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REPORT

Trends in Intra- and Inter-Annual Temperature Variabilities Across Sudan

Nadir Ahmed Elagib

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Abstract Four mean temperature variables, namely maximum (MAX), minimum (MIN), mean (MEAN) and diurnal temperature range (DTR), were considered for 14 selected observational stations throughout Sudan. The objectives were to investigate the seasonal and annual regimes, the seasonal and annual trends, the intra-annual variability (IAV) by the coefficient of variation (CV), and the inter-relationships between the temperature variables and percent of possible sunshine. A mounting evidence of daytime and nighttime warming since the 1940s until 2005 is presented. The exception is the dry season which is dominated by daytime cooling attributable to the damping effect of dust haze/storms. Apparently, the progressive drought across inland locations has raised the MAXs, and to a lesser extent the MINs, of the wet season over those for the hot season. Accordingly, maximum rates of 0.451 and 0.336°C decade^{-1} were found for the nighttime and daytime temperatures, respectively. The extreme eastern and western locations have been frequently dominated by the warmest trend rates obtained nationwide. The prevalence of significant decreases (increases) of DTR is more apparent in the dry, hot and annual series (wet series). Depending on the temperature variable under consideration, many stations possessed significant trends toward either increased or decreased variability of the within-year monthly values, i.e. IAV. The correlation between the time series of annual CV and extreme values for each of the four temperature variables shows generally that warmer climate in Sudan is associated with higher intra-annual temperature variability and vise versa, i.e. the CV is directly correlated with the highest value within the year, but inversely correlated with the lowest one. The findings of this investigation also indicate that the DTR is directly related to percent of possible sunshine, but the relationship of the latter parameter is not so clear with MAX, MIN and MEAN.

Keywords Temperature variables · Climate variability · Climate change · Sunshine · Sudan

INTRODUCTION

Since the early 1990s (e.g. Karl et al. 1993), much attention has been paid to the investigation of trends in MAX and MIN in response to the major scientific challenge of global warming. The results showed differential changes in these two temperature variables. In consequence, the evolution of day-night difference in temperature, i.e. the DTR, revealed contrasting trends on both temporal and spatial scales (Plantico et al. 1990; Dessens and Bücher 1995; Lough 1995; Peterson et al. 1995; Razuvaev et al. 1995; Al-Fahed et al. 1997; Easterling et al. 1997; Przybylak 1997; Price et al. 1999; Trenberth et al. 2007). Most of the above studies investigated or postulated the possible local climatic and non-climatic as well as large-scale anthropogenic effects on DTR. Among the climatic factors, the effect of cloud amount has received particular attention. In general, decreasing DTR has been associated with increasing cloud amount.

During about the last decade, the African regions and countries have been the subject of a number of assessments and interpretations of temperature trends. Over eastern Africa, nighttime warming and daytime cooling in the northern part of the region and cooling during both times of the day in the Mozambique channel region were evident (King'uyu et al. 2000). Observations in Addis Ababa, Ethiopia (Conway et al. 2004) showed increasing MINs at a larger rate than the MAXs. New et al. (2006) found that the DTR over 1961–2000 exhibits contrasting trends across the region of south and west Africa. However, a zone

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across Namibia, Botswana, Zambia and Mozambique showed consistent DTR increases, coinciding with more rapid increases in MAX than MIN. In Libya (El Kenawy et al. 2009), the temperature trends over the second half of the twentieth century presented a strong evidence of rising annual MIN and downward trends in annual MAX and DTR. The seasonal MEANs show that most of the warming is identified in the summer and fall. Using MEAN data, Elagib and Mansell (2000a) showed significant trends in wet- and hot-season series for Sudanese stations located south of latitude 16°N for the period since the 1940s to 1996, with the rising trends in the former series being higher and more significant. Aguilar et al. (2009) found a decrease in cold extremes and an increase in warm extremes over western central Africa, Guinea Conakry and Zimbabwe.

The evidence of a gradual warming trend in global mean temperature (Hansen and Lebedeff 1988; Jones and Briffa 1992; Jones 1994) has also led to a heightened attention to changes in climate variability in recent decades. Climate models indicated that temperature changes are sufficiently large to have corresponding changes in the frequency of extreme events (Hansen et al. 1988). Both for the transient and double CO_2 climate simulations, the results showed that the temperature variability tends to decrease in the warmer climate (Rind et al. 1989). In the light of the increasing awareness of the importance of the study of climate variability (Katz and Brown 1992), a number of investigators examined the long-term temperature observations (Karl et al. 1995; Przybylak 1997; Michaels et al. 1998; Elagib and Mansell 2000a; Pal and Al-Tabbaa 2009) in a search for changing variability in a changing climate.

Results of projected climate changes indicate that all Africa is very likely to warm in all seasons this century. Adequate knowledge of the spatial distribution of changes and variability of temperature extremes is insufficient. In this study, further analysis of recent temperature trends and variability is performed for Sudan over that conducted by Elagib and Mansell (2000a) by updating the time series to the year 2005 and including, in addition to MEAN, the records on MAX, MIN and DTR. The paper also expands upon Karl et al.'s (1993) study which considered the nationwide MAX, MIN and DTR series during 1951–1987.

DATA AND METHODS

Fourteen stations, the locations of which on a map of Sudan are displayed in Fig. 1, were selected to cover the four main regions of the country, i.e. the southern region (south of 10°N), the central region (10-16°N), the northern region (north of 16°N) and the coastal region of the Red Sea in the north-east (Elagib and Mansell 2000a). Available data

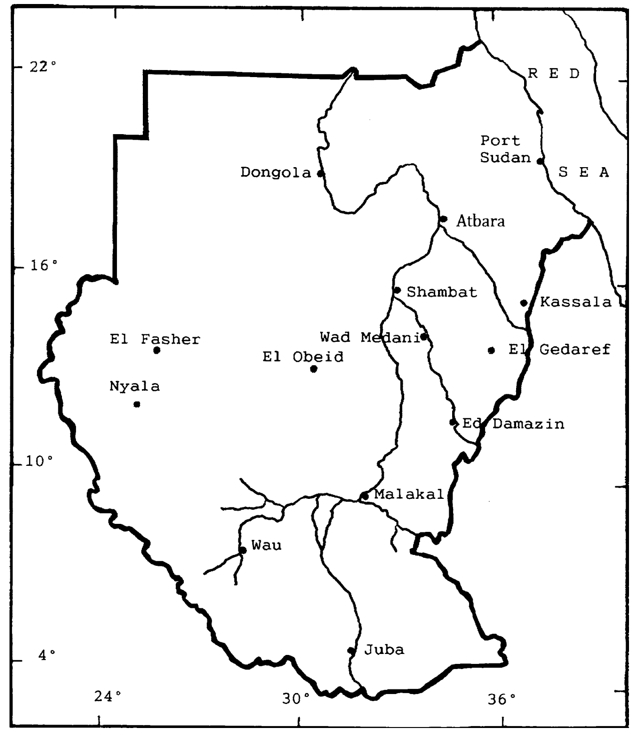

Fig. 1 Map of Sudan showing the location of the selected temperature stations

since the 1940s on mean monthly maximum and minimum temperatures for these stations were acquired from the Sudan Meteorological Authority. The reason for considering the data from the 1940s, the treatment of the data and the infilling of single missing data were discussed earlier (Elagib and Mansell 2000a). First, the problem of data discontinuity and inhomogeneity, if any, would be avoided. Second, individual missing data have been substituted, as suggested by Qureshi and Khan (1994), by the average of six records, i.e. the three preceding and the three following records for the given month. Such missing values, however, were less than 5% of the total for an individual series in the most extreme case.

Two of the stations under consideration, namely Atbara and Dongola, have their records starting, respectively, in 1944 and 1945 instead of 1941. The temperature records for all the stations extend to 2005. There were intermittent or no data for Wau (latitude: 7.70°N; longitude: 28.02°E; altitude: 435 m) during the period 1988–1995 due to the civil war at that time. These data were estimated using correlation methods, as adopted by King'uyu et al. (2000) and López-Morino et al. (2006), by expressing Wau observations as a function of those for Raga (latitude: 08.47°N; longitude: 25.68°E; altitude: 545 m). A cubic equation was obtained using combined maximum and minimum temperature data for the normal period 1951–1980, 1994–1997 and 2000 with determination coefficient of 0.943.

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The monthly mean temperatures and diurnal temperature range were calculated as an average of and difference between the MAX and MIN temperatures, respectively. To measure the intra-annual variability (IAV), simply the coefficient of variation (CV) was calculated on an annual basis by considering the 12 monthly temperature values of the year. Thus, the CV for each year was determined as 100 × standard deviation/mean. It is to be noted that the values of CV for temperature herein are dependent on the units used, i.e. °C. Since this measure is dependent on the mean (denominator), the values would be different if other units, e.g. °F or °K, were used. The non-parametric Spearman rank correlation test (Kanji 1997) was performed: (1) on the data with time to indicate the direction and statistical significance of trend in IAV, (2) to investigate the correlation between the IAV and the highest and lowest temperatures of the four temperature parameters and (3) to investigate the potential association between the observed inter-annual characteristics of the four temperature variables and the percent of possible sunshine. The percent of possible sunshine, referred to thereafter as sunshine, is the ratio of the duration between sunrise and sunset to the day length. The former data were those used by Elagib and Mansell (2000b) for 22–36 years within the period 1961–1996, while the latter data were taken from Elagib et al. (1999). No data on sunshine hours were available for this study for the stations of Nyala and Atbara. The simple linear regression was used to obtain the trend rates of the time series of the four temperature variables.

Three main seasons, viz. dry, hot and wet, can be identified for the four geographical regions considered in the analysis as follows (Elagib and Mansell 2000a):

(1) Southern region: dry (January, November and December), hot (February and March) and wet (April–October).
(2) Central region: dry (January, February, November and December), hot (March–May) and wet (June-October).
(3) Northern region: dry (January–March and October–December), hot (April-June) and wet (July–September).
(4) Coastal region: Dry (February–April), hot (May–September) and wet (January and October–December).

RESULTS AND DISCUSSION

Seasonal and Annual Regimes

Typical examples of the temperature patterns are given in Figs. 2, 3, 4, and 5, respectively, for MAX, MIN, MEAN and DTR. For the MAX (Fig. 2), three regimes can be identified. First, the semi-arid and dry sub-humid stations located within the southern and east central parts of the country have their hot season temperatures greater than those for the dry season, which in turn exhibits temperature values higher than the wet season ones. Second, the arid locations of central Sudan have higher temperatures for the wet season than those occurring in the dry season but lower than the hot-season temperatures. This is also a characteristic of the hyper-arid coastal area (Port Sudan), where rain falls during the cold part of the year, though the dry season temperatures approach those for the wet season. Third, in the driest one-third of the country (northernmost part) represented by Shambat, Atbara and Dongola, the temperatures registered during the wet season approach those recorded for the hot season.

Figure 3 for the MIN shows cooler air for the wet season than the hot season in Juba, El Gedaref, Ed Damazin and Port Sudan. However, in the remaining two wet stations in the south, namely Wau (dry sub-humid) and Malakal (semi-arid), the regime is reversed. It is possible that the proximity of these two stations to large water bodies, namely Bahr el Ghazal basin and the Sudd flood region, respectively, may have moderated the temperatures of the hot season through the cooling effect of the evaporated water from the basins. Similar findings were noted earlier by Lough (1995) for the summer and winter in Queensland, Australia. In the rest of the country, the MINs have values for the hot season less than their counterparts during the wet season and have dry-season temperatures extremely lower than those for the other seasons. These may reflect features of aridifying conditions and dry lands. Further finding is that the coastal influence causes the MINs to be higher in Port Sudan compared with inland stations, a results coinciding with Lough's (1995).

The regimes of the MEANs (Fig. 4) have been addressed earlier by Elagib and Mansell (2000a). The areas receiving heavier rainfall amounts (semi-arid and dry sub-humid) register MEANs during the wet season that tend to approach the MEANs during the dry season. Opposite behaviour occurs in the drier areas, where the drier conditions raise the wet-season temperatures to levels approaching those for the hot season. The exception is Port Sudan which experiences rainfall during the cold part of the year; here the temperature regime resembles those for the wetter areas.

Regarding the patterns displayed by DTR in Fig. 5, the distribution of DTR clearly reflects the degree of aridity of the location, i.e. the magnitude of DTR increases northward with increasing aridity. Likewise, the DTR is smallest during the wettest part of the year and is largest during the driest period of the year. In the wettest areas, the DTR for the hot season is slightly less than that for the dry season

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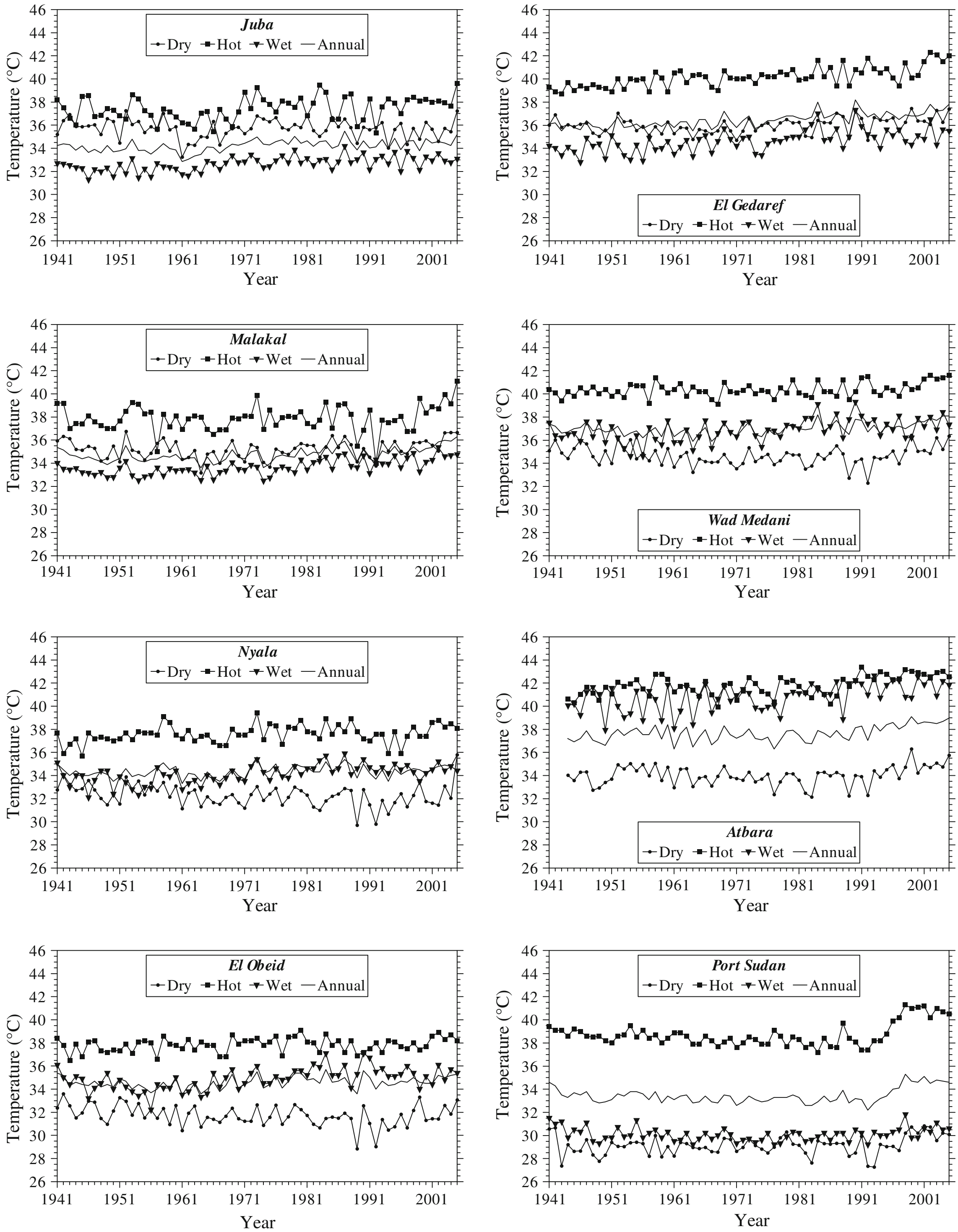

Fig. 2 Plot of mean maximum temperatures

since there is still some rain that falls during the former season. More arid areas show almost equal DTRs for both the dry and hot seasons. Although the coastal area is located in the hyper-arid zone of Sudan, it possesses the lowest DTR values in the country, possibly due to the high humidity of the atmosphere. Moreover, there are also distinct DTR values for the seasons, with less DTR for the dry season (with slight rain) than for the hot season. The explanation for the regimes of DTR discussed above is that clouds and rainfall, which enhances the soil moisture

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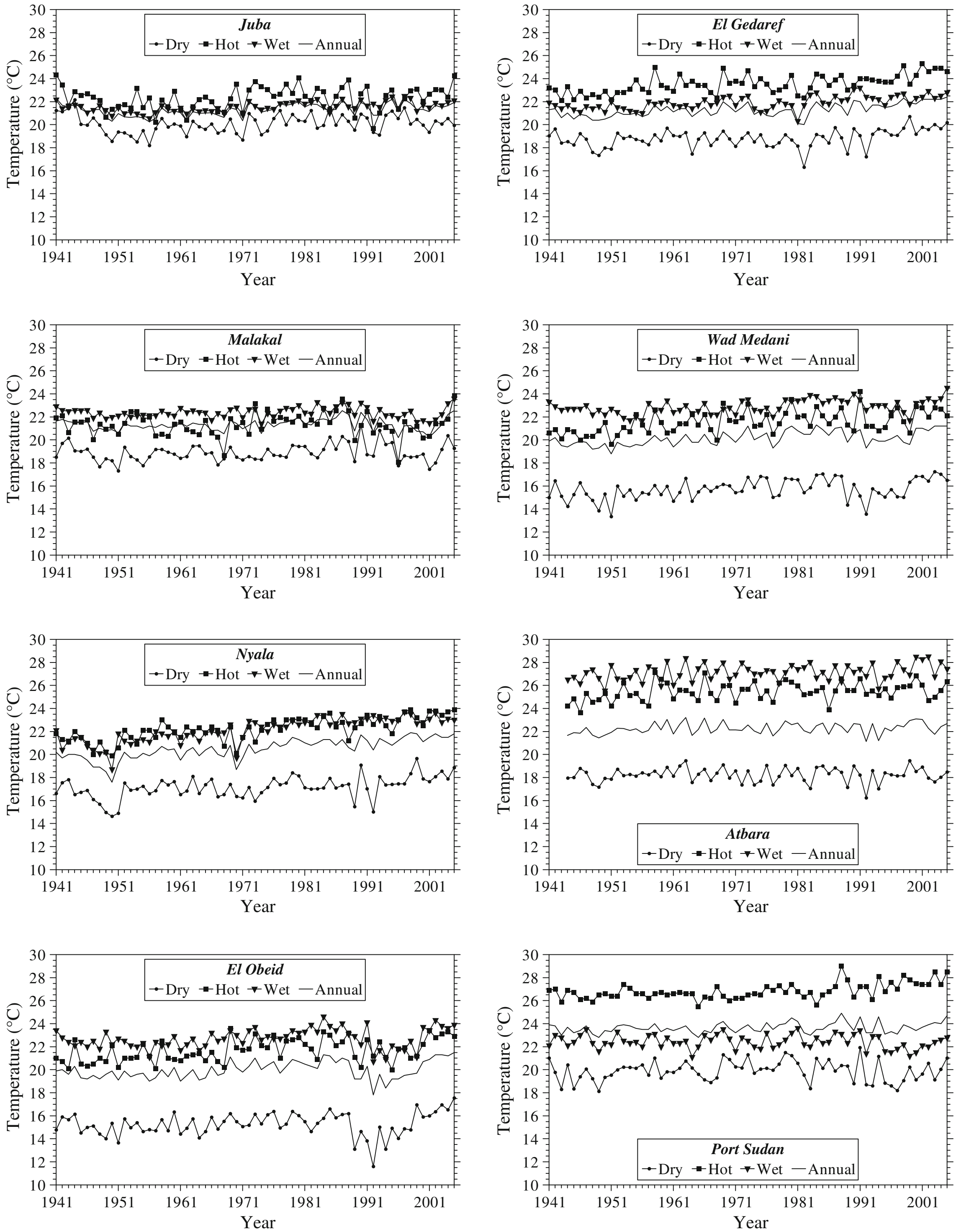

Fig. 3 Plot of mean minimum temperatures

content, reduce the surface DTR compared with clear sky (Dai et al. 1999).

Referring to the same figures, the following remarks can be noted for the annual temperature variables. The MAX is lowest in the coastal region and the humid extreme south of the country and is highest in the extreme north (Fig. 2). Figure 3 shows that the MIN reduces to its lowest value in the elevated western locations, especially El Fasher, reaches its highest value in the coastal area and moderates in the rest of the country. Interestingly, the temperature at Wad Medani

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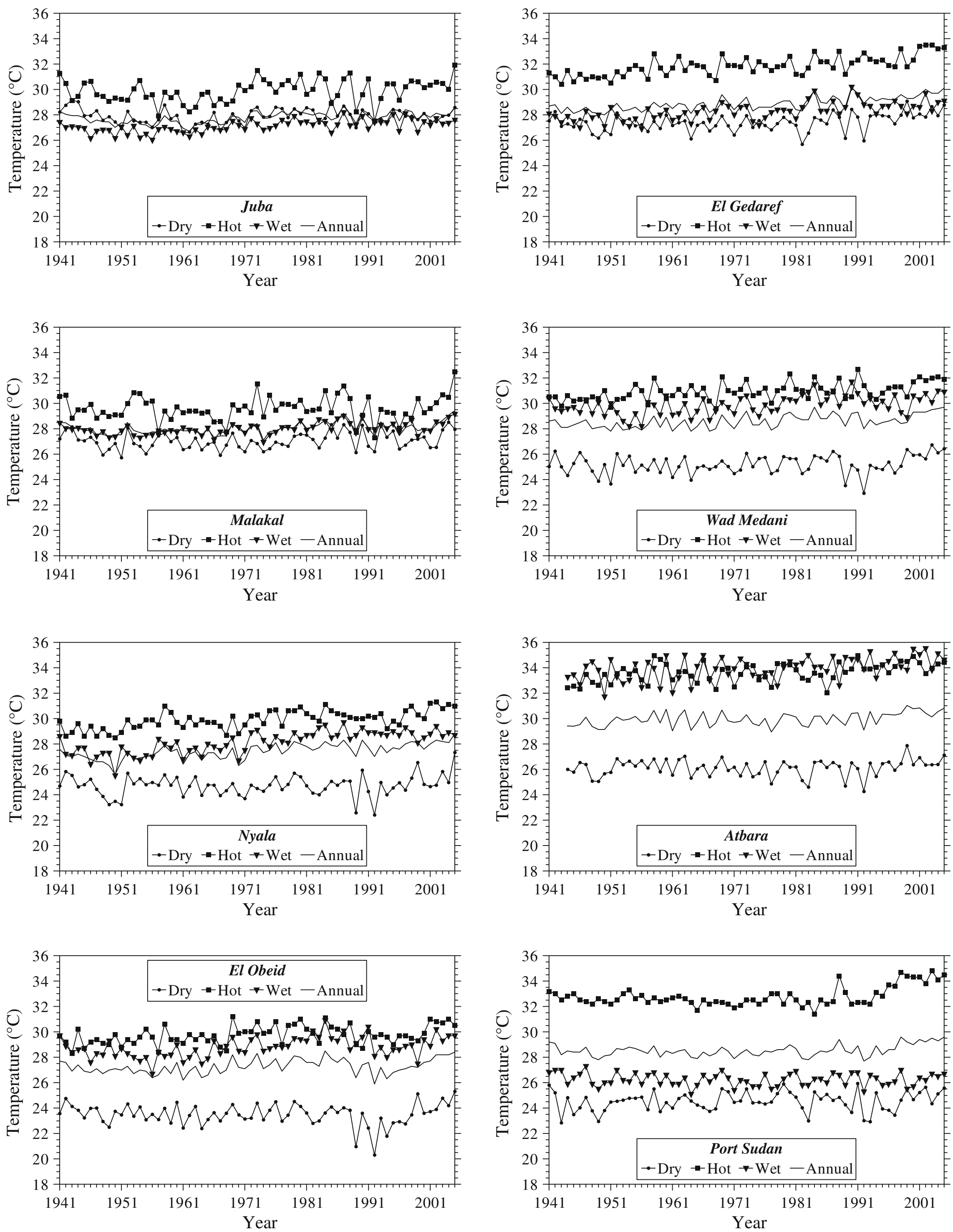

Fig. 4 Plot of mean Temperatures

and Ed Damazin also shows the lowest levels experienced in the country. The first station is situated within a vast area that has come for decades under large-scale irrigation, whereas the other is in the vicinity of Er Roseires Dam. The MEAN (Fig. 4) increases from south to north, and the lowest value is observed in the western part, particularly El Fasher. In the coastal region, values almost the same as those recorded in the mid- and east-central Sudan are evident. The DTR registers its lowest values in the coastal area and increases generally from the south to the north (Fig. 5).

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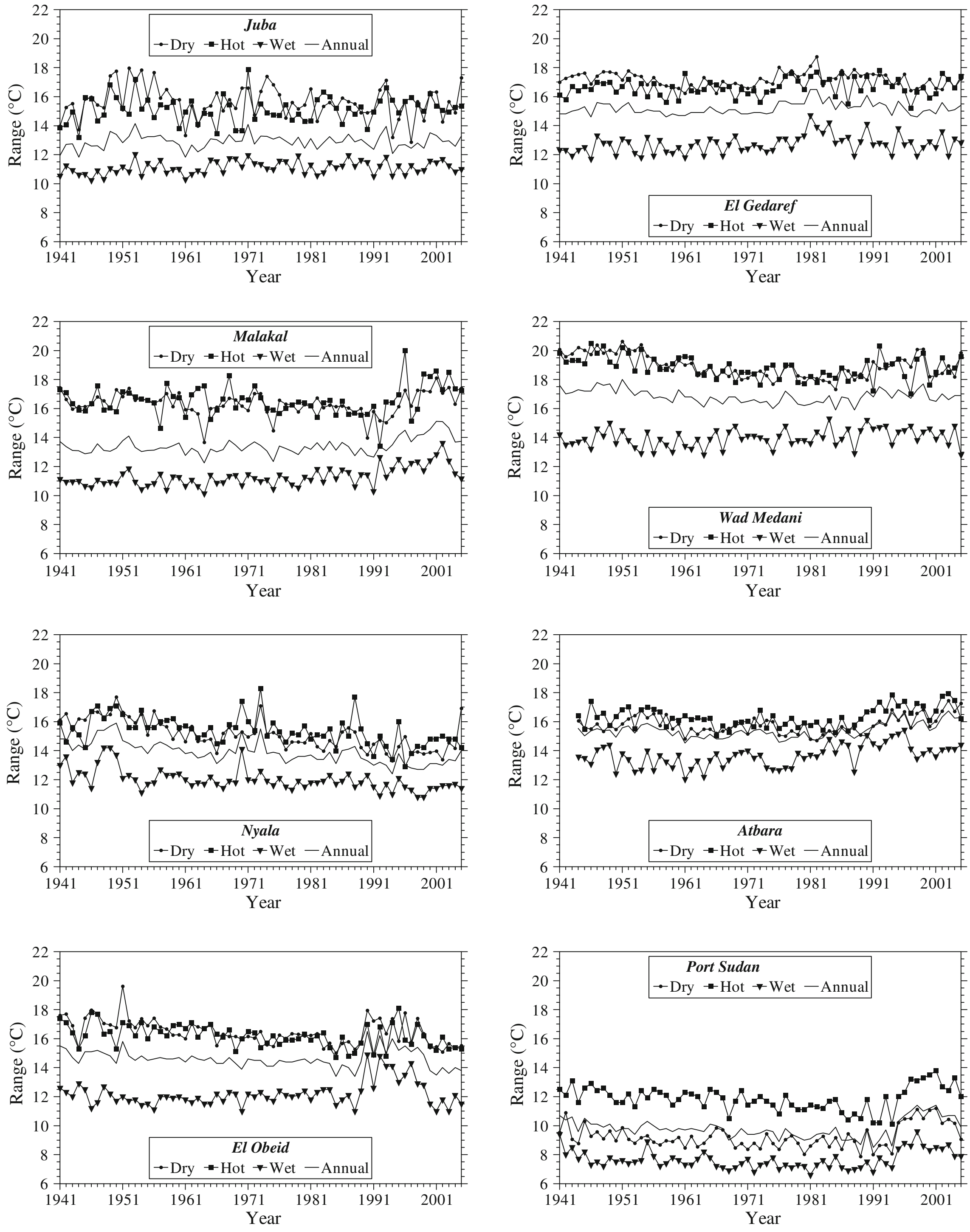

Fig. 5 Plot of mean diurnal temperature ranges

Intra-annual Variability

Figure 6 shows, for index stations, the plot of intra-annual temperature CV for the four temperature parameters. As shown, the IAV in MAX for central Sudan is lowest and is followed by the IAV in MEAN. The reverse is true for the most humid locations in the south (Malakal, Wau and Juba), where the IAV value for MEAN is lowest and is slightly lower than that for MAX. In the semi-arid locations of El Gedaref and Ed Damazin, the MAX and MEAN IAV values alternate but they almost approach each other. In the coastal area of Port Sudan, the MAX, MIN and MEAN IAV series

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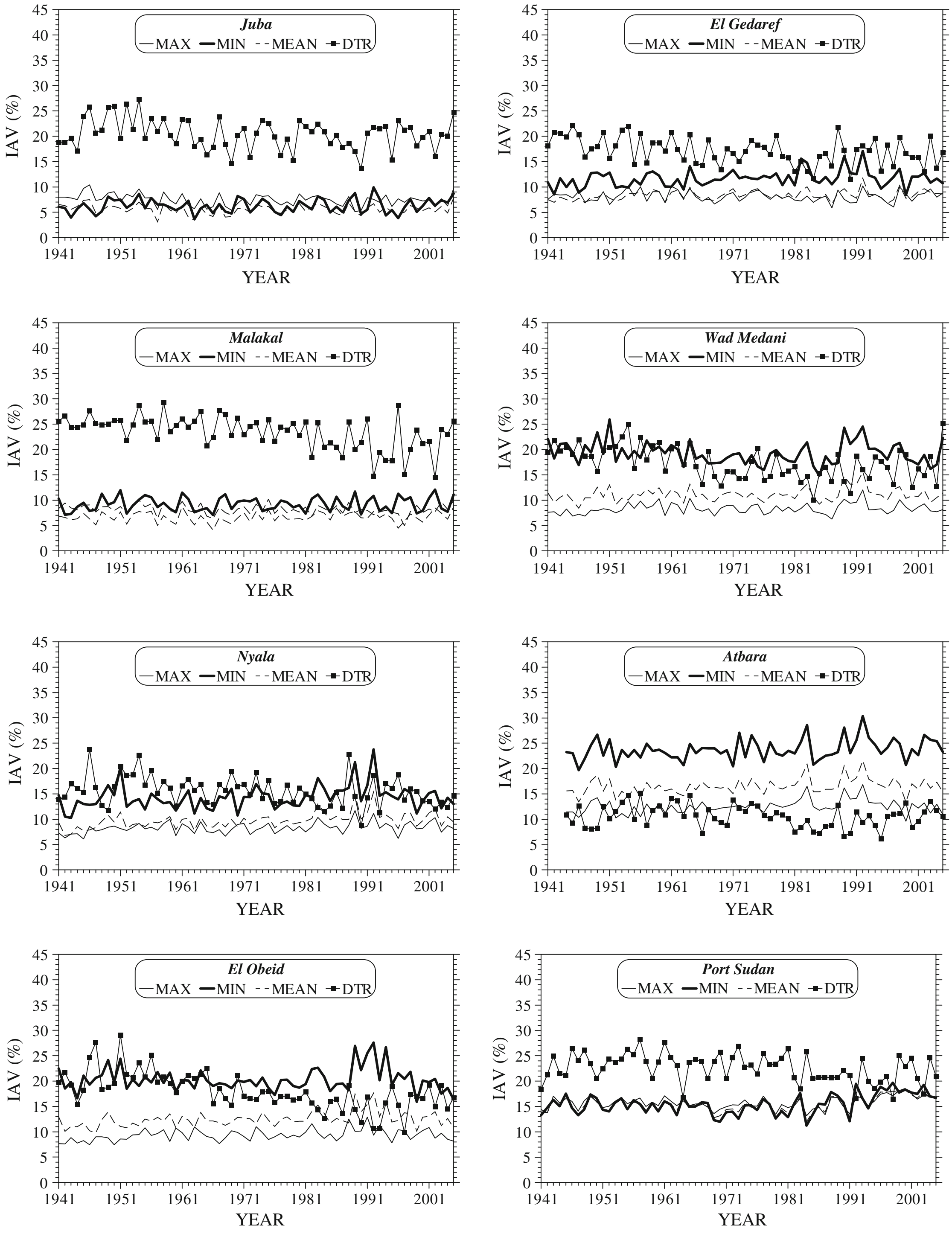

Fig. 6 Plot of intra-annual temperature variability

overlap and have lower values of IAVs than those existing in DTR IAV series. It can also be seen that the MIN series starts at the level of MEAN series in the extreme south (Juba) and rises as one goes north until it reaches its maximum value in Dongola, representing the highest IAV magnitude among the four series. A reverse situation can be noticed for the DTR series, which registers highest IAV in the humid south and decreases northward. The coastal area, however, indicates levels of IAV in DTR comparable with those for the extreme south.

Downward trends in DTR and upward trends in MEAN series can be detected in the western area (Nyala, El Fasher

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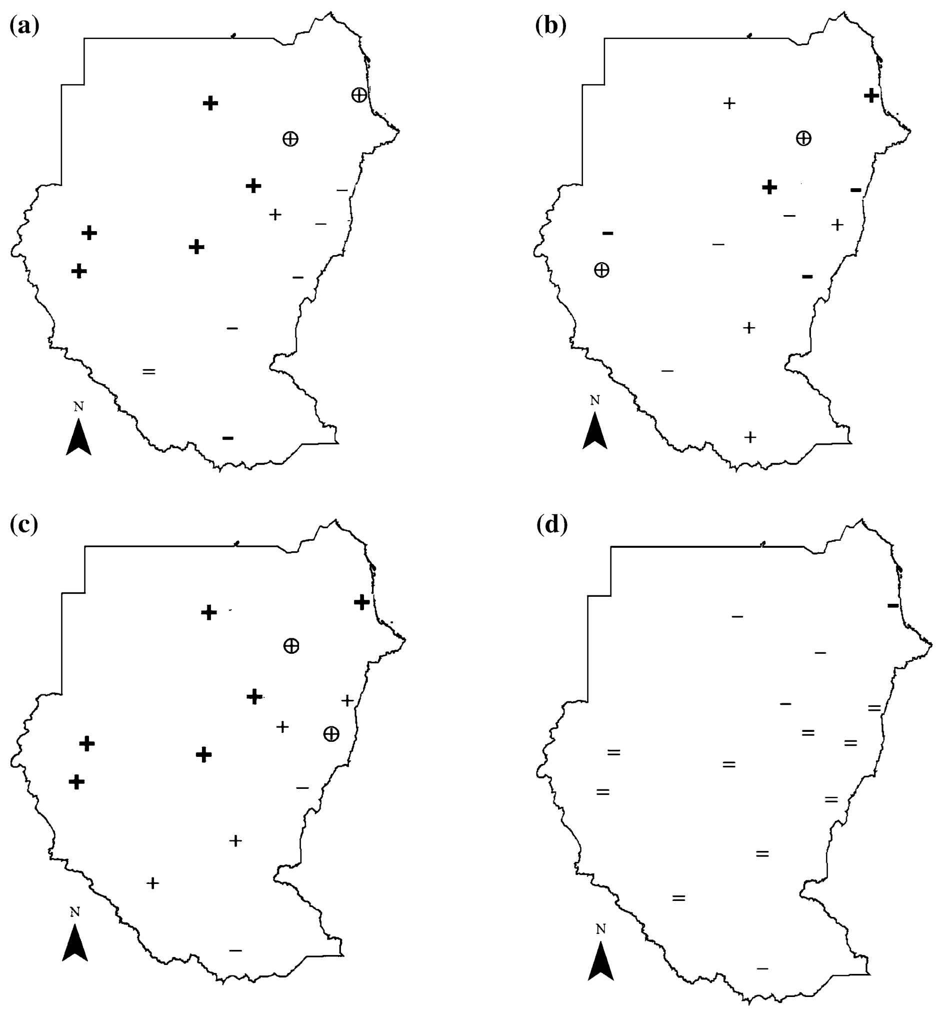
and El Obeid), producing an intersection of the two IAV lines since the mid-1980s. Wad Medani and El Obeid also show intersecting lines of the DTR and MIN IAVs during about the early 25 years of the study period. Other clear intersecting lines of these two temperature parameters dominate during the entire period of the study for Kassala and Nyala. Similar intersection behaviour is also observed for Shambat in its IAV lines of the DTR and Mean.

The results of the trend analysis by Spearman rank correlation test are given in Fig. 7. MAX results indicate significant negative trends in the extreme southern stations (Wau and Juba) and significant positive trends from Shambat and northward in addition to the western part of the country. Mixed results, i.e. statistically significant positive and negative trends, are characteristics of the IAV time series of MIN for seven of the stations, but no significant trends were found for the three southernmost stations. All of the eight significant trends obtained for MEAN are positive and these trends typify the western region, northern arid and hyper-arid parts in addition to El Gedaref in the east. The downward trend in all of the time series for DTR IAV is very striking, though the significance characterizes ten out of the 14 stations. These cover the stations located at the latitude of Wau in the south to the latitude of Kassala in east-central Sudan in addition to the coastal station (Port Sudan).

The results of the correlation between IAV and the temperature extremes show interesting results. Overall, increasing IAV was found to be associated with increasing highest temperatures of MIN, MAX, MEAN and DTR and vise versa (Table 1). This means that temperature increases are associated with higher intra-annual temperature variability, i.e. unstable temperatures, a result thus commensurate with what has been documented elsewhere (Kunkel



Increasing		Decreasing	
⊕	$0.01 \le \alpha < 0.05$	$\_$	$0.01 \le \alpha < 0.05$
+	$0.001 \le \alpha \le 0.006$	**=**	$0.001 \le \alpha \le 0.006$
+	Insignificant	–	Insignificant

Fig. 7 Spatial distribution of trend directions of intra-annual temperature variability: **a** MAX, **b** MIN, **c** MEAN and **d** DTR

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Table 1 Association between IAV and extreme temperatures examined by Spearman rank correlation test

Correlation	IAV vs. lowest MAX	IAV vs. highest MAX
Spearman statistic	−0.728 to −0.480	0.301 to 0.627
Significance level	$\alpha = 0.000$	$0.000 \leq \alpha \leq 0.015$
Correlation	IAV vs. lowest MIN	IAV vs. highest MIN
Spearman statistic	−0.775 to −0.527	0.299 to 0.649
Significance level	$\alpha = 0.000$	$0.000 \leq \alpha \leq 0.015$
Correlation	IAV vs. lowest MEAN	IAV vs. highest MEAN
Spearman statistic	−0.713 to −0.339	0.249 to 0.666
Significance level	$0.000 \leq \alpha \leq 0.006$	$0.000 \leq \alpha \leq 0.045$
Correlation	IAV vs. lowest DTR	IAV vs. highest DTR
Spearman statistic	−0.827 to −0.508	0.295 to 0.676
Significance level	$\alpha = 0.000$	$0.000 \leq \alpha \leq 0.017$

Note: Only the range of the significant results is given

et al. 2008). It is worthwhile mentioning that results (not shown) presented evidence of an overwhelming significant increasing trend in the highest MAX ($0.000 \leq \alpha \leq 0.011$), indicating warming of the climate in the recent decades in Sudan. In about 86% of the cases, the lowest temperatures had higher association with IAV than the highest temperatures. For MAX, the highest temperatures have no influence on IAV in Atbara, Shambat and El Gedaref. No association was registered for the MIN between the highest temperatures and IAV in Ed Damazin, Kassala, Wad Medani, El Fasher, Wau and Dongola. Also, no influence on the IAV in MEAN and DTR was shown in the case of Atbara and El Gedaref, respectively.

Trends and Association with Sunshine

Dry Season

The results of the trend analysis and the relationship between the dry season temperature and sunshine are presented in Table 2. A general cooling of the air is quite evident by MAX (64% of the stations), especially in the western sector of the central region. However, the steepest negative trend (−0.166°C decade^{-1}) is registered for Dongola in the northern region. Middleton (1985) and Goudie and Middleton (1992) showed a marked rise in dust-storm activity from the analysis they conducted for Sudan and attributed that to the dryness of the wet season. This phenomenon may partly be responsible for the observed decrease in MAX (Jones 1995) and DTR (Price et al. 1999; Lockwood 1998), especially that dust haze/storms over Sudan in this season usually occur during the daytime. A distinct significant positive trend (0.124°C decade^{-1}) is shown for El Gedaref in the east. This is an area that has not been affected much by drought during the period of study compared to the rest of the central Sudan (Elagib 2009). In contrast, the MINs

Table 2 Trend rates of temperature variables by linear regression in °C decade^{-1} and significant Spearman correlation statistic (R_s) of temperature variables versus sunshine for the dry season

Station/region	MAX		MIN		MEAN		DTR	
	Rate	R_s	Rate	R_s	Rate	R_s	Rate	R_s
Southern								
Juba	−0.037		0.068		0.015		−0.105	0.729§
Wau	0.042	−0.649§	0.151‡	−0.484†	0.082*	−0.643§	−0.093	
Malakal	0.073		0.076		0.074		−0.004	0.330*
Central								
Ed Damazin	−0.078		0.123*		0.033		−0.221§	
Nyala	−0.131*		0.245§		0.057		−0.376§	
El Obeid	−0.139*	0.323*	0.086		−0.026		−0.225§	
El Fasher	−0.158†	0.446‡	0.264§		0.053	0.320*	−0.422§	0.308*
El Gedaref	0.124‡		0.140‡		0.132‡		−0.016	−0.449†
Wad Medani	−0.020		0.185§		0.082		−0.204§	0.353*
Kassala	−0.077	0.341*	0.357§		0.140‡		−0.435§	0.398†
Shambat	−0.060		−0.065		−0.063		0.005	0.389†
Northern								
Atbara	0.086		0.005		0.045		0.081	
Dongola	−0.166*	0.360*	0.084		−0.041		−0.250§	0.795§
Coastal								
Port Sudan	0.102		0.021		0.062		0.081	0.286*

Significance level: * $0.01 \leq \alpha \leq 0.05$, † $0.005 < \alpha \leq 0.009$, ‡ $0.001 < \alpha \leq 0.005$, § $\alpha \leq 0.001$

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show positive trends for all the stations, except Shambat in the northernmost part of the central region. However, the significant trends only dominate the central region. The exception of significant positive trend extends to a single station in the south (Wau). The largest trend rate of MIN is noticed for Kassala as 0.357°C decade^{-1}, followed by the extreme western stations of El Fasher then Nyala. These asymmetric trends in MAXs and MINs resulted in remarkably moderate changes (mostly positive) in MEAN and noticeable changes in DTR (mostly negative). The number of stations revealing significant rates for MEAN is only three. It is worth mentioning that seven stations show significant decline of their DTR, while none of the three increasing DTR trends is statistically significant. Neither the sign nor the significance of trend is consistent in the northern hyper-arid region with regard to MEAN and DTR. The negative and almost equal rates of MAX and MIN trends for Shambat stabilized its DTR rate. Kassala and El Fasher witnessed the steepest decline of DTR among the stations under consideration of more than −0.4°C decade^{-1}. Stations with positive signs of both MAX and MIN trends indicate a rate for MAX of up to 4.75 times as large as that for MIN (Port Sudan) and rates for the MIN of up to 3.63 times that for the MAX (Wau).

It can be seen from Table 2 that the relationship between the inter-annual variations of temperature and sunshine is mostly positive, almost non-existent for MIN and MEAN, and spatially weaker for MAX than for DTR. Marked attenuation of sunshine and incoming solar radiation was noted for Sudan (Elagib and Mansell 2000b). This means that, as sunshine decreased (hazy sky due to dust activity), both the MAX and the DTR decreased in this season.

Hot Season

Table 3 presents the results of the analysis carried out on the hot season data. The overall feature of the observed trends is that warming has occurred everywhere in the country. Considerable domination of significant positive trends is seen for the MIN and MEAN, but warming still occurred in the MAX. Such trends prevailed over 12, 11 and 9 stations, respectively, out of the 14 stations under investigation. Nighttime temperatures have risen dramatically over daytime temperatures; the maximum rate of the former is 0.424°C decade^{-1} (Kassala) while that of the latter is 0.325°C decade^{-1} (El Fasher). At the station level, the nighttime has risen by rates of 1.13 (Port Sudan) to 14.3 (Kassala) times that for the daytime. On the other hand, greater warming of the MAX over the MIN is pronounced for six stations by rates of 1.23 to 3.87 times. It should be observed that the western stations of Nyala, El Obeid and El Fasher have consistent warmer air during the nighttime over the daytime. The results also point out the following:

Table 3 Trend rates of temperature variables by linear regression in °C decade^{-1} and significant Spearman correlation statistic (R_s) of temperature variables versus sunshine for the hot season

Station/region	MAX		MIN		MEAN		DTR	
	Rate	R_s	Rate	R_s	Rate	R_s	Rate	R_s
Southern								
Juba	0.157*		0.095		0.126*		0.062	0.570§
Wau	0.146†		0.229§	−0.654§	0.187§	−0.438*	−0.084	0.604§
Malakal	0.090		0.023	−0.355*	0.057		0.067	0.653§
Central								
Ed Damazin	0.077		0.040		0.059		0.036	0.390*
Nyala	0.122*	–	0.390§	–	0.255§	–	−0.263§	–
El Obeid	0.078*	0.304*	0.251§		0.160§		−0.175§	0.385*
El Fasher	0.077		0.321§	−0.281*	0.202§		−0.242§	0.303*
El Gedaref	0.325§		0.264§		0.294§		0.059	
Wad Medani	0.113†		0.270§	−0.311*	0.191§	−0.332*	−0.153‡	0.387*
Kassala	0.030		0.424§	−0.702§	0.227§	−0.366*	−0.389§	0.711§
Shambat	0.165‡		0.129*	−0.411†	0.150‡	−0.388*	0.031	0.425‡
Northern								
Atbara	0.244§	–	0.136*	–	0.190§	–	0.107*	–
Dongola	0.084		0.245§	−0.358*	0.165‡		−0.161†	
Coastal								
Port Sudan	0.178†		0.201§		0.187§		−0.026	0.454‡

Significance level: * $0.01 \le \alpha \le 0.05$, † $0.005 < \alpha \le 0.009$, ‡ $0.001 < \alpha \le 0.005$, § $\alpha \le 0.001$

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- Significant rising trends of MIN can be seen over the area extending from the latitude of Nyala and northward.
- The MEAN indicates that this area is also marked by significant gain of heat by the air, but additional locations in the south (Wau and Juba) also reveal such behaviour.
- Malakal and Ed Damazin show a lack of significant trends for this season and even have increasing MIN trends of smaller magnitudes than those experienced during the dry season.

According to the nature of these changes, the DTR changes varied over the stations between both increasing and decreasing trends. Despite the almost equal number of stations possessing positive and negative DTR trends, there are six stations with significant decreases in DTR of up to −0.389°C decade^{-1} (Kassala) in comparison to a single station (Atbara) displaying a significant increase in DTR of 0.107°C decade^{-1}. It should be noted that no significant trend exists in DTR for the southern and the coastal regions.

By taking a closer look at the relationships between the temperature variables and sunshine for this season (Table 3), interesting features emerge. Only one station (El Obeid) shows a significant correlation (positive) between the MAX and sunshine. The DTR contributed the most, followed by the MIN, while the MEAN contributed the least to the significance of the relationship. The correlation indicates inverse (positive) association between MIN and MEAN (DTR) and sunshine. High sunshine (clear sky) in this season means very high temperatures during the day and very likely increases the chances for dust storms, especially during nighttime. The amount of solar radiation received at the surface thus reduces and in turn lowers the nighttime temperatures.

Wet Season

Over the common period of study, the MAX and MEAN in the central and northern regions have very similar spatial pattern in terms of the direction and significance of trend (Table 4). All of the positive trends are significant, prevailing over 86% of the locations. The rest of the stations, namely Ed Damazin and Port Sudan, indicate insignificant negative trends. Significant increase of the MIN is common in central Sudan, except Ed Damazin, and in the northern region, but not in the south where significant warming affects only the southernmost station of Juba. Further evidence to support the warming of the wet season can be provided by comparing Tables 3 and 4. These results clearly emphasize that a warmer climate exists during the wet season compared to the hot season, particularly with regard to the MAX and the MEAN. Spatially, about 79 and

Table 4 Trend rates of temperature variables by linear regression in °C decade^{-1} and significant Spearman correlation statistic (R_s) of temperature variables versus sunshine for the wet season

Station/region	MAX		MIN		MEAN		DTR	
	Rate	R_s	Rate	R_s	Rate	R_s	Rate	R_s
Southern								
Juba	$0.179^{\S}$	$0.472^{\dagger}$	$0.116^{\S}$		$0.147^{\S}$		0.063*	$0.719^{\S}$
Wau	$0.205^{\S}$		0.026		$0.117^{\S}$	−0.353*	−0.084	
Malakal	$0.222^{\S}$	−0.336*	0.016		$0.119^{\S}$	0.435*	$0.206^{\S}$	
Central								
Ed Damazin	−0.069	0.416*	0.027		−0.023		−0.092*	
Nyala	$0.227^{\S}$	–	$0.451^{\S}$	–	$0.340^{\S}$	–	$-0.222^{\S}$	–
El Obeid	$0.238^{\S}$		0.118*		$0.182^{\S}$		0.120*	
El Fasher	$0.269^{\S}$		$0.334^{\S}$		$0.301^{\S}$		−0.068	
El Gedaref	$0.281^{\S}$		$0.179^{\S}$		$0.228^{\S}$		0.102*	0.356*
Wad Medani	$0.238^{\S}$		$0.150^{\S}$		$0.191^{\S}$		0.088*	$0.419^{\ddagger}$
Kassala	0.150*	$0.417^{\dagger}$	$0.285^{\S}$		$0.217^{\S}$		$-0.139^{\ddagger}$	$0.618^{\S}$
Shambat	$0.236^{\S}$		$0.117^{\S}$	$-0.464^{\ddagger}$	$0.246^{\S}$	−0.370*	−0.013	0.310*
Northern								
Atbara	$0.336^{\S}$	–	$0.130^{\dagger}$	–	$0.233^{\S}$	–	$0.206^{\S}$	–
Dongola	$0.216^{\S}$		$0.284^{\S}$	$-0.766^{\S}$	$0.250^{\S}$	$-0.612^{\S}$	−0.068	$0.592^{\S}$
Coastal								
Port Sudan	−0.009		−0.047		−0.027		0.035	0.293*

Significance level: * $0.01 \leq \alpha \leq 0.05$, † $0.005 < \alpha \leq 0.009$, ‡ $0.001 < \alpha \leq 0.005$, § $\alpha \leq 0.001$

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57% of the inland stations display more warmth, respectively. All maximum rates of upward trends in MAX (0.336°C decade^{-1} recorded for Atbara), MIN (0.451°C decade^{-1} recorded for Nyala) and MEAN (0.340°C decade^{-1} recorded also for Nyala) are slightly higher than the maximum rates registered for the hot season. These findings are in line with the views presented earlier (Elagib and Mansell 2000a) that "the period of greater warmth in Sudan appears to coincide with that of rainfall depletion reported post mid-1960s". Recently, Elagib (2009) also noted for the period 1941–2005 over central Sudan that "The region has become generally drier at significant rates in the areas designated with hyper-arid and arid climates. Conditions of extreme drought have become recurrent and widespread during the recent 35 years". Moreover, a closer look into the results obtained for the wet and hot season points out the increased number of stations having warming rates of MAX greater than MIN for the former season. During the wet season, the MIN rose by a rate almost twice that for the MAX, as in the case of Nyala. On the other hand, the warming rate of the MAX over that of the MIN for individual stations was as great as 13.58 times, as in the case of Malakal. Elsewhere, higher MAX also occurred in years of reduced rainfall (Lough 1995). Given that the inland stations receive summer rainfalls, and in view of the dry conditions afflicting Sudan as mentioned before, the current results of faster warming rates exhibited by the MAX over the MIN are in total agreement with those presented by Durre and Wallace (2000) for the USA. They found that the summer time MAX and hot days tend to get hotter as the soil gets dry. This is explained by the fact that less rainfall results in depletion of the soil moisture. With enhanced radiation receipt, the release of sensible heat fluxes at the surface in lieu of latent heat of vaporization limits the evaporative cooling agent.

At a glance, the results for Ed Damazin (MAX and MEAN) and Port Sudan (MAX, MIN and MEAN) indicate downward trends, though insignificant. Such trends could be a result of the location of the two stations. The first is located where Er Rosieres Dam is constructed, while the other is a coastal station. The construction of a very large reservoir has a measurable influence on the immediate vicinity (lake effect), including reduction in temperature extremes, an increase in humidity and small-scale circulations of the land- and lake-breeze type (Landsberg 1970). The influence of the sea moderates the MAX reached in both the summer and the winter (Lough 1995), given that rain falls in Port Sudan during the cold part of the year. Price et al. (1999), citing some literature for eastern Mediterranean, found similar trends for MAX and MIN. He suggested that a decrease in cloudiness in the winter months in arid regions could result in the increase of radiative day and night cooling.

Although the consequence of the observed MAX and MIN trends during the wet season was a geographically balanced distribution of both increasing and decreasing trends in DTR, the statistical significance is displayed by 86% of the upward trends compared to only 43% of the downward trends. The steepest decline of DTR was observed for Nyala at −0.222°C decade^{-1}, whereas the sharpest rise was indicated for Malakal and Atbara as 0.206°C decade^{-1}.

In terms of magnitude and significance of the correlation statistic, there are large geographical variations in the relationship between temperature variables and sunshine (Table 4). Spearman correlation statistics even show cases of different signs for the same temperature variable (see MAX and MEAN). In spite of these contrasts, the significant relationships indicate: (1) a dominant direct association between DTR and sunshine and (2) that, spatially, the weakest association is observed for the MIN versus sunshine.

Annual

Table 5 shows the linear trends of the four temperature parameters together with their significant association with sunshine based on Spearman rank correlation tests. The annual trends seem to correspond closely with the trends for the wet and hot seasons, particularly those related to the inland stations. Those for the coastal station of Port Sudan appear to vary more closely with the hot- and dry-season trends. There are both upward and downward trends in DTR, but the large number of stations having significant trends relate to the latter group. The largest drop in DTR occurred in Kassala (−0.301°C decade^{-1}) whilst the strongest rise in DTR (0.130°C decade^{-1}) happened at Malakal. Among the group of stations possessing significant falling trends in DTR is Ed Damazin in the southeast of the central region and Dongola in the northern region with a slight heat loss and a marked heat gain by the air during the daytime and nighttime, respectively.

The daytime temperature increased over the period of study at a greater rate than the nighttime temperature across the southern region and in the coastal station of Port Sudan, Atbara in the north and El Gedaref in the east. This rate is largest in Malakal (fivefold) and second largest in Atbara (nearly three-fold). Among the stations, which are marked with a larger increase in MIN relative to MAX, Kassala in the east experienced an increase in its MIN temperatures nearly eight times that in the MAX. Next come Nyala and El Fasher in the west with trend rates for their MIN time series more than four times those for the MAX series. The warmest rate of MIN was observed for Nyala as 0.369°C decade^{-1} which corresponds to a strongest warming rate of 0.241°C decade^{-1} in the MAX,

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Table 5 Trend rates of temperature variables by linear regression in °C decade^{-1} and significant Spearman correlation statistic (R_s) of temperature variables versus sunshine for the year

Station/Region	MAX		MIN		MEAN		DTR	
	Rate	R_s	Rate	R_s	Rate	R_s	Rate	R_s
Southern								
Juba	$0.121^{\S}$		$0.101^{\ddagger}$		$0.111^{\S}$		0.021	$0.592^{\S}$
Wau	$0.153^{\S}$	$-0.459^{\dagger}$	$0.085^{\ddagger}$	−0.373*	$0.122^{\S}$	$-0.554^{\ddagger}$	$0.096^{\S}$	
Malakal	$0.163^{\S}$		0.033		$0.098^{\S}$		$0.130^{\S}$	
Central								
Ed Damazin	−0.035		0.064		0.016		$-0.108^{\dagger}$	
Nyala	0.086*	–	$0.369^{\S}$	–	$0.219^{\S}$	–	$-0.286^{\S}$	–
El Obeid	0.075*		$0.141^{\ddagger}$		$0.107^{\ddagger}$		−0.066	
El Fasher	0.074*		$0.307^{\S}$		$0.195^{\S}$		$-0.231^{\S}$	
El Gedaref	$0.241^{\S}$		$0.189^{\S}$		$0.210^{\S}$		0.054	−0.409*
Wad Medani	$0.120^{\S}$		$0.192^{\S}$		$0.155^{\S}$		−0.072*	
Kassala	0.044	0.382*	$0.346^{\S}$		$0.196^{\S}$		$-0.301^{\S}$	$0.620^{\S}$
Shambat	$0.119^{\dagger}$		$0.253^{\S}$	$-0.392^{\dagger}$	$0.120^{\S}$	−0.305*	0.003	0.344*
Northern								
Atbara	$0.188^{\S}$	–	0.069*	–	$0.128^{\S}$	–	$0.118^{\S}$	
Dongola	−0.008		$0.175^{\dagger}$		0.083		$-0.182^{\S}$	–
Coastal								
Port Sudan	0.095*		0.071*		$0.086^{\ddagger}$		0.021	0.356*

Significance level: * $0.01 \le \alpha \le 0.05$ † $0.005 < \alpha \le 0.009$ ‡ $0.001 < \alpha \le 0.005$ § $\alpha \le 0.001$

registered for El Gedaref. On the basis of MEAN data, the country experienced changes of up to 0.219°C decade^{-1}.

The temperature-sunshine relationship shows very weak spatial patterns (Table 5), especially in terms of MAX, MIN and MEAN, where only two stations indicate statistical significance in each case. The MAX shows even conflicting signs. In terms of DTR, the relationship is overwhelmingly positive, characterizing the extreme southern station and the northern half of the country, including the coastal region. El Gedaref in the east-central Sudan has negative DTR-sunshine relationship.

SUMMARY AND CONCLUSIONS

This work provides a clear picture of the temperature variability and trends across Sudan. The principal findings of this investigation are:

(1) Since the detailed study conducted by Elagib and Mansell (2000a) on MEAN records, the climate in Sudan has become even warmer in most of the locations considered, especially during the dry-season nights, hot season and wet season. Consequently, the overall annual temperatures have increased.

(2) Significant warming trends of the MAX of up to 0.325 and 0.336°C decade^{-1} occurred during the hot and wet seasons, respectively. On the other hand, the MIN trends had warming rates of 0.357, 0.424 and 0.451°C decade^{-1}, respectively, for the dry, hot and wet seasons.

(3) MAX temperatures show cooling tendencies of the air for the dry season of up to −0.166°C decade^{-1}, possibly connected with the rise of dust haze/storm activities.

(4) The trends of the hot and wet seasons are more similar to the annual ones than the trends of the dry season, especially for the inland locations. In the coastal region, the annual time series is a reflection of the hot- and dry-season series.

(5) In particular, the daytime and nighttime warming observed for the hot and wet seasons as well as for the year has not been consistent, neither spatially nor temporally. The greater warmth sometimes took place during the day and sometimes during night, leading to the observed positive and negative trends in DTR.

(6) There has been more heating of the air as reflected by the MAX and MEAN during the wet season over that occurring during the hot season, thus suggesting a real warming of the wet season due to the dry conditions

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that have been afflicting the country during the recent decades. This maybe due to enhanced radiative heat gain at the surface during this period.

(7) Regionally, the extreme eastern and western parts of the central region were more frequently affected by the greatest warming over the country. These are followed by the northern part, particularly Atbara area.

(8) Very complex changes have been witnessed for the DTR time series over the country and within the year. It is possible to discern both decreases and increases even for the same location for the different seasons. However, by looking into the significant changes, the reduction in DTR becomes more discernible in the time series for the dry and hot seasons as well as the year, while the marked increase is noticeable for the wet season. More precisely, the significant negative trends dominated the central regions and Dongola area, while the significant positive ones were detected among the southern, central and northern regions in terms of wet-season time series but over the southern and Atbara area on annual basis. No significant trends were identified for the coastal region. Thus, the significant narrowing of DTR occurred at rates of up to −0.435°C decade^{-1} (dry season), −0.389°C decade^{-1} (hot season), −0.222°C decade^{-1} (wet season) and −0.301°C decade^{-1} (annual). On the other hand, significant widening of the DTR was: (1) absent in the dry season, (2) indicated by only a single station (Atbara in the north) with a rate of 0.107°C decade^{-1} in the hot season, (3) evident for the wet season by rates reaching 0.206°C decade^{-1} and (4) shown in the annual series at a rate of up to 0.130°C decade^{-1}.

(9) Evidence of changing temperature variability toward either increased or decreased intra-annual coefficients of variation has also been presented in this study. More than half of the stations under study showed statistically significant trends toward increased intra-annual variability in MAX and MEAN, while the significant results pertinent to MIN combine both negative and positive trends. The DTR series are overwhelmed by significant trends towards reduced intra-annual variability. It was generally found that the IAV is inversely correlated with lowest temperatures but directly correlated with highest temperatures of the four parameters.

(10) This study serves to highlight how different localities can demonstrate different results, thus emphasizing the need for more representative investigations on this issue at regional and local levels.

(11) There are several possible local causes of the observed changes in the MAXs and MINs and the associated DTR changes. These include urbanization, moisture availability, desertification, proximity to large water basins, extra-urban effects in the form of large-scale irrigation and lake effect of dam construction, etc., each of which needs to be delineated by further detailed investigation. If the observed cases of increased warming of MIN over MAX were considered as an indication of urbanization (Karl et al. 1993); then, the study would suggest that urban effects on temperature in Sudan is strongest in the hot season and weakest during the dry season. Some investigators are, however, convinced that the general increasing nighttime temperatures and decreasing DTR occurring in both rural and urban areas reflect a real warming that cannot simply be deciphered by the urban effect (Lough 1995; Lockwood 1998). Others have shown even increased DTR as a result of enhanced effect of urban heat island during the daytime over the nighttime (Al-Fahed et al. 1997; Elagib and Abdu 2009). This study has also shown that climatic effects such as sunshine can be partly responsible for the observed changes in DTR, although somewhat inconsistent and/or weakness reveals in the relationships between sunshine and the other temperature variables. The wet-season trends in particular reinforce the views that rainfall has a principal effect on temperature regimes in Sudan. The major large-scale systems, especially El Niño Southern Oscillation (ENSO), were also found to influence the patterns of MAX/MIN temperature variability in East Africa (King'uyu et al. 2000).

(12) Climate variability poses threats to food production and water supply, leading to serious social and economic implications. Evapotranspiration, soil moisture, plant growth and other ecological and agricultural factors are strongly influenced by daytime warming (Lockwood 1998), especially in a country like Sudan whose economy is agriculture-based. For Sudan, high positive correlation coefficients were found between rainfall parameters, such as total monthly and annual depths as well as annual number of rain-days, and national crop yields (Larsson 1996; Ayoub 1999).

(13) In conclusion, the present findings confirm many of the earlier results obtained for Africa (Elagib and Mansell 2000a; King'uyu et al. 2000; Conway et al. 2004; New et al. 2006; Aguilar et al. 2009; El Kenawy et al. 2009). Since Sudan embraces a large area extending over more than 2.5 million km^2, with climatic zones of hyper-arid to humid, these findings

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may contribute to compliment the understanding of the temperature variation across the continent of Africa.

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AUTHOR BIOGRAPHY

Nadir Ahmed Elagib (✉) is an Assistant Professor in engineering hydrology and hydrometeorology at the Department of Water Resources Engineering. He holds a PhD from Paisley University (currently University of the West of Scotland), UK. His current research works include contemporary hydrological/climatic change and variability, urban effects on the climate, inter-comparison of evaporation and evapotranspiration methods in Sudan and the Arabian Gulf.

Address: College of Water and Environmental Engineering, Sudan University of Science and Technology, P.O. Box 352, 13311 Khartoum North, Sudan.

e-mail: elagib@hotmail.com

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