under milder and wetter climatic conditions (which gave rise to high lake levels in the Rift Valley Lakes of Ethiopia, Grove *et al.*, 1975). Growth of the travertine deposits and lacustrine-swampy sediments suggest maintenance of similar conditions during almost all of the early Holocene. The remains of wood and richness of organic matter are indicative of the vegetation cover during the period. The travertine deposition ended 5160 ± 80 yr BP and was followed by deposition of alluvial and colluvial sediments indicative of widespread reworking of sediments eroded from the surrounding slopes which underwent progressive denudation. Dwelling structures and ceramic fragments were found at the base of this sequence suggesting that the denudation processes were associated with human activity (*i.e.*, deforestation). Given the difficulty of accurately separating human and natural effects on slope erosion Ogbaghebriel Berakhi *et al.* (1998) concluded that both climatic change and anthropic deforestation may have induced slope erosion processes.

On more recent time scales Street-Perrott (1982) analysed historical changes in lake levels in the Ziway-Shala Basin during the 20th Century and Wood (1977) constructed a preliminary chronology of droughts in Ethiopia based on historical and oral records extending back to the third century. Conway *et al.* (1998) identified two tree species (*Juniperous procera* and *Ekebergia capensis*) with cyclical growth rings and potential for dendroclimatological research from 18 tree species sampled in the Simien Mountains National Park (SMNP) and Taragadem Forest (just East of Lake Tana). Nearly all the samples, however, contained areas with unclear ring boundaries and false rings. Attempts to match up cores from the same tree were only successful in one or two cases and it was not possible to achieve the same degree of unequivocal cross-matching between different trees as is routinely possible in other (non-African) regions. Kaeppeli (1998) identified cyclical growth rings in *Erica arborea* in the SMNP but was unable to cross-date ring series because of problems due to eccentric growth, loss of biomass (due to wood cutting and goat browsing) leading to the formation of ring wedges and the complicating influence of stand dynamics on annual tree growth. Kaeppeli (1998) found that on some mountain ridges in the SMNP the upper limit of *Erica arborea* had risen by up to 120 m in altitude during the last three decades partly in response to more favourable climatic conditions (*i.e.*, increased temperatures) at some sites.

## CLIMATE VARIABILITY DURING THE HISTORICAL PERIOD

### *Instrumental data*

There are very few long duration rainfall series available for Wollo and Tigray. The longest unbroken rainfall series that exists for Ethiopia as a whole is Addis Ababa, which began in 1898, and for Eritrea it is the record for Massawa, which began in 1885 (Asmara began in 1903). Most rainfall records, however, begin during the 1950s and 1960s when the Ethiopian National Meteorological Services Agency (ENMSA) was first established. Fantoli's *Contributo Alla Climatologia Dell'Etiopia* published by the Ministero Degli Affari Esteri in Rome is the most comprehensive early study of climate in Ethiopia using data from before the establishment of the ENMSA (it includes data up to 1942, Fantoli, 1965). In Wollo and Tigray the oldest records date back to 1908 for Combolcha, 1962 for Dessie and 1963 for Mekele. The record at Combolcha is missing between 1916 and 1936. During the Italian occupation rainfall observations were made in the region at Combolcha and Adigrat (1937 to May 1940, Fantoli, 1965). There are now many rainfall recording stations located in the region, however, only a few of these have records that are continuous and at least 30 years in length (essential for climatological purposes). Not including meteorological observations made in transit by European travellers the earliest continual series of observations made in Ethiopia began at the Italian *Società Geografica* field station set up in 1877 near Ankober, and in Eritrea experimental studies were begun in 1893 (McCann, 1995, p. 17). Fantoli (1965) only contains the monthly temperature and rainfall for the *Società Geografica* field station for the period 1877–1878.

It is highly likely that the longer rainfall records have been subject to changes in location and instrumentation during the past. This is definitely the case with Addis Ababa where the site moved from its first position which was most likely located at the Italian Embassy to its present site near Black Lion Hospital in central Addis Ababa *circa* 1948. It has not been possible to obtain detailed histories for the stations used in this study. The records for Combolcha (Fig. 3) and Gonder (Fig. 6) highlight the problems of discontinuities in rainfall records which are often associated with a change in gauge location, type or observer, all of which may lead to a change in the mean rainfall. This has clearly occurred at Gonder, between the observations made before 1959 and those from 1965 onwards, where there is a change in the mean rainfall. Other changes in gauge conditions are not always so noticeable such as the change in the location of the gauge in Addis Ababa *circa* 1948 which did not produce a marked effect on gauge catch (Fig. 6). Rainfall records are used here from gauges situated within or close to the study region with at least 30 years duration of record (Fig. 1, Table 1). These incorporate records from Fantoli (1965) and recent updates from the ENMSA. Although rainfall records for many other gauges within the region do exist, only those with long duration records are considered here.

### *Seasonal characteristics of the regional climate*

The seasonal variation in temperature, rainfall and Penman potential evaporation for three stations (Mekele, Dessie and Addis Ababa) representative of some of the wide range of climatic conditions found within the region is shown in Fig. 2 (scales set to follow agro-bioclimatic format with PET shown *0.35). There is little variation in temperature through the year, roughly between 3–6° C from the warmest months (between April and June) to the coolest months (between November and February). The hottest period is March to May, before the onset of the major rains. This produces a smaller range of seasonal temperature variation than might be expected and in some instances results in two cooler and warmer periods. There is significant variation in climate, particularly temperature and mean rainfall, due to the effects of altitude, for instance, at Dessie (2460 m) mean annual temperature is 14.9° C, rainfall is 1129 mm and at Combolcha (1916 m) they are 18.7° C and 1011 mm, respectively. On average temperatures fall by 5.8° C for every 1000 m increase in elevation (the lapse rate is greater in the winter dry season from September to March and during the wet season from May to August it falls to roughly 5.3° C per 1000 m). The traditional Ethiopian classification of climate is based on elevation and recognises at least three zones: the *Kolla* zone below 1800 m with mean annual temperatures ranging from 20–28° C; the *Woina Dega* zone between 1800–2400 m with mean annual temperatures ranging from 16–20° C; the *Dega* zone above 2400 m with mean annual temperatures ranging from 6–16° C. Figure 2 also shows the mean monthly Penman potential evaporation (FAO, 1984) for the three sites. As with temperatures, there is little variation in potential evapotranspiration, which ranges by roughly 50 mm from its lowest monthly values in July and August to its highest value in April or May - mainly driven by seasonal variations in temperature but also changes in radiation, humidity and wind speed.

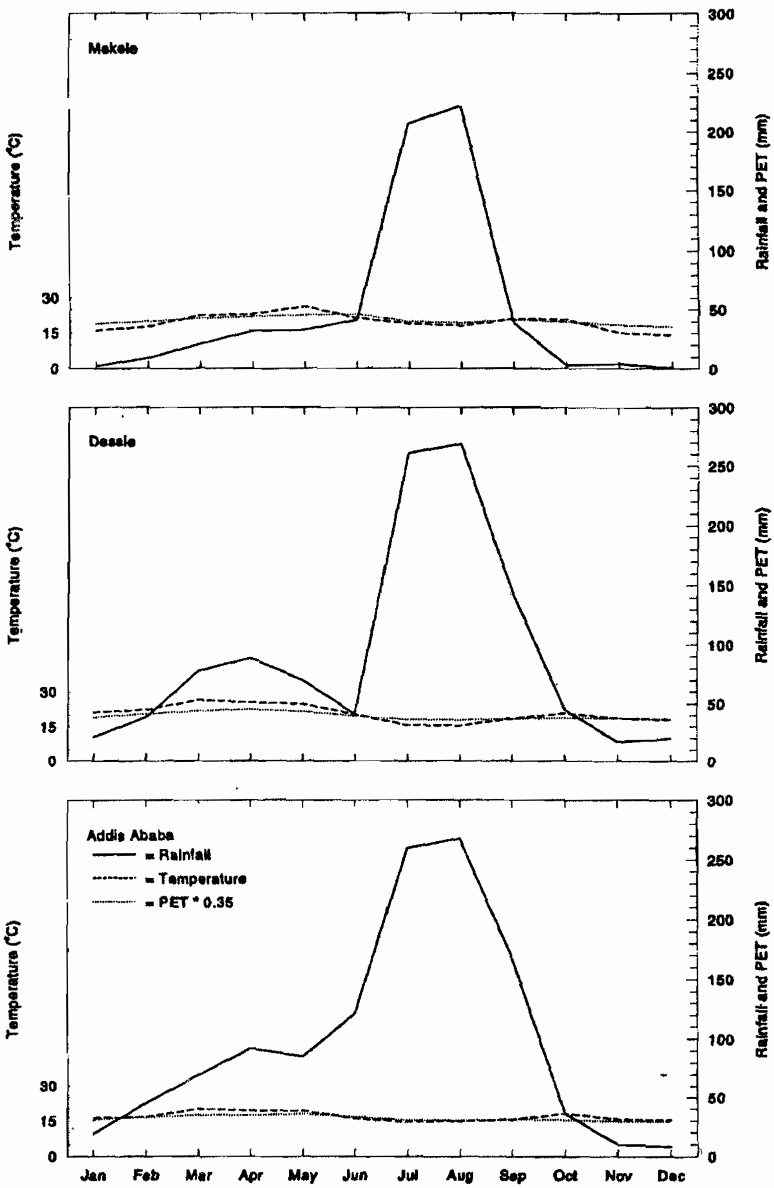


**Fig. 2. Annual variation in temperature (dotted line), potential evaporation (dashed line) and rainfall (solid line) at three sites in the region.** The scales set to follow agro-bioclimatic format with PET shown as Penman * 0.35. Where possible all means are based on the period 1961–1990.

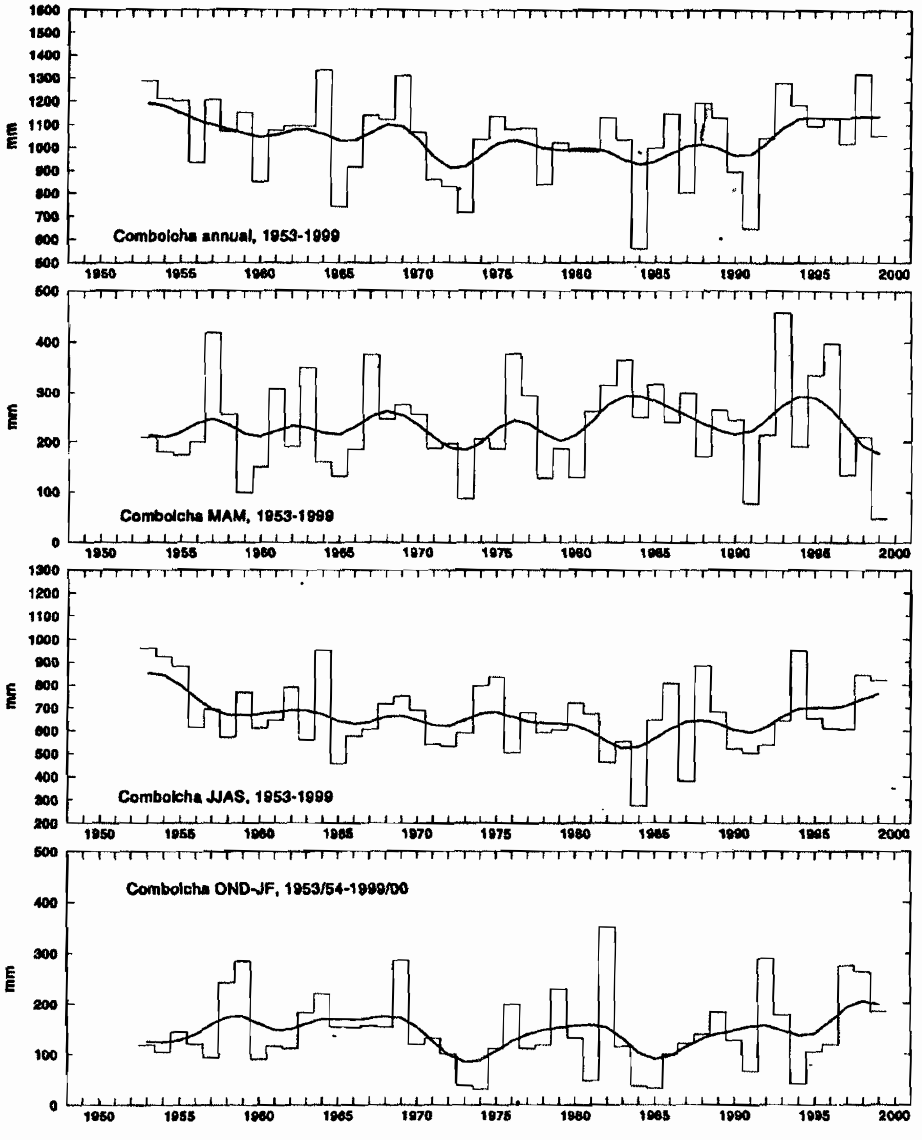


**Fig. 3 a-d. Time series of rainfall at Combolcha, 1953-1996.** a, Annual; b, March to May - *Belg* season; c, June to September - *Krempt* season; d, October to February - *Bega* season. The smooth curves are obtained using a 10-year Gaussian filter.

The causes and characteristics of rainfall in Ethiopia are described in Griffiths (1972) and Daniel Gamachu (1977). Rainfall is influenced by three mechanisms: the summer monsoon (Inter-tropical Convergence Zone, ITCZ), tropical upper easterlies, and local convergence in the Red Sea coastal region. During the winter dry season (traditionally known as Bega) the ITCZ lies south of Ethiopia and rainfall occurs only along the Red Sea coast. The region north west of the Rift Valley, is affected by northeast continental air controlled by a large Egyptian zone of high pressure. This cool air-stream from the desert produces the dry season. From March, the ITCZ returns bringing rain to the southern, central and eastern parts of the country, particularly the high ground in southwestern Ethiopia. This short period of rainfall is known as the *Belg* or 'small rains' season. In May, the Egyptian high consolidates and checks the northward movement of the ITCZ producing a short dry season before the main wet season, the *Krempt*. Around June, the ITCZ moves further north and the southwest air-stream extends over all high ground in Ethiopia to produce the main rainy season, lasting until the north-easterly continental air stream is re-established in autumn.

The various causes of Ethiopian rainfall lead to a wide range in seasonal rainfall distribution. In the study region, the summer months account for a large proportion of mean annual rainfall; roughly 70 per cent occurs between June and September and this proportion generally increases with latitude ranging from 69 per cent at Addis Ababa in the south, to 84 per cent at Mekele (see Fig. 2). Ethiopia is often divided into regions according to seasonal rainfall patterns and the distinctive characteristics of the three main regions are as follows: an extended single wet season in the southwest (*e.g.,* Gore); a shorter single wet season further north (e.g. Mekele or Gonder); and a bi-modal pattern in the east with *Belg* rains in April-May preceding the main wet season *Krempt* (e.g. Dessie), which is typical of the study region along much of the eastern escarpment.

### *Temporal variability of rainfall*

Table 1 lists details of the stations with long duration records located within or close to the study area. Mean annual rainfall generally decreases from the southwest to the northeast and with decreasing elevation, ranging from about 1200 mm in Addis Ababa and Gonder to 563 mm in Adigrat. Interannual variability is not particularly high in the wetter areas where the coefficient of variation of annual rainfall in most parts of the basin is generally less than 20 per cent, however, it reaches much higher levels in drier areas to the north and at lower altitudes. The longer-term trends in rainfall are illustrated in Figs 3–5 where the annual and seasonal rainfall records are plotted for Combolcha, Dessie, and Mekele, respectively. There is no overall trend in the annual series at Combolcha, a slight increase in *Belg* rainfall from the beginning of the 1980s up to 1996 (1999 driest on record), and a very slight decrease in *Krempt* rainfall up to the mid-1980s. The three driest years in the record were 1984, 1991 and 1973 with the driest *Krempt* occurring in 1984 followed by 1987 and 1965. Further up the escarpment at Dessie (550 m higher up and 15 km west) interannual rainfall variability shows many similarities with the variability observed at Combolcha. Like Combolcha, there was no overall trend in annual rainfall at Dessie, although from 1993–1996 it was particularly wet, there was a more marked positive trend in *Belg* rainfall until 1996 (1999 driest on record), but no trend in either *Krempt* (1999 wettest on record) or *Bega* rainfall. 1984 was the driest year on record followed by 1965 and 1976 (1973 missing), and the driest *Krempt* seasons occurred in 1982, 1984 and 1987. There are fewer similarities between the records at Dessie and Combolcha with the record at Mekele. Missing data makes it difficult to identify any trend that might have occurred in the annual and seasonal rainfall series for this site. *Belg* rainfall was particularly high in 1993 and also the lowest on record in 1999. 1984 was again the driest year followed by 1979 and 1968, both of which were above average years at Combolcha and Dessie.

Annual rainfall is shown in Figure 6 for Combolcha, Dire Dawa, Addis Ababa, Gonder, and an area average for the Blue Nile region taken from Conway (2000). None of the series shows any marked evidence of long term trend in rainfall. 1984 was the driest year on record at Dire Dawa and Combolcha, the second driest year in the Blue Nile series but it was not notably dry at Gonder or Addis Ababa. Other notable dry years in the Blue Nile series were 1902, 1912, and 1913 (driest on record, 1148 mm), and wet years were 1903 (wettest on record, 1757 mm), 1917, 1947, 1961 and 1964. A slight increasing trend occurred between 1900 and 1965 followed by a prolonged decline which reached its nadir in 1984 from when totals have steadily increased, with 1996 the wettest year since 1964 (33 years) and 1997 the second wettest in 30 years. Since 1990, March to May rainfall has increased substantially with 1996 the third wettest on record (Conway, 2000).

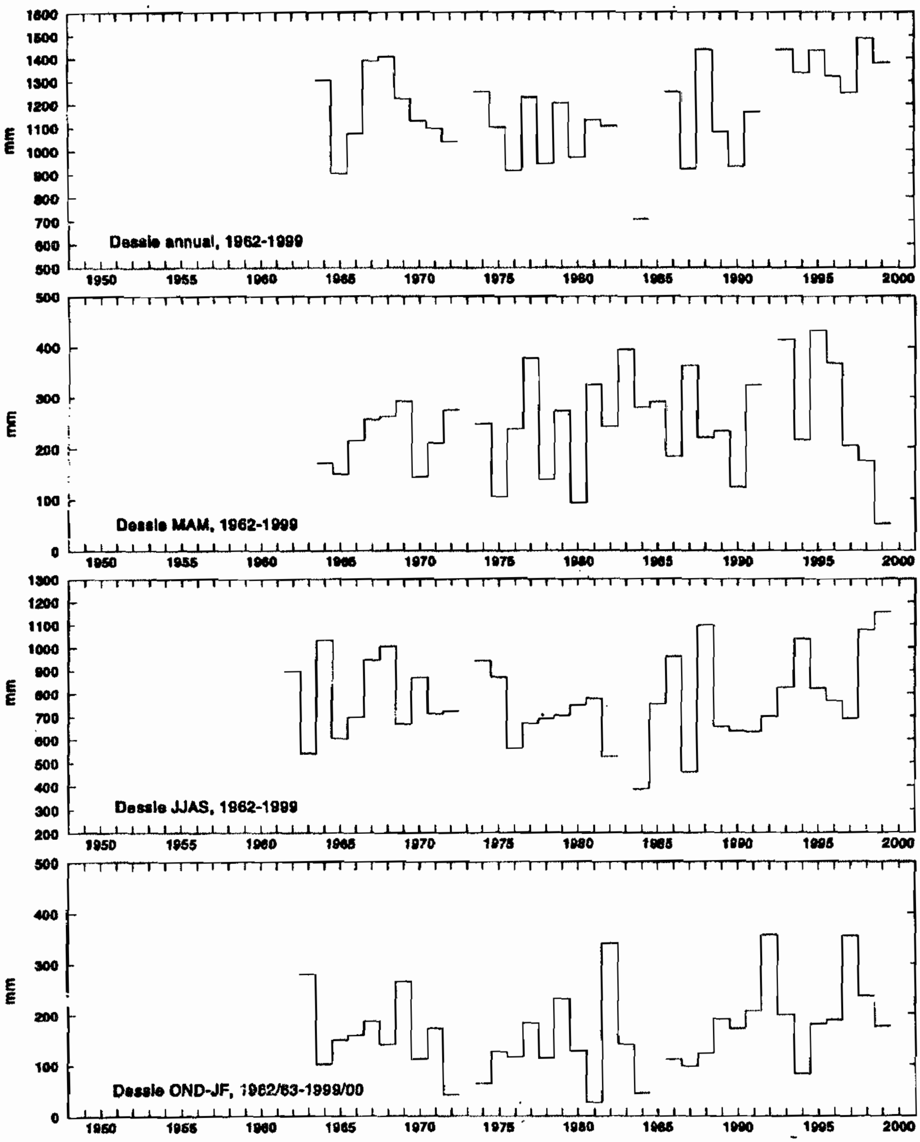


**Fig. 4 a-d. Time series of rainfall at Dessie, 1962–1997.** a, Annual; b, March to May - *Belg* season; c, June to September - *Krempt* season; d, October to February - *Bega* season.

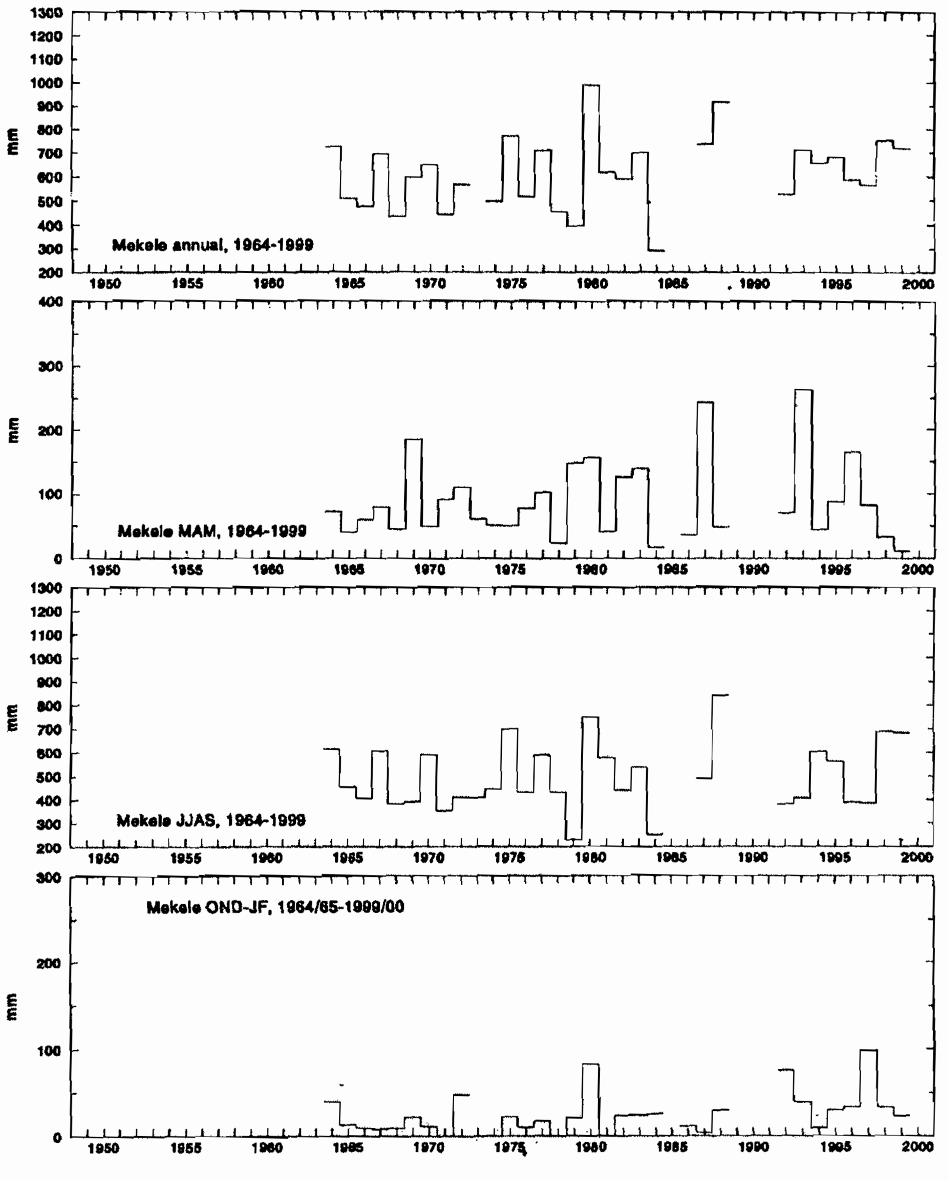


**Fig. 5 a-d. Time series of rainfall at Mekele, 1964–1996.** a, Annual; b, March to May - *Belg* season; c, June to September - *Krempt* season; d, October to February - *Bega* season.

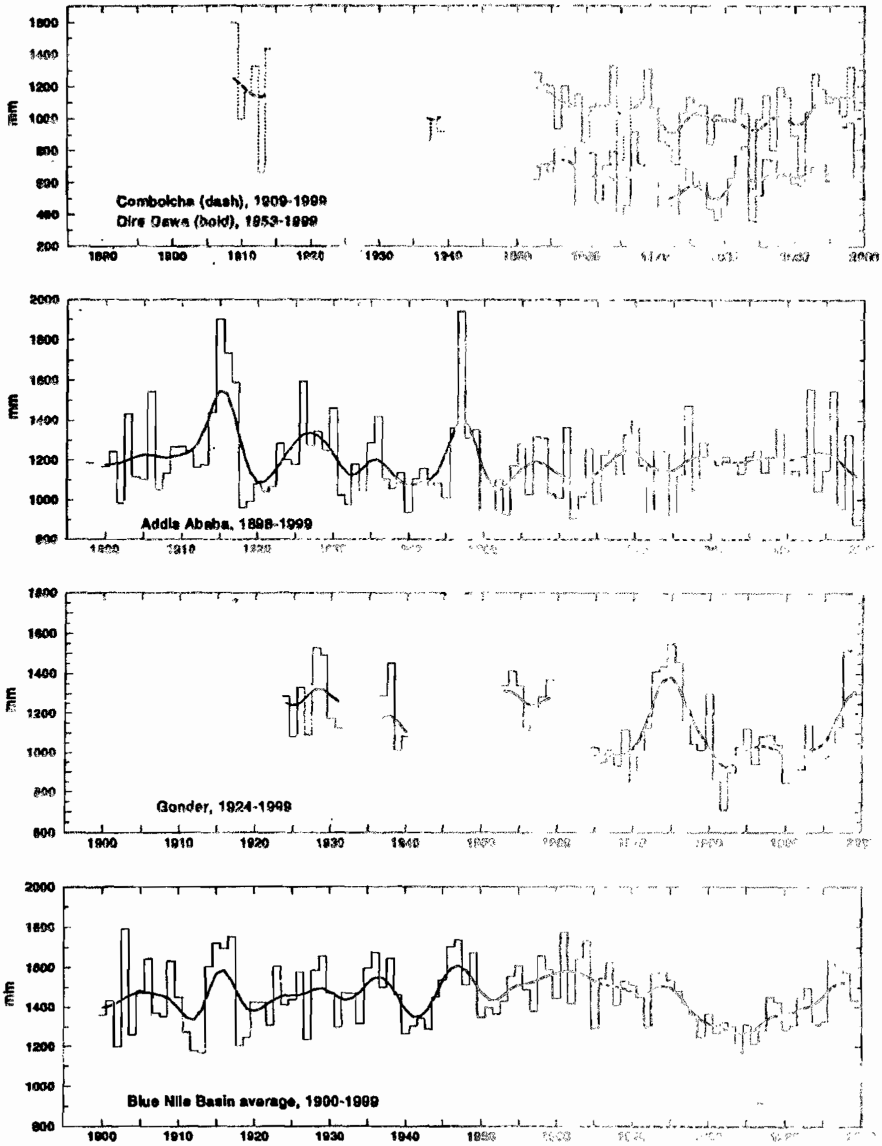


**Fig. 6 a-d. Time series of annual rainfall at: a. Combolcha and Dire Dawa, b. Addis Ababa, c. Gonder, d.** Area-average of between one and eleven gauges over the Blue Nile basin (see text for station list, from Conway, 2000). The smooth curves are obtained using a 10-year Gaussian filter.

## FACTORS INFLUENCING RAINFALL VARIABILITY IN ETHIOPIA

Rainfall throughout the Sahel from the Atlantic to the Red Sea is modulated by changing patterns of global sea surface temperatures (SSTs), with the different oceans having varying degrees of influence on different regions. It is suggested that El Niño-Southern Oscillation (ENSO) events, which have been associated with Nile flows, may also affect rainfall in the west and central Sahel in certain years (Folland *et al.*, 1986; Janicot, 1996). Certain patterns in Atlantic SSTs, which have been correlated with Sahelian rainfall, have been shown to be part of a general variation of SSTs on a near-global scale, (*e.g.*, Folland *et al.*, 1986). Rainfall in the Sahel is also linked to variability in the Indian and Pacific Oceans. SST variations in these oceans are also associated with rainfall changes in Ethiopia and East Africa in general (*e.g.*, Beltrando and Camberlain, 1993; Yilma Sileshi *et al.*, 1995). Hence the patterns of global oceanic and atmospheric circulation which modulate SST may be inferred to modulate rainfall throughout the Sahel and the Ethiopian plateau, although the degree of influence of a particular oceanic region will vary with longitude within this area.

The region lies within the same latitudinal band as the African Sahel, where annual rainfall varies from 600–700 mm in the south to 100 mm in the north. However, it is often considered as a separate climatic region from the Sahel due to its elevation and where orographic influences have a large impact: annual rainfall over much of the Highlands is up to 1500 mm. Despite these differences, twentieth century rainfall fluctuations and Blue Nile flows show some similarities to Sahel rainfall, particularly the decline in rainfall since the mid 1960s. The severe Sahelian droughts of the 1970s and 1980s were mirrored in the region, with 1972 and 1984 particularly dry across the Sahel and parts of Ethiopia. Rainfall in Ethiopia since 1988, however, has slowly returned to levels more typical of those before the prolonged dry period, unlike in the Sahel where drier conditions still prevail.

A number of studies have analysed the relationship between rainfall over the region and Nile river flows and ENSO events. On the basis of an established relationship, Quinn (1992) used the long duration series of annual maximum Nile flood levels from the Roda-gauge (the famous Nilometer in Cairo) extending back to the early 7th Century to reconstruct the record of low

Southern Oscillation Index (SOI) behaviour (related to below normal flood levels at Cairo). When the SOI is positive, a large low pressure system extending over India and the Arabian Sea is well developed and summer monsoon rainfall is likely to be heavy. When the SOI is negative, the large low pressure system is not well developed and/or is displaced to the east and the summer monsoon rainfall is likely to be low (Quinn, 1992). Whetton and Rutherford (1994) used the series back to 1587 to analyse changes in the relationship between ENSO and Nile flood levels over time. They found Nile floods were significantly lower than average in all El Niño years, but that the strong relationship develops only after about 1830 and continues up to the 1980s. Eltahir (1996) obtained correlation coefficients of about 0.5 between Nile flows at Aswan and an ENSO index averaged over the months of September to November (1872 to 1972). Yilma Sileshi *et al.* (1995) found significant negative correlations between monthly Darwin sea level pressure (a component of the SOI) and regional rainfall series for North Central Ethiopia (in June, September and March) and Eritrea (in September and July).

Conway (2000) noted a weak spatial pattern in the relationship between rainfall over the region and ENSO. The more easterly and southerly stations, in particular those close to the rift valley (Jimma, Gore and Addis Ababa) and along the eastern escarpment (Dessie) show little or no association with ENSO. This may reflect differences in circulation and influences from the Atlantic and Indian Oceans. The western, central and northern highlands are more affected by south-westerly flow advecting moisture from the Congo basin, while the Ethiopian Rift Valley and Eastern Escarpment are more affected by southerly flow in the Somali Jet advecting moisture from the Indian Ocean. Unfortunately there are no radiosonde or air balloon data available for the Ethiopian Highlands to explore these upper air characteristics in more detail. Camberlain (1995; 1997) has investigated the nature of rainfall anomalies in the region and their association with the SOI and in particular with the Indian Summer Monsoon. He found strong association between summer (July-September) rainfall variations in east Africa (including the Blue Nile region) and India and even stronger association with Bombay pressure. Negative pressure anomalies over Bombay were associated with increased rainfall over East Africa. This relationship is stronger than, more stable over time and independent of, the relationship with the SOI. Camberlain (1997) concludes that active monsoon conditions enhance the west-east pressure gradient near the equator and produce stronger westerly winds that advect moisture from the Congo Basin to Ethiopia and other parts of East Africa.

Interestingly, there are marked differences in the interannual behaviour of *Belg* and *Krempt* season rainfall, reflecting different oceanic influences in these seasons. Shanko and Camberlain (1998) found that years with consecutive occurrence of several tropical depressions over the Southwest Indian Ocean coincided with drought years in Ethiopia. In their analysis, *Belg* rainfall was much more influenced by cyclonic activity than *Krempt* rainfall, and on interannual time-scales an increased (reduced) frequency of tropical depressions during November to January tended to be followed by unusually low (high) *Belg* rainfall. The October to February dry season in 1997/98 was the wettest on record (> 400 mm) due to unseasonally high rainfall particularly in October and November, responsible for widespread flooding across Ethiopia and also parts of Somalia and Kenya. The details of this event are described in Birkett *et al.* (1999) and Kousky *et al.* (1998) which was associated with a widespread warming across the western equatorial Indian Ocean with persistent anomalous low and mid-tropospheric easterly flow leading to the advection of anomalously moist and highly unstable air over the Indian Ocean into East Africa. Using satellite altimetry data Birkett *et al.* (1999) have identified large increases in lake levels across East Africa as a result of the heavy rainfall, for instance Lake Victoria has risen by ~ 1.7 m, Lake Tanganyika by ~ 2.1 m and Lake Malawi by ~ 1.8 m. Such hydrological impacts are similar in magnitude to those which occurred after a previous heavy rainfall event over East Africa and southwest Ethiopia in 1961.

## CONCLUSION

The climate experienced in the Ethiopian Highlands has shown major shifts over long time scales such as during the Holocene (the last 10,000 years). The rainfall regime has fluctuated between wetter and drier periods as evidenced by changes in the levels of the Ethiopian Rift Valley lakes and the sedimentation rates and channel forms of the Blue Nile downstream in Sudan and Egypt. To date very few studies have considered Holocene climate change to the north of the Blue Nile and Rift Valley Lakes in Tigray and Wollo - however there is great potential for environmental reconstruction in the region using palaeosoil analysis (for instance, Ogbaghebriel Berakhi *et al.*, 1998), archaeological techniques (for instance, work ongoing at Aksum) and lake level reconstruction (for instance, lakes Ashangi and Hayk on the eastern escarpment, Lamb, University of Wales, UK, pers. com.). Future research will help reveal the magnitude and spatial extent of climate variability in greater detail and begin to unravel the complexities of climate, environmental and anthropogenic change in the Highlands of Ethiopia.

On more recent time scales rainfall in Wollo is characterised by a distinctive bimodal pattern with minor *Belg* rains (March to May) and main *Krempt* rains (July to September). Further north in Tigray the *Belg* rains are less marked and the *Krempt* rains dominate the seasonal pattern. Only three stations possess records that are relatively unbroken and extend back to the 1950s and early 1960s. In all of these, 1984 stands out as the driest year on record due to very low rainfall during the *Krempt* season. There is no evidence of any long-term trend or changes in the rainfall in either region during the last 30 years. Rainfall during the 1990s has seen a return to more humid conditions since the dry period from the late 1970s into the 1980s. *Belg* 1999 was the driest on record for Combolcha, Dessie and Dire Dawa. Interannual variability is high, particularly in areas experiencing low annual rainfall totals. There is difference between the temporal behaviour of *Belg* and *Krempt* rainfall reflecting different levels of influence from the Indian and Atlantic Oceans, respectively. The causes of interannual rainfall variability over the Ethiopian Highlands are not fully understood, however, the main influences include the following:

- the El Niño-Southern Oscillation - El Niño events tend to be associated with lower than average rainfall although this is not always the case, for instance a major El Niño event occurred in 1997 but rainfall over much of the Highlands was above average.

- Atlantic, Indian and Pacific Oceans SSTs - with differing levels of influence in different seasons and areas of Ethiopia.

- the strength of the Indian Summer Monsoon - Camberlain (1997) found strong association between summer (July-September) rainfall variations in east Africa (including the Ethiopian Highlands) and India.

- Shanko and Camberlain (1998) found that years with consecutive occurrence of several tropical depressions over the Southwest Indian Ocean coincided with drought years in Ethiopia.

Much remains to be discovered about the relative importance of these phenomena, particularly the sources of moisture for rainfall over Ethiopia. Drought has been a feature of life in the Highlands (and consequently downstream of the Blue Nile in Egypt) throughout history (Pankhurst and Johnson 1988; Wood, 1977). Although rainfall records from Wollo and Tigray only date back to the 1950s and early 1960s, records from other sites in Eritrea and the Blue Nile suggest that the events of the 1970s and 1980s were not unprecedented in terms of individual dry years but were unprecedented in terms of the prolonged period of successively drier than average years. The climatic nature of these events and their devastating impacts needs to be put into context with the historical and contemporary dynamics of socio-economic, political and environmental driving forces acting in the region.

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