Global and Planetary Change 165 (2018) 114–127

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Invited research article

Rainfall over the African continent from the 19th through the 21st century

Sharon E. Nicholson[a,*], Chris Funk[b,c], Andreas H. Fink[d]

[a] *Florida State University, Tallahassee, FL 32306, USA*
[b] *US Geological Survey Center for Earth Resources Observations and Science, USA*
[c] *Climate Hazards Group, University of California at Santa Barbara, Santa Barbara, CA 93106-4060, USA*
[d] *Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany*

ARTICLE INFO

Editor: Zhengtang Guo

Keywords:
Africa
Rainfall
Drought
Teleconnections
Multi-decadal variability
Interannual variability

ABSTRACT

Most of the African continent is semi-arid and hence prone to extreme variations in rainfall from year to year. The extreme droughts that have plagued the Sahel and eastern Africa are particularly well known. This article uses a markedly expanded and updated rainfall data set to examine rainfall variability in 13 sectors that cover most of the continent. Annual rainfall is presented for each sector; the March-to-May and October–November seasons are also examined for equatorial sectors. In each case, the article includes the longest and most comprehensive precipitation gauge series ever published. All time series cover at least a century and most cover roughly one and one-half centuries or more.

Although towards the end of the 20th century there was a widespread trend towards more arid conditions, few significant trends are evident over the entire period of record. The largest were downward trends in the Sahel and western sectors of North Africa. In those regions, an abrupt reduction in rainfall occurred around 1968, but a synchronous change occurred many other parts of Africa. A recovery did occur in the Sahel, but to varying degrees across the east-west expanse of the region. Noteworthy is that the west-to-east rainfall gradient across the region appears to have weakened in recent decades. For the continent as a whole, another change began in the 1980s decade, with more arid conditions persisting at the continental scale until early in the twenty-first century. No other such period of dry conditions occurred within the roughly one and one-half centuries evaluated here. A notable change also occurred at the seasonal level. During the period 1980 to 1998 rainfall during March-to-May was well below the long-term mean throughout most of the area from 20° N to 35° S. At the same time rainfall was above the long-term mean in most of eastern sectors within this latitude span, indicating a change in the seasonality of rainfall of a large part of Africa.

1. Introduction

The African continent is home to over one billion people, most of whom reside in semi-arid, drought-prone regions. The West African Sahel is infamous for the extreme droughts that began in the late 1960s and took a tremendous toll on the food-insecure population. More recently the world's attention has been focused on the extreme droughts of eastern Africa. The drought of 2011 produced famine conditions in Somalia, where tens of thousands died of malnutrition; some 11 million in eastern Africa faced severe food shortages (Tran, 2011). Devastating floods have also occurred (Samimi et al., 2012; Tschakert et al., 2010). Of great concern is the projection that Africa may be the continent most impacted by climate change (Niang et al., 2014) and that droughts could become more intense and frequent in some areas (Gizaw and Gan, 2017). Such a change appears to have occurred already in parts of eastern Africa (Funk et al., 2015; Nicholson, 2016).

The purpose of this article is to document the continent-wide interannual to multi-decadal variability of annual and seasonal rainfall over the last century and a half. This is by far the longest and most detailed record available. The analysis relies on a recently updated data set and it parallels and extends the continent-wide analysis of Nicholson (2001). Time series of rainfall are examined for 13 sectors of relatively homogeneous interannual variability. Analysis of seasonal contributions to the variability is included for equatorial regions, which experience two rainy seasons during the course of the year. Decadal-scale fluctuations for the continent as a whole are also presented.

The results are presented first for variability of annual rainfall, separately considering the sectors in northern, western, equatorial, and southern Africa (Section 3.1). Although the causes of the variability are beyond the scope of this article, a brief overview of the relevant, recent

* Corresponding author.
E-mail addresses: snicholson@fsu.edu (S.E. Nicholson), chris@geog.ucsb.edu (C. Funk), andreas.fink@kit.edu (A.H. Fink).

https://doi.org/10.1016/j.gloplacha.2017.12.014
Received 31 May 2017; Received in revised form 6 December 2017; Accepted 10 December 2017
Available online 13 December 2017

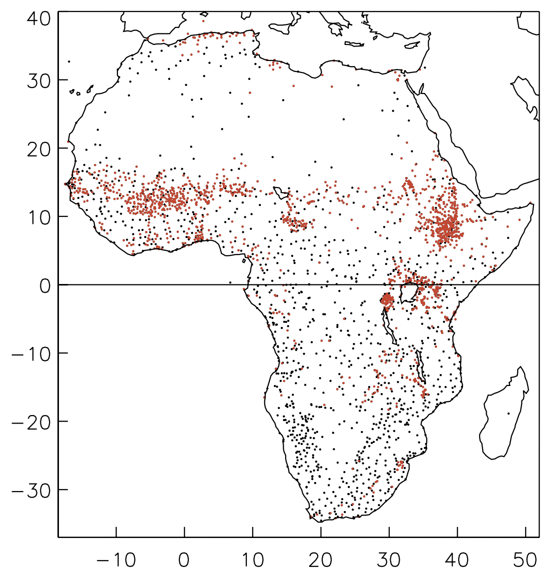

Fig. 1. Map of available rainfall stations. Black = original data set, red – new stations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

literature is presented at the end of each regional discussion. A discussion of seasonal trends in the equatorial sectors follows (Section 3.2). Teleconnections are then considered briefly in the context of changes in each rainfall regime (Section 3.3). In Section 3.4 maps of decadal scale fluctuations over the continent as a whole are presented. Section 4 summarizes the observed trends and suggests areas where further research is needed.

2. Data and methodology

The first author assembled a gauge data set that was used in numerous publications and described in Nicholson (1986) and Nicholson et al. (2000). Most records extended only to 1998. This data set was recently updated for western and equatorial Africa and now includes 2000 station records (Fig. 1). Updates for southern African and Mediterranean countries were obtained from the Global Historical Climatology Network. Historical data described in Nicholson (2000) and Nicholson et al. (2012a, 2012b) were added to the modern records to produce time series that extend well back into the nineteenth century. Fig. 2 shows the number of stations available each year and Fig. 3 presents a histogram of the length of record for individual stations. Roughly half of the stations cover the period 1930 to 2000, with roughly 1800 stations being available for the period 1950 to 1990. Some 100 records are available as of the 1880s. The decline in the number of records since circa 1980 is a result both of the decline of the networks in many countries and the increased difficulty and cost for obtaining records. Over half the station records are 50 years or longer and some 700 stations have 70 or more years of data. From this gauge data set, a gridded data set is being prepared and it will be available to the research community. For eastern Africa the gridded Centennial Trends data set has already been prepared (Funk et al., 2015).

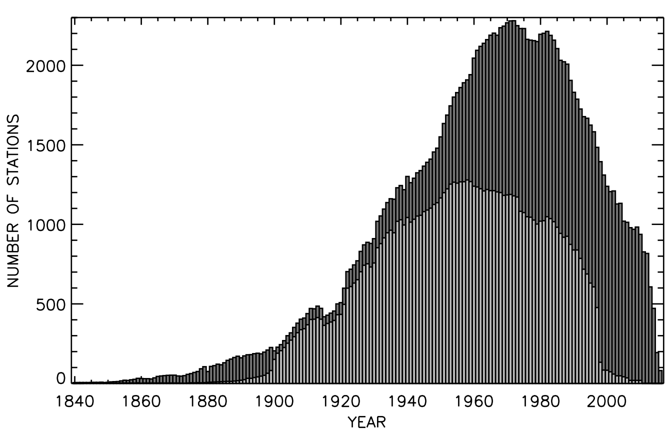

Fig. 2. Number of stations available in each year. The dark area shows current number of stations per year; lighter shading shows the number of stations in each year in the prior data set.

For many past studies of the first author (e.g., Nicholson, 1986; Nicholson and Kim, 1997; Nicholson et al., 2012b) the gauge data were combined into 90 regions spread across the continent. Each region was determined to be relatively homogeneous with respect to interannual variability. The updated data set included many new stations and in some cases additional data for stations already in the original data set. To determine the appropriate region for new and enhanced stations, the rainfall time series for each station was correlated with the time series for several regions near its geographical location. Each station was assigned to the region with which it was best correlated, if a correlation above roughly 0.4 was found. The cutoff for inclusion was subjectively determined, as it depended on the record length between correlated and the spatial homogeneity of the rainfall regime in the region.

This regionalization process was used as part of the quality control procedure for the data. The procedure was three-fold. First, each individual record was subjectively scanned by the first author to identify any obvious problems and extreme values. The latter were further examined via comparison with values at nearby stations. Then records were further scrutinized for stations with low station-region correlations, i.e., those which could not be assigned to a rainfall region. If no outliers or inhomogeneities were evident, the gauge record was retained in the overall data set but not included in regional averages.

In the current analyses, multi-regional sectors (Fig. 4) are examined. Each consists of several highly correlated regional time series. In some cases, subsets of the regions shown in Fig. 4 were evaluated. For example, several Sahelian/Soudanian sectors were initially considered. However, the time series of regional subsets considered were so similar, that it was decided to present only one time-series.

The calculation for each sector commences with individual station records. The value for each year j and station i is expressed as a standardized departure from the station mean $\bar{r}_i$:

$$X_{ij} = (r_{ij} - \bar{r}_i)/\sigma_i$$

In the above X_{ij} is the standardized departure and σ_i is the standard deviation over the period for which the mean is calculated. Such calculations can be done for annual, seasonal or monthly time series. The use of standardized departures allows for the use stations with diverse means and variances. This is particularly important when the station network varies over time and station records may contain extensive gaps. For that reason, this formulation is conventionally used in studies of interannual variability of African rainfall.

For the multi-region sector average R_j, the first step is an arithmetic average of the standardized departures from all I stations within the sector that are available for the season or year in question. For example, in the case of annual values:

$$R_j = I_j^{-1} \sum_{i=1}^{I} X_{ij}$$

This means that a sector value is not the arithmetic average of values for each region in the sector, but is instead based on an average of all stations within the sector.

The second step is an adjustment for cases in which only a small number of stations comprise the average. Adjustment factors were determined, as in Nicholson (1986), by computing the ratio of the

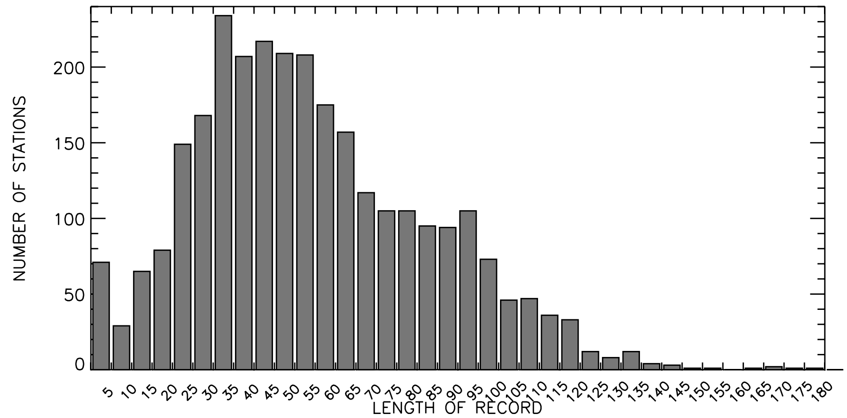

Fig. 3. Histogram of record length at the stations shown in Fig. 1.

standard deviation of the time series for the full complement of stations versus the standard deviation when the time series consists of I number of stations.

In prior work the long-term mean, i.e., the mean over the entire length of each station record, has been utilized. The justification is that in some regions, such as the Sahel, the mean can change remarkably

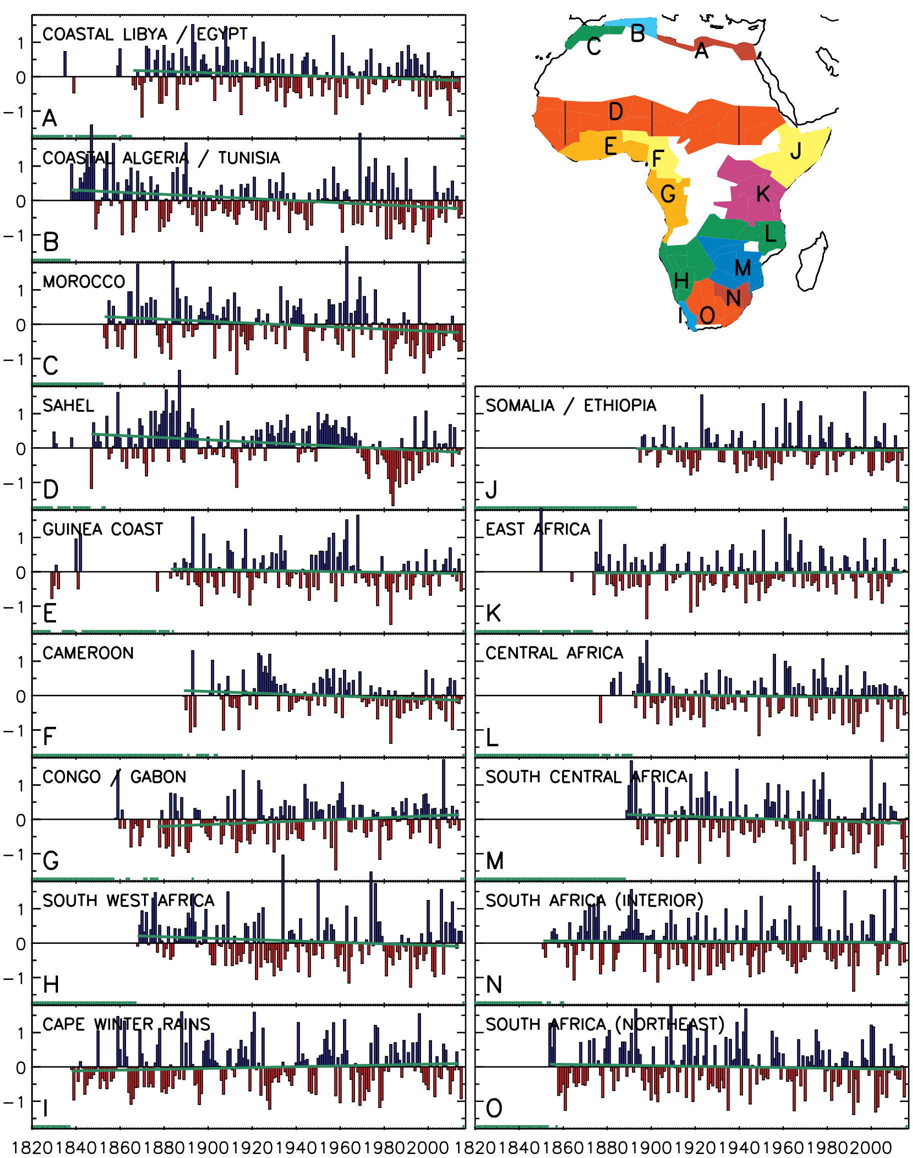

Fig. 4. Annual time series over the length of record for multi-regional sectors shown in the inset. Rainfall is expressed as a spatially-averaged standardized departures. The dashed vertical lines within sector D are sub-divisions of the Sahel shown in Fig. 5.

over the 30-year periods traditionally used to establish a mean. Since most station records in this data set are considerably longer, a mean over the entire period of record is more robust. Thus, this is used for calculating time series of rainfall. Spatial maps are also presented in this paper and, because of the direct comparison between individual locations, a common mean for each station is appropriate. The time span chosen for calculation is 1931 to 1970 mean. This 40-year period is utilized as opposed to the typical 30-year mean because the varying time spans over which individual stations are available (Fig. 2).

3. Results

3.1. Annual time series

Fig. 4 shows the multi-regional sectors considered. Interannual variability is highly homogeneous within each. The Sahara is not represented because there are few stations and because spatial coherence is weak. Much of central equatorial Africa is not represented because spatial coherence is also weak here and regions on the periphery tend to represent transition zones between other homogeneous sectors. Moreover, recent station coverage is sparse. A few very small areas in southern Africa are also omitted because they represent transition zones. The names applied to these sectors (Fig. 4) are not strict geographical designations, but labels attached for the sake of convenience in discussion. For example, the term Cameroon is applied to a sector that includes primarily Cameroon but also parts of northern Nigeria.

Rainfall is highly seasonal in each of the sectors, with a unimodal distribution in extra-tropical and subtropical sectors and a bimodal distribution in the low latitudes. In the three Mediterranean sectors rainfall peaks in the boreal winter. In the sector just south of the Sahara rainfall is similarly unimodal but with a peak in the boreal summer, in August on average. It is labeled Sahel, but includes Soudanian rainfall zones as well. In the four equatorial regions rainfall tends to peaks in the boreal spring and autumn. In most of southern Africa, rainfall peaks in the austral summer/boreal winter. However, there are exceptions to this pattern. Stations very close to the Benguela coast tend to experience a peak in early autumn. The Cape of South Africa is a region of winter rains and other sectors further east along the coast tend to experience a bimodal rainfall distribution, similar to what occurs in equatorial regions. The annual time series for each sector is shown in Fig. 4.

For each sector the trend in annual rainfall is calculated over the time period indicated in Table 1. This is the period over which the times series is continuous. The Mann-Kendall test is applied and the trend lines are indicated in Fig. 4. The regions showing trends over the analysis period that are significant include coastal Algeria, Morocco, the Sahel, Cameroon, and Congo/Gabon. In the first three cases, trends are negative and significant at better than the 1% level. In the last two, the trends are significant at the 3% level. Trends are negative in all of these sectors except Congo/Gabon. However, the trends mask some major periods of wet or dry conditions. Further description of the interannual variability is presented in the following sections.

3.1.1. North Africa

Fig. 4 shows the annual time series for each sector. In the Mediterranean areas of Algeria and Tunisia (sector B) relatively wet conditions prevailed until the 1890s, while the twentieth century has been relatively dry, particularly from the beginning through the 1940s. A few very wet years occurred in the 1970s and 1980s, but on the whole abnormally dry conditions have prevailed since the 1980s. Also apparent is an increase in year-to-year variability since roughly 1960. Trends in Morocco (sector C) are in a general sense similar: wetter conditions in the 19th century and extremely dry conditions since the 1980s. However, prior to 1980 few very dry years occurred. Decadal trends have been quite different in the eastern Mediterranean region (Libya/Egypt, sector A). Relatively wet conditions prevailed until the 1920s; from 1926 to 1943 rainfall reached or exceed the long-term mean in only 3 years. The biggest contrast is evident in recent decades. The 1980s and 1990s are relatively wet, with conditions similar to those in the nineteenth century. Dry conditions have since been the rule.

Table 1
The period over which trends in annual and seasonal rainfall were calculated for the 13 sectors considered. The unit for the trend is standardized departures per century. The statistical significance of the trend is also shown for cases with a significance level of < 5%.

Region	Season	Trend	First year	Last year	Signif. level
Coastal Libya/Egypt	Year	− 0.20	1866	2014	–
Coastal Algeria/Tunisia	Year	− 0.31	1838	2014	< 1%
Morocco	Year	− 0.29	1853	2014	< 1%
Sahel	Year	− 0.32	1847	2014	< 1%
Guinea Coast	Year	− 0.10	1883	2014	–
Cameroon	Year	− 0.22	1889	2014	3%
Congo/Gabon	Year	0.25	1877	2014	3%
South West Africa	Year	− 0.21	1868	2014	–
Cape Winter Rains	Year	0.12	1838	2014	–
Somalia/Ethiopia	Year	− 0.04	1893	2014	–
East Africa	Year	0.01	1874	2014	–
Central Africa	Year	− 0.09	1892	2014	–
South Central Africa	Year	− 0.20	1889	2014	–
South Africa (interior)	Year	− 0.03	1851	2014	–
South Africa (northeast)	Year	− 0.09	1854	2014	–
Guinea Coast	MAM	− 0.17	1883	2014	–
Guinea Coast	ON	− 0.13	1883	2014	–
Cameroon	MAM	− 0.35	1889	2014	< 1%
Cameroon	ON	− 0.08	1889	2014	–
Congo Gabon	MAM	− 0.04	1877	2014	–
Congo Gabon	ON	0.13	1877	2014	–
Somalia	MAM	− 0.15	1893	2014	–
Somalia	ON	0.11	1893	2014	–
East Africa	MAM	− 0.11	1874	2014	–
East Africa	ON	0.16	1874	2014	–

The increasing aridity and occurrence of very dry conditions since the 1980s is confirmed by tree-ring studies and gauge data in Morocco (Esper et al., 2007), Algeria, and Tunisia (Kherchouche et al., 2013; Touchan et al., 2008; Ghenim and Megnounif, 2013). This has resulted in a die-back of cedar forests throughout the region. Studies based on station data further confirm the increasing aridity. In Algeria and Tunisia, the drought of 1999–2002 appears to have been the worst since the 15th century (Touchan et al., 2008). In much of this region, especially the northwestern areas, the NAO plays a major role in regulating internal variability via impacts on storm tracks and other aspects of regional atmospheric circulation (Knippertz et al., 2003).

3.1.2. West Africa

Rainfall variability in the Sahel (sector D) is relatively homogeneous over a large area, extending across the continent. While zonal variations are evident (e.g., Nicholson and Palao, 1993; Nicholson, 2005; Lebel and Ali, 2009), the time series presented in Fig. 4 is largely representative of the region as a whole. The most striking aspects of the time series are the abrupt decline in rainfall in 1968 and the long run of generally wet years from the 1920s through the 1960s. Wettest conditions occurred in the 1870s and 1880s and in the 1950s and early 1960s. Since that time rainfall has reached or exceeded the mean in very few years (Fig. 4) and a major change in the rainfall regime appears to have occurred after 1968 (Losada et al., 2012; Nicholson et al., 2017).

There are many similarities in the rainfall variability along the Guinea Coast (Fig. 4, sector E), but year-to-year persistence is much weaker and the anomalies are generally less extreme than in the Sahel. Also, rainfall has tended to be near or above average since around 2000 and dry and wet years were roughly equally frequent prior to 1950. Guinea Coast rainfall is discussed further in Section 3.2.2.

It is not surprising that decadal rainfall variability in the Sahel and Guinea Coast have some similarities because these regions are conjoined via the dominance in both of the West African monsoon. More surprising are the similar trends evident in Morocco, a region of predominantly boreal winter rains north of the Sahara. On the whole, rainfall tended to be fairly reliable since the beginning of the record, with particularly wet conditions in much of the late 19th century and again in the 1950s and 1960s. As in the Sahel and Guinea Coast, an abrupt change to dry conditions subsequently occurred and these have persisted almost without interruption since that time. However, the change occurred around 1978, compared to 1968 in the Sahel and Guinea Coast (Nicholson et al., 2017). Notably, rainfall in all three regions is strongly influenced by the Atlantic (Knippertz et al., 2003). This might account for the similarities.

The increase in Sahel rainfall since the 1980s had been documented by several previous studies. Most concluded that the drought was nevertheless continuing (e.g., Nicholson et al., 2000; L'Hôte et al., 2002; Lebel and Ali, 2009). Ozer et al. (2003), however, had claimed that the region had entered into a more humid period, citing frequent flooding. Others have produced evidence that other causes of the floods, such as increased runoff coefficients, were at play (L'Hôte et al., 2003; Mahé and Paturel, 2009; Galy-Lacaux et al., 2009).

This recovery was not uniform across the Sahel, but was substantially greater in the west than in the east (Fig. 5). This suggests a reduction in the west-to-east rainfall gradient across the Sahel. This and other aspects of intra-Sahelian rainfall contrasts are discussed in Nicholson et al. (2017).

Indisputably, rainfall in the Sahel (Fig. 4) has increased since the 1980s. Yet, since the 1980s, rainfall exceeded the long term mean for the region as a whole in only seven years. The recovery has been mainly in the August to October period (Sanogo et al., 2015), although recovery in August has been relatively weak (Nicholson, 2005) and in some areas the August peak has disappeared (Lebel and Ali, 2009). The recovery has also been non-uniform across the region (Nicholson, 2005; Lebel and Ali, 2009).

There has not been a consensus on the cause of the recovery; presumably several factors have played a role. Both modeling and observational studies have suggested that warming in the North Atlantic was a principal cause of the recovery (Park et al., 2015; Rodríguez-Fonseca et al., 2015; Hoerling et al., 2006). Hagos and Cook (2008) and Mohino et al. (2011) implicate the Atlantic Multidecadal Oscillation (AMO) specifically, while Diatta and Fink (2014) find a stronger relationship to the tropical Atlantic Meridional SST mode, with its influence confined mostly to the central Sahel. Lutz et al. (2015) suggest that cold anomalies, i.e., Atlantic Niñas, play a greater role than warm anomalies. Park et al. (2016) conclude since the late 1990s the recovery has likely been dominated by the Mediterranean SST. Although the link to Sahel rainfall is very strong, the Mediterranean SST anomalies may be a "fingerprint" of larger-scale forcing (Polo et al., 2008). Tippett and Giannini (2006) emphasize the relationship to ENSO, which has become stronger in recent decades (Diatta and Fink, 2014).

3.1.3. Western equatorial Africa

To the south of the Sahel and Guinea Coast is the western equatorial sector (sector F). The Guinea Coast appears to be a transition between this region and the Sahel and frequently anomalies are of the opposite sign in the Sahel and western equatorial Africa. Here western equatorial Africa is represented by two time-series (Fig. 4), one that encompasses primarily parts of Cameroon (and is so labeled) and a second that encompasses primarily Gabon, the Congo, and northwestern Angola. In both areas the seasonal distribution is bimodal at most stations.

In Cameroon the annual rainfall trends tend to mimic those in the Sahel and Guinea Coast: good rainfall in the 1950s and early 1960s, then an abrupt reduction of rainfall in 1968 and a continuation of dryness to the present, with little recovery. Relatively wet conditions did occur in 1999, 2002, 2009, 2010, and 2012. Most of those years were relatively wet in the Sahel and Guinea Coast as well. Overall the wettest period in the Cameroon region was in the 1920s.

In the Congo/Gabon region, annual anomalies were primarily negative from the 1860s until around 1920, in contrast to the strong positive anomalies prevailing then in the Sahel. As in the Sahel, wetter conditions prevailed between then and the early 1960s. In contrast to the Sahel, year-to-year variability was quite large and many very dry years occurred within this time, resulting in an opposition between the two regions. After circa 1961 year-to-year variability was quite weak with alternating wet and dry years. However, rainfall has generally been above or near the long-term mean since about 1980, in contrast to the severe drought conditions ravishing the Sahel over much of the same period. However, in both the Sahel and the Congo/Gabon region rainfall generally increased from around 1980 to present.

A number of other studies have examined long-term trends in rainfall in western areas of equatorial Africa. There is general

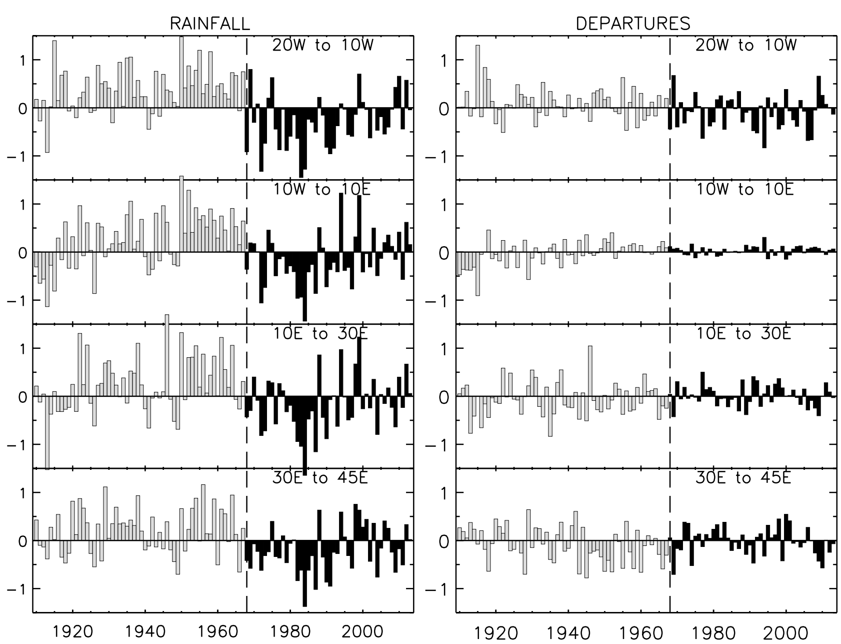

Fig. 5. Rainfall in five longitudinal sectors of the Sahel, between latitudes 11° N and 17° N. Left: standardized departure, as in Fig. 3. Right: departure of sector rainfall from rainfall in the Sahel as a whole, between 11° N and 17° N. The values indicated represent the difference between the Jul–Aug–Sep anomaly for the indicated sector and the Jul–Aug–Sep anomaly for the region as a whole, roughly approximated by sector D in Fig. 4. The dashed vertical line represents 1968.

agreement that a drying trend has occurred since the 1970s over much of the western equatorial region, particularly north of the equator (i.e., in the Cameroon region) and that is has not been as strong or as continuous as that in the Sahel (e.g., Laraque et al., 1997; Mahe et al., 2001; Conway et al., 2009; Samba and Nganga, 2012). There has also been a decrease in heavy precipitation (Aguilar et al., 2009).

Unfortunately, a lack of up-to-date gauge data precludes the evaluation of Congo basin rainfall in the current study. However, three studies provide relatively up-to-date information on the Congo Basin. Zhou et al. (2014) show a downward trend in boreal spring rainfall since the mid-1980s. This trend appears to have reduced the productivity in some parts of the Congo rain forest. However, several years between 1985 and 2007 were probably wetter than any that occurred between 1950 and 1984. Asefi-Najafabady and Saatchi (2013) confirmed the drying trend in the basin, but also find a trend towards increasing rainfall in the western-most equatorial Africa. They also noted that rainfall deficits were particularly strong in 2005 to 2007.

A large number of papers have evaluated factors in rainfall variability in western equatorial Africa. No general consensus has been reached because the factors are so varied spatially and on different time scales (e.g., Balas et al., 2007; Laing et al., 2011). There is however agreement that low-level and mid-tropospheric westerlies tend to be associated with above-average rainfall (Gu et al., 2009; Sinclaire et al., 2015; Tazalika and Jury, 2008; Todd and Washington, 2004), especially in western-most equatorial regions (Dezfuli and Nicholson, 2013; Nicholson and Dezfuli, 2013). Berhane et al. (2015) found that in the boreal spring the Madden-Julian Oscillation (MJO) augments precipitation by 20% to 50% and that the MJO tends to be associated with low-level westerly anomalies, which advect moisture from the Atlantic. On interannual time scales, links have been found to the AMO (Diem et al., 2014), ENSO (Balas et al., 2007; Sandjon et al., 2012), the intensity of equatorial zonal circulations (Dezfuli et al., 2015; Hua et al., 2016), and to SSTs in various parts of the globe (Balas et al., 2007; Dezfuli and Nicholson, 2013; Nicholson and Dezfuli, 2013; Hua et al., 2016).

3.1.4. Eastern equatorial Africa

Eastern equatorial Africa is represented by time series for Somalia/Ethiopia and for the traditional East Africa sector that includes mainly Kenya, Uganda, and Tanzania (Fig. 4). In the former region, rainfall is concentrated in the boreal season while a bimodal equatorial rainfall regime prevails in the latter region. Despite the contrasting seasonality, the rainfall time series for the two sectors are similar and interannual variability is strong in both. No particular trends are apparent in annual rainfall in the two eastern regions. However, the annual variability belies some strong trends evident in the seasonal times series discussed in Section 3.2. A comparison of individual years shows that the anomalies are frequently of opposite sign in eastern and western equatorial Africa. This characteristic is examined in further detail in 3.3. An upward trend since the mid-nineteenth century is evident in western equatorial Africa.

Most of the literature focused on trends in rainfall in eastern Africa examines the two rainy seasons but not the annual total. The former will be reviewed in Section 3.2.1.

3.1.5. Southern Africa

Southern Africa is represented by six time-series in Fig. 4 (H, I, L, M, N, O). The five with maxima in the boreal summer tend to show similar decadal scale variations: relatively low rainfall early in the 20th century, improvement in the 1920s through the 1970s, and a tendency towards low rainfall since the 1980s. A notable exception is the recent run of relatively wet years in southwestern Africa since circa 2005. Also notable is the high frequency of dry years in the 1980s and 1990s and the predominantly dry conditions in southwestern Africa circa 1900 through 1940. In the winter rains region of South Africa fewer aspects of the variability stand out. The nineteenth century on the whole was relatively dry but a number of very wet years occurred. Within the twentieth century the driest periods were the 1920s and 1930s and the 1960s and 1970s for this region.

The results shown in Fig. 4 show that no long-term trends in rainfall have occurred over southern Africa. A similar conclusion was reached by most studies that have evaluated rainfall variability in individual countries of southern Africa. Mazvimavi (2010) and Aguilar et al. (2009), examining annual and seasonal trends, have reached this conclusion for Zimbabwe, as did Ngongondo et al. (2011) for Malawi. Nicholson et al. (2014) found this to be true for the southern half of Malawi, but documented an abrupt shift to dry years in northern sectors around 1987. This is generally true for South Africa as well, although there are local exceptions (Kruger, 2006). For example, in areas around the Drakensberg, Nel (2009) found a decrease in autumn rainfall and MacKellar et al. (2014) found a significant increase in rain days in spring and summer over the period 1960 to 2010. The latter source also showed a significant decrease in rainfall and in the number of rain days over the central and northeastern parts of South Africa in the autumn months.

In some locations significant trends have been identified in rainfall extremes, i.e., droughts and high intensity rain events. Usman and Reason (2004) found an increasing frequency of heavy rainfall events in Angola and Namibia in the west and in Tanzania and Mozambique in the east between 1979 and 2002. Kruger (2006) found an increase in extreme wet seasons and extreme dry seasons over parts of South Africa, as well as an increase in high daily rainfall totals. On the other hand, Rouault and Richard (2005) documented an increase in the spatial extent of drought over southern Africa since the 1970s, attributing this to a strengthening of the ENSO-southern African rainfall relationship. Recent analysis of the 2015/16 El Niño-induced drought for this region suggests that an anthropogenic contribution to stronger El Niño events may produce stronger El Niño-related droughts in Southern Africa (Funk et al., 2016).

Studies have been in agreement in suggesting that the main factors in rainfall variability over southern Africa, i.e., in regions with mainly summer rainfall, are ENSO and Indian Ocean SSTs, including the IOZM (Nicholson and Kim, 1997; Hoerling et al., 2006; Hoell et al., 2015; Zhang et al., 2015). Although ENSO and Indian Ocean SSTs are interrelated, the Indian Ocean appears to be more important than ENSO (e.g., Manatsa and Mukwada, 2012). However, there has been significant coupling between rainfall and the IOZM since roughly 1997 (Manatsa et al., 2012). New analysis also suggests that the Southwest Indian Ocean Dipole can modulate El Niño impacts in this region (Hoell et al., 2015). Fewer recent studies have examined interannual variability in the winter rains region of the Cape. ENSO appears to have a significant influence on the length and frequency of wet spells since the 1976/77 climate shift in the Pacific (Philippon et al., 2012).

3.2. Seasonal time series for equatorial regions

Fig. 6 presents interannual time series for the two rainy seasons in each of the equatorial sectors with bimodal seasonality. Although the character of the seasonal cycle may differ somewhat from region to region, for comparative purposes all time-series are calculated for March–April–May and October–November. These are the principal months of the two East African rainy seasons, with the former season being termed the “long rains” and the latter being termed the “short rains” (Liebmann et al., 2012). In western equatorial Africa these tend to be the peak months of the two seasons as well.

3.2.1. Eastern equatorial Africa

In both sectors of eastern Africa, a shift to markedly wetter conditions in October–November occurred in 1961 and these conditions have persisted until present (Fig. 6). This has been recognized by Manatsa and Behera (2013) and by Nicholson (2015) as a time of a major regime change in eastern Africa. In contrast, a less abrupt trend (Funk et al.,

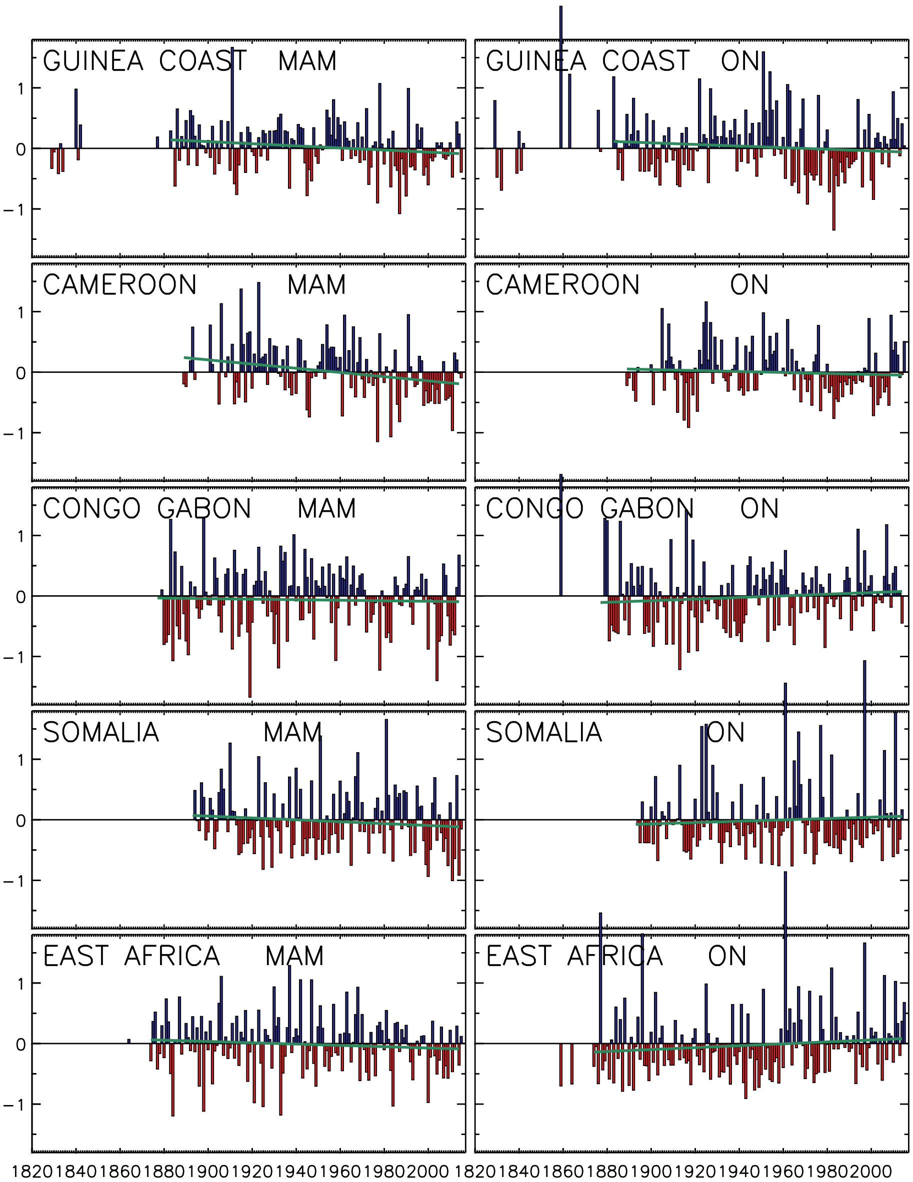

Fig. 6. Seasonal time-series (March-to-May and October–November) for the Guinea Coast and East Africa.

2005, 2008, 2015; Williams and Funk, 2011) towards drier conditions in the long rains has occurred (Fig. 6). Rainfall in western equatorial Africa shows some similarities on the seasonal time scale. During March–April–May a dry episode commenced around 1972 and has persisted almost without interruption to the present time. As in eastern equatorial Africa, a number of very wet years have occurred during October–November since around 1994 and a major shift to wetter conditions occurred in the 1940s following a multi-year drought. The similarity in recent decades contrasts with the interannual variability, which often exhibits an out-of-phase relationship between eastern and western sectors (Nicholson, 2014a).

Rainfall trends in eastern Africa have been evaluated by numerous studies because of the frequent incidence of extreme drought in recent years. The decline of the long rains was first shown by scientists working the Famine Early Warning Systems Network (Funk et al., 2005; Funk et al., 2008; Funk et al., 2015; Williams and Funk, 2011). Lyon and DeWitt (2012) elaborated on these trends, emphasizing recent drying and the important of Pacific SSTs. Liebmann et al. (2014) further documented the decline and showed a simultaneous but weaker increase in the short rains. The decline in the long rains has affected both the equatorial and summer rainfall regions (Mengistu et al., 2014; Rosell, 2011). In contrast, increased summer rainfall has occurred over much of summer rainfall region (Rosell, 2011; Williams et al., 2012; Funk et al., 2012; Viste et al., 2013). However, internal variability is strong and the increasing trends in the summer and short rains have been overshadowed by the more frequent and more severe droughts that have occurred in recent years (Funk, 2012; Viste et al., 2013; Hoell and Funk, 2014; Nicholson, 2016). In some cases, these have extended over two or more rainy seasons.

The causes of the decline of the long rains remains controversial, but it appears that changes in the Indo-Pacific played a major role (Funk et al., 2014). Funk et al. (2008) linked the decline of the long rains to warming in the South-Central Indian Ocean and a westward extension of the warm pool in the Indian Ocean. Williams and Funk (2011) related the decline to an increase the first principal component of Indo-Pacific vertical velocity, precipitation and 2 m temperatures, and argued that warming in the Indian Ocean and Western Pacific (55° E–120° E) supported an overturning circulation between the Warm Pool and East Africa that disrupted moisture transports and increased subsidence over Eastern Africa. Lyon and DeWitt (2012), Lyon et al. (2014) and

Lyon (2014) implicated tropical Pacific warming as a cause of the decline, especially post-1999. Lott et al. (2013), Funk and Hoell (2015) and Rowell et al. (2015) suggested that an anthropogenic component could also be playing a role via greenhouse and aerosol forcing of SSTs, a suggestion disputed by Lyon (2014). Liebmann et al. (2014) added an additional factor to the suggested causes of the long rains decline, an enhanced east-west SST gradient in the western Pacific. This was primarily a result of warming in the western Pacific, especially near Indonesia. This would have enhanced the Walker-like circulation over the Indian Ocean, increasing subsidence over eastern Africa. Statistical analysis of the first and second principal components (PCs) of East African rainfall (Funk et al., 2014) suggest that the 1st and 2nd PCs relate, respectively, to the West Pacific/East Pacific gradient (PC1) and Indian Ocean (PC2), with warming in the West Pacific and Indian Ocean both related to East African drying.

Variability during the short rains is much better understood. The Indian Ocean Walker cell appears to have played a role as well in the increasing trend. A steady intensification of the October–November cell occurred between 1948 and 2012 (Nicholson, 2015). While this implies increased subsidence over eastern Africa and would thus presumably be conducive to drought, the ascending branch of the Atlantic Walker cell over eastern Africa also increased. The juxtaposition of the two cells over eastern Africa suggests that slight changes in the influence of the Indian versus Atlantic Oceans might account for the abrupt shifts between drought and flood during the short rains in recent years (Liebmann et al., 2014; Nicholson, 2014b, 2015, 2016).

3.2.2. Western equatorial Africa

Western equatorial Africa is represented by the sectors labeled Cameroon and Congo/Gabon. The Cameroon region is somewhat of a transition zone, in that most of the sector also experiences a significant amount of summer rainfall. In both Cameroon and Congo/Gabon a decline of the March–April–May rains, as seen is eastern regions, is apparent. The increase in October–November rainfall experienced over eastern equatorial Africa is strongly apparent in Congo/Gabon as well. In Cameroon, an upward trend over the last few decades is apparent, but overall October–November rainfall was very weak from the 1980s onward, with the exception of primarily the last few years.

The literature contains much material on interannual variability in parts of western equatorial Africa, but the regions examined are very diverse and don't coincide with the regions represented by the time series in Fig. 6. These studies have limited applicability to the sectors examined here because the factors in variability over western equatorial regions are so complex that they depend on the season and specific area considered (Farnsworth et al., 2011), as well as on the timescale considered (Balas et al., 2007). Most studies examine the Congo Basin (e.g., Hua et al., 2016; Cook and Vizy 2016; Jury et al., 2009), only a small portion of which is represented in Fig. 6. However, there are a few studies that have direct implications for interannual variability in the sectors labeled Cameroon and Congo/Gabon.

One factor in both regions and seasons is SST along the eastern Atlantic coast (Nicholson and Entekhabi, 1987; Balas et al., 2007; Hirst and Hastenrath, 1983). In that sector SSTs vary greatly from year to year and upwelling frequently occurs. Warm conditions in the Atlantic and Pacific tend to reduce rainfall. The Pacific influence appears to be greatest in MAM, with the Atlantic playing a greater role in the ON season. Todd and Washington (2004) found Atlantic influence (specifically NAO) in the MAM season as well. The location and intensity of the tropospheric jets and the intensity of the zonal circulation cell are also important (Farnsworth et al., 2011; Dezfuli and Nicholson, 2013; Nicholson and Dezfuli, 2013; Hua et al., 2016).

3.2.3. Guinea Coast

Along the Guinea Coast (Fig. 6) the March–April–May season has been relatively dry since the 1970s, echoing the trend seen in other equatorial regions during this season. Wettest conditions occurred from the 1920s until the early 1970s, with some very dry seasons occurring during this interval. Western equatorial Africa and eastern equatorial Africa were also relatively wet at this same time, but dry years were nevertheless common. The rainfall fluctuations along the Guinea Coast during October–November are similar to those during March–April–May. In both there has been an upward trend since the early 1980s. However, rainfall remained generally below the long-term mean during March–April–May, but as of the mid-1990s most October–November seasons have been relatively wet.

As indicated earlier March-to-May is considered for this sector in order to examine this season across equatorial Africa. It should be noted that peak rainfall along the Guinea Coast occurs May and June, the first rainy season (Fink et al., 2017). Several studies have examined rainfall on a seasonal scale in Ghana, in the heart of the Guinea Coast region. The short dry season (boreal summer) has become wetter since 1980 and the second rainy season has become drier and shorter (Owusu and Waylen, 2013a, b). Since 1960 the start of the wet season has occurred progressively later and the length of the dry spells during the rainy season has increased (Lacombe et al., 2012).

The causes of interannual variability here are less complex than in the Sahel. SSTs in the equatorial Atlantic drive interannual variability during most of the year (Diatta and Fink, 2014; Tippett and Giannini, 2006; Lutz et al., 2015; Nnamchi et al., 2013; Vizy and Cook, 2001; Wagner and DaSilva, 1994; Paeth and Friederichs, 2004). The correlation with SSTs in the Gulf of Guinea reaches 0.75 for July–August over the 60-year period 1926 to 1985 (Opoku-Ankomah and Cordery, 1994). While this is the driest portion of the year along the Guinea Coast, most of the interannual rainfall variability is associated with conditions during this season (Nicholson and Palao, 1993). In some years, a tremendous peak in rainfall occurs here during the boreal summer (Nicholson, 2011).

3.3. Teleconnections

Several major changes in rainfall conditions in recent years have been noted in the last section. Although an analysis of the causes of these changes is beyond the scope of this article, a simple analysis of teleconnections sheds some light on the potential driving factors. There are several pairs of sectors for which one of the most common teleconnections is an out-of-phase relationship. Here we will use the term "dipole" for the sake of convenience, although physical links as required for a true dipole have not been confirmed. The out-of-phase relationships are highlighted in Nicholson (2014a). The "dipole" pairs considered are the Sahel and Guinea Coast, western (i.e., Congo/Gabon) and eastern equatorial Africa north, southern Africa and eastern equatorial Africa north, and south-central and southwest Africa (see Fig. 4 for location).

Fig. 7 illustrates the teleconnections by plotting only the years with anomalies of the opposite sign. In this simple way, the frequency and intensity of the "dipole" are apparent. Calculations were done for both annual and seasonal time series. Except for the Guinea Coast/Sahel pairing, only MAM is presented here because the changes were most noticeable in that season. An analysis of the time series is summarized in Table 2, which calculates the number of years with a dipole before and after 1982.

In all four cases examined, the frequency of the "dipole" has decreased in recent decades, starting in the early 1980s in all areas except the Sahel/Guinea Coast, where the shift started around 1970. In each case, the examination of the seasonal time series indicated that the change was most apparent during March–April–May. This suggests two potential factors. ENSO tends to have its maximum impact on African rainfall during the March–April–May period (Nicholson and Kim, 1997), a fact that points towards changes in ENSO as one factor. Moreover, the East Africa/Southern Africa dipole is strongly linked to ENSO. The reduced frequency of the dipole across the equator suggests changes a second factor, the equatorial zonal circulation. This factor is

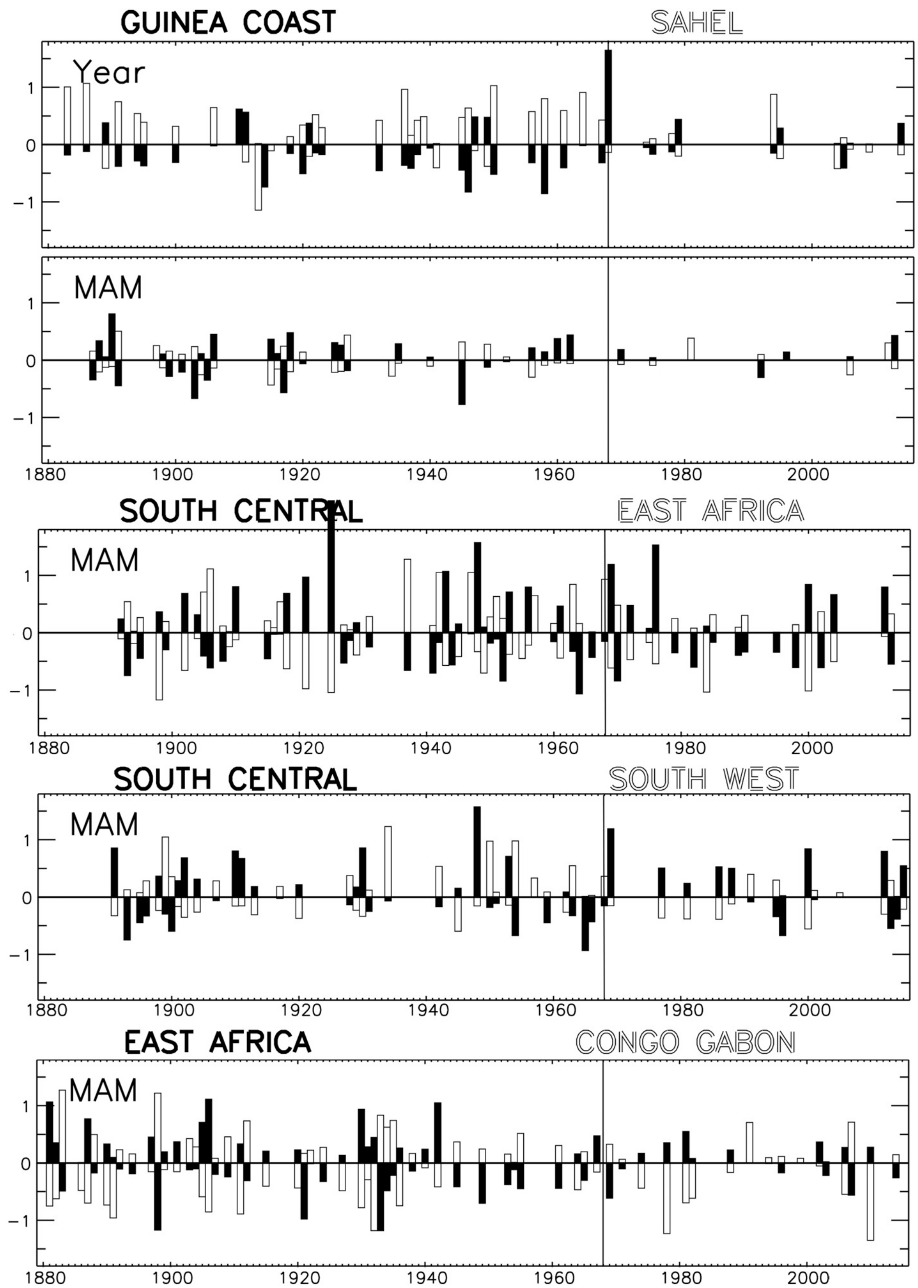

Fig. 7. The occurrence of "dipole" years at select pairs of rainfall sectors. Only those years are indicated at which rainfall anomalies have the opposite sign in the two paired sectors. The value of the anomaly for the year in both sectors is plotted, with shaded bars representing the first station indicated. Except for the annual analysis in the top diagram, all series are for March-to-May. A vertical line shows the year 1968.

also suggested by the reduction of dipole years between southwestern Africa and southeastern Africa.

In view of the apparent change in teleconnections around 1980, decadal anomalies in the March–April–May period are also presented (Fig. 8). The calculation is confined to the period 1980 to 1998 because a significant change in the station network occurred in 1998. However, the stations available (as seen in Fig. 9) show that the general pattern continued into the 21st century. During the period 1980–1998, deficits

Table 2
The occurrence of "dipole" years in four pairs of sectors. Values indicate the number of dipole years before 1968 and from 1968 onward, with both a number of years and a percent of years indicated.

Sectors compared	Period	Years before 1968		1968 and later	
Guinea Coast/Sahel	Year	35 of 84 years	42%	13 of 48 years	27%
Guinea Coast/Sahel	MAM	31 of 84 years	37%	8 of 48 years	17%
East Africa north/Congo-Gabon	MAM	47 of 86 years	55%	17 of 47 years	36%
South Central/East Africa north	MAM	44 of 78 years	56%	19 of 48 years	40%
South Central/Southwest	MAM	34 of 79 years	43%	16 of 48 years	33%

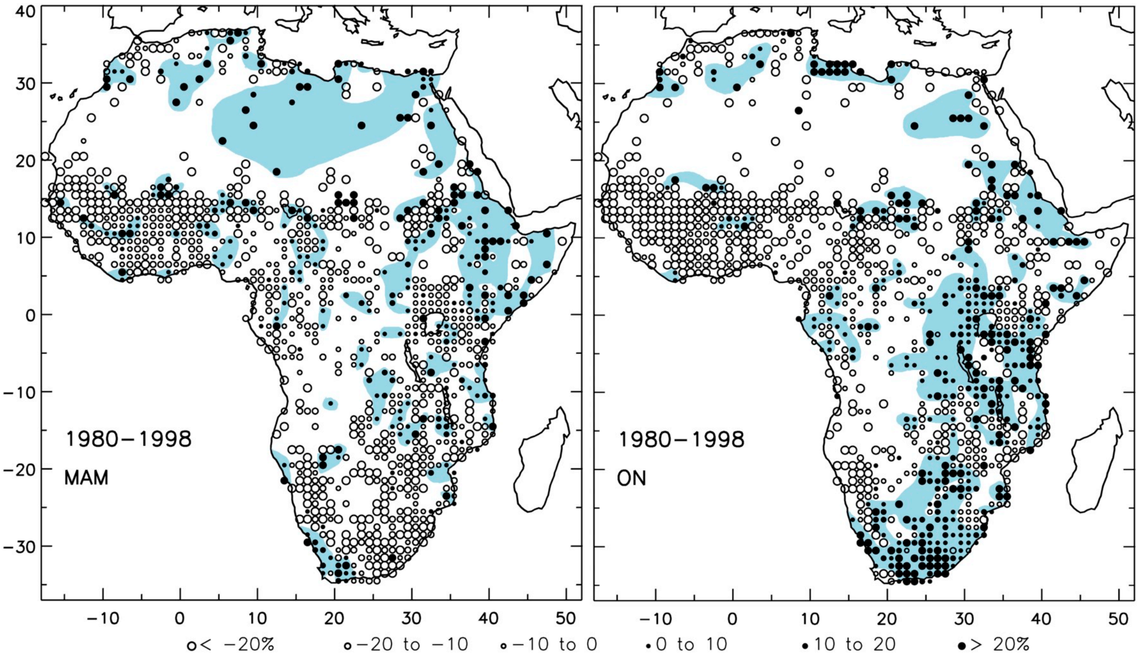

Fig. 8. Mean rainfall for the period 1980–1998 during the March-to-May and October–November seasons, expressed as a standardized departure from the long-term mean at each station. Data represent averages of all stations within a one-degree grid cell.

were negative, and generally at least 20% of the 1931–70 mean, over most of the continent. A similar analysis for October–November (Fig. 8) shows a very different pattern. Although extremely negative deficits prevailed throughout most of the Sahel/Soudan and western equatorial Africa, positive departures prevailed in eastern equatorial Africa and much of southern Africa. Overall this suggests a major change in the seasonal cycle over Africa. Over West Africa this might imply a weaker monsoon and/or a briefer season in Sahelian latitudes. In the equatorial latitudes, it suggests a reduction in the zonal rainfall gradient in October, when eastern areas are generally drier than western areas. This also suggests an increased importance of the short rains over East Africa.

3.4. Decadal variability

The previous analyses provide strong evidence that a regime shift may have occurred not only in the Sahel, but perhaps throughout a large part of the African continent in the 1980s. Decadal variability is illustrated by plotting annual anomalies for each successive ten-year period starting in 1930. Although the use of decadal partitioning is arbitrary, many major changes occurred towards the beginning of a calendar decade. Eight decades are shown in Fig. 9. In contrast to earlier analyses, these are based on individual stations and are presented as a percent departure from the mean. Here a standard mean for 1931–70 is utilized and the plotted values represent an arithmetic average of all stations within one-degree by one-degree grid points. When no station is available, no value is plotted. For most decades, the continent is well represented except in the desert regions. However, commencing in the 1990s, data become scarce for Angola and the Democratic Republic of the Congo (formerly Zaire), countries in which political instability led to a serious decline in the meteorological services provided. For the 2000–2009 decade, gaps are instead related to the lack of updating for many countries, especially central and southern Africa.

During the 1930s rainfall anomalies were not spatially coherent over large areas of the continent (Fig. 9). This is especially in the case in Sahelian Africa, where the anomalies appear almost randomly distributed. However, there is a tendency for positive anomalies to prevail from roughly 20° N to 10° S. An extensive but narrow area of negative anomalies is evident close to the equator. In general, the anomalies are relatively small. Exceptions are large negative anomalies in the western and central Sahara and the desert's northern margin, as well as in a large, coherent sector of southern Africa. The arid conditions expanded in the 1940s, with negative anomalies strongly dominant throughout the continent, with the exception of miscellaneous sectors of equatorial Africa. The magnitude of the aridity also increased, compared to the 1930s.

A striking change occurred in the 1950s, with very wet conditions being prevalent throughout both the Sahel and southern Africa (Fig. 9). Decadal averages were above the 1931–70 mean over most of the continent, but they were below the mean in much of the equatorial region (10° N to 15° S). Positive anomalies were particularly strong in subtropical latitudes of southern Africa and in nearly all of northern Africa except in narrow coastal sectors. The anomalies were particularly strong in the Sahel, where in many locations the decadal average exceeded the mean by 10% to 20% or more. The strongest negative anomalies were in eastern equatorial regions and in locations relatively near the coast of the equatorial Atlantic. A near reversal of the 1950s anomaly pattern is apparent in the 1960s. Positive anomalies, often over 20% of the mean, prevailed throughout most of the equatorial region from 15° N to 15° S. Negative anomalies equally large in northern Africa, prevailed in the subtopics.

A very different pattern emerges in the 1970s (Fig. 9). It is largely represented by a contrast between the hemispheres, with very large negative departures in the Sahel and very large positive departures in southern Africa. In the equatorial region, however, relatively wet conditions prevailed in eastern areas and relatively dry conditions prevailed in the west. Rainfall was above average over most of the Mediterranean region.

The 1980s commenced a multi-decadal period in which the prevailing anomalies in Africa were negative, with extreme droughts occurring in the 1980s in the Sahel, North Africa, much of the equatorial region, and much of southern Africa. Scattered positive anomalies were confined mainly to equatorial and subtropical regions of eastern Africa (e.g., circa 10° N to 20° S) and far southern latitudes of South Africa. The data set is somewhat sparser for the 1990s, especially for Angola

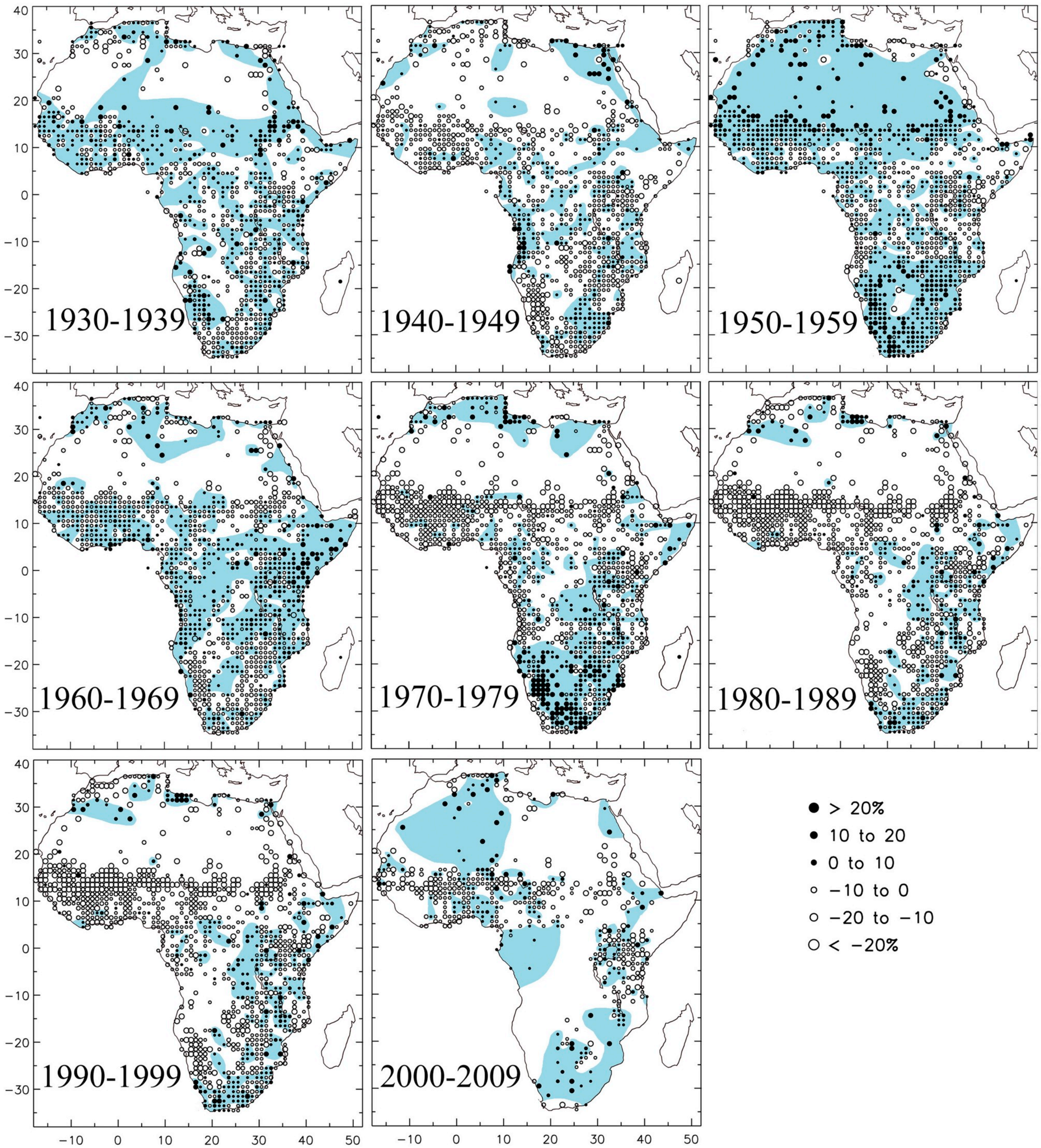

Fig. 9. Annual rainfall during for eight decades, expressed as a standardized departure from the long-term mean at each station. Data represent averages of all stations within a one-degree grid cell.

and the Congo Basin. However, it is evident that a pattern similar to that of the 1980s prevailed, although with less extreme dry conditions in Northern-Hemisphere regions. The few locations for which data are available for the 2000s suggest a persistence of relatively dry conditions over most of Africa.

Fig. 10 integrates the results of this analysis into a graph of the percent of grid points covered by negative anomalies. This allows for a comparison between decades with varying station coverage. On average, in a given year negative (positive) anomalies cover roughly 60%/40% of the grid points. This skewed distribution is typical of arid and semi-arid regions, such as those prevailing over Africa. While the relatively arid conditions of the 1940s are apparent, they are dwarfed by the anomalies of the 1980s and early 1990s, when in most years 70% to over 80% of the grid points were marked by negative rainfall anomalies. Annual anomalies exceeded 20% to 30% in over 50% of the continent. Overall, the period 1968 to 2005 stands out for its dryness.

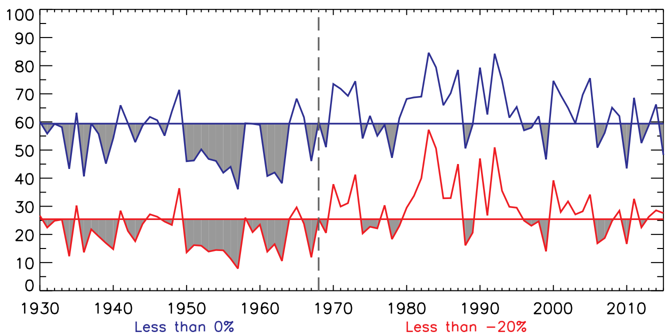

Fig. 10. (top) Percent of grid points with negative anomalies in each year, 1930 to 2015. (bottom) Percent of grid points with negative departures exceeding 20% of the long-term mean.

However, the aridity appears to have peaked in the early 1990s and conditions have improved over the continent as a whole. Yet there has been no recovery to the prevailing conditions prior to 1968.

4. Summary and conclusions

This article provides a description of rainfall variability throughout Africa on a regional basis for time spans ranging from one to nearly two centuries. Decadal variability is clearly apparent, with significant downward trends in annual rainfall occurring in West and North Africa (Table 1). In those regions, an abrupt reduction in rainfall occurred around 1968. However, a change for the continent as a whole is apparent as well, with rainfall being predominantly below or very near the mean in all grids points in nearly every year. For the continent as a whole, another change appeared with the 1980s decade, with more arid conditions persisting at the continental scale until early in the twenty-first century. During the roughly one-and one-half centuries evaluated, there is no analog for the aridity of the period 1980 to 1998. The last occurrence of such ubiquitous conditions of reduced rainfall occurred in the 1820s and 1830s (Nicholson, 2014a). It is also noteworthy that the pan-African decline in rainfall occurred shortly after the well-known 1976/77 shift in the equatorial Pacific (Graham, 1994).

The most striking result of this study is a change at the seasonal scale that appears to have affected most of the continent. A downward trend in MAM rainfall in eastern equatorial Africa has long been of concern (e.g., Funk et al., 2014; Zhou et al., 2014). The current results show that this trend impacted nearly all of the African continent (Fig. 8). A similar decline occurred during October–November over most of northern-hemisphere Africa and the western equatorial regions, while rainfall during this season increased in eastern sectors of equatorial and southern Africa. The decline in both seasons over West Africa, in addition to the well-known decline during the boreal summer rainy season (e.g., Lebel and Ali, 2009), documents a general weakening of the West African monsoon. Notably, the trends are generally not significant when calculated over the entire period of record. However, that does not diminish the impact of the late 20th century anomalies on populations adjusted to a higher mean.

The shift to more arid conditions circa 1968 does not bode well for the food and economic security of the one billion people for whom Africa is home. This shift has been especially problematic because most African countries became independent in 1960 and the agriculture, economy, and infra-structure left behind was based on the wetter conditions that had earlier prevailed. The seasonality changes occurring in the 1980s likely compounded an already tenuous food security situation. In many regions of Africa, the population is growing rapidly, croplands are expanding into more marginal growing regions, and yield growth is slow or stagnant (Funk and Brown, 2009). Some rainfall recovery appears to have occurred in the last decade or so, but confirmation of the increase over the continent as a whole will require the acquisition of additional data.

Acknowledgments

The assistant of Douglas Klotter in preparing the figures is gratefully acknowledged. The authors would like to acknowledge support for research from the National Science Foundation (SEN, #AGS1445605, AGS1535439, AGS1158984), the United States Geological Survey (#G009AC000001) and from the United States Geological Survey's Land Change Science Program. Andreas H. Fink acknowledges support from BMBF Grant No. 01LP1520D (MIKLIP Promisa).

References

Aguilar, E., Barry, A.A., Brunet, M., Ekang, L., Fernandes, A., Massoukina, M., Mbah, J., Mhanda, A., do Nascimento, D.J., Peterson, T.C., Umba, O.T., Tomou, M., Zhang, X., 2009. Changes in temperature and precipitation extremes in western central Africa, Guinea Conakry, and Zimbabwe, 1955–2006. J. Geophys. Res. Atmos. 114. https://doi.org/10.1029/2008JD011010.

Asefi-Najafabady, S., Saatchi, S., 2013. Response of African humid tropical forests to recent rainfall anomalies. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 368, 20120306. https://doi.org/10.1098/rstb.2012.0306.

Balas, N., Nicholson, S.E., Klotter, D., 2007. The relationship of rainfall variability in West Central Africa to sea-surface temperature fluctuations. Int. J. Climatol. 27, 1335–1349. https://doi.org/10.1002/joc.1456.

Berhane, F., Zaitchik, B., Badr, H.S., 2015. The Madden-Julian oscillation's influence on spring rainy season precipitation over equatorial West Africa. J. Clim. 28, 8653–8672. https://doi.org/10.1175/JCLI-D-14-00510.1.

Conway, D., Persechino, A., Ardoin-bardin, S., Hamandawana, H., Dieulin, C., Mahé, G., 2009. Rainfall and water resources variability in Sub-Saharan Africa during the twentieth century. J. Hydrometeorol. 10, 41–59. https://doi.org/10.1175/2008JHM1004.1.

Cook, K.H., Vizy, E.K., 2016. The Congo Basin Walker circulation: dynamics and connections to precipitation. Clim. Dyn. 47, 697–717.

Dezfuli, A.K., Nicholson, S.E., 2013. The relationship of rainfall variability in western equatorial africa to the tropical oceans and atmospheric circulation. Part II: the boreal autumn. J. Clim. 26, 66–84. https://doi.org/10.1175/JCLI-D-11-00686.1.

Dezfuli, A.K., Zaitchik, B.F., Gnanadesikan, A., 2015. Regional atmospheric circulation and rainfall variability in south equatorial Africa. J. Clim. 28, 809–818. https://doi.org/10.1175/JCLI-D-14-00333.1.

Diatta, S., Fink, A.H., 2014. Statistical relationship between remote climate indices and West African monsoon variability. Int. J. Climatol. 34, 3348–3367. https://doi.org/10.1002/joc.3912.

Diem, J.E., Ryan, S.J., Hartter, J., Palace, M.W., 2014. Satellite-based rainfall data reveal a recent drying trend in central equatorial Africa. Clim. Chang. 126, 263–272.

Esper, J., Frank, D., Buentgen, U., Verstege, A., Luterbacher, J., 2007. Long-term drought severity variations in Morocco. Geophys. Res. Lett. 34, L17702. https://doi.org/10.1029/2007GL030844.

Farnsworth, A., White, E., Williams, C.J.R., Black, E., Kniveton, D.R., 2011. Understanding the large scale driving mechanisms of rainfall variability over Central Africa. In: Williams, C.J.R., Kniveton, D. (Eds.), African Climate and Climate Change: Physical, Social and Political Perspectives, Advances in Global Change Research, pp. 101–122.

Fink, A.H., Engel, T., Ermert, V., van der Linden, R., Schneidewind, M., Redl, R., Afiesimama, E., Thiaw, W., Yorke, C., Evans, M., 2017. Mean climate and seasonal cycle. In: Parker, D.J., Diop-Kane, M. (Eds.), Meteorology of Tropical West Africa: The Forecasters' Handbook. John Wiley & Sons, Ltd, Chichester, UK, pp. 1–39. https://doi.org/10.1002/9781118391297.ch1. (ISBN: 978-1-118-39130-3).

Funk, C.C., 2012. Exceptional warming in the western Pacific-Indian Ocean warm pool has contributed to more frequent droughts in eastern Africa. Bull. Am. Meteorol. Soc. 93, 1049–1051.

Funk, C.C., Brown, M.E., 2009. Declining global per capita agricultural production and warming oceans threaten food security. Food Sec. 1, 271–289.

Funk, C.C., Hoell, A., 2015. The leading mode of observed and CMIP5 ENSO-residual sea surface temperatures and associated changes in indo-pacific climate. J. Clim. 28, 4309–4329. https://doi.org/10.1175/JCLI-D-14-00334.1.

Funk, C.C., Senay, G., Aswaw, A., Verdin, J., Rowland, J., Korecha, D., Eilerts, G., Michaelsen, J., Amer, S., Choularton, R., 2005. Recent drought tendencies in Ethiopia and equatorial-subtropical eastern Africa. In: Famine Early Warming System Network Special Report. US Agency for International Development.

Funk, C.C., Dettinger, M.D., Michaelsen, J.C., Verdin, J.P., Brown, M.E., Barlow, M., Hoell, A., 2008. Warming of the Indian Ocean threatens eastern and southern African food security but could be mitigated by agricultural development. Proc. Natl. Acad. Sci. U. S. A. 105, 11081–11086. https://doi.org/10.1073/pnas.0708196105.

Funk, C.C., Michaelsen, J., Marshall, M.C., 2012. Mapping recent decadal climate variations in precipitation and temperature across eastern Africa and the Sahel. In: Wardlow Anderson, B., Verdin, J. (Eds.), Remote Sensing of Drought: Innovative Monitoring Approaches, pp. 331–358 Cambridge.

Funk, C., Hoell, A., Shukla, S., Blade, K., Liebmann, B., Roberts, J.B., Robertson, F.R., Husak, G., 2014. Predicting East African spring droughts using Pacific and Indian

Ocean sea surface temperature indices. Hydrol. Earth Syst. Sci. 18, 4965–4978.
Funk, C.C., Nicholson, S.E., Landsfeld, M., Klotter, D., Peterson, P., Harrison, L., 2015. The Centennial Trends Greater Horn of Africa precipitation dataset. Sci. Data. https://doi.org/10.1038/sdata.2015.50.
Funk, C., Harrison, L., Shukla, S., Hoell, A., Korecha, D., Magadzire, T., Husak, G., Galu, G., 2016. Assessing the contributions of local and east Pacific warming to the 2015 droughts in Ethiopia and Southern Africa. Bull. Amer. Meteor. Soc. 97, S75–S77. https://doi.org/10.1175/BAMS-D-16-0167.1.
Galy-Lacaux, C., Laouali, D., Descroix, L., Gobron, N., Liousse, C., 2009. Long term precipitation chemistry and wet deposition in a remote dry savanna site in Africa (Niger). Atmos. Chem. Phys. Discuss. 8, 5761–5812. https://doi.org/10.5194/acpd-8-5761-2008.
Ghenim, A.N., Megnounif, A., 2013. Ampleur de la sécheresse dans le bassin d'alimentation du barrage Meffrouche (Nord-Ouest de l'Algérie). Géographie Physique e environnement 7, 35–49.
Gizaw, M.S., Gan, T.Y., 2017. Impact of climate change and El Niño episodes on droughts in sub-Saharan Africa. Clim. Dyn. 49, 665–682. https://doi.org/10.1007/s00382-016-3366-2.
Graham, N.E., 1994. Decadal-scale climate variability in the tropical and North Pacific during the 1970s and 1980s: observations and model results. Clim. Dyn. 10, 135–162. https://doi.org/10.1007/BF00210626.
Gu, W., Li, C., Wang, X., Zhou, W., Li, W., 2009. Linkage between Mei-yu precipitation and North Atlantic SST on the decadal timescale. Adv. Atmos. Sci. 26, 101–108. https://doi.org/10.1007/s00376-009-0101-5.
Hagos, S.M., Cook, K.H., 2008. Ocean warming and late-twentieth- century Sahel drought and recovery. J. Clim. 21, 3797–3814.
Hirst, A.C., Hastenrath, S., 1983. Atmosphere-ocean mechanisms of climate anomalies in the Angola Tropical Atlantic sector. J. Phys. Oceanogr. 13, 1146–1157.
Hoell, A., Funk, C., 2014. Indo-Pacific sea surface temperature influences on failed consecutive rainy seasons over eastern Africa. Clim. Dyn. 43 (5–6), 1645–1660. https://doi.org/10.1007/s00382-013-1991-6.
Hoell, A., Funk, C., Magadzire, T., Zinke, J., Husak, G., 2015. El Niño–Southern Oscillation diversity and Southern Africa teleconnections during Austral Summer. Clim. Dyn. 45, 1583–1599. https://doi.org/10.1007/s00382-014-2414-z.
Hoerling, M.P., Hurrell, J., Eischeid, J.K., Phillips, A., 2006. Detection and attribution of twentieth-century northern and southern African rainfall change. J. Clim. 19, 3989–4008. https://doi.org/10.1175/JCLI3842.1.
Hua, W., Zhou, L., Chen, H., Nicholson, S.E., Raghavendra, A., Jiang, Y., 2016. Possible causes of the Central Equatorial African long-term drought. Environ. Res. Lett. 11. https://doi.org/10.1088/1748-9326/11/12/124002.
Jury, M.R., Matari, E., Matitu, M., 2009. Equatorial African climate teleconnections. Theor. Appl. Climatol. 95, 407–416.
Kherchouche, D., Kalla, M., Gutierrez, E., Briki, A., Hamchi, A., 2013. La secheresse et le deperissement du cedre de l'Atlas (Cedrus atlantica Manetti) dans le massif du Belezma (Algerie). Secher 24, 129–137. https://doi.org/10.1684/sec.2013.0384.
Knippertz, P., Christoph, M., Speth, P., 2003. Long-term precipitation variability in Morocco and the link to the large-scale circulation in recent and future climates. Meteorog. Atmos. Phys. 83, 67–88. https://doi.org/10.1007/s00703-002-0561-y.
Kruger, A.C., 2006. Observed trends in daily precipitation indices in South Africa: 1910-2004. Int. J. Climatol. 26, 2275–2285.
Lacombe, G., McCartney, M., Forkuor, G., 2012. Drying climate in Ghana over the period 1960-2005: evidence from the resampling-based Mann-Kendall test at local and regional levels. Hydrol. Sci. J. 57, 1594–1609.
Laing, A.G., Carbone, R.E., Levizzani, V., 2011. Cycles and propagation of deep convection over equatorial Africa. Mon. Weather Rev. 139, 2832–2853. https://doi.org/10.1175/2011MWR3500.1.
Laraque, A., Olivry, J.C., Orange, D., Marieu, B., 1997. Spatio-temporal variation in rainfall and water levels in Central Africa since the early 20th century. In: Gustard, A., Blazkova, S., Brilly, M., Demuth, S., Dixon, J., VanLanen, H., Llasat, C., Mkhandi, S., Servat, E. (Eds.), Friend'97-Regional Hydrology: Concepts and Models for Sustainable Water Resource Management. IAHS Publication, pp. 257–263.
Lebel, T., Ali, A., 2009. Recent trends in the Central and Western Sahel rainfall regime (1990–2007). J. Hydrol. 375, 52–64. https://doi.org/10.1016/j.jhydrol.2008.11.030.
L'Hôte, Y., Mahé, G., Somé, B., Triboulet, J.P., 2002. Analysis of a Sahelian annual rainfall index from 1896 to 2000; the drought continues. Hydrol. Sci. J. 47, 563–572. https://doi.org/10.1080/02626660209492960.
L'Hôte, Y., Mahé, G., Some, B., 2003. Reply to "The Sahelian drought may have ended during the 1990s". The 1990s rainfall in the Sahel: the third driest decade since the beginning of the century. Hydrol. Sci. J. 48, 493–496. https://doi.org/10.1623/hysj.48.3.493.45283.
Liebmann, B., Blade, I., Kiladis, G., Carvalho, L.M.V., Senay, G.B., Allured, D., Leroux, S., Funk, C., 2012. Seasonality of African precipitation from 1996-2009. J. Clim. 25, 4304–4322.
Liebmann, B., Hoerling, M.P., Funk, C.C., Bladé, I., Dole, R.M., Allured, D., Quan, X., Pegion, P., Eischeid, J.K., 2014. Understanding recent eastern Horn of Africa rainfall variability and change. J. Clim. 27, 8630–8645. https://doi.org/10.1175/JCLI-D-13-00714.1.
Losada, T., Rodríguez-Fonseca, B., Kucharski, F., 2012. Tropical influence on the summer Mediterranean climate. Atmos. Sci. Lett. 13, 36–42. https://doi.org/10.1002/asl.359.
Lott, F.C., Christidis, N., Stott, P.A., 2013. Can the 2011 East African drought be attributed to human-induced climate change? Geophys. Res. Lett. 40 (6), 1177–1181. https://doi.org/10.1002/grl.50235.
Lutz, K., Jacobeit, J., Rathmann, J., 2015. Atlantic warm and cold water events and impact on African west coast precipitation. Int. J. Climatol. 35, 128–141.
Lyon, B., 2014. Seasonal drought in the Greater Horn of Africa and its recent increase during the March–May long rains. J. Clim. 27, 7953–7975. https://doi.org/10.1175/JCLI-D-13-00459.1.
Lyon, B., Dewitt, D.G., 2012. A recent and abrupt decline in the East African long rains. Geophys. Res. Lett. 39. https://doi.org/10.1029/2011GL050337.
Lyon, B., Barnston, A.G., DeWitt, D.G., 2014. Tropical Pacific forcing of a 1998–1999 climate shift: observational analysis and climate model results for the boreal spring season. Clim. Dyn. 43, 893–909. https://doi.org/10.1007/s00382-013-1891-9.
MacKellar, N., New, M., Jack, C., 2014. Observed and modelled trends in rainfall and temperature for South Africa: 1960–2010. S. Afr. J. Sci. 110, 51–63. https://doi.org/10.1590/sajs.2014/20130353.
Mahé, G., Paturel, J.E., 2009. 1896–2006 Sahelian annual rainfall variability and runoff increase of Sahelian Rivers. Compt. Rendus Geosci. 341, 538–546. https://doi.org/10.1016/j.crte.2009.05.002.
Mahe, G., L'hote, Y., Olivry, J., Wotling, G., 2001. Trends and discontinuities in regional rainfall of West and Central Africa: 1951–1989. Hydrol. Sci. J. 46, 211–226. https://doi.org/10.1080/02626660109492817.
Manatsa, D., Behera, S.K., 2013. On the epochal strengthening in the relationship between rainfall of East Africa and IOD. J. Clim. 26, 5655–5673. https://doi.org/10.1175/JCLI-D-12-00568.1.
Manatsa, D., Mukwada, G., 2012. Rainfall mechanisms for the dominant rainfall mode over Zimbabwe relative to ENSO and/or IODZM. Sci. World J. 2012, 926310. https://doi.org/10.1100/2012/926310.
Manatsa, D., Reason, C.J.C., Mukwada, G., 2012. On the decoupling of the IODZM from southern Africa Summer rainfall variability. Int. J. Climatol. 32, 727–746. https://doi.org/10.1002/joc.2306.
Mazvimavi, D., 2010. Investigating changes over time of annual rainfall in Zimbabwe. Hydrol. Earth Syst. Sci. 14, 1–9.
Mengistu, D., Bewket, W., Lal, R., 2014. Recent spatiotemporal temperature and rainfall variability and trends over the Upper Blue Nile River Basin, Ethiopia. Int. J. Climatol. 34 (7), 2278–2292. https://doi.org/10.1002/joc.3837.
Mohino, E., Janicot, S., Bader, J., 2011. Sahel rainfall and decadal to multi-decadal sea surface temperature variability. Clim. Dyn. 37, 419–440.
Nel, W., 2009. Rainfall trends in the KwaZulu-Natal Drakensberg region of South Africa during the twentieth century. Int. J. Climatol. 29, 1634–1641. https://doi.org/10.1002/joc.1814.
Ngongondo, C., Xu, C.-Y., Gottschalk, L., Alemaw, B., 2011. Evaluation of spatial and temporal characteristics of rainfall in Malawi: a case of data scarce region. Theor. Appl. Climatol. 106, 79–93. https://doi.org/10.1007/s00704-011-0413-0.
Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J., Urquhart, P., 2014. Africa. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1199–1265.
Nicholson, S.E., 1986. The spatial coherence of African rainfall anomalies: interhemispheric teleconnections. J. Clim. Appl. Meteorol. 25, 1355–1381. https://doi.org/10.1175/1520-0450(1986)025<1365:TSCOAR>2.0.CO;2.
Nicholson, S.E., 2000. The nature of rainfall variability over Africa on time scales of decades to millenia. Glob. Planet. Chang. 26, 137–158. https://doi.org/10.1016/S0921-8181(00)00040-0.
Nicholson, S.E., 2001. Climatic and environmental change in Africa during the last two centuries. Clim. Res. 17, 123–144. https://doi.org/10.3354/cr017123.
Nicholson, S.E., 2005. On the question of the "recovery" of the rains in the West African Sahel. J. Arid Environ. 63, 615–641. https://doi.org/10.1016/j.jaridenv.2005.03.004.
Nicholson, S.E., 2011. Dryland Climatology. Cambridge University Press, Cambridge, pp. 516.
Nicholson, S.E., 2014a. The predictability of rainfall over the Greater Horn of Africa. Part I. Prediction of seasonal rainfall. J. Hydrometeorol. 16https://doi.org/10.1175/JHM-D-13-062.1. (140117143344004).
Nicholson, S.E., 2014b. Spatial teleconnections in African rainfall: a comparison of 19th and 20th century patterns. The Holocene 24, 1840–1848. https://doi.org/10.1177/0959683614551230.
Nicholson, S.E., 2015. Long-term variability of the East African "short rains" and its links to large-scale factors. Int. J. Climatol. 35, 3979–3990. https://doi.org/10.1002/joc.4259.
Nicholson, S.E., 2016. An analysis of recent rainfall conditions in eastern Africa. Int. J. Climatol. 36, 526–532. https://doi.org/10.1002/joc.4358.
Nicholson, S.E., Dezfuli, A.K., 2013. The relationship of rainfall variability in western equatorial Africa to the tropical oceans and atmospheric circulation. Part I: the boreal spring. J. Clim. 26, 45–65. https://doi.org/10.1175/JCLI-D-11-00653.1.
Nicholson, S.E., Entekhabi, D., 1987. Rainfall variability in equatorial and southern Africa - relationships with sea-surface temperatures along the southwestern coast of Africa. J. Clim. Appl. Meteor. 26, 561–578.
Nicholson, S.E., Kim, J., 1997. The relationship of the El Nino–southern oscillation to African rainfall. Int. J. Climatol. 17, 117–135. https://doi.org/10.1002/(SICI)1097-0088(199702)17:2<117::AID-JOC84>3.0.CO;2-O.
Nicholson, S.E., Palao, I.M., 1993. A re-evaluation of rainfall variability in the sahel. Part I. Characteristics of rainfall fluctuations. Int. J. Climatol. 13, 371–389. https://doi.org/10.1002/joc.3370130403.
Nicholson, S.E., Some, B., Kone, B., 2000. An analysis of recent rainfall conditions in West Africa, including the rainy seasons of the 1997 El Nino and the 1998 La Nina years. J. Clim. 13, 2628–2640. https://doi.org/10.1175/1520-0442(2000)013<2628:AAORRC>2.0.CO;2.

Nicholson, S.E., Dezfuli, A.K., Klotter, D., 2012a. A two-century precipitation dataset for the continent of Africa. Bull. Am. Meteorol. Soc. 93, 1219–1231. https://doi.org/10.1175/BAMS-D-11-00212.1.

Nicholson, S.E., Klotter, D., Dezfuli, A.K., 2012b. Spatial reconstruction of semi-quantitative precipitation fields over Africa during the nineteenth century from documentary evidence and gauge data. Quat. Res. (United States) 78, 13–23. https://doi.org/10.1016/j.yqres.2012.03.

Nicholson, S.E., Klotter, D., Chavula, G., 2014. A detailed rainfall climatology for Malawi, Southern Africa. Int. J. Climatol. 34, 315–325.

Nicholson, S.E., Fink, A.H., Funk, C., 2017. Assessing recovery and change in West Africa's rainfall regime from a 161-year record. Int. J. Climatol (in press).

Nnamchi, H.C., Li, J.P., Kang, I.S., Kucharshki, F., 2013. Simulated impacts of the South Atlantic Ocean Dipole on summer precipitation at the Guinea coast. Clim. Dyn. 41, 677–694.

Opoku-Ankomah, Y., Cordery, I., 1994. Atlantic Sea surface temperatures and rainfall variability in Ghana. J. Clim. 7, 551–558. https://doi.org/10.1175/1520-0442(1994)007 < 0551:ASSTAR > 2.0.CO;2.

Owusu, K., Waylen, P.R., 2013a. The changing rainy season climatology of mid-Ghana. Theor. Appl. Climatol. 112, 419–430.

Owusu, K., Waylen, P.R., 2013b. Identification of historic shifts in daily rainfall regime, Wenchi, Ghana. Climatic Change 117, 133–147.

Ozer, P., Erpicum, M., Demaree, G., Vandiepenbeeck, M., 2003. Discussion of "Analysis of a Sahelian annual rainfall index from 1896 to 2000; the drought continues". Hydrol. Sci. J. 48, 489–492.

Paeth, H., Friederichs, P., 2004. Seasonality and time scales in the relationship between SST and African rainfall. Clim. Dyn. 23, 815–837.

Park, J.-Y., Bader, J., Matei, D., 2015. Northern-hemispheric differential warming is the key to understanding the discrepancies in the projected Sahel rainfall. Nat. Commun. 6, 5985. https://doi.org/10.1038/ncomms6985.

Park, J.-Y., Bader, J., Matei, D., 2016. Anthropogenic Mediterranean warming essential driver for present and future Sahel rainfall. Nat. Clim. Chang. 6, 941–945.

Philippon, N., Rouault, M., Richard, Y., Favre, A., 2012. The influence of ENSO on winter rainfall in South Africa. Int. J. Climatol. 32, 2333–2347. https://doi.org/10.1002/joc.3403.

Polo, I., Rodriguez-Fonseca, B., Losada, T., Garcia-Serrano, 2008. Tropical Atlantic variability modes (1979-2002). Part I: time-evolving SST modes related to West African rainfall. J. Clim. 21, 6457–6475.

Rodríguez-Fonseca, B., Mohino, E., Mechoso, C.R., Caminade, C., Biasutti, M., Gaetani, M., Garcia-Serrano, J., Vizy, E.K., Cook, K.H., Xue, Y., Polo, I., Losada, T., Druyan, L., Fontaine, B., Bader, J., Doblas-Reyes, F.J., Goddard, L., Janicot, S., Arribas, A., Lau, W., Colman, A., Vellinga, M., Rowell, D.P., Kucharski, F., Voldoire, A., 2015. Variability and predictability of west African droughts: a review on the role of sea surface temperature anomalies. J. Clim. 28, 4034–4060. https://doi.org/10.1175/JCLI-D-14-00130.1.

Rosell, S., 2011. Regional perspective on rainfall change and variability in the central highlands of Ethiopia, 1978–2007. Appl. Geogr. 31, 329–338. https://doi.org/10.1016/j.apgeog.2010.07.005.

Rouault, M., Richard, Y., 2005. Intensity and spatial extent of droughts in southern Africa. Geophys. Res. Lett. 32. https://doi.org/10.1029/2005GL022436.

Rowell, D.P., Booth, B.B.B., Nicholson, S.E., Good, P., 2015. Reconciling past and future rainfall trends over East Africa. J. Clim. 28, 9768–9788. https://doi.org/10.1175/JCLI-D-15-0140.1.

Samba, G., Nganga, D., 2012. Rainfall variability in Congo-Brazzaville: 1932–2007. Int. J. Climatol. 32, 854–873. https://doi.org/10.1002/joc.2311.

Samimi, C., Fink, A.H., Paeth, H., 2012. The 2007 flood in the Sahel: causes, characteristics and its presentation in the media and FEWS NET. Nat. Hazards Earth Syst. Sci. https://doi.org/10.5194/nhess-12-1-2012.

Sandjon, A.T., Nzeukou, A., Tchawoua, C., 2012. Intraseasonal atmospheric variability and its interannual modulation in Central Africa. Meteorog. Atmos. Phys. 117, 167–179. https://doi.org/10.1007/s00703-012-0196-6.

Sanogo, S., Fink, A.H., Omotosho, J.A., Ba, A., Redl, R., Ermert, V., 2015. Spatio-temporal characteristics of the recent rainfall recovery in West Africa. Int. J. Climatol. 35, 4589–4605. https://doi.org/10.1002/joc.4309.

Sinclaire, Z., Lenouo, A., Tchawoua, C., Janicot, S., 2015. Synoptic Kelvin type perturbation waves over Congo basin over the period 1979–2010. J. Atmos. Sol. Terr. Phys. 130, 43–56. https://doi.org/10.1016/j.jastp.2015.04.015.

Tazalika, L., Jury, M.R., 2008. Intra-seasonal rainfall oscillations over central Africa: space-time character and evolution. Theor. Appl. Climatol. 94, 67–80. https://doi.org/10.1007/s00704-007-0349-6.

Tippett, M.K., Giannini, A., 2006. Potentially predictable components of African summer rainfall in an SST-forced GCM. J. Clim. 19, 3133–3144.

Todd, M.C., Washington, R., 2004. Climate variability in central equatorial Africa: influence from the Atlantic sector. Geophys. Res. Lett. 31, 1–4. https://doi.org/10.1029/2004GL020975.

Touchan, R., Anchukaitis, K.J., Meko, D.M., Attalah, S., Baisan, C., Aloui, A., 2008. Long term context for recent drought in northwestern Africa. Geophys. Res. Lett. 35. https://doi.org/10.1029/2008GL034264.

Tran, M., 2011, July 12. Explainer. The East Africa Food Crisis. Guardian.

Tschakert, P., Sagoe, R., Ofori-Darko, G., Codjoe, S.N., 2010. Floods in the Sahel: an analysis of anomalies, memory, and anticipatory learning. Clim. Chang. 103, 471–502. https://doi.org/10.1007/s10584-009-9776-y.

Usman, M.T., Reason, C.J.C., 2004. Dry spell frequencies and their variability over southern Africa. Clim. Res. 26, 199–211. https://doi.org/10.3354/cr026199.

Viste, E., Korecha, D., Sorteberg, A., 2013. Recent drought and precipitation tendencies in Ethiopia. Theor. Appl. Climatol. 112, 535–551. https://doi.org/10.1007/s00704-012-0746-3.

Vizy, E.K., Cook, K.H., 2001. Mechanisms by which Gulf of Guinea and eastern North Atlantic sea surface temperature anomalies can influence African rainfall. J. Clim. 14, 795–821.

Wagner, R.G., DaSilva, A.M., 1994. Surface conditions associated with anomalous rainfall in the Guinea coastal region. Int. J. Climatol. 14, 179–199.

Williams, A.P., Funk, C.C., 2011. A westward extension of the warm pool leads to a westward extension of the Walker circulation, drying eastern Africa. Clim. Dyn. 37, 2417–2435. https://doi.org/10.1007/s00382-010-0984-y.

Williams, A.P., Funk, C.C., Michaelsen, J.C., Rauscher, S.A., Robertson, I., Wils, T.H.G., Koprowski, M., Eshetu, Z., Loader, N.J., 2012. Recent summer precipitation trends in the Greater Horn of Africa and the emerging role of Indian Ocean sea surface temperature. Clim. Dyn. 39, 2307–2328. https://doi.org/10.1007/s00382-011-1222-y.

Zhang, Q., Holmgren, K., Sundqvist, H., 2015. Decadal rainfall dipole oscillation over southern Africa modulated by variation of austral summer land–sea contrast along the east coast of Africa. J. Atmos. Sci. 72, 1827–1836. https://doi.org/10.1175/JAS-D-14-0079.1.

Zhou, L., Tian, Y., Myneni, R.B., Ciais, P., Saatchi, S., Liu, Y.Y., Piao, S., Chen, H., Vermote, E.F., Song, C., Hwang, T., 2014. Widespread decline of Congo rainforest greenness in the past decade. Nature 508, 86–90. https://doi.org/10.1038/nature13265.