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Exploratory analysis of rain days in central Sudan

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Abstract The changes in six rain-day categories occurring since the 1940s have been explored in central Sudan, considering two case studies representing important productive agricultural regions under semi-arid rain-fed and arid irrigated schemes. Drought conditions have persisted in Kosti (arid) in the form of a decline in rain-day frequencies, with significant trends in trace, weak and moderate falls. El Gedaref (semi-arid) exhibited both positive and negative trends, though significance characterizes the sequences of trace (falling) and weak and very strong (both rising) falls. The total annual rainfall in El Gedaref behaves depending solely on the heaviest falls contrary to Kosti, the annual values of which follow five fall categories, but with the heaviest events also have the strongest strength. Trace events occur more frequently in the arid area than in the semi-arid one, whereas weak to very strong events have opposite behaviour. Although El Niño-Southern Oscillation is one potential forcing of the variability of rainfall events, especially in Kosti, the paper arguably proposes a complex combination of factors at smaller scale that may also contribute to the large non-uniformity in rainfall patterns between the two areas, including local moisture recycling and convective activity, natural and anthropogenic aerosol loadings in the atmosphere and influence of the Ethiopian highlands.

1 Introduction

Different forms of climatic changes and variations have been reported for Sudan during the past few decades (Alvi and Elagib 1996; Elagib and Alvi 1996; Elagib and Mansell 2000a, b; Elagib 2009, 2010). Among the climatic elements, rainfall received particular attention during the 1980s and early 1990s because the knowledge of its amount is vital for food security and economic planning in Sudan. Rainfall amounts on annual (Trilsbach and Hulme 1984; Perry 1986; Elsayem 1986; Walsh et al. 1988; Eldridge et al. 1988; Eltahir 1988, 1989, 1992; Hulme 1990), monthly (Zahran 1986; Eldridge et al. 1988; Hulme 1987, 1990) and daily scales (Trilsbach and Hulme 1984; Perry 1986; Hulme 1987, 1990; Walsh et al. 1988) were analysed. These studies used a variety of techniques, meteorological stations, regions and periods in the analyses of rainfall data. The conclusion drawn from these investigations was that a dramatic decline of rainfall amounts is unequivocal since the mid-1960s, peaking in the 1980s, resulting in the existence of distinct wet and dry sequences.

Analysis of daily rainfall parameters is of vital importance, since the impact of climate on the physical and human landscapes occurs through these parameters (Trilsbach and Hulme 1984; Walsh et al. 1988). Analysis of rain days has not been widely performed for Sudan. This pilot study, therefore, has been written to show how these rainfall indices have changed during the past few decades in two areas of central Sudan.

2 Location and climate of the study areas

Central Sudan is composed of (SomaliPress.com 2010; Fig. 1) a vast clay plain bounded on the far west by the

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Fig. 1 Location of the central stations under consideration on the topographic map of Sudan (*Adapted* from Maps of the World, mapsof.net, 2010)
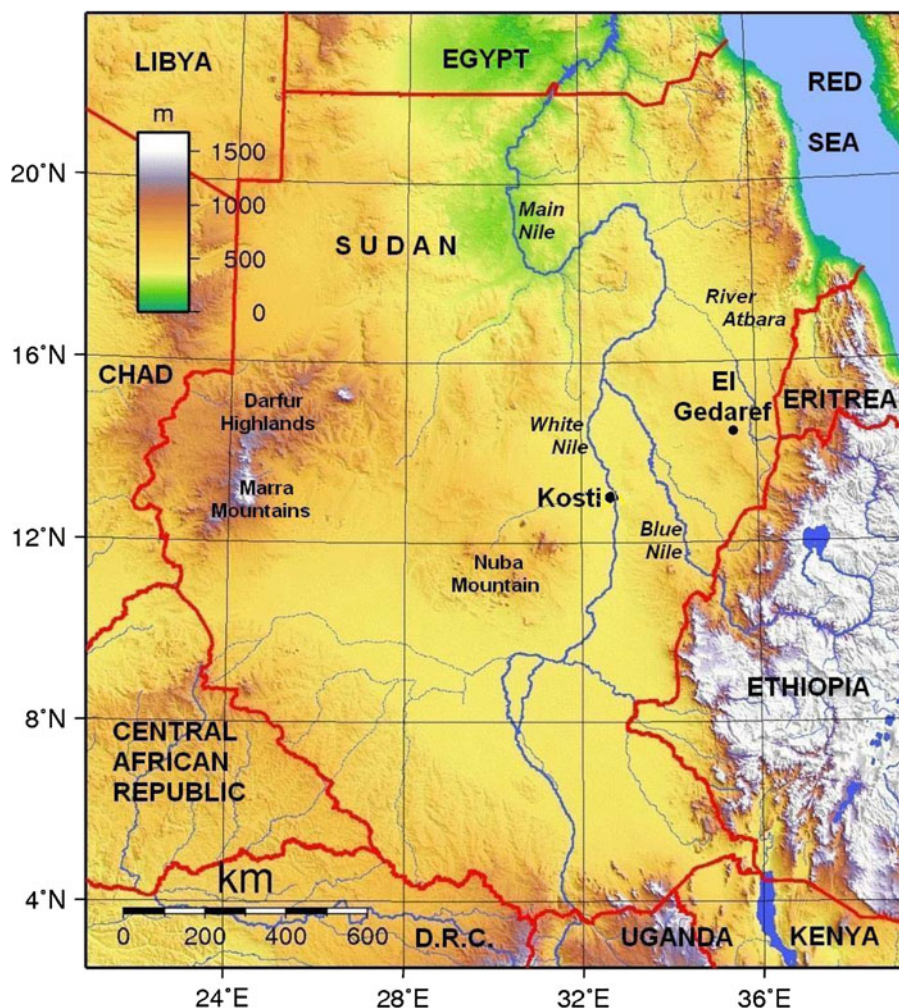
Nile-Congo watershed and the highlands of Darfur and on the east by the Ethiopian Plateau. This plain is marked by inselbergs (isolated hills rising abruptly from the plains), a unique feature of which is the Nuba Mountain west of the White Nile. The highlands of the Marra Mountains rise out of the Darfur Plateau farther west to altitudes of between approximately 900 and 3,000 m above sea level. The eastern uplands constitute the foothills of the Ethiopian highland massif.

Two areas in central Sudan, namely El Gedaref and Kosti (Fig. 1), are selected as case studies because they represent important productive agricultural regions under rain-fed sorghum and sesame schemes and irrigated sugar cane schemes, respectively. Furthermore, local studies are important in adaptation strategies to understand the impact and the priorities to adopt. El Gedaref (El Gedaref State) is located in the eastern part of Sudan at latitude of 14°02′ N, longitude of 35°24′ E and altitude of 600 m, while Kosti (latitude: 13°10′ N; longitude: 32°40′ E; altitude: 380 m) is situated in the mid-central region of the country within the White Nile State. Following the classification of UNEP

(UNEP 1992; Hare 1993), El Gedaref lies in the semi-arid zone, whereas Kosti is categorized as arid (Elagib 2001). Based on the definition of temperature regimes (UNESCO 1977), both stations experience very warm summer and warm winter. The temperature during the summer season can reach up to 46.0°C in Kosti and 45.4°C in El Gedaref. During the winter season, the temperature drops to as low as 8.6 and 7.6°C, respectively. On average, the rainfall per annum amounts to 611.7 mm in El Gedaref and 341.0 mm in Kosti, with 31.8 and 34.1% of this amount falling in the wettest month of August respectively. The daily rainfall can reach up to 92.3 mm in the arid station and 106.9 mm in the semi-arid station.

3 Data and methods

The data used in this study are two sets of daily, monthly and annual rainfall observations for El Gedaref and Kosti for the period 1941–2006 obtained from Sudan Meteorological Authority. First, the rainfall records were checked

for missing data. For Australian daily rainfall analysis, Hennessy et al. (1999) considered a station accepted in a particular year if it had less than 10% of days missing and less than five consecutive days missing. Missing daily data in the present study were found in July and August 1987 and October 1988 for Kosti and in July and August 1987 for El Gedaref. None of the two stations had more than 8 days (amounting only around 2%) with missing data in a given year.

Second, the frequency of trace events (Tr) recorded for the month each year is extracted from the daily data. A trace rainfall is defined as a rainfall amount greater than 0.0 mm, but less than 0.05 mm (Meteorological Office 1952). Such amounts are registered as Tr, since they are very small and unquantifiable by the measuring cylinder of the rain gauge. Thus, these events are assumed to be equal to zero and are not counted to the total rainfall amount. Amounts ≥ 0.05 to <0.1 mm is rounded off to 0.1 mm, since the measured rainfall is recorded to one decimal place. The year 1987 had a case of five consecutive days with missing data at both stations. Hence, the method suggested by Qureshi and Khan (1994) and applied by Elagib and Mansell (2000a) and Elagib (2010) for infilling the missing data from neighbouring values was adopted herein, i.e. by taking the average of the three preceding and the three following monthly records. If the resulting number of Tr cases for the month was found less than the registered one, then the recorded (available) frequency of the Tr cases was considered in stead of the average. There is an evidence for autocorrelation in the data for the months with missing data. Thus, it is believed that these few missing data and the corresponding treatment do not harmfully affect the results. Two years, namely 1941 and 1942, were excluded from the analysis for Kosti, since no Tr events were found to be registered in them, and thus, the reliability of their Tr records was considered suspect. In addition to the monthly series, series of the annual maximum number of Tr events (frequencies of Tr) was also developed. The monthly analysis was confined to April–October which is the main period of rainfall events at the two stations. Another group of series was established from the Tr data: (1) number of months within the year with trace events and (2) coefficients of variation and skewness of the within-year monthly trace data.

A third set of series was calculated for the two stations, consisting of the annual frequency of rain events (in days) with trace, weak, moderate, moderately strong, strong and very strong rainfalls. These rainfall classes have the ranges greater than 0.0 mm and less than 0.05, 0.1–1.0, 1.1–10.0, 10.1–20.0, 20.1–30.0 mm and greater than 30.0 mm, respectively. The last three ranges were exactly those used by Bielec-Bakowska and Lupikasza (2009), who further considered a class of no or trace precipitation and merged the weak and moderate classes in one range of 0.1–10.0 mm.

Changes in large-scale atmospheric circulation, which are triggered by multidecadal variations in global sea surface temperature (SST), have been proposed among the modulators of rainfall over most of the African continent (e.g. Camberlin 1995; Nicholson and Kim 1997; Indeje et al. 2000; Kerr 2003; Zeng 2003; Dai et al. 2004; Balas et al. 2007). Series of 3-month running mean of the mode of variability, i.e. El Niño-Southern Oscillation (ENSO) index, was available from the Internet (JISAO 2009) since 1950. The anomalies are computed with respect to the period 1971–2000.

A number of analysis methods have been performed on the time series. The non-parametric test of Kendall-tau, τ (Kanji 1997) was used to test the significance of changes in the established series over time. Since this test determines only the sign of trend, this method was supplemented with a linear regression analysis to evaluate the magnitude of change during the data period (see e.g., Hennessy et al. 1999). To investigate the link between the rainfall variables, the correlation coefficient using Kendall-tau test was calculated between the annual and monthly rainfall amounts and the frequency of Tr events, between the annual frequency of Tr events and the rain-day classes developed above and between the normalized rainfall indices (total rainfall amounts and rain days) and ENSO-SST anomalies. The potential connection of rainfall events to ENSO was investigated over the common period 1950–2006. One-tailed test is used since a direction of the effect is already hypothesized. For this purpose, the rainfall series was standardized based on the period 1971–2000 similar to ENSO anomalies data. The correlations were investigated seasonally for April–June, May–July, June–August, July–September, August–October and annually. For annual analysis, the ENSO index was calculated as the average of anomalies for four seasons, namely January–March, April–June, July–September and October–December.

Although the changes in trace observations will not have much effect on the total rainfall amount, it has been noticed that they do occur frequently than other rainfall categories and represent an appreciable number of occurrences of the total annual rainfall events as will be seen later. Hence, an emphasis has been put in this study on the analysis of Tr events to address the answers to the questions: (a) Is the rainfall variability connected to the variability of Tr events? and (b) Do the changes in trace events have any importance in other ways or, in other words, would they explain an underlying phenomenon?

The rain-days data were also divided into two equal sets to shed more light on the changes which have occurred over the time period considered by investigating:

1. the significance of the difference between the means of trace events for the two periods, using the *t* test (IFA Services Statistical Tests 2010).
2. the significance of the difference between the distributions of the two sub-sets, using Kolmogorov–Smirnov test (Kirkman 1996).

4 Results and discussion

4.1 Long-term trends and changes

The monthly series of the frequency of trace events and the annual frequency of rain days are depicted in Figs. 2 and 3, respectively. Striking features emerge from the two figures that the arid station registers higher number of trace events, but lower rain days for the other categories compared to the semi-arid station. However, the higher weak rain days for the former station over the first half of the record period should be noted. Despite the interannual variability and existence of peaks, the trend lines for most of the series are dropping. This drop is, in all the cases, steeper for the arid station of Kosti than for the semi-arid station of El Gedaref (Table 1). The only time series which shows rising trends, though insignificant, is those for April and October for El Gedaref. This station demonstrates significant falling trends in the frequency of Tr events for June to August (peak wet season) and maximum series. Except the series for April and May (early wet season), the rest of the series for Kosti shows significant downward trends. Figure 1 shows, however, clear upward trends in the frequency of Tr for Kosti since the mid-1980s for July and since the mid-1990s for May, August and the maximum time series. The observed partial recovery is consistent with others' results on the Sahel and east African rainfalls (Dai et al. 2004; Olsson et al. 2005; Nicholson 2005; Elagib 2009; Bewket and Conway 2007). Both stations have the steepest drop in monthly series in July, with the rate reaching -0.802 events decade^{-1} for Kosti and -0.541 events decade^{-1} for El Gedaref. The rates of the annual trends in frequency are -3.65 and -1.56 events per decade, respectively. Table 1 also shows significant decreasing trends in the annual frequencies for the first three rain-day classes (trace, weak and moderate) for Kosti. El Gadaref, on the other hand, had significant decline of the frequency of trace events (but at a lower rate) and significant increase in the number of weak rain days due to sudden high jump in the time series since the mid-1960s. Although the reason for this step change is obscured, it does not seem to be due to changes in observation practice since the other rain-day classes do not exhibit similar behaviour in their time series.

Histograms showing frequency distribution of the different classes for earlier and later periods are exhibited in Fig. 4, while the statistical significance of these changes is assessed in Table 2. The highest frequency is shown for the moderate (El Gedaref) and trace (Kosti) classes, while the situation is reversed for the second highest frequency at the stations. Between the two periods, Kosti had less frequent rain days in all the classes, while El Gedaref experienced reduced frequencies only for the trace and moderately strong classes. Elagib (2009) also found that the pace of drying conditions is faster and significant in the arid areas of central Sudan compared to the semi-arid ones. The *t* test indicates the significant changes in mean values between the two periods for the trace and weak rain-day classes for both stations, but further significant results are notable for the moderate class in the case of Kosti. Significant differences between the distributions also occurred in these classes according to Kolmogorov–Smirnov test.

The plots and directions of trends in the annual number of months registering trace events are given in Fig. 5 and Table 3, respectively. Negative trends occur at both stations at a significant level of less than 0.001. In most of the years, Kosti had more cases of months with trace events compared to El Gedaef. The same table gives the trends in the coefficients of variation and skewness. It should be mentioned here that the comparison of the coefficients of variation was not performed on normalized data based on, for instance, the mean since the mean for some of the months was zero. The coefficients of variation (Fig. 6) display positive trend, demonstrating increasing variability in the intra-annual frequency of Tr, but the significance is only a characteristic of the series for Kosti. Generally, the coefficient has higher values for the semi-arid location than the arid one since the norm for the former location is the high magnitude of rainfall events rather than the smaller amounts. Comparing the time series of annual trace days (Fig. 3) and the corresponding intra-annual variability (Fig. 6), one can notice contrasting trends. An inverse relationship between the two series is found as $\tau = -0.327$ ($\alpha = 0.000$) for Kosti and $\tau = -0.440$ ($\alpha = 0.000$) for El Gedaref. Similarly, the upward trend of the coefficient of skewness (Fig. 7) is significant for the arid location. Both series reveal dominance of positive values. Since the skewness coefficient provides, to some degree, a statistical measure for extreme events (Gong and Ho 2004), this result indicates a tendency toward the occurrence of higher monthly frequencies of Tr events in the more recent decades, especially in Kosti. These arguments are supported further by the results of analysis of the change in the contribution made by the month to the annual frequency of trace events (not shown) which show highly increasing trend of the time series of maximum monthly Tr ($\alpha = 0.004$ using Kendall-tau test). In other words, there is
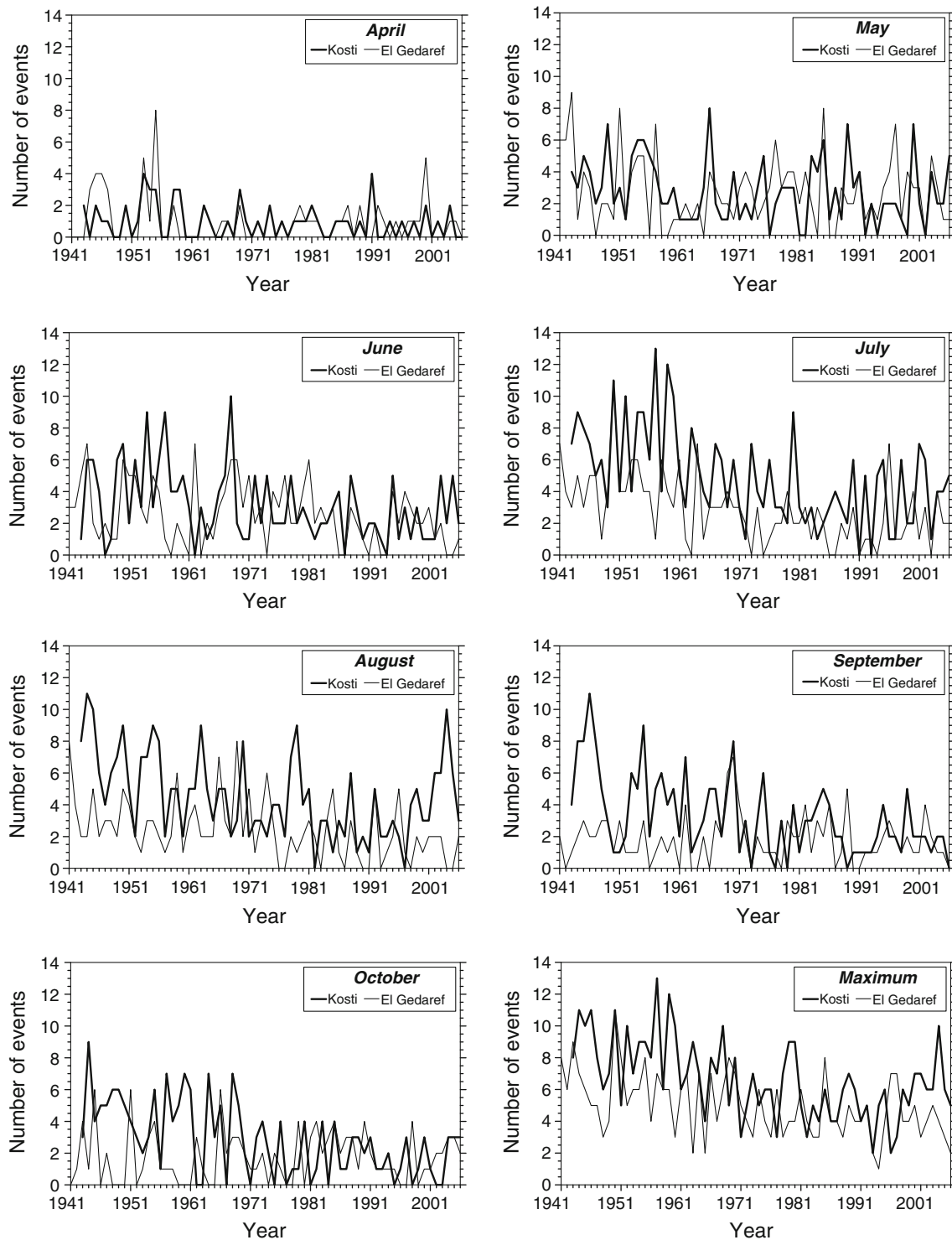
Fig. 2 Number of days of the month with trace rainfall events for Kosti and El Gedaref

a significant trend towards the concentration of trace events in few months within the year.

Based on the above results, a question arises: What are the possible causes of: (a) the more occurrences of trace events observed in the arid area (Kosti) over those recorded in the semi-arid area (El Gedaref) and (b) the drying and higher decreasing rates of rainfall indices for Kosti over those for El Gedaref? The factors influencing the production of rain may include: (1) the stability of the atmosphere, (2) the column water content, which is determined by the
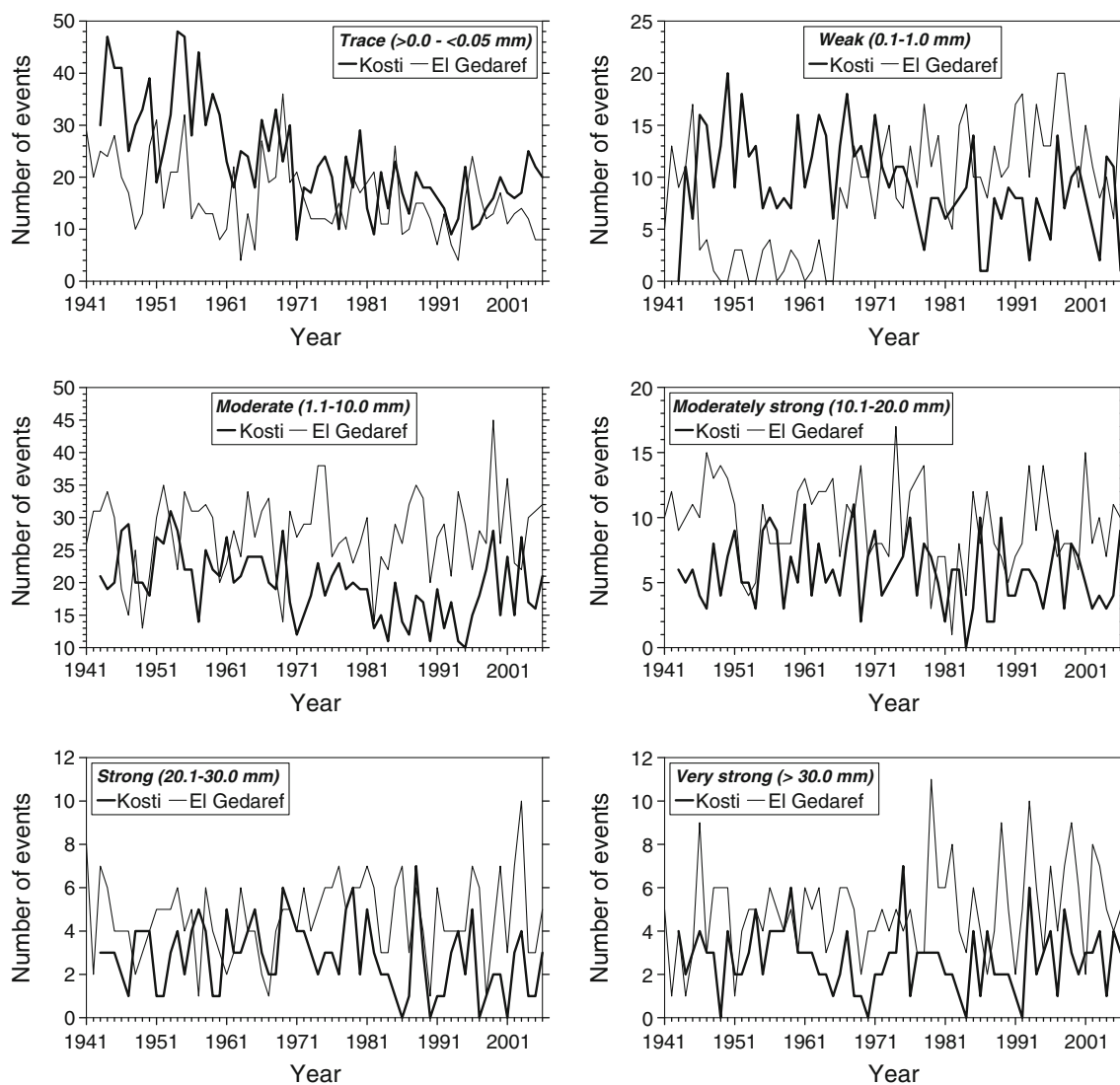
Fig. 3 Number of rain days of the year for Kosti and El Gedaref

lifting condensation of the cloud and (3) the type of cloud. Both convective and stratiform clouds can give little amount of rain. These events can occur throughout the rainy season, i.e. in the beginning, in the middle and at the end of the season. In the case of medium-level clouds, the water content is small and the path of rain drops is longer so that some of these drops evaporate before reaching the ground. If this amount of rain is coming from convective clouds, it is likely that the sub-cloud air is dry enough to evaporate the bulk of the rain drops. Hence, the effect of drying would be to increase the trace events and to reduce rainfall across all rain-day classes.

Several hypotheses have been put forth by Hulme (1990, 1992, 1998) for the causes of the substantial changes and variability in rainfall either for the Sahel situation in general or for the Sudanese case in particular, including:

(a) regional changes in land surface characteristics, such as land degradation and deforestation,
(b) large-scale oceanic circulation and the associated patterns of SSTs,
(c) regional atmospheric aerosol concentrations and
(d) climatic changes induced by global warming caused by greenhouse gas emissions.

The first factor has been investigated extensively using satellite data, and the conclusion was that a slight improvement in vegetation conditions occurred in central Sudan through 2003 as a result of partial recovery of rainfall (Anyamba and Tucker 2005) and migration (Olsson et al. 2005), despite the identification of localities with serious degradation (Prince et al. 1998) and the falling vegetation greenness (Herrmann et al. 2005). Factor (b)

Table 1 Trends in the frequency of rainfall events (rain days) during the entire period

	El Gedaref (1941–2006)				Kosti (1943–2006)			
	Kendall-tau test		Linear regression		Kendall-tau test		Linear regression	
	Sign	α	Rate	α	Sign	α	Rate	α
Monthly trace events								
April	+	0.957	−0.124	0.207	−	0.147	−0.125	0.093
May	−	0.707	−0.144	0.311	−	0.097	−0.180	0.177
June	−	0.020	−0.296	0.015	−	0.009	−0.419	0.006
July	−	0.000	−0.541	0.000	−	0.000	−0.802	0.000
August	−	0.001	−0.383	0.002	−	0.002	−0.558	0.001
September	−	0.596	−0.032	0.733	−	0.000	−0.702	0.000
October	+	0.275	+0.043	0.687	−	0.000	−0.629	0.000
Maximum	−	0.000	−0.471	0.000	−	0.000	−0.686	0.000
Annual rain days								
Trace	−	0.000	−1.560	0.000	−	0.000	−3.650	0.000
Weak	+	0.000	1.820	0.000	−	0.002	−0.916	0.002
Moderate	+	0.731	0.365	0.358	−	0.000	−1.200	0.000
Moderately strong	−	0.171	−0.287	0.170	−	0.262	−0.198	0.256
Strong	+	0.086	0.110	0.358	−	0.066	−0.189	0.086
Very strong	+	0.147	0.271	0.043	−	0.443	−0.056	0.578

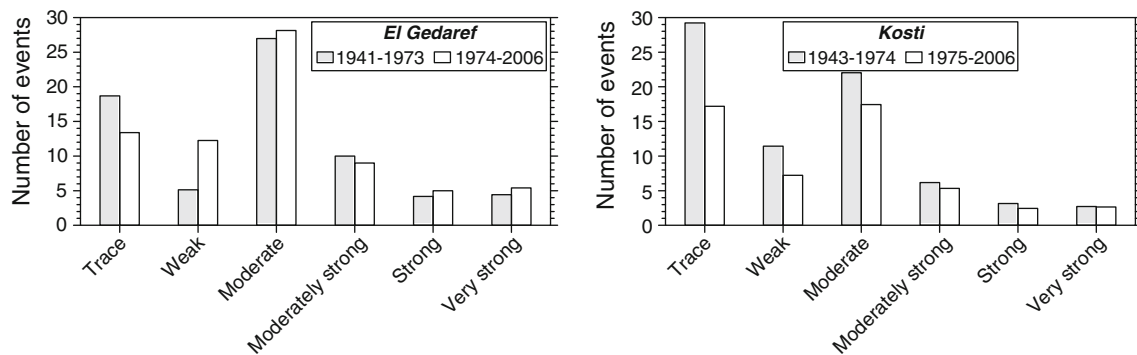α is the level of significance. The rate is given in events decade^{-1}

Fig. 4 Changes in annual rain days with different rainfall classes between two periods

Table 2 Results of the *t* and Kolmogorov–Smirnov (K–S) tests for comparing the means and distribution, respectively, between two sub-sets (Kosti between 1943–1974 and 1975–2006; El Gedaref between 1941–1973 and 1974–2006)

	El Gedaref		Kosti	
	t test	K–S test	t test	K–S test
Trace	S (0.005)	S (0.008)	S (0.001)	S (0.000)
Weak	S (0.000)	S (0.000)	S (0.000)	S (0.001)
Moderate	N.S.	N.S.	S (0.001)	S (0.001)
Moderately strong	N.S.	N.S.	N.S.	N.S.
Strong	N.S.	N.S.	N.S.	N.S.
Very strong	N.S.	N.S.	N.S.	N.S.

α value is given in parentheses
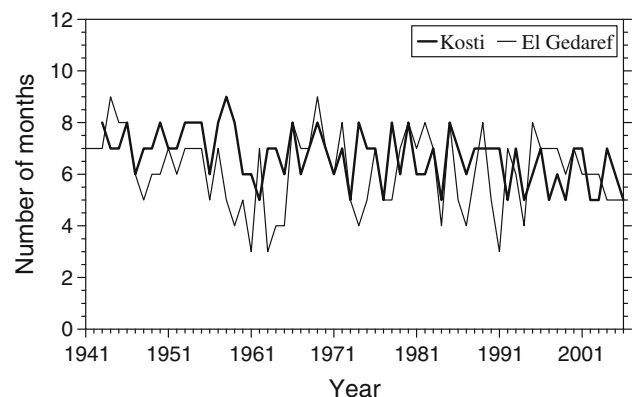N.S. not significant, S significant (α ≤ 0.05)

Fig. 5 Number of months within the year with trace events for Kosti and El Gedaref

Table 3 Trends in the annual number of months with Tr events and coefficients of variation and skewness using Kendall-tau test

	El Gedaref (1941–2006)		Kosti (1943–2006)	
	Sign	α	Sign	α
Months with Tr	−	0.000	−	0.000
Coefficient of variation	+	0.539	+	0.000
Coefficient of skewness	+	0.974	+	0.007

α is the level of significance
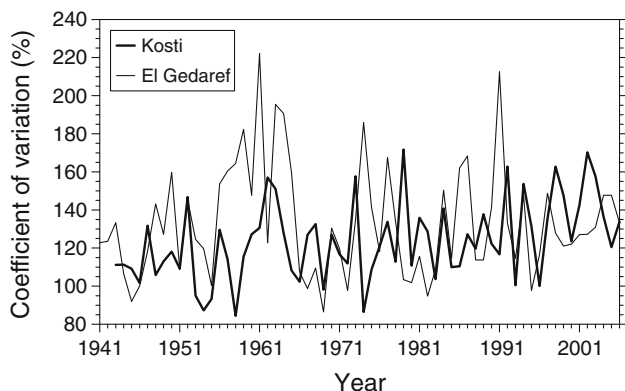
Fig. 6 Intra-annual variability of trace events
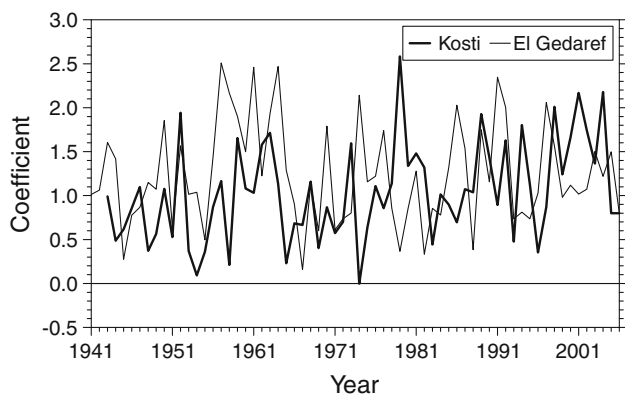
Fig. 7 Skewness of intra-annual trace events

and a fifth factor concerning local climatic controls will be discussed later in the next sub-sections. It is interesting to discuss at this stage factors (c) and (d).

Middleton (1984) and Goudie and Middleton (1992) reported increasing dust storms in the Sahel during the decades when the region had experienced severe drought. It has been argued that soil dust aerosols can enhance atmospheric stability and cause a decrease in rainfall (Lockwood 1986), since clouds would not form when stable conditions prevail in the atmosphere (Satheesh and Moorthy 2005), because cloud forming within a large abundance of desert dust in the atmosphere contains small droplets and produce little precipitation by drop coalescence (Rosenfeld et al. 2001). The suppression of rainfall further enhances the drier conditions at the soil surface which is conducive to raising more dust (Ramanathan et al. 2001; Rosenfeld et al. 2001). In fact, recently Hui et al. (2008) have supported the above arguments statistically by presenting a significant inverse relationship between dust and daily rainfall for five African Sahel stations, although they acknowledge that the analysis does not conclusively prove the occurrence of rainfall suppression by atmospheric dust. Elsewhere, observational, satellite and simulation evidences suggest: (a) significant negative correlations between dust aerosol and precipitation in the dust source regions and (b) that significantly increasing concentrations of aerosol are at least partly responsible for the decreased light rain events (days with precipitation less than 2 and 5 mm) (Han et al. 2009; Qian et al. 2009). These results are in line with the observations for Kosti, where significant decreases in trace, weak and moderate rainfall events have occurred.

Human activities releasing aerosols into the atmosphere also lead to a weaker hydrological cycle and suppression of rainfall (Ramanathan et al. 2001). The Sahel drying suggests anthropogenic forcings of the Northern Hemisphere sulphate aerosols, which force a meridional gradient in Atlantic SST, hence reduced moisture flux by anomalous winds (Biasutti and Giannini 2006). Very recently, Jury and Whitehall (2010) found through analysis of observations of air temperature that desert dust and biomass burning emissions influence the atmospheric energy budget, thus leading to warming in the elevated 925–600 hPa layer over tropical west Africa and the east Atlantic, which in turn stabilizes the atmosphere and inhibits rainfall. As mentioned before, Kosti is located within an area of extensive sugar cane agricultural and industrial schemes, namely Assalaya and Kenana, thus exemplifying anthropogenic sources of cloud condensation nuclei (CCN) through the burning of vegetative matter (sugar cane) to remove leaf and trash before harvesting (Cotton and Pielke 1996). The negative effect of such a practice on rainfall downwind of the sugar cane burning areas is expressed by Cotton and Pielke (1996) in their words as:

> Large number of CCN and cloud droplets would slow down collision and coalescence growth of precipitation by virtue of their smaller size and, consequently, small collection efficiencies and small collection kernels. Slower coalescence growth should therefore lead to less rainfall, at least from smaller clouds which do not contain large amount of liquid water.

Hence, all the abovementioned factors may clarify at least in part the more frequent days of trace events, higher

Table 4 Significant correlations between rainfall amounts (RF) and frequencies of rain days based on Kendall-tau test (one-tailed)

El Gedaref (1941–2006)			Kosti (1943–2006)		
Correlation	τ value	α	Correlation	τ value	α
Monthly					
April RF vs. April Tr	+0.227	0.024	Apr RF vs. Apr Tr	+0.266	0.015
May RF vs. May Tr	+0.182	0.042			
July RF vs. July Tr	−0.205	0.022			
Annual					
			Annual RF vs. Annual Tr	+0.194	0.031
			Annual RF vs. moderate	+0.253	0.004
			Annual RF vs. m. strong	+0.211	0.019
Annual RF vs. strong	+0.288	0.000	Annual RF vs. strong	+0.356	0.000
Annual RF vs. v. strong	+0.632	0.000	Annual RF vs v. strong	+0.564	0.000

α is the level of significance

m moderate, v very

rates of decreasing trends in rain days and less amount of rainfall received in the arid area of Kosti.

4.2 Relationships between rain days and total rainfall

Table 4 gives the Kendall-tau results for the significant correlations between rain days and total rainfall. On monthly basis, the table reveals inverse correlation between July rainfall and July Tr for El Gedaref, indicating that high frequency of Tr in July produces less rainfall amount in this month. Large number of Tr events during the early period of the wet season hints at high total rainfall for the month of April (at both stations) and for May in El Gedaref. It can be seen, on the long-term basis, that the annual frequency of Tr varies positively with the amount of rainfall for Kosti. However, the sub-periods data (not given in the table) showed contrasting results for El Gedaref, i.e. inverse relationships for 1941–1973 ($\tau = -0.206$; $\alpha = 0.048$) and direct relationship for 1974–2006 ($\tau = 0.276$; $\alpha = 0.014$). The above results indicates unclear link between the frequency of trace events and total rainfall both temporally and spatially. This would mean that the two indices are controlled by different factors, which in turn varied between the two wet and dry sub-periods. Some potential factors governing the trace events have already been discussed in the previous sub-section.

In El Gedaref, the annual rainfall is highly dependent on heavy rainfalls (strong and very strong events) and is independent on light and medium rainfall events (trace, weak, moderate and moderately strong). This would mean that heavy rainfalls are more likely to diminish in drought years and increase in wet years, while light and medium events tend to vary independently of either drought or wet years. On the contrary, Kosti annual rainfall shows very

close dependence on a wide range of rainfall classes (trace, moderate, moderately strong, strong and very strong). This implies that the number of rain days in all classes, except weak rainfall, tend to decline in drought periods and vice versa. These conclusions may be authenticated by the results presented in Fig. 4 and Tables 1 and 2, which display reduced events in all rain-day classes for Kosti, but significant changes for El Gedaref in only light-fall classes (decreasing trace days and increasing weak days) that do no contribute much to the total annual rainfall.

The observations for El Gedaref are very fortunate and may explain the successfulness of rain-fed agriculture practiced in this semi-arid area. This is especially true in view of the significant role played by the Ethiopian highlands in rainfall regime herein (Pedgley 1969a, b) and the occurrence of a large portion of rain during the hours of darkness (cooler part of the day), despite the characteristic rainfall variability, rainfall concentration in a few months, small number of rain days and the relatively large contribution to the annual total from a few heavier showers (Oliver 1965). Although the immediate usefulness of water supply to the plant during the nighttime will be less, the great proportion of annual total made by the days with heavy night rainfall is effective for plants since: (a) transpiration would be minimal when generally the stomata are closed and (b) the intensity of rain may not produce runoff, but the supply of water may exceed the evaporative capacity and the water storage in the soil be greater, such that it can be effectively made use of later when active growth and photosynthesis occur (Oliver 1969). Additionally, this possibly allows for recycling of moisture through evapotranspiration during the growing wet season (Savenije 1995; Taylor 2000). Pedgley (1969b) mentioned that the rainfall nearer to the Ethiopian highlands is more

Table 5 Significant correlations between the frequencies of trace and higher rainfall events (one-tailed)

Station	Weak		Moderate		Moderately strong		Strong		Very strong	
	τ	α	τ	α	τ	α	τ	α	τ	α
Entire period										
El Gedaref							0.165	0.036		
Kosti	0.288	0.001	0.284	0.001						
First period										
El Gedaref	0.211	0.050								
Kosti									0.226	0.050
Second period										
El Gedaref					−0.229	0.039	0.329	0.007	0.308	0.009
Kosti	0.262	0.023								

α is the level of significance

evenly distributed throughout the day. However, Elagib (2010) found highly significant ($\alpha \leq 0.001$) warming of air in the wet season both during the daytime (rate = −0.28°C decade^{-1}) and during the nighttime (rate = −0.18°C decade^{-1}) for the period 1941–2005. Moreover, the daily reference evapotranspiration for El Gedaref during April–October was estimated by Elagib (2001) to be in the range of 5.2–6.7 mm. These climatic conditions have important implications for rain-fed agricultural activities and warn of possible evaporation of rain, especially slight and medium falls (0.1–10.0 mm), before either plants or soil can benefit.

Correlation analysis carried out between the frequencies of trace and higher rainfall events (Table 5) indicated highly significant results for Kosti in terms of weak and moderate rainfall amounts for the entire and latter periods, while El Gedaref indicates significant positive relationship for the strong and very strong rainfall events. These would mean that higher rainfalls are independent of (closely follow) trace events in Kosti (El Gedaref), suggesting the spatial variation in rainfall behaviour between the two areas. The phenomenon of such patchy nature and localization of rainfall in central Sudan was discussed earlier by Oliver (1969), Hammer (1972) and Trilsbach and Hulme (1984). The sub-periods reveal different correlation characteristics, including the strength and sign, thus pointing to the intriguing distinction between the two rainfall periods during the last seven decades which were characterized earlier by Todorov (1985) for the Sahel region in general and by Trilsbach and Hulme (1984), Eldridge et al. (1988), Walsh et al. (1988) and Hulme (1990) for central Sudan in particular as an earlier wet and a later dry.

4.3 Effect of ENSO

Table 6 gives the results of the Kendall-tau test performed to investigate the linkage between ENSO indices and three

Table 6 Correlation between the normalized rainfall indices and ENSO-SSTs over the period 1950–2006 (one-tailed)

	El Gedaref		Kosti	
	τ value	α	τ value	α
Seasonal trace events				
April to June	−0.322	0.000	−0.149	0.059
May to July	−0.206	0.015	−0.206	0.015
June to August	−0.357	0.000	−0.185	0.025
July to September	−0.267	0.003	−0.237	0.006
August to October	−0.156	0.053	−0.227	0.008
Annual rain days				
Trace	−0.162	0.042	−0.200	0.016
Weak	−0.043	0.322	−0.226	0.008
Moderate	−0.135	0.075	−0.111	0.118
Moderately strong	−0.186	0.023	−0.168	0.039
Strong	−0.037	0.348	−0.081	0.202
Very strong	−0.045	0.324	−0.151	0.063
Total rainfall amounts				
April to June	−0.051	0.291	−0.075	0.208
May to July	−0.049	0.298	−0.054	0.281
June to August	0.015	0.434	−0.106	0.127
July to September	−0.131	0.079	−0.208	0.012
August to October	−0.091	0.162	−0.210	0.011
Annual	−0.082	0.185	−0.201	0.014

α is the level of significance

rainfall indices, namely seasonalized and annual frequencies of rain days and rainfall amounts. The relationship is dominantly negative, i.e. increasing ENSO index decreases both the number of rain days and rainfall amounts. In other wards, these results further confirm the findings of the studies mentioned earlier in Sect. 3 that warm ENSO episodes enhance the drought conditions in many regions in Africa. ENSO has been shown to have significant influence on annual rainfall variability in Sudan (Osman and

Shamseldin 2001; Osman et al. 2002). The strongest relationship in the monthly trace cases is found with June-August data for El Gedaref and July-September data for Kosti. No significant relationship ($\alpha > 0.05$) has been obtained for the early season (April–June) at the station of Kosti and for the end of the season at the station of El Gedaref, hinting at other powerful factors, more likely local-scale ones, affecting the process during the given periods of the year.

On annual basis, the relationship of rain days and ENSO is stronger at the arid station than at the semi-arid station for the trace and weak rainfall cases, though the relationship with the weak rainfall events is not significant for El Gedaref. However, the semi-arid station indicates stronger relationship between ENSO and number of moderately strong rain days compared to that for the arid site. Salient features are the significant results for Kosti in terms of seasonal (July–September and August–October) and annual rainfall amounts in comparison to dominant insignificant results for El Gedaref, giving further accentuation on the existence of influential factors other than ENSO on rainfall in El Gedaref.

To assess these results, it is useful to discuss the results in the regional context. Citing some works in the literature, Anyamba and Tucker (2005) concluded that the teleconnection linkage between ENSO and Sahel rainfall variability is not a straight forward relationship. For the eastern part of the Sahel, they further speculated a combined maritime influence from the adjacent Indian Ocean and orographic influences from the Ethiopian highlands. However, an earlier study by Beltrado and Camberlin (1993) indicated weak teleconnections between summer rains in Eritrea and peak-season rainfall (July and August) over Ethiopian highlands and the ENSO or the Indian Ocean, indicating much more relation either to local convective activity or to the characteristics of the Atlantic Congolese south-west monsoon flow. Diro et al. (2008) also emphasized that including contemporaneous SST does not necessarily lead to significant improvement of the forecast skill of rainfall in Ethiopia. In fact, Bewket and Conway (2007) observed high levels of spatial variability in daily rainfall indices on sub-regional scales in Ethiopia that are unlikely to be fully explained by large-scale climatic forcing. Rather, they support the argument of local-scale climatic controls.

5 Conclusions

There has been a profound drought over central Sudan during the past few decades. Based on two case studies of semi-arid rain-fed and arid irrigated agricultural areas, the analysis confirms the occurrence of distinct rainfall behaviours between past wet and recent dry spells of the study period. This drought condition has been shown to have affected more the arid area (Kosti). Since the 1940s, significant decreases in the annual frequency of rain days have characterized the trace, weak and moderate categories for Kosti, compared to significant trends in rain days with trace (decreasing) and weak and very strong (both increasing) in El Gedaref. Moreover, Kosti shows more occurrences of rain days in the trace class, but less events in the other classes in comparison to El Gedaref.

Additional contrast between the two stations is that falls ≤ 20.0 mm do not reflect the annual rainfall in El Gedaref, while the annual rainfall totals in Kosti is dependent significantly on the changes in the various magnitudes of daily rainfall frequencies, except the weak falls. However, the annual rainfall observed at the latter station also most closely follows the very strong events. This dependence on heaviest falls could be associated with an increase in the flood risk in certain years.

The correlation between the ENSO-SST anomalies and rainfall indices was found to be negative, confirming the results of earlier studies that warm ENSO episodes inhibit rainfall. However, it may be noted that this factor does not explain all the variation, and in fact, the relationship between ENSO and rainfall totals in El Gedaref is not significant. Thus, the considerable proportion of the variation still remains to be determined indicates that other underlying factors also contribute to the differences in rainfall regimes between the two stations.

It is argued that more frequent aerosol emissions from soil dust haze/storms and smoke from sugar cane burning may have contributed to or exacerbated the suppression of rainfall processes in Kosti, while the location of El Gedaref close to the Ethiopian highlands probably has more influence on the increased rain days, especially in the weak and very strong classes. The patchy nature of rainfall resulting from local moisture recycling in the central region could also be an inherent factor in the rainfall patterns detected in the two areas.

To some extent, this pilot study has laid a basis for how rain days have changed in central Sudan and offered a discussion on relevant causes. The results emerged from this study were in line with findings from other works pertinent to neighbouring countries in east Africa and elsewhere as referenced earlier. Further investigations on a larger scale would cast a light on the spatial behaviour of rain days in the region over the recent decades.

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