INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **24**: 77–91 (2004)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/joc.989

OVER ONE CENTURY OF RAINFALL AND TEMPERATURE OBSERVATIONS IN ADDIS ABABA, ETHIOPIA

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Received 18 April 2003
Revised 30 October 2003
Accepted 30 October 2003

ABSTRACT

A detailed historical reconstruction and analysis is presented of the longest record of climate observations for Ethiopia, from 1898 to 2002 in Addis Ababa. Prior to 1951 the record comprises rainfall and minimum and maximum temperatures recorded in different locations by different observers. The rainfall series is complete except for 1899 and 1900, but the temperature series are very incomplete. Using documentary evidence, we attempt as far as is possible to establish the origins of all the pre-1951 observations. Rainfall observations originate from at least six different sites. After establishment of an Ethiopian meteorological department in 1951 the records are complete and, to our understanding, originate from the same location, the Addis Ababa Observatory (AAO). A revised rainfall series for 1898–1950 is derived using observations from sites with the longest records.

The minimum and maximum temperature records show evidence of statistically significant inhomogeneities. Homogeneity tests on the full rainfall record (the revised series plus AAO) show it is reliable, with evidence of minor but not statistically significant breaks in the record before establishment of the AAO. Some, but not all, breaks can be accounted for using the historical information. Analysis of the records shows increasing trends in annual minimum and maximum temperatures from 1951 to 2002 (0.4 °C/decade and 0.2 °C/decade, respectively). There is little trend in rainfall from 1901–50, 1951–2002 and 1901–2002, dry years do not correspond with known drought years elsewhere in Ethiopia, and interannual variability is poorly correlated with another long rainfall series in Ethiopia (Gore), Blue Nile river flows and the southern oscillation index. This suggests strongly that the record for Addis Ababa should not be used as a proxy for conditions in Ethiopia, particularly the more drought-prone areas to the north and east. We conclude that the temperature series are suspect but that the full rainfall record is useful for analysis of long-term rainfall conditions in Addis Ababa. Copyright © 2004 Royal Meteorological Society.

KEY WORDS: Ethiopia; climate records; rainfall; temperature; homogeneity; trend

1. CLIMATE OBSERVATIONS IN ETHIOPIA

Systematic measurements of surface climate in sub-Saharan Africa, like many other parts of the tropics, are relatively poorly located in terms of spatio-temporal coverage (Houghton *et al*., 2001). In addition, for locations where observations do exist, the supporting information on the instrumental and station history is often unavailable, or at best it is sketchy. Ethiopia is a prime example of a country that is extremely large in area ($>1.1 \times 10^6$ km^2) with very few well-documented long series of climate observations. Whilst accurate climate data are essential for planning and management across a range of societal activities, long-term climate records are also required to understand the complexity of local climatic variability and to contribute to reconstructions of recent environmental change, which are often based on limited empirical evidence. Such information may also be useful for the development of appropriate policies for enhancing food security and

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natural resource management, particularly in a country such as Ethiopia, with a long and complex history of drought and associated famine (Wood, 1977; Degefu, 1987; Pankhurst and Johnson, 1988). The complex role of drought and interaction with other confounding factors such as land tenure, war and economic policies in recent devastating famines (Rahmato, 1991; De Waal, 1997), underscores the need for improved climatic analysis to feed into this contentious policy area. Reliable observation records are also useful for calibrating proxy records for longer term climate reconstruction (Conway *et al*., 1998; Lamb, 2001).

The search for seasonal rainfall predictive capacity also requires relatively long records of known reliability. Investigations into the potential for seasonal forecasting of rainfall in the Ethiopian Highlands have been mainly based on linkages with the El Niño–southern oscillation (e.g. Sileshi and Demarée, 1995; Bekele, 2000; Wolde-Georgis, 2000). In addition, Camberlin (1997) found strong association between summer (July–September) rainfall variations in East Africa, including the Ethiopian Highlands, and India. Dula Shanko and Camberlin (1998) found that years with consecutive occurrence of several tropical depressions over the southwest Indian Ocean coincided with drought years in Ethiopia. Pfaff *et al*. (1999) discuss the generic use and benefits of seasonal forecasts, and Broad and Agrawala (2000) discuss these issues with specific reference to the 1999–2000 food crisis in parts of Ethiopia. At the time of writing, spring 2003, after a sequence of below-average wet seasons, although no detailed climate analysis is published yet, the prospect of widespread crop failure and massive food insecurity looms again for Ethiopia.

Most of the longest rainfall records for Ethiopia begin during the 1950s and 1960s, and many other records begin during the 1980s following expansion of the network, partly in response to the mid-1980s drought. A small meteorological unit was first established within the Civil Aviation Department in Ethiopia in 1951 to provide information solely for flying purposes. As the need for meteorological information grew, a Meteorological Department was established in 1964 under the Civil Aviation Authority. This became the present Ethiopian National Meteorological Services Agency (ENMSA) after designation as an autonomous organization on 31 December 1980 (ENRAEMED, 2003).

The longest unbroken climate record that exists for Ethiopia is the rainfall record at Addis Ababa, which began in 1898. For Eritrea, the longest record is at Massawa, which began in 1885, and the record for Asmara began in 1903. Fantoli's *Contributo Alla Climatologia Dell'Etiopia*, published by the *Ministero Degli Affari Esteri* in Rome, is the most comprehensive study of climate in Ethiopia using records from before the establishment of an Ethiopian meteorological institution and includes observations up to 1940 (Fantoli, 1965). Prior to this point, relatively long records also exist for Gambela (1905–93) and Gore (1908–present), both associated with British interests in the coffee trade through southwest Ethiopia, and a few other locations, notably Harrar (started 1902) and Adamitullu (Lake Ziway, started 1908). During the Italian occupation (1936–41), rainfall observations were made throughout Ethiopia. There are now hundreds of rainfall recording stations located in Ethiopia; however, only a few of these have records that are continuous and at least 30 years in length, as required for many climatological purposes. Not including meteorological observations made in transit by European travellers, the earliest continuous series of observations made in Ethiopia began at the Italian *Società Geografica* field station set up in 1877 near Ankober (McCann, 1995), although Harris cited by Lyons (1906) also made partial recordings at this site from 1841–42 onwards. Fantoli (1965) only contains the monthly temperature and rainfall for the *Società Geografica* field station for the period 1877–78. In Eritrea, experimental studies were begun in 1893 (McCann, 1995).

It is very likely that the earliest rainfall records have been subject to changes in location and instrumentation, raising questions about their reliability. This is definitely the case with Addis Ababa, as will be shown later in this paper. The rainfall record for Gonder, in northern Ethiopia, highlights discontinuities in rainfall records of the sort associated with breaks in the record, changes in gauge location, type or observer, all of which may lead to a systematic change in the gauge catch, as appears to have occurred between observations made before 1959 and those from 1965 onwards (Figure 1). It will be seen for Addis Ababa that changes in location and instrumentation are not always so obvious.

Although there exists an almost unbroken rainfall record for Addis Ababa from 1898 (1899 and 1900 missing) to the present, the temperature record prior to 1951 is very incomplete, and apart from Fantoli (1965) has never been published in any detail. It is a little surprising that, although Fantoli (1965) contains an almost complete rainfall record from 1898 to 1940, he gives no direct reference to the origins of this

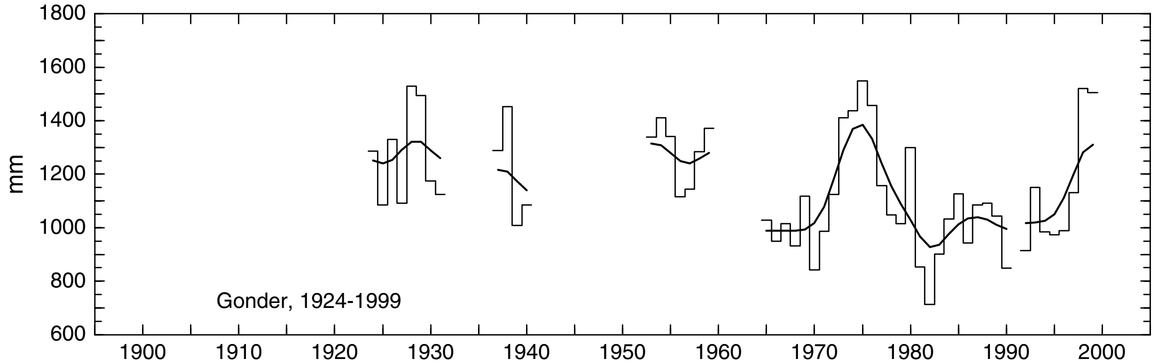

Figure 1. Annual rainfall in Gonder, northern Ethiopia, 1924–99 with 10 year filter applied

record or why the temperature record is incomplete. The long rainfall record for Addis Ababa has been used extensively, sometimes on its own, but more often as a contributing record to national and regional studies of African climate. Slightly different versions of the record exist elsewhere, e.g. in the *World Weather Records* 1941–50 (WWR, 1959) there is a record for 1902–50 that is very similar to the record held by the Climatic Research Unit (CRU; Hulme, 1994) that is used as a template in this analysis. WWR (1959) cite the source for the 1902–39 data as a private individual (Dr Kraus) and for post-1939 data the Civil Aviation Department, Meteorological Service. Nicholson *et al.* (1988) also include a record for Addis from 1898 to 1984 without the exact source, but they mention the WWR (1959) in their principal sources of data. A version of the record is cited by NOAA (2001) in their database on African climate, one is used in Lovett and Wood (1976), whilst Hulme (1996), Conway (2000) and New *et al.* (2000) all use the CRU record.

The objectives of this paper are twofold. First, to present a detailed history of the longest records of rainfall, and maximum and minimum temperature in Ethiopia at Addis Ababa, and second, to present an assessment of homogeneity and an analysis of these records during the 20th century. The climate records used here are primarily from Fantoli (1965) up to the year 1940, with supporting sources, and subsequently from the ENMSA. The paper is organized as follows: Section 2 provides historical context and detailed reconstruction of station history, Sections 3 and 4 examine the observed rainfall and temperature records respectively, in terms of their homogeneity and temporal variability. Section 5 presents conclusions regarding the use of the climate records for Addis Ababa.

2. DETAILED HISTORY OF RAINFALL AND TEMPERATURE OBSERVATIONS IN ADDIS ABABA

2.1. Rainfall and temperature observations in Addis Ababa, 1898–1940

This section reviews the history of climate observations at Addis Ababa before the establishment of the Addis Ababa Observatory (AAO) and is primarily based on Fantoli (1965) with additional sources. As stated above, Fantoli (1965) presents an almost complete rainfall record up to 1940 but does not elaborate on its derivation. However, using other sources, it is possible to attribute Fantoli's (1965) series as follows. Lyons (1906) presents observations for Addis from 1898 to 1905 from four intermittent sources: Russian (1898–1903), Italian (1903–04), British (1901–04) and French (1898). The locations are not given for the gauges, but Lyons (1906) does note that temperature observations during this period were made by officials residing at the court of Emperor Menelik, however, the rainfall observations were unlikely to have all been made there, because they often overlap and diverge. Lyons (1906) also presents a derived record from 1898 to 1905 (with 1899, and some other months, missing) from the four sources, citing a location at 09.03 °N, 38.72 °E and 2440 m elevation. Hurst and Black (1937) published rainfall records for three sites in Addis Ababa for which they note that, prior to the Italian occupation, originated from stations organized by the Egyptian Meteorological Service: the British Legation (1898–1908); the Italian Legation (1907–14); and the

Bank of Abyssinia (1907–37); all sited at 9.03 °N 38.73 °E and 2440 m. In fact, Hurst and Black's (1937) series for the British Legation is the same as Lyons' (1906) derived series (from four sources), with some minor differences in a couple of months; and 3 months missing during 1903 in Lyons (1906) are present in Hurst and Black (1937). Hurst and Black's (1937) British Legation series extends to June 1908.

Fantoli (1965) has some observations in italics; it appears that these represent infilled values, because the same values are used for each month in different years, but these do not appear to be averages. For 1898, and from June 1900 to December 1901, the Fantoli (1965), Lyons (1906) and Hurst and Black (1937) records are the same; however, only Fantoli (1965) has observations from January to May 1900, and these are infilled values. From 1902 to May 1905 the records are different and, by comparison with the other records in Hurst and Black (1937), it is apparent that Fantoli (1965) used observations from the Italian Legation for at least part of this period. From June 1905 until the end of 1906 they are the same (Lyons (1906) ends in 1905) and finally they diverge from the beginning of 1907 until Hurst and Black's (1937) series ends in June 1908. From May 1907 to June 1911 the Fantoli (1965) series is almost exactly the same as the Hurst and Black (1937) Italian Legation series, except for 3 months (source unknown) and some infilled months (July 1908, July to December 1911). The WWR (1959) record and the CRU record are almost the same from 1902 (start of the WWR (1959) record) to 1950. Both records are essentially the same as the Fantoli (1965) record up to 1911 except for 6 months in 1911 (unknown source for the WWR (1959) and CRU observations). Fantoli (1965), WWR (1959) and CRU are the same for 1912 and 1913 but they do not come from Hurst and Black's (1937) Bank of Abyssinia or Italian Legation, which have data for these years.

From 1914 to 1936 Fantoli (1965), WWR (1959) and CRU are all based on Hurst and Black's (1937) Bank of Abyssinia record, with the exception of Fantoli (1965) during 1923–26 and 1933 (different observations that we cannot account for). Griffiths and Hemming (1964) contains annual rainfall for several sites in Addis Ababa, including the Bank of Abyssinia (referred to as Addis Ababa Bank, with the same location coordinates as in Hurst and Black (1937)) from 1901 to 1947, which starts earlier than Hurst and Black's (1937) record and ends much later. The earlier part of this record corresponds to Fantoli (1965) from 1903 to 1907, and then Hurst and Black's (1937) Bank of Abyssinia from 1908 to 1936, but not 1937. Annual totals in Griffiths and Hemming's (1964) Bank series and Fantoli's (1965) series match in 1937 and 1940 but not in 1938–39.

Additional sources of early Ethiopian data are contained in the Meteorological Office's World Climate Records (Meteorological Office, 1967). The records for Addis Ababa are cited from a variety of old French (1911–19), German (1904, 1909), Italian (1937–40) and Egyptian (1938) sources based on a gauge location given as 09.33 °N and 38.75 °E and 2449 m elevation. Unfortunately, only monthly means are presented based on 15 years of maxima and 18 years of minima for temperature and 37 years of rainfall data. Griffiths (1972) also gives a location with the modern WMO coordinates for Addis Ababa but at 2450 m elevation with 14 years of mean temperature and 42 years of rainfall, and without citing the exact dates of the recording periods.

Fantoli (1965) presents a very sporadic record of temperature observations in Addis Ababa, with only nine complete years before 1950, during 1902–11 and 1938–39. Lyons (1906) also published a temperature record for July 1898 to December 1904 (cited with the same origins as the rainfall series above) but given as monthly mean values, so comparison with Fantoli (1965) is not possible. We have not been able to identify any other sources of temperature observations during this period. The systematic collection of weather data is one product of a settled society, but for most of the 20th century Ethiopia has had a turbulent history of political change, invasion, colonial administration and civil war. Many societal interests are more concerned with rainfall than temperature, and it is often the case, as it is here, that rainfall records exist without temperature records. Coffee is a major export industry in Ethiopia, and whilst temperature is important it is the rainfall that is the most crucial factor, with around 1500 to 2000 mm per annum required. Hence, it is possible that more attention might have been paid to recording rainfall than temperature because of its value to cash crops and the potential for irrigation, particularly in southwest Ethiopia. The early Italian–French steam railway also reported observations to a central office (Fantoli, 1965) and this suggests that rainfall, and hence water supply, would be of more interest than temperature, both during construction and operation. Clearly, the chance of data being lost during the social and political upheaval around WWI is high, although the main theatre of war was German East Africa and Palestine (Gilbert, 1985). It is possible that (some) records were destroyed during the Italian invasion (1937–40) and during the liberation and restoration of the independent state under Hailie Selassie in 1941–42, although Addis Ababa was liberated in a very short campaign from January to April 1941 (Keegan *et al*., 1989; Pankhurst, 1998). It is of note that some of Fantoli's (1965) rainfall records at specific sites in and around Addis Ababa end in April 1941, but the main record stops in 1940. The period after liberation until 1948–50 was a low point in British–Ethiopian relations, with a *de facto* military government and the establishment of British economic interests and control (Bahru, 1991; Pankhurst, 1998).

2.2. *The rainfall record during the 1940s*

The sources for observations from the end of Fantoli's (1965) record in 1940 up to the beginning of the AAO record in 1951 are disparate. The record used here as our template originates from the data holdings of the CRU at the University of East Anglia (Hulme, 1994). Lovett and Wood (1976) use a record for Addis Ababa from 1900 to 1975 based on Fantoli (1965) up to 1946 (although Fantoli's (1965) record actually ends in 1941) and then mostly from the Ethiopian Climatological Service Summaries published by the Civil Aviation Administration, which we have been unable to obtain. Griffiths and Hemming (1964) contains annual totals for Addis Ababa Bank up to 1947 and Addis Ababa meteorological station from 1946 to 1960. The CRU record is the same as Addis Ababa Bank from 1940 to 1945, but different in 1946–47. The CRU series follows Addis Ababa meteorological station from 1946; they are the same from 1946–47, 100 mm different in 1948 but within 3 mm in 1949 and within 11 mm in 1950. The series are generally within 20 mm from 1951 to 1960 and, therefore, very likely to be from the same record (i.e. AAO). It is a little surprising that Griffiths and Hemming's (1964) Addis Ababa meteorological station record pre-dates by at least 3 years the establishment of the AAO around 1949–51. The CRU observations during 1941–50 match with the Global Historical Climatology Network (GHCN) from 1941 to 1945 and WWR (1959) for 1946–50 (Camberlin, personal Communication)

2.3. *The locations of the observations up to 1951*

Fantoli (1965) includes several locations for contemporaneous and independent measurements in Addis Ababa during the late 19th and early 20th centuries. He suggests that the first systematic, but not continuous, climate recording in Addis Ababa began between 1882 and 1902 at a sanatorium by the Russian Legation, with rainfall measurement on a trimester basis. This fits with Lyons' (1906) Russian source for rainfall data from 1898 to 1905. Bahru (1991) states that the early foreign legations settled on the northern outskirts, which suggests an elevated location, as Addis Ababa slopes down from north to south. The present Russian Legation is situated northeast of Addis Ababa city centre at about 2600 m elevation, but it may have been closer to the embryonic administrative centre during the turn of the 19th–20th centuries. Fantoli (1965), citing the work done by de Castro and Oddone (1905, 1909) and de Castro and Eredia (1914), suggests that an early station was set up in Addis Ababa in 1901 in the centre of the lawn near the Mausoleum of Menelik 2nd (the *Grand Ghebi* or *palace)* and generated observations for the period 1905–14. It appears from Fantoli (1965) that the mausoleum site was reactivated and improved in 1937 and then moved to St George's Square in 1940, a distance of roughly 2.5 km and approximately 30 m increase in elevation. The mausoleum site is probably the location of the temperature observations from 1902 to 1911 and 1938–39 in Fantoli (1965). Fantoli (1965) also mentions that observations of temperature, some using balloons, were made at the original airport site (Lidetta), adjacent to the railway station, a significant change of location from the mausoleum site. It should be noted that aviation is one area where temperature is of greater importance than rainfall, as there is an important association between temperature and engine output in taking off from equatorial high-altitude airports.

For rainfall, Fantoli (1965) notes the work done by Hurst and Philips (published as volumes of the *Nile Basin*; e.g. Hurst and Black, 1937) and rain gauges situated by the French, Greek (for which no observations appear to exist) and British Legations, but gives no details of these stations. Fantoli (1965) makes no mention of the Bank of Abyssinia site, which comprises so much of his main record. He also states that a rain gauge at the Italian Vice Regal Residency (*Piccolo Ghebi*) was transported to the Hydrological Centre (*Avenue Entoto*) around 1940. Abate (1984), in a study of climate data from three modern sites in Addis Ababa, suggests that the station from which the long rainfall series was derived was moved to the Italian embassy (at present in the foothills to the northeast of Addis Ababa with elevation ∼2600 m) during 1939–40, but he does not give the previous location for the site. This is slightly at odds with Fantoli (1965), although it is possible that Abate (1984) is actually referring to the Italian Vice Regal Residency gauge which Fantoli (1965) records as moving to the Hydrological Centre. We have not been able to find any other references to records from the Italian Vice Regal Residency or Hydrological Centre, but it is possible that observations from these sites were used by Fantoli (1965) to complete his rainfall series in the months we have been unable to account for.

It is beyond the limits of this analysis to consider errors associated with instrumentation, site conditions and observer practice; however, as we have enough information to identify changes in site location, it is possible to consider the effects of elevation on the rainfall and temperature series prior to 1950. For temperature, Linacre (1992) suggests a number of possible sources of error due to change in elevation, whereby elevation affects mean daily temperatures and is a positive factor in the *range* between maxima and minima. Fantoli (1965) quotes a temperature lapse rate of 1 °C for 180 m increase in elevation for Addis Ababa, whereas Griffiths (1972) suggests 0.7 °C per 100 m (similar to other studies; e.g. Gamachu, 1977; Conway, 1997); hence, changes in the location of the thermometer with respect to elevation of the order of those discussed above would have introduced systematic and identifiable changes in temperature. The records may also have been influenced by urban warming, although because of Addis Ababa's relatively small size in 1950 (∼40 000 population in 1900, ∼443 700 in 1965 compared with >1.6 million in 1990; MacAlester, 2002) this is more likely to be an influence on the post-1950 record and is discussed in Section 4. Horizontal displacement could also be an error source, particularly for rainfall. Based on 1° of equatorial latitude being approximately 115 km (and roughly the same for longitude), a 0.01° change in location, therefore, would be 1.2 km, which may, in fairly steep topography, introduce a change due to elevation and/or horizontal displacement.

Fantoli (1965) also lists intermittent rainfall data from another seven sites in and around Addis Ababa, covering various periods between 1937 and 1941 and a short temperature data set for the modern airport site (Bolé). The data from these sites are fragmented and the elevation and precise location are not always known. Moreover, there are differences between these observations and the Fantoli (1965) complete main record. A comparison of these sites, all centrally based except Forestry Militia, using the year with the most complete records (1939) is given in Table I to highlight the spatial variability of rainfall in and around this hilly city. Rainfall ranges by 474 mm, but there is no consistent relationship between total rainfall and elevation. These large variations in rainfall catch within Addis Ababa highlight the homogeneity problems associated with the 1898–1950 record, which is comprised of observations from at least six different sites.

2.4. A revised rainfall record: 1898–1950

To summarize, it would appear that Fantoli (1965) has used Lyons (1906; or the same sources) up to 1901, another source up to May 1905, Lyons (1906; same as Hurst and Black (1937)) to 1907, the Italian Legation series to June 1911, and from then to the end of 1913 a source that we cannot account for. From 1914 to 1937 Fantoli (1965) and Hurst and Black's (1937) Bank of Abyssinia records are essentially the same,

Table I. Comparison of rainfall in 1939 recorded at five sites in and around Addis Ababa (Fantoli, 1965)

Location	Elevation (m)	Annual rainfall (mm)	Difference to mausoleum (mm)	Difference in elevation (m)
Mausoleum (Fantoli's (1965) main record)	2450	1133	0	0
Vice Regal Residence	—	1150	+17	—
Aqueduct office Av. Mussolini	—	1324	+191	—
Radio station by railway	2370	851	−283	−80
Forestry Militia	2640	1043	−91	+190

with the exception of 6 years in Fantoli (1965) that are unaccounted for. We cannot account for Fantoli's (1965) source from 1938 to 1940, and this may well be because he used an alternative Italian source during this period of occupation (the CRU and WWR (1959) records also use these values). From thereafter, up to 1950, the CRU and WWR (1959) records appear to be a mixture of Addis Ababa Bank (6 years) and Addis Ababa meteorological station (possibly the same site as AAO). Prior to 1940, the CRU and WWR (1959) records are slightly different to Fantoli (1965) because they are based fully on the Bank of Abyssinia record from 1912 to 1936 and then from 1940 to 1945, with the break again likely to be associated with the Italian occupation. Table II presents a revised record for Addis from 1898 to 1950 based upon: Lyons' (1906) derived series (1898–1907, four sites, missing data for 1900 because Fantoli's (1965) were infilled); Hurst and Black's (1937) Bank of Abyssinia record (1908–37, 1941–45); Fantoli's (1965) unaccountable source (1938–40); and WWR (1959; for 1946–50), which although unaccounted for may come from early Ethiopian meteorological observations. The main criteria for compiling this revised series has been to base it on as few sites as possible, and the resulting series originates from six to seven different locations but with the bulk of the record (35 years) from one location.

2.5. Rainfall and temperature observations in Addis Ababa after establishment of the AAO

The longest climate records the ENMSA holds are those for the AAO, which date back to its establishment around 1949–51. The ENMSA does not hold records for earlier than this, as they did not collect the data and cannot, therefore, guarantee their source and quality. The AAO series of minimum and maximum temperature and rainfall are unbroken from 1951 onwards and relate to a single site in the heart of Addis Ababa at the ENMSA, close to the Black Lion hospital. 1999 is missing from our temperature series and has been infilled using long-term mean monthly values, 1971–2000. Nevertheless, inconsistencies for the location of this record sometimes occur due to the existence of several other modern sites in the capital (listed in Table III). Bolé airport has almost the same coordinates as the AAO, but is approximately 10 km to the southeast and ~75 m lower. Abate (1984) compared observations from three sites in Addis Ababa and noted differences in the physical surroundings of the gauges and the number of recording years, which precluded direct comparison in his study. As far as we have been able to determine, the AAO site has remained in the same location since its establishment. Changes in instrumentation cannot be discounted, but the station file held by the ENMSA does not record whether and when such changes may have occurred. In the following analysis, rainfall and temperature observations will be split into those recorded prior to and after the beginning of the AAO record.

3. RAINFALL HOMOGENEITY AND TREND IN ADDIS ABABA, 1898–1950, 1951–2002 AND 1898–2002

Figure 2 shows the annual and seasonal rainfall for the complete duration of record. Seasons are defined broadly according to traditional Ethiopian classification with a dry season (October to following February: ONDJF), early rains (March to May: MAM) and main rainy season (June to September: JJAS). The vertical line is shown to highlight the start of the AAO record. Annual and seasonal rainfall characteristics are presented in Table IV. Only JJAS rainfall shows much sign of trend during the 1951–2002 period, increasing at 18 mm per decade, which is primarily responsible for the increasing trend in annual rainfall along with the relatively dry years at the start of the 1950s. The 1898–1950 period seasonal values have negligible trend and a slightly higher mean annual rainfall and coefficient of variation (CV) with respect to rainfall post-1951, suggesting reduced interannual variability, which is apparent in Figure 2.

Cross-validation of the Addis Ababa record is not really possible in the usual manner because of the large distance from Addis Ababa to other sites with records for the same period. One method would be to use a series of local gauges and a double mass calculation, but Addis Ababa is in the Showa (Scioa/Shewa) region (an area of roughly 12 000 km^2 ranging between 500 and >3000 m altitude). Gore, in southwest Ethiopia, and Asmara (~380 km and ~720 km from Addis Ababa respectively) have long records, but it is not realistic to cross-validate rainfall records over such distances; for example, New *et al.* (2000) calculate correlation decay lengths for monthly rainfall between 0° and 15° north of the equator of about 250 km, which is considerably

Table II. A revised rainfall record for Addis Ababa, 1898–1950. Sources: Lyons' (1906) derived series (1898–1907 (four sites); Hurst and Black's (1937) Bank of Abyssinia record (1908–37, 1941–45); Fantoli's (1965) unaccounted for source (1938–40); and WWR (1950, for 1946–50). September 1915 infilled with long-term mean value (see Section 3)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1898	8	15	105	73	41	121	352	290	151	19	10	0	1185
1899	2	11	—	—	—	—	—	—	—	—	—	—	—
1900	—	—	—	—	—	108	283	328	194	0	13	5	—
1901	16	54	124	100	36	222	277	250	128	21	0	13	1241
1902	1	76	49	89	42	172	236	291	184	0	11	1	1152
1903	29	25	83	88	268	191	269	267	224	20	0	8	1472
1904	0	37	136	57	58	124	350	196	172	40	0	0	1170
1905	5	7	48	74	41	94	294	352	113	1	45	0	1072
1906	9	156	189	103	60	132	380	358	119	16	28	0	1550
1907	0	20	11	140	22	72	181	293	108	15	81	0	944
1908	32	6	12	56	8	100	295	343	227	7	6	0	1092
1909	47	0	16	133	138	194	204	357	182	0	2	1	1274
1910	0	1	24	39	59	135	241	299	194	19	0	14	1025
1911	6	4	40	49	18	159	291	214	155	40	58	0	1034
1912	53	139	51	36	22	165	290	287	110	0	0	0	1153
1913	0	64	64	109	90	103	199	306	124	0	0	0	1059
1914	10	53	77	128	22	51	299	329	329	109	0	32	1439
1915	3	23	105	126	133	121	345	378	185	59	27	11	1516
1916	65	57	91	74	148	294	248	419	321	5	0	7	1730
1917	28	39	10	115	194	279	281	287	270	53	0	34	1591
1918	0	85	70	104	74	106	208	264	51	0	0	0	960
1919	11	47	66	32	43	90	317	253	133	0	0	0	992
1920	2	10	61	74	26	151	280	300	165	5	3	0	1076
1921	3	4	0	29	68	106	300	279	221	14	16	1	1039
1922	0	17	22	1	110	76	265	345	211	15	0	0	1062
1923	0	81	32	64	96	79	242	352	237	3	96	0	1282
1924	17	59	122	60	65	101	339	303	129	5	0	0	1200
1925	0	30	21	23	177	183	210	184	211	56	64	20	1179
1926	9	63	103	244	223	129	215	354	216	23	16	0	1595
1927	1	53	45	119	69	92	340	271	260	2	19	0	1271
1928	7	5	44	81	201	125	283	400	102	55	40	0	1343
1929	0	18	24	74	109	202	275	301	219	13	0	10	1244
1930	69	39	173	190	79	130	397	169	160	34	0	20	1461
1931	23	11	118	65	93	64	249	209	138	53	0	0	1022
1932	0	0	51	67	65	108	261	233	169	0	0	22	975
1933	0	25	23	105	48	110	294	362	186	12	16	0	1179
1934	0	6	62	59	58	170	239	231	193	0	3	6	1027
1935	0	4	16	117	302	206	225	168	235	6	0	4	1283
1936	104	150	110	73	77	68	399	302	111	3	22	0	1419
1937	6	49	167	63	73	87	272	190	151	0	27	5	1090
1938	24	4	15	20	26	177	265	212	301	10	0	0	1055
1939	6	37	35	117	70	105	212	314	136	102	0	0	1133
1940	47	69	100	40	51	73	259	237	55	0	6	0	937
1941	0	76	52	62	67	178	213	195	222	40	0	0	1105
1942	0	44	146	111	132	108	228	213	172	0	0	0	1154
1943	24	2	16	32	91	164	249	220	248	8	1	0	1055
1944	0	25	27	150	50	72	260	307	153	0	14	25	1083

(*continued overleaf*)

Table II. (*Continued*)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1945	0	0	0	0	62	77	275	282	243	3	64	0	1006
1946	0	0	11	97	124	186	311	476	155	2	0	0	1362
1947	0	115	250	316	39	91	476	404	247	1	0	0	1937
1948	22	25	0	56	69	216	337	267	288	31	2	0	1313
1949	0	0	87	34	187	136	358	274	229	4	40	5	1354
1950	8	2	18	48	56	100	264	273	164	13	0	0	946

Table III. Commonly cited modern observation sites in Addis Ababa (Abate, 1984; NOAA, 2001). Coordinates in decimals

Modern site	Elevation (m)	Latitude (N)	Longitude (E)	Notes
WMO referenced site #634500	2408	08.98	38.75	Probably the ENMSA site
Bolé airport	2333	09.02	38.80	75 m lower than AAO
Geophysical observatory (Arat Kilo)	2442	09.03	38.75	34 m higher than AAO
Addis Ababa Observatory, ENMSA, Black Lion site	2408	09.02	38.73	Probably the WMO site

less than the distances involved here. Conway (2000) found that rainfall at Addis Ababa was not significantly correlated with flows of the Blue Nile (representing rainfall to the north and west) or the southern oscillation index (SOI). The 20-year running correlations between Addis Ababa rainfall and Gore rainfall, Blue Nile river flows and the SOI (not shown) are nearly all statistically insignificant at the 5% level, non-linear over time and show no evidence of discontinuity when the record changes before and after 1950.

The nearest site with pre-1950 data is Adamitullu (near Lake Ziway, 1909–39, ~800 m lower and 130 km from Addis Ababa), which has an annual correlation with Addis Ababa of $r = 0.45$, significant at the 1% level. In the record for Addis Ababa, 1915 stands out as anomalous because of a very high September rainfall of 570 mm. This is the wettest of all months from 1900 to 1950, over 70% higher than the second wettest September on record, whereas rainfall at Adamitullu was close to normal. This value has, therefore, been replaced with the long-term mean September value, which improves the annual correlation with Adamitulu to 0.57. 1916–17 were also very wet in Addis Ababa, and although 1916 was not very wet at Adamitulu, 1917 was, and both years were very wet in other parts of East Africa and in the Blue Nile catchment (Conway, 2002). None of the monthly values is an outlier, and so the values are likely to be reasonably reliable and are included here. The extreme observation for 1947 (1937 mm, very wet MAM), however, looks a little suspect. Neither Gore rainfall nor the Blue Nile river flows were particularly high in this year. Griffiths and Hemming's (1964) Addis Ababa Bank recorded a much more normal year in 1947 (1261 mm, but monthly values not available); however, this observation is not used in the CRU series, nor by the GHCN. The reliability of the extreme observation for 1947 is, therefore, rather questionable, but it is used here nevertheless.

Of the significant drought events to have affected adjacent regions of Ethiopia, such as 1957–58, 1964–65, 1971–72 and 1983–85 (Degefu, 1987) only 1972 was extremely dry in Addis Ababa. This supports other evidence that the station is 'insulated' from climatic conditions to the north and east, probably due to its elevation and location in the Rift Valley.

We followed the statistical approaches used by Wijngaard *et al*. (2003) to test the homogeneity of the full rainfall and temperature records and sub-periods in the rainfall record. Four tests were used: standard normal homogeneity test (SNHT), the Buishand range test, the Pettitt test and the Von Neumann ratio test. The alternative hypothesis for the Von Neumann test is that the series is not randomly distributed and for the other three tests it is that a stepwise shift in the mean is present. Table V shows the results of the tests for the full period and sub-periods. The long record shows moderate but not statistically significant evidence of

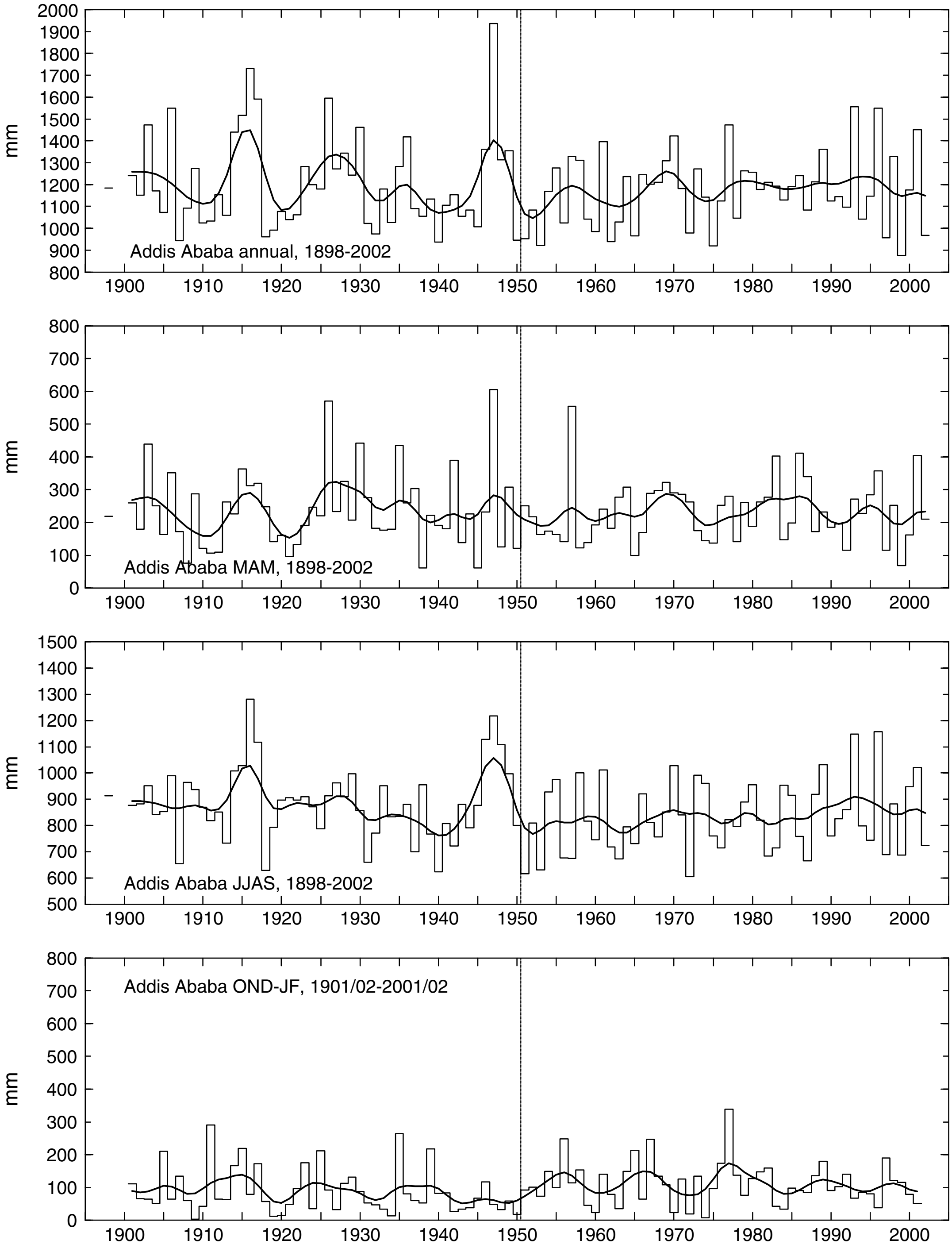

Figure 2. Annual and seasonal rainfall in Addis Ababa, 1898 to 2002 with 10 year filter applied to annual series. Vertical line highlights start of AAO record

breaks prior to 1950, with minor breakpoints in 1917–18 (very wet year), 1930–31, 1936–37 (close to the change from the Bank series to Fantoli's (1965) unaccounted for source), 1945–46 (change to WWR (1959) site which is unaccounted for) and 1949 (close to the move to the AAO gauge). The most notable difference

Table IV. Seasonal and annual rainfall statistics

	MAM	JJAS	ONDJF	Annual
1898–1950				
R^2	0.00	0.00	0.02	0.00
Trend (mm/decade)	+4	−4	−7	−7
Mean (mm)	238	894	87	1220
SD	109	153	67	236
CV (%)	50	17	77	19
1951–2002				
R^2	0.00	0.04	0.01	0.03
Trend (mm/decade)	+3	+18	−4	+17
Mean (mm)	231	831	111	1171
SD	93	135	64	165
CV (%)	40	16	58	14
1898–2002				
R^2	0.00	0.02	0.01	0.01
Trend (mm/decade)	0	−7	+2	−6
Mean (mm)	234	862	99	11 196
SD	106	147	67	204
CV (%)	45	17	67	17

Table V. Results of four homogeneity tests on rainfall and temperature records for Addis Ababa (SNHT: standard normal homogeneity test; the Buishand range test; the Pettitt test; the Von Neumann ratio test; see Wijngaard *et al.* (2003)). Breakpoint years shown in parentheses are not statistically significant

	Pettitt	Buishand	SNHT	Von Neumann	Classification
Rainfall period					
1901–2002 (revised early series + AAO)	No shift present (1917, 1930, 1936, 1949)	No shift present (1917, 1930, 1936, 1949)	No shift present (1918, 1931, 1937, 1949)	No shift present	Useful
1901–1950 (revised early series)	No shift present (1917, 1930, 1936, 1945, 1949)	No shift present (1917, 1930, 1936, 1945, 1949)	No shift present (1918, 1930, 1945)	Shift present at 5% level	Useful
1951–2002 (AAO)	No shift present (1965, 1976)	No shift present (1965, 1976)	No shift present (1954, 1966, 1976)	No shift present	Useful
Temperature 1951–2002					
T_{min}	Shift present at 1% level: 1975	Shift present at 1% level: 1968, 1974	Shift present at 1% level: 1962, 1966	Shift present at 1% level	Suspect
T_{mean}	Shift present at 1% level: 1978	Shift present at 1% level: 1978	Shift present at 1% level: 1979	Shift present at 1% level	Suspect
T_{max}	Shift present at 1% level: 1962, 1979, 1985	Shift present at 1% level: 1979	Shift present at 5% level: 1979	Shift present at 1% level	Suspect

between the two main sub-periods is the decrease in coefficient of variation (CV; decline in persistence) of annual rainfall from the pre-1950 record (lag-1 autocorrelation function (ACF) = 0.30, significant at the 5% level) and the post-1950 record, which shows reduced clustering of wet and dry years (lag-1 ACF = −0.36, significant at the 1% level). The change is primarily accounted for by behaviour of JJAS rainfall, but it is difficult to account for either in terms of change in site location or observation routine or physical change in the rainfall regime. Given the moderate effects of changes in site on the observations, it is reasonable to assume that the full record is homogeneous and, therefore, representative of long-term rainfall conditions in Addis Ababa during the 20th century.

4. TEMPERATURE HOMOGENEITY AND TREND IN ADDIS ABABA, 1898–1950 AND 1951–2002

The early temperature record is very short, intermittent and subject to changes in location and elevation, precluding analysis of its longer term temporal characteristics and detailed comparison with the later continuous record. Figure 3 shows that the pre-1950 maximum temperatures, particularly from 1902 to 1911, were slightly higher than post-1950 and that the pre-1950 diurnal range was slightly greater than post-1950. Table V shows the results of the tests for the temperature records; in nearly all cases, statistically significant shifts occur in the series with various years identified as breakpoints without much consistency between series and tests. Comparison with Figure 3 confirms 1962 (possible outlier) and 1979 as breakpoints. From 1951 onwards there has been a positive trend in minimum and maximum temperatures in all seasons with greater increase in minimum temperatures (Table VI). The mean minimum temperature increase occurs between 1955 and 1984 and is more consistent over time, whereas the mean maximum temperature shows a slight cooling between 1959 and 1978. The trend is greatest for minimum temperatures during the dry season. The anomalously high minimum temperature in 1962 is due to high values in all months of that year, and we include the data here with caution. Given the statistically significant homogeneities with all four tests, the temperature series should be considered as suspect using Wijngaard *et al.*'s (2003) terminology and, therefore, the trends identified here should be treated with caution.

The regional trend in temperature given by Houghton *et al.* (2001) shows trend for grid boxes located northwest (and southwest) of Addis Ababa in the order of +0.25 °C/decade (and 0.00 °C/decade) from 1946 to 1975 (*q.v.* for this Addis Ababa record trend is −0.1). For the period 1976 to 2000, Houghton *et al.* (2001) show a trend of about +0.30 °C/decade (*q.v.* for this Addis Ababa record trend is +0.40). Hulme *et al.* (2001) found a decreasing diurnal temperature range for Ethiopia between 1952 and 1990, and an African mean trend of about 0.50 °C/century. King'uyu *et al.* (2000) analysed 71 long daily maximum and minimum temperature records for the Horn, eastern and southern Africa, including Addis Ababa. They identified a significant, but spatially nonuniform, rise in minimum temperatures at several locations, but with many coastal areas and stations near large water bodies showing a significant decrease. The northern part of their study region generally exhibited cooling in maximum temperatures. It is not clear from their study, however, exactly what periods were used for individual records, so direct comparison here is not possible.

The effects of increasing industrialization and urbanization on the record are difficult to quantify. One effect of the urban heat island is to raise the minimum temperature (Barry and Chorley, 1992) and trends in minimum temperature due to global warming are estimated to increase at twice the rate of the maximum temperatures (Houghton *et al.*, 2001). The AAO is located centrally in Addis Ababa and the city has grown significantly in size from 1950 to 2000 (∼0.3 million to ∼2.5 million; CIA, 2000). Both phenomena are, therefore, likely to contribute to the observed increase in minimum and maximum temperatures and the reduction in the diurnal range. King'uyu *et al.* (2000) categorized stations as rural or urban based on a 2000 population threshold, but only for stations for which they had data (Kenyan ones); however, accurate quantification of urban influences on the Addis Ababa record is not possible here.

5. CONCLUSIONS

The history of climate observations in Addis Ababa has been reviewed with the objective of establishing the provenance and characteristics of the longest climate record available for Ethiopia, a rainfall record beginning in 1898 and temperature records beginning in 1951. The main conclusions to this exercise are as follows.

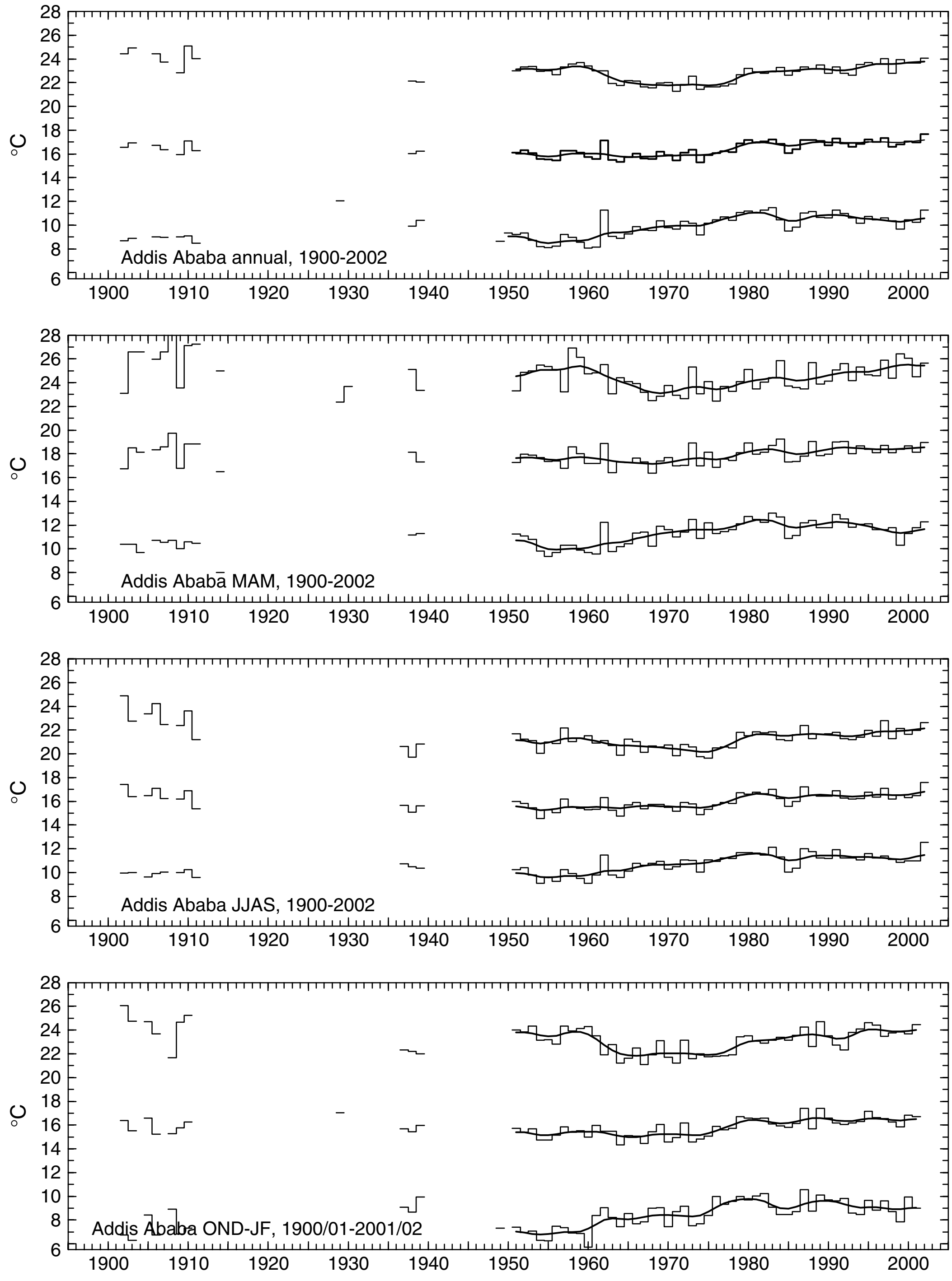

Figure 3. Annual and seasonal temperature in Addis Ababa, 1898 to 2002 with 10 year filter applied to post-1950 data

- The observations have two separate sources: pre-1951 they originate from a number of historical documents and post-1951, after establishment of an Ethiopian meteorological department, they originate from this agency in various forms.

Table VI. Seasonal and annual temperature statistics for 1951–2002

	JJAS		MAM		ONDJF		Annual	
	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}
Mean (°C)	21.2	10.8	24.4	11.4	23.1	8.5	22.8	10.0
SD (°C)	0.7	0.8	1.1	1.0	1.0	1.2	0.8	1.0
CV	3.4	7.6	4.5	8.6	4.4	13.6	3.3	9.6
R^2	0.23	0.51	0.02	0.37	0.05	0.46	0.10	0.50
Trend (°C/decade)	0.2	0.4	0.1	0.4	0.2	0.5	0.2	0.4

- According to the ENMSA, from 1951 onwards both the temperature and rainfall records have been based at the AAO in central Addis Ababa. Although it is highly likely that changes in instrumentation, observer practice and exposure have occurred since 1951, no records of such changes exist in the station file held by the ENMSA. This site represents the longest continuous records of temperature and rainfall (53 years as of now) for Ethiopia, an area of $>1.1 \times 10^6$ km^2.
- The minimum and maximum temperature records prior to 1951 are very intermittent and preclude detailed analysis.
- Minimum and maximum temperatures show increasing trends from 1951 to 2002 of 0.4 °C/decade and 0.2 °C/decade respectively. Both series, however, show statistically significant inhomogeneities with four homogeneity tests and, therefore, should be considered as suspect.
- Documentary sources have allowed us to trace the origins of most of the rainfall observations prior to 1951 and to compile a revised rainfall series for Addis Ababa from 1898 to 1950 using as few sites as possible.
- A full rainfall record from 1898 to 2002, consisting of the early revised series (composed from at least six sites) joined with the AAO record, has no statistically significant inhomogeneities. Five minor breakpoints exist in the record prior to 1951, not all of which can be accounted for in the station history.
- There is no major shift or trend in annual and seasonal rainfall during the periods 1898–1950, 1951–2002 and 1898–2002. There are only a few records in Ethiopia of similar length for comparison with Addis Ababa rainfall, including Blue Nile river flows and Gore rainfall, and neither series is correlated with Addis Ababa. Well-known drought years in northern and northeastern Ethiopia are not picked out in the Addis Ababa rainfall record, suggesting that the series should not be used as a proxy for interannual rainfall variability in these parts of the Ethiopian highlands.

ACKNOWLEDGEMENTS

We are very grateful to the ENMSA for provision of climate data for AAO. We also acknowledge Pierre Camberlin for helpful comments on an earlier version of the manuscript and provision of additional data.

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