MAY 8, 2020

BUILDING RESILIENCE IN THE FACE OF CLIMATE CHANGE WITHIN TRADITIONAL RAIN-FED AGRICULTURAL AND PASTORAL SYSTEMS IN SUDAN

ANALYSIS OF TRENDS IN AVAILABLE WEATHER STATION DATA AND CRU TS 4.02 DATASETS

Additional Information on changes in observed climate and implications for crop production

Introduction and data sources

This annex provides a summary of an analysis of observed climate-related trends for key climate indices related to extremes in rainfall, temperature and potential evapotranspiration (ET_0). These analyses were undertaken at locations for which weather station data were available and which span the range of locations where project interventions are targeted. The available data from weather stations is sparse, contains periods of missing data, is highly variable (as expected for a mostly arid and semi-arid region), and is only available for the recent 1990-2019 period (30 years). Importantly from a trends perspective, this period does not include the well-established drought periods which affected much of the Sahelian zone during the 1970s and 1980s. Therefore, to provide a longer-term context from which to understand potential multi-decadal variability in the region we use gridded data (0.5°) for the 1950-2018 period (69 years) from the Climate Research Unit (CRU TS 4.03)[1] of the University of East Anglia, UK.

Figure 1: Map of Sudan showing target states(Marked red-target localities in each state)

Figure 1 shows the map of Sudan with the target states for project activities as well as the locations of target sites within each state. Table 1 below further shows the corresponding weather stations used in the analysis below for each target state.

Table 1: List of weather stations corresponding to each target state with project activities.

[1] https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.02/

Weather Station	Target State
El Geneina	West Darfur-Central Darfur-East Darfur
EL Nuhod	West Kordofan
Kadogli	South Kordofan
Port Sudan	Red Sea
Khartoum	Khartoum
Kassala	Kassala
Dongola	Northern State

Daily observations of rainfall, minimum and maximum temperatures were obtained for each of the weather stations for the 1990-2019 period. Whilst these weather stations represent each of the corresponding states, the CRU TS 4.03 data is available for locations covering the target sites of the project and so was extracted for the data points covering the project sites given in Table 2 (the location of most villages in each state was taken as the target location). The CRU data only provides monthly data and so cannot be used to calculate trends in extremes using the ClimPact software (see below), but was used to compare with trends of total rainfall, mean temperatures and ET_0.

Table 2: Locations of project sites.

Region	State		Locality		Villages	Location	
	#	Name	#	Name		Longitude	Latitude
Darfur States	1	West Darfur State	1	Genana	4	22° 32′ E to 22° 5′ E	12° 47′ N to 13° 57′ N
			2	Krenik	1	22° 32′ E to 23° 16′ E	13° 38′ N to 13° 10′ N
				Subtotal	*5*		
	2	Central Darfur State	3	Zalingi	9	23° 30′ E to 23° 45′E	12° 30′ N to 13° 30′N
			4	Azoom	4	23° E to 22°30′ E	12° 30′ N to 14° 30′ N
				Subtotal	*13*		
	3	East Darfur State	5	ELdain	3	26° 15′ E to 26° 40′ E	11° 46′ N to 12° 18′ N
			6	Firdous	2	25° 46′ E to 26° 8′ E	11° 10′ N to 11° 45′ N
			7	Asalia	5	25° 80′ E to 26° 15′E	11° 30′ E to 11° 30′ E
				Subtotal	*10*		
	Region total						
Kordofan States	4	West Kordofan State	8	Asalam	9	27° 42′ E to 29° 01′ E	10° 50′ N to 12° 30′ N
			9	Al Nohoud	9	27° 56′ E to 28° 52′ E	12° 20′ N to 14° 07′ N
			10	Alsunut	10	28° 42′ E to 29° 35′ E	11° 28′ N to 12° 27′ N
				Subtotal	*28*		
	5	South Kordofan State	11	El Goz	12	29° 29′ E to 30° 34′ E	12° 06′ N to 12° 45′ N
			12	Dilling	12	29° 12′ E to 29° 58′ E	11° 39′ N to 12° 11′ N
				Subtotal	*24*		
	Region total						
Eastern States	6	Kassala State	13	Kassala	6	36° 11′ E to 36° 48′ E	15° 20′N to 15° 81′N
			14	Telkuk	5	36° 99′ E to 36° 18′ E	15° 71′N to 16° 95′N
			15	Rural Nhr Atbra	5	34° 36′ E to 35° 35′ E	15° 40′N to 16° 72′N
				Subtotal	*16*		

	7	Red Sea State	16	Agig	6	37° 45′ E to 38° 45′ E	17° 22′ to 18° 32′ N
			17	Dordaib/Haya	3	35° 0′ E to 36° 45′ E	17° to 18° 3′ N
			18	Guneb Olib	6	35° E to 37°15′ E	18° 58′ to 20° 40′ N
				Subtotal	*15*		
	Region total						
Nile States	8	Northern State	18	Dongala	7	27° 36′ E to 31° 15′ E	19° N to 19° 30′N
			20	Marawi	7	31° E to 32° 48′ E	16° 35′N to 18° 45′N
			21	AlDabaha	4	27° 36′ E to 31° E	18° 15′N to 18° 40′N
				Subtotal	*18*		
	9	Khartoum State	22	Rural Umdorman	5	31° 35′ E to 32° 30′ E	15° 45′N to 16° 35′N
			23	Rural Sharg ElNil	4	32° 30′ E to 34° 30′ E	15° 30′N to 15° 45′N
				Subtotal	*9*		

Changes in observed climate

The main climate factors affecting crops in Sudan are:

- Rainfall extreme variability (onset, duration, cessation and intensity);
- Unpredictable periods of droughts;
- Changes in temperature, high rates of ET_0 and consequent high evaporative losses of soil moisture;
- Short growing season;
- Ecological and natural resources degradation.

The seven weather stations representing different regions of Sudan (Table 1) were analysed for trends in climate extremes using the Climpact2 software[2]. Daily data for rainfall, minimum and maximum temperature for each of the seven weather stations (Table 3 below) were analysed for the period 1990-2019 (30 years).

Table 3: Position (latitude, longitude and altitude) of the seven weather stations with available daily data 1990-2019.

Station	Longitude (decimal degrees)	Latitude (decimal degrees)	Altitude (m)
El Geneina	22.45	13.483	805
El Nuhod	28.433	12.7	564
Kadugli	29.717	11.0	499
Kassala	36.4	15.467	500
Port Sudan	37.233	19.433	138
Khartoum	32.549	15.6	380
Dongola	30.483	19.167	226

Trends in rainfall

Trends in total annual rainfall from the weather stations are mixed (Figure 2) with mostly negative trends during MAM and SON and mostly positive trends during JJA (main rainfall season). This leads to slightly

[2] https://climpact-sci.org/get-started/

positive trends on average during the whole year, but with declines indicated during the shoulder seasons which may have implications for the length of the rainfall season.

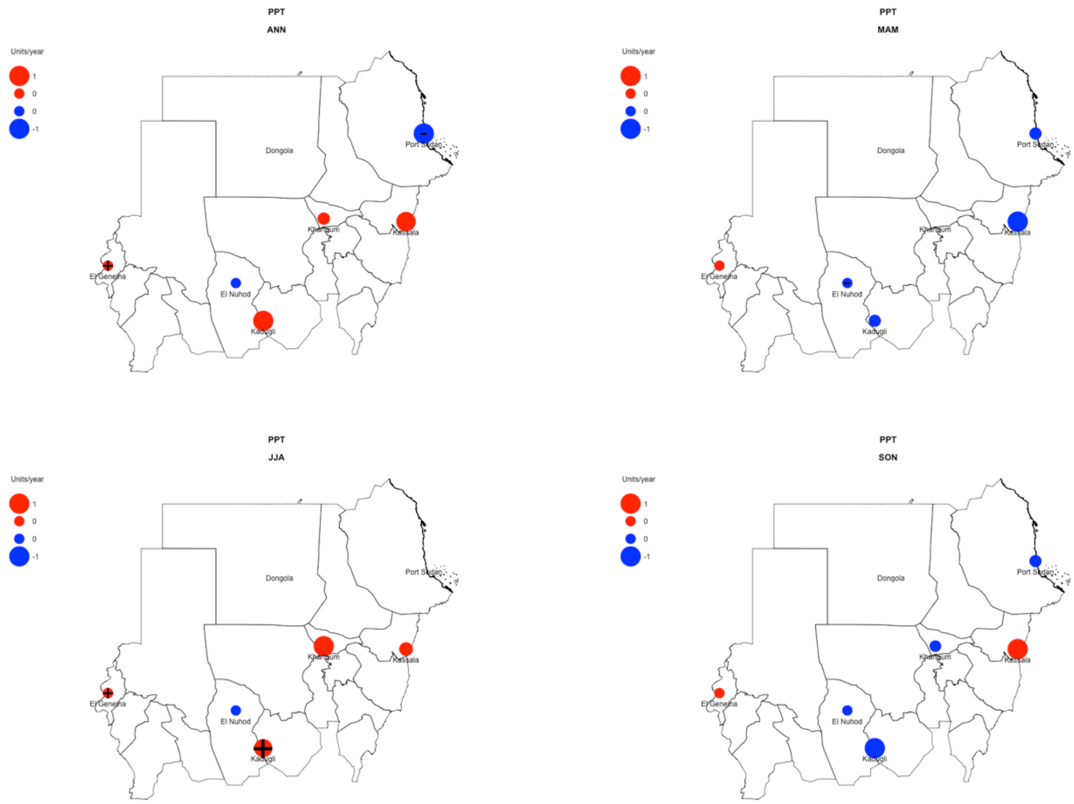


Figure 2: Trends in total rainfall for annual (ANN), March-May (MAM), June-August (JJA) and September-November (SON) – red +ve, blue -ve (zero trend not shown). Trends +ve/-ve at the 90% confidence level shown by +/-.

However, these trends over the 1990-2019 period are shown in the CRU data to be reversed or very close to zero, when considering the longer 1950-2018 period. Examples of these reversed trends in the CRU data are provided in Figure 3 for West Darfur (corresponding to the El Geneina station) and South Kordofan (corresponding to the Kadugli station). Trends for both total annual (ANN) and JJA rainfall are shown to be zero or negative, which is the opposite to trends indicated in Figure 2. Furthermore, the positive trends in Figure 2 can be seen to be a consequence of the low rainfall values in the 1980s which influences the trend calculations for the later period.

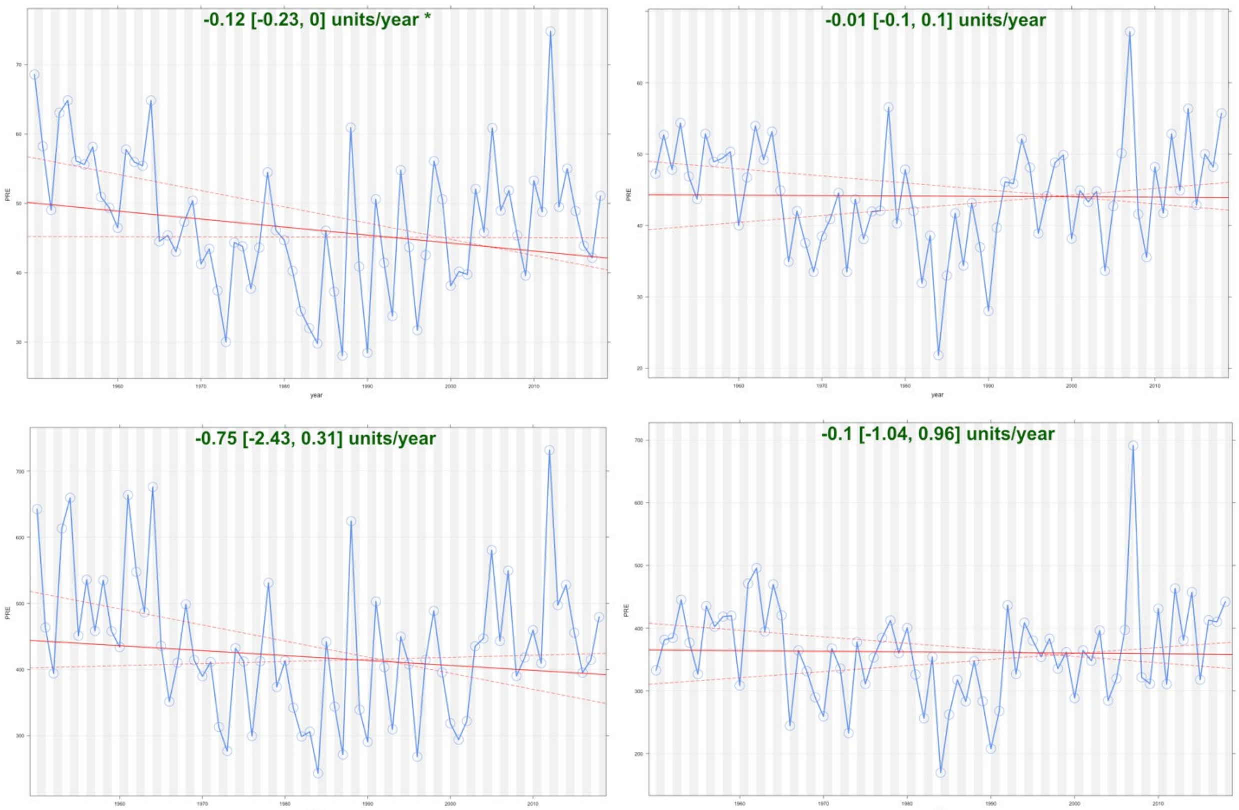


Figure 3: Trends in total annual rainfall (top) and June-August rainfall (bottom) for West Darfur (left) and South Kordofan (right). The 90% confidence interval of trends are shown by dashed red lines. Source CRU TS 4.03.

Trends in ET_0

Trends in ET_0 from the weather stations are shown in Figure 4 and are mostly positive during DJF but mostly negative during JJA, with more mixed trends during MAM and SON. This leads to similar patterns in rainfall-ET0 (P-ET0) as shown in Figure 6; trends are mostly negative during DJF and positive during JJA.

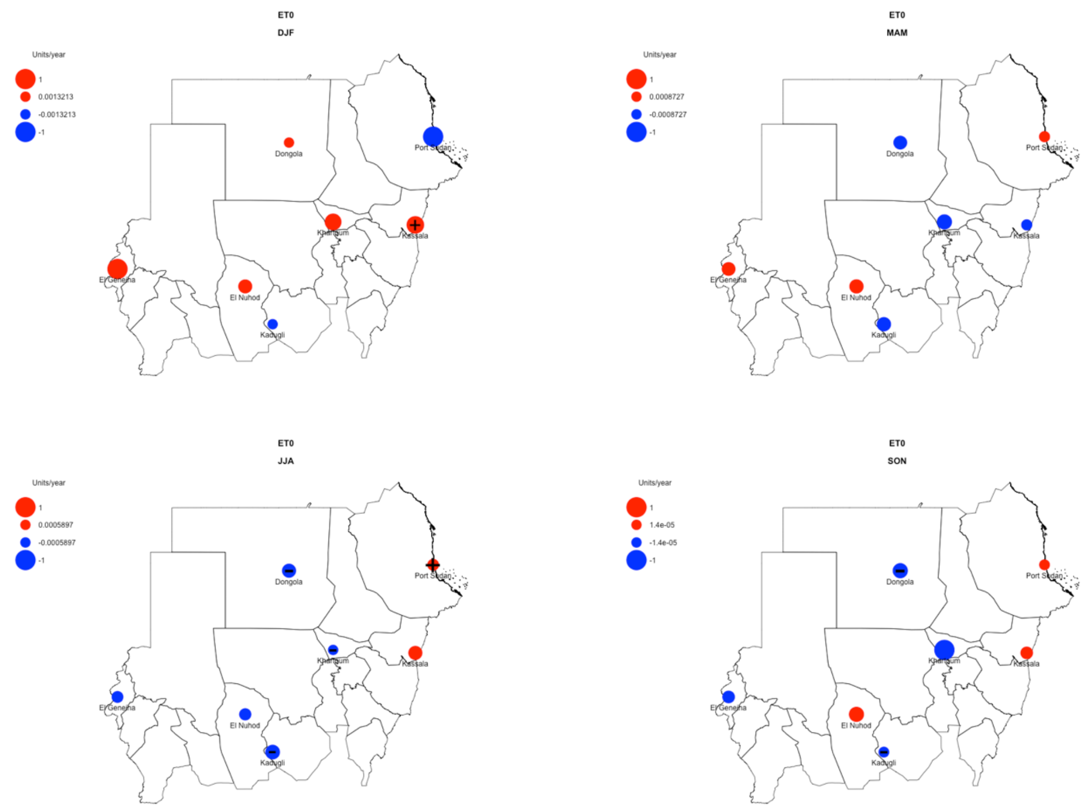


Figure 4: Trends in potential evapotranspiration (ET0) for annual (ANN), March-May (MAM), June-August (JJA) and September-November (SON) – red +ve, blue -ve (zero trend not shown). Trends +ve/-ve at the 90% confidence level shown by +/-.

As with rainfall, trends in ET_0 over the 1950-2018 period in CRU data show different and more clearly positive trends. Figure 5 illustrates this and shows annual ET_0 trends over site locations in West Darfur, East Darfur, Central Darfur, West Kordofan, Kassala, Red Sea, Northern, Khartoum and South Kordofan. All positive trends are statistically significant at the 99% confidence level or higher.

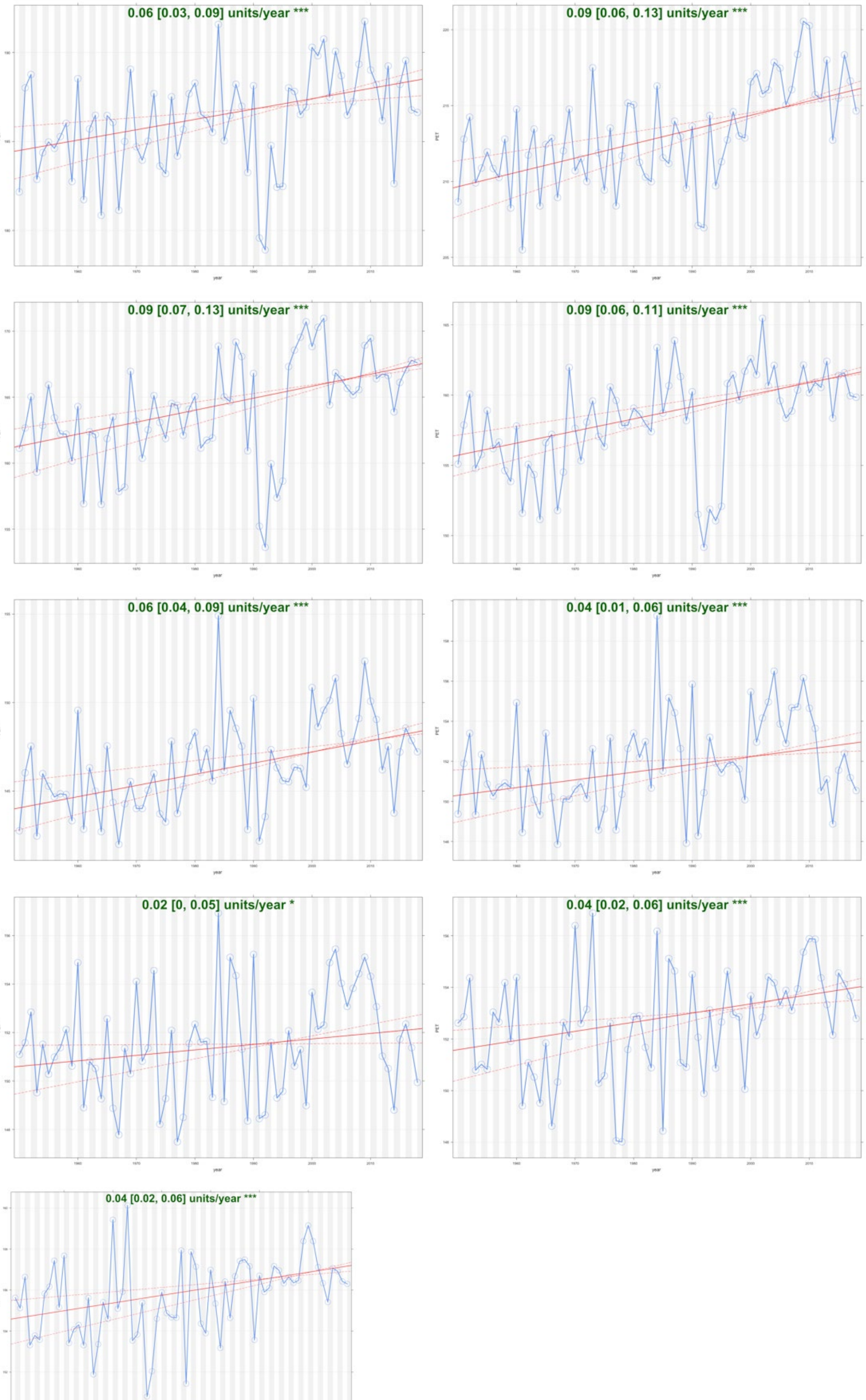


Figure 5: Trends in total annual ET_0 for site locations in West Darfur, East Darfur, Central Darfur, West Kordofan, Kassala, Red Sea, Northern, Khartoum and South Kordofan. The 90% confidence interval of trends are shown by dashed red lines. Source CRU TS 4.03.

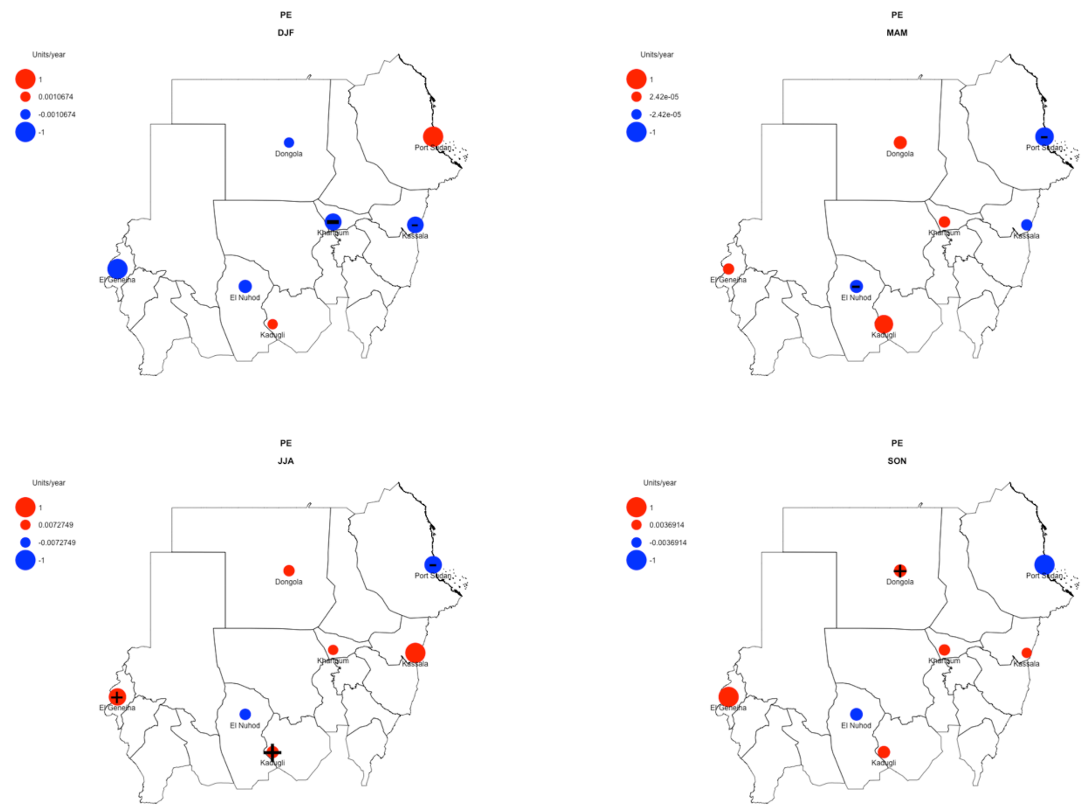


Figure 6: Trends in rainfall -potential evapotranspiration (P-ET0) for annual (ANN), March-May (MAM), June-August (JJA) and September-November (SON) – red +ve, blue -ve (zero trend not shown). Trends +ve/-ve at the 90% confidence level shown by +/-.

<u>*Trends in ET_0*</u>

Rainfall minus ET_0 ($P-ET_0$) is shown in Figure 6 as an index representing drought (available water for crops and vegetation once the evaporative demand has been included – assuming evapotranspiration takes place at the potential rate). Whilst Figure 6 shows that $P-ET_0$ trends in the weather station data since 1990 have been both positive (beneficial for crop growth) during JJA and negative (detrimental for crop growth) during DJF, these trends are likely dependent on the limited time period over which trends are calculated as shown in the figures above for rainfall and ET_0 separately. Figure 7 demonstrates that when trends over the longer 1950-2018 period are considered in the CRU data then annual $P-ET_0$ trends are for reductions over time in all locations (significantly so at 7 out of 9 locations). Similar trends (all negative) are seen for the individual seasons (not shown).

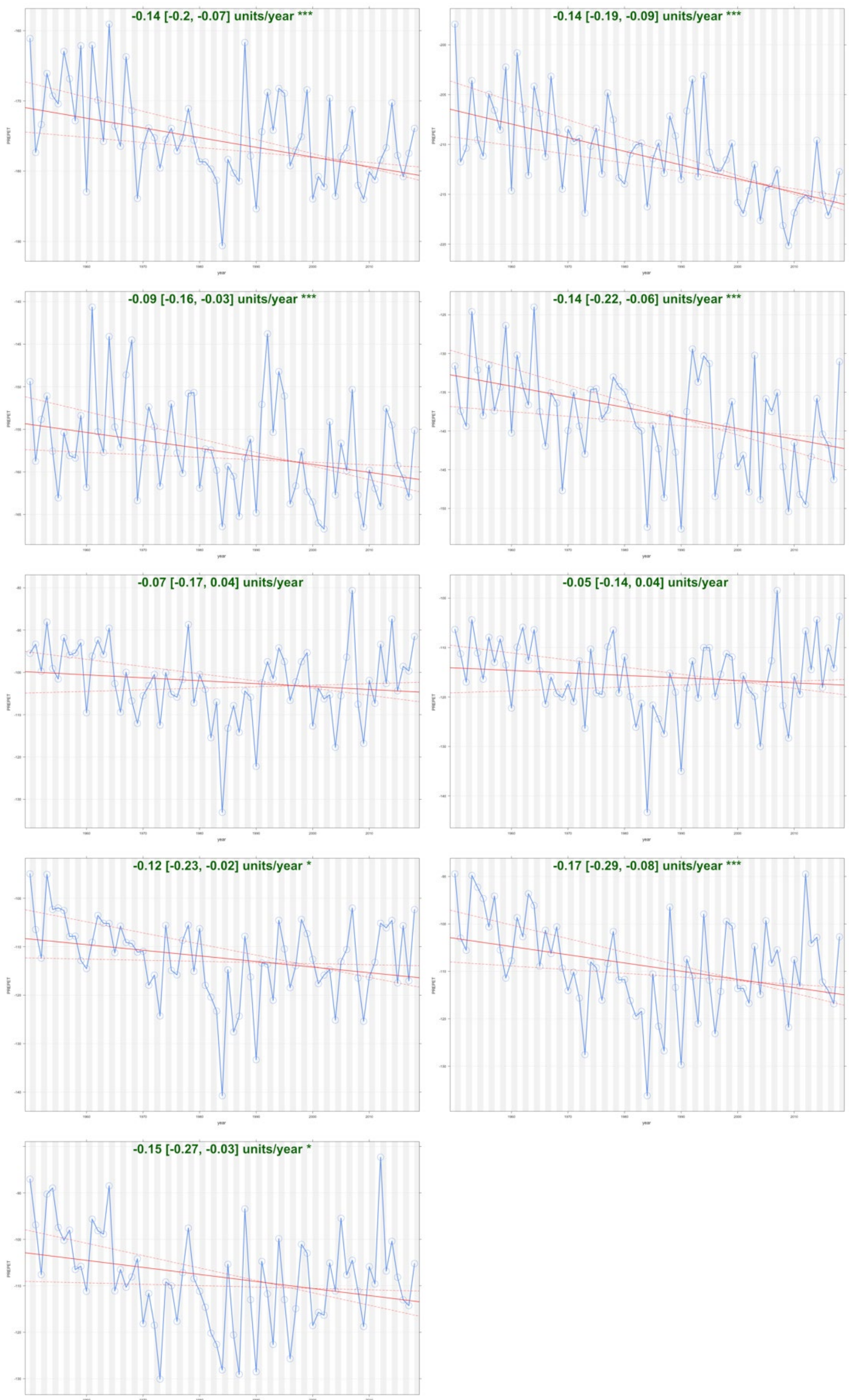


Figure 7: Trends in total annual P-ET$_0$ for site locations in West Darfur, East Darfur, Central Darfur, West Kordofan, Kassala, Red Sea, Northern, Khartoum and South Kordofan. The 90% confidence interval of trends are shown by dashed red lines. Source CRU TS 4.03.

Trends in extreme rainfall and temperature indices

To investigate the impacts of changes in rainfall and temperature characteristics, extreme indices (see examples in Table 4) were calculated for each year between 1990 and 2019 for each of the stations in Table 3 using Climpact software[3]. Trends were calculated for the period using standard linear regression routines using the R software. Most of the analysed trends were not statistically significant (at the 90% confidence level), indicated significant data gaps, and were highly variable. Many of the climate indices also measure aspects of climate that are either not relevant to Sudan or to impacts on agriculture. We therefore only present those indices that had statistically significant changes, were reasonably consistent in the sign of change (positive/negative) between stations and were likely to have an impact on agriculture. We also note that these trends are for the limited period since 1990 and do not include earlier periods, which the CRU data above have shown to significantly change the determined trend in total rainfall, ET_0 and P-ET_0.

Table 4: Sample of extreme climate indices analysed using Climpact*, 1990-2019*

№	Indices	Name	Definition	Unit
1	FD	Frost days	Annual count when daily minimum temperature < 0^{o}C	Days
2	SU	Summer days	Annual count when daily maximum > 25^{o}C	Days
3	GSL	Growing season length	Annual count between first span of at least 6 days with daily mean temperature >5ºC and first span after July 1 of 6 days with daily mean temperature TM<5ºC	Days
4	Txx	Maximum of daily maximum temperature	Monthly maximum of daily maximum temperature	^{o}C
5	Tnn	Minimum of daily minimum temperature	Monthly minimum of daily minimum temperature	^{o}C
6	WSDI	Warm spell duration index	Annual count of days with at least 6 consecutive days when daily maximum temperture >90th percentile	Days
7	CSDI	Cold spell duration index	Annual count of days with at least 6 consecutive days when daily minimum temperture <10th percentile	Days
8	RX1day	Maximum 1-day precipitation	Monthly maximum 1-day precipitation	mm
9	RX5day	Maximum 5-day precipitation	Monthly maximum 1-day precipitation	mm
10	CDD	Consecutive dry days	Maximum length of dry spell: maximum number of consecutive days with daily precipitation <1mm	Days
11	CWD	Consecutive wet days	Maximum length of wet spell: maximum number of consecutive days with daily precipitation P>1mm	Days
12	SPEI3/6/12	Standardised precipitation evapotranspiration Index	Measure of "drought" using the Standardised precipitation evapotranspiration Index on time scales of 3, 6 and 12 months	Dimensionless

Here we focus on the main climate indices that impact crop yields in Sudan: i) Maximum temperatures greater than 35 ºC (which cause damages to sorghum and millet during the growing period); ii) shortened rainfall seasons which do not allow crops to reach maturity and which are inversely proportional to the length of the dry season (CDD); and iii) drought indices (SPEI) which measure rainfall – evapotranspiration for 3 month and longer periods.

Maximum temperatures

[3] https://climpact-sci.org/

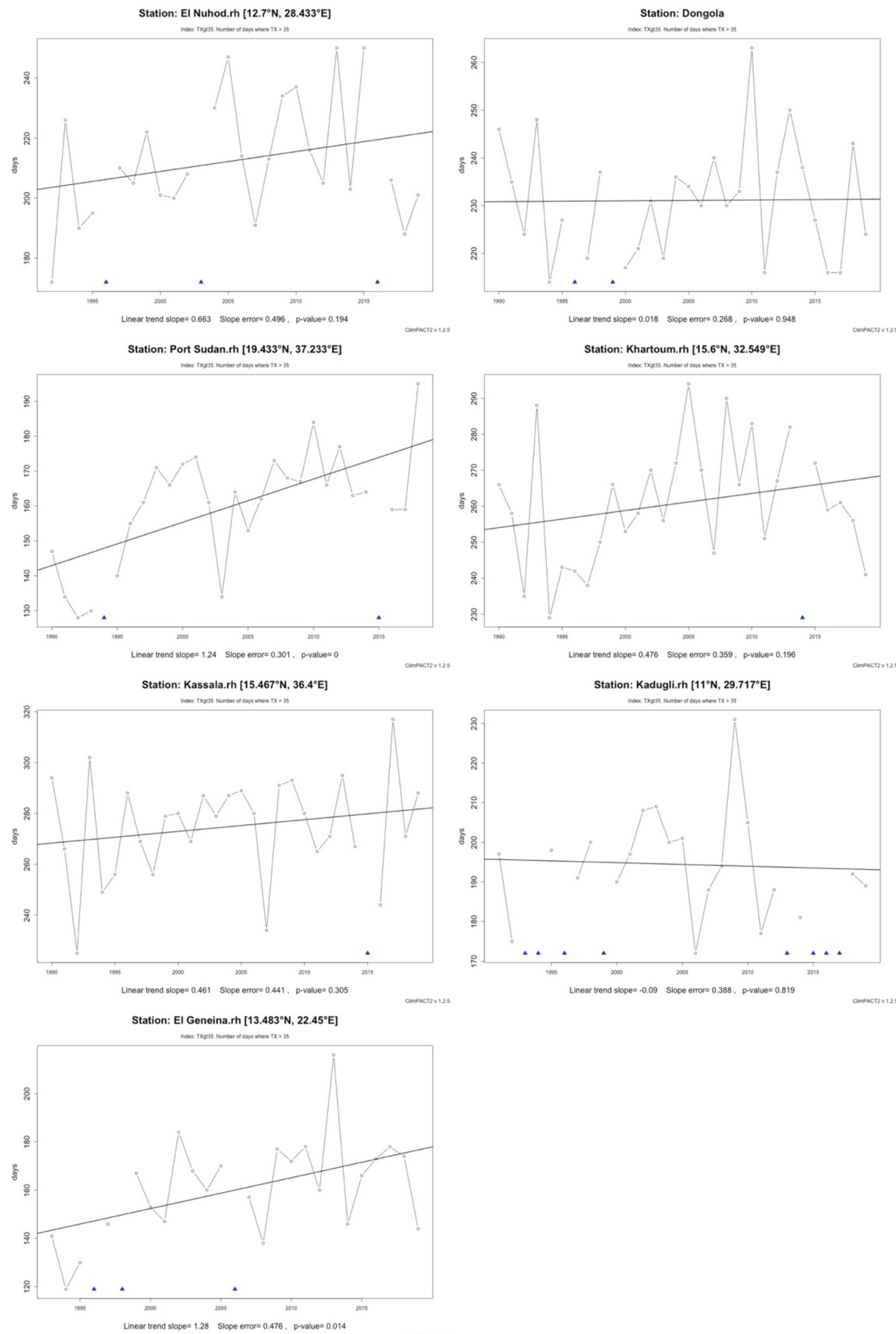
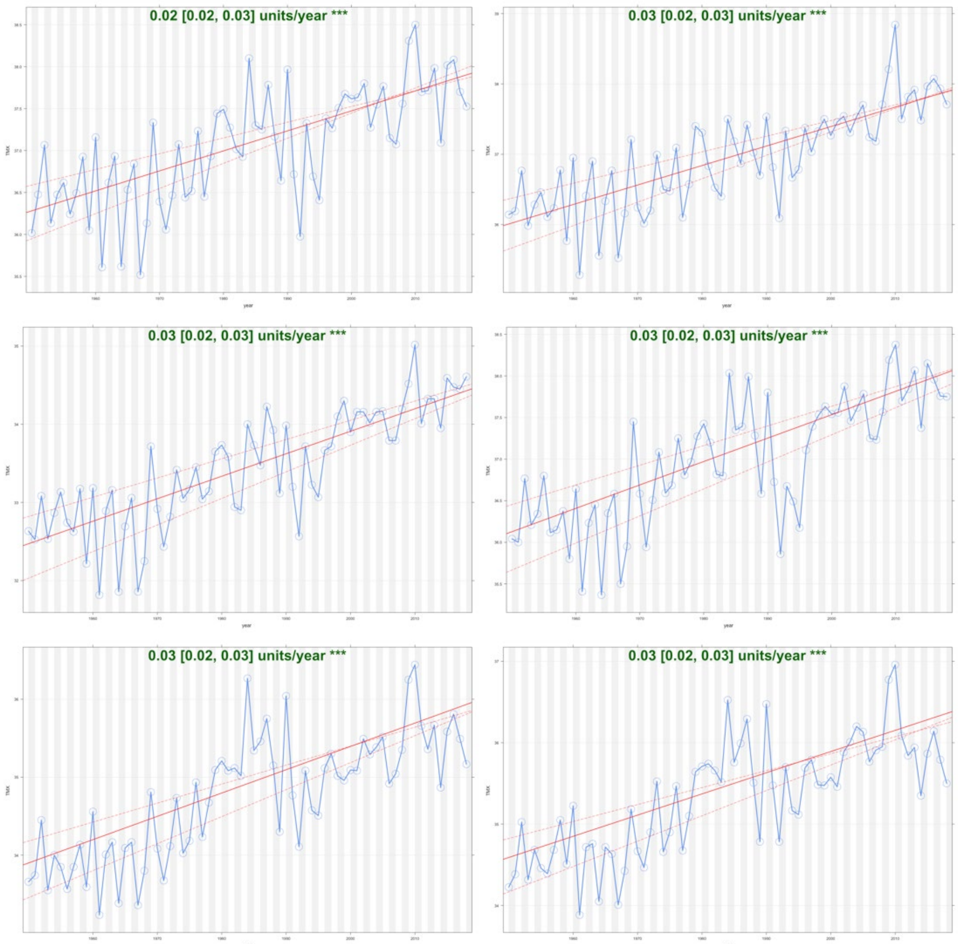


Figure 8: Trends in the number of days during the year when Tx > 35 C.

Figure 8 shows trends in number of days when maximum temperatures are greater than 35 ºC at all 7 weather stations. Trends have been positive i.e. increasing risks at all but 2 of the stations (Dongola and Kadugli. It can also be seen that many years are missing in the timeseries, especially at Kadugli. Figure 9 using the CRU data back to 1950 clearly demonstrates that maximum daily temperatures have been steadily increasing at each location (all statistically significant at the 99% confidence level or higher). It is therefore likely that those stations not showing increases are because they either have too many missing data or that the sampled timeseries does not extend far enough back in time to register the positive trends.



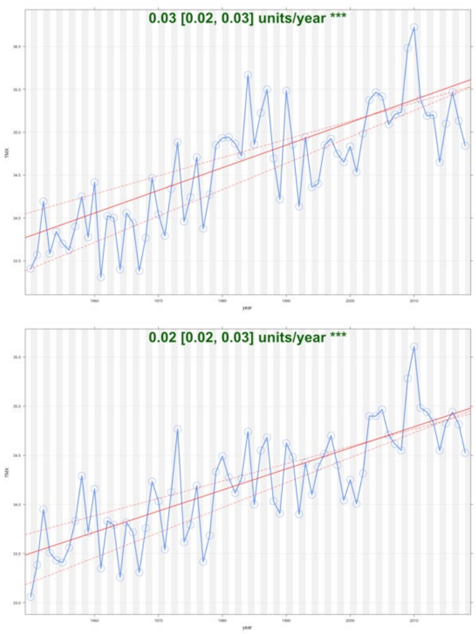
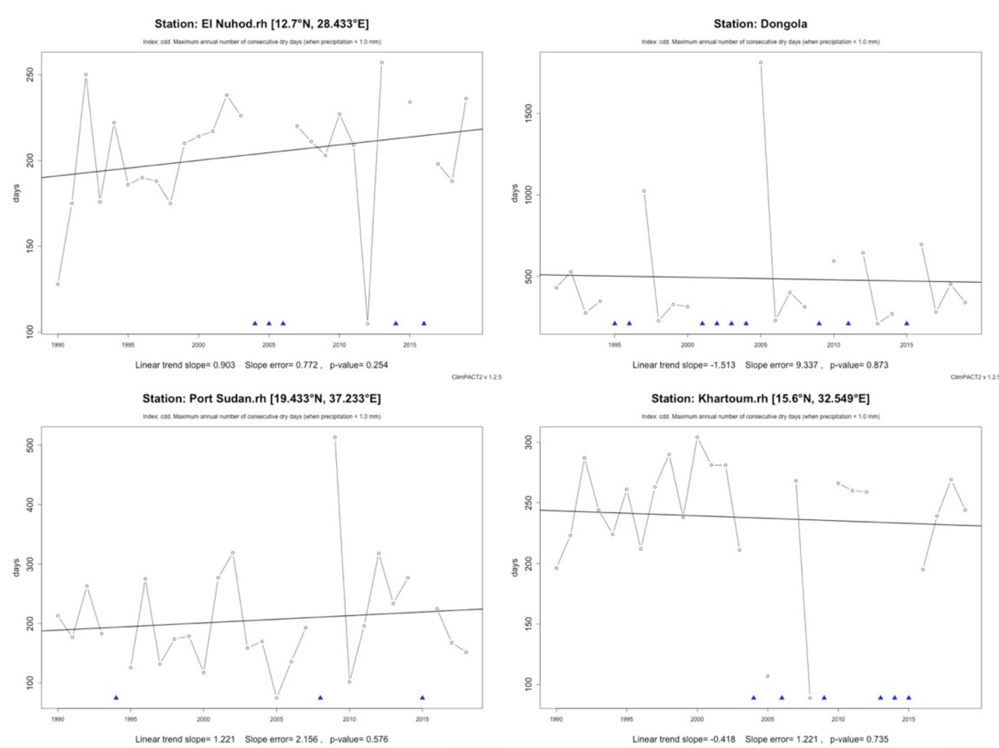


Figure 9: Trends in total annual average maximum daily temperatures for site locations in West Darfur, East Darfur, Central Darfur, West Kordofan, Kassala, Red Sea, Northern, Khartoum and South Kordofan. The 90% confidence interval of trends are shown by dashed red lines. Source CRU TS 4.03.

Consecutive dry days



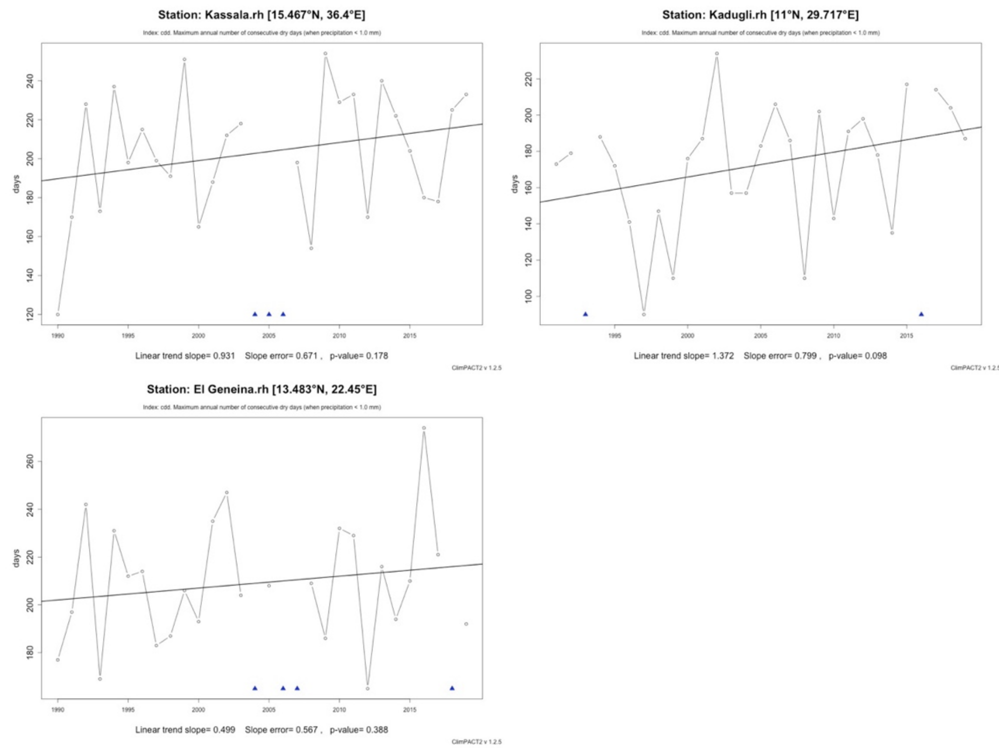


Figure 10: Trends in the maximum number of consecutive dry days (length of the dry season) at each weather station.

Figure 10 shows that the maximum number of consecutive dry days (length of the dry season) has been increasing at all stations except Khartoum. Note that Dongola is so dry that the values for CDD are more than a year in many cases, invalidating its use as a metric in this environment. This suggests that the dry season has been getting longer and consequently the wet season shorter in most locations. This hypothesis is also consistent with the reductions in rainfall during MAM and SON shown in Figure 2.

Standardised precipitation evapotranspiration index (SPEI)

Figure 11 shows that besides Khartoum which indicates no trend, half the stations indicate significant -ve trends in SPEI over 24 months. This is consistent with the seasonal differences in P-ET0 shown in Figure 6, but is likely not consistent with long term changes which are demonstrated in the CRU data in Figure 7. It is therefore likely that if SPEI were calculated for the 1950-2018 period it would show similar trends to those for P-ET_0 in Figure 7.

Overall impacts

Overall the most consistent trends (between stations) of aspects of climate affecting crops are for both shorter rainfall seasons and for more days with high daily maximum temperatures. Taking the longer term view as seen in the CRU data, there have also been trends for reductions in water balance (supply) with the atmosphere, which will place additional strain on supplying crops with sufficient water in already arid environments.

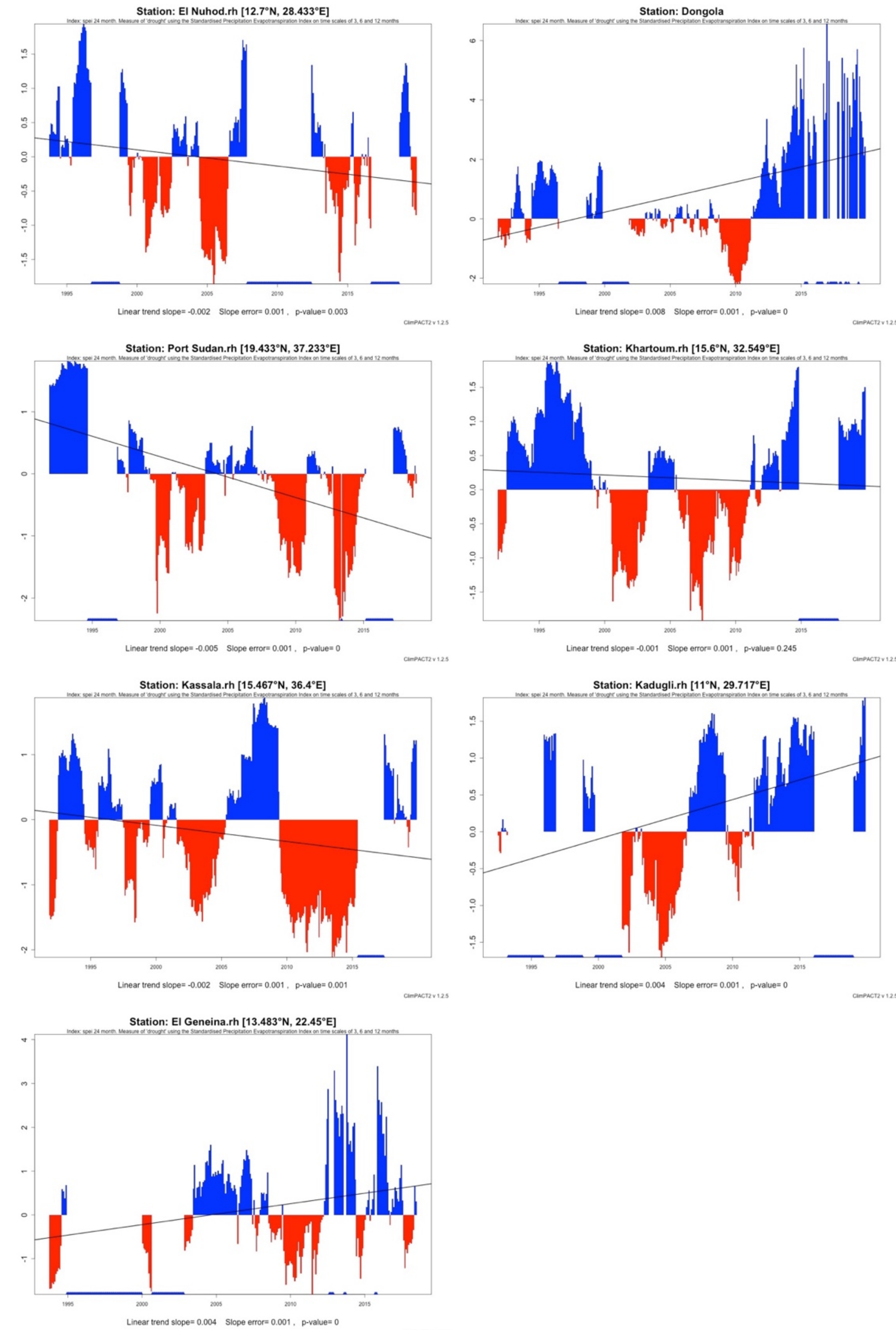


Figure 11: Trends in SPEI over 24 months at each weather station.

Climate impacts on crops

Grain sorghum (*Sorghum bicolor* L. Moench) is the main staple crop with high acreage in Sudan. It ranks first in terms of both area and volume of crop production and is sown all over Sudan in both the irrigated and the rain-fed sectors. Recent studies (2016) indicate a strong correlation between sorghum yields and climate parameters (see Table 5 below).

Table 5: Correlation between sorghum yield and climate parameters. Source: Hudo, N.A. (2016) assessing the impact of climate variability and change on sorghum yield over Gadaref area in Sudan, MSc, Thesis,2016

Parameters	Correlation coefficient	Relationship description
Sorghum yield and rainfall	0.59	Significant
Sorghum yield and maximum temperature	-0.34	Significant
Sorghum yield and minimum temperature	-0.31	Significant

Comparison of the average productivity (kg/ha) of the main crops in the target states with those of the international, regional, national traditional rain-fed sector and record yields are shown in Table 6.

Table 6: Average yields of main crops compared to world regions.

Region	Sorghum	Millet	Sesame	Groundnut
International	1570	790	405	959
Africa	871	619	362	762
World drylands	800	600	500	1299
Sudan traditional sector	690	380	186	543
North Kordofan	320	119	166	383
North Darfur	428	164	156	419
West Kordofan	459	280	179	547
West Darfur	800	583	286	869
South Kordofan	662	357	339	762
South Darfur	607	333	245	583
Central Darfur	621		275	753
East Darfur	530	366	-	628
Blue Nile	550	-	245	-
Kassala	428	-	238	-
Research (South Kordofan)	952	660	593	933
Records (International)	4003	1616	862	2899

Source: Osman A. K. and Mohamed ElFatih K. Ali.2010. Crop Production under Traditional Rain-Fed Agriculture. Proceedings of the National Symposium on: Sustainable Rain-Fed Agriculture in Sudan. Al-Sharga Hall, University of Khartoum, Khartoum, Sudan 17 –18 November 2009.Edited by Prof M A Mustafa. Published by: UNESCO Chair of Desertification Studies, University of Khartoum, January 2010. Updated by A K Osman.

Given the significant correlations between rainfall, maximum temperature and sorghum yields shown in Table 5 and the demonstrated declines in precipitation and increases in maximum daily temperatures shown in Figures 2, 3 and 9, it is not surprising that there have been significant declines in observed yields of both Sorghum and Millet between 1971 and 2001 (see Figure 12). In part this is due to the increases in temperature seen above as well as reductions in the length of the growing season, which is the duration between the onset and end of significant rains. In Sudan rain-fed sector, planting occurs on the date of onset of the effective rain (10mm and more), normally during the first week of July, with harvesting at the end of significant rains (about late September/early October). The length of the growing period also influences the selection of crop variety (short/medium/late maturing) and the reduction in the length of the growing period (implied from increases in consecutive dry days) also likely contributes to the observed declines in yields.

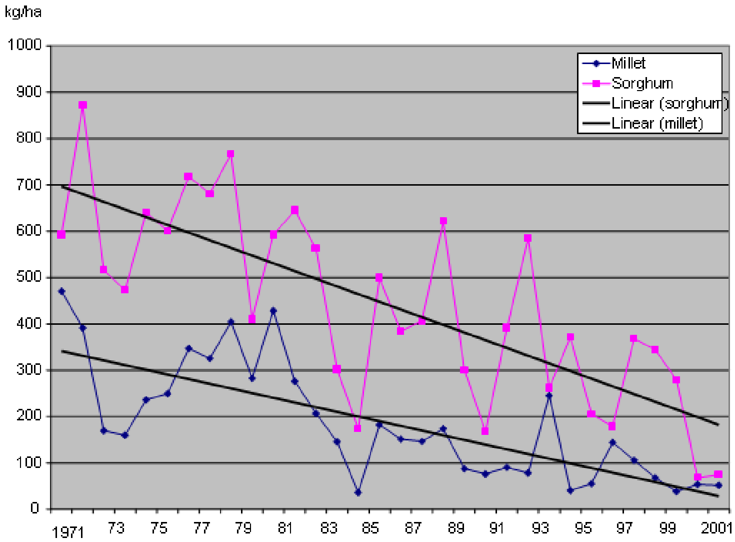


Figure 12: Trend of millet and sorghum productivity in the rain-fed sector in Sudan. Source :Ibrahim El-Dukheri et al 2011. Review of the Food Security and Natural Resource Situation in Sudan. DCG Report No.63.

These trends in yields are also consistent with further reductions in yields as a result of climate change, which are predicted to continue in the future (see Figure 13).

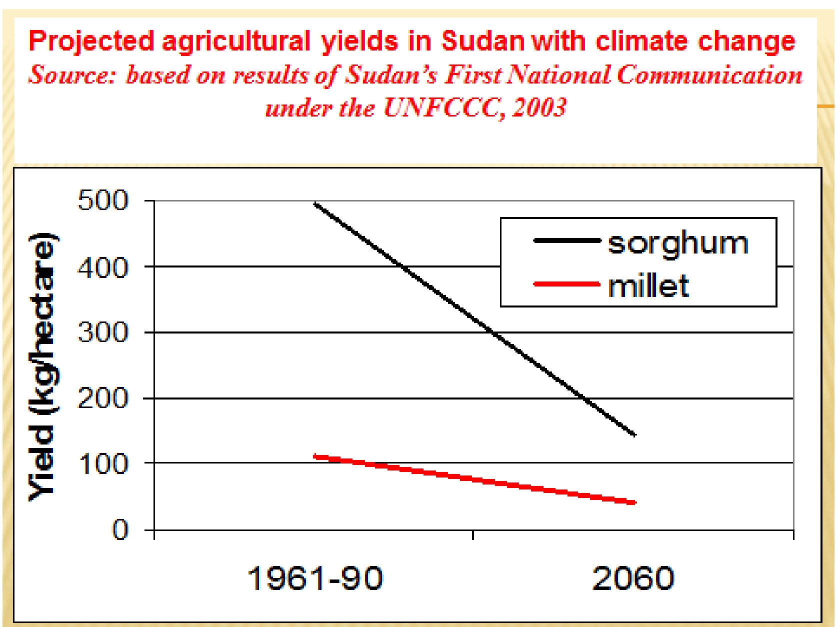


Figure 13: Projected sorghum and millet yields. Report: Sudan First National Communication under the UNFCCC, 2003