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RESEARCH ARTICLE

DETECTION OF DROUGHT PATTERN IN SUDAN USING STANDARDIZED PRECIPITATION-EVAPOTRANSPIRATION INDEX (SPEI)

[1,2,3]*Yousif Elnour Yagoub, [1]Zhongqin Li, [2]Omer Said Musa, [1]Feiteng Wang, [4]Mohammad Naveed Anjum, [3]Zhang Bo and [3]Ji Ding-min

[1]State Key Laboratory of Cryospheric Sciences/Tian Shan Glaciological Station, Northwest Institute of Eco-Environment and Resources, CAS, 320 Donggang West Road, Lanzhou, 730000, China
[2]University of Khartoum, Faculty of Forestry, Department of Forest Protection and Conservation, Code 13314, Shambat, Sudan
[3]Northwest Normal University, College of Geography and Environmental Science, Anning Road, Lanzhou 730000, P. R. China
[4]Division of Hydrology Water-Land Resources, Northwest Institute of Eco-Environment and Resources, CAS, 320 Donggang West Road, Lanzhou, 730000, China

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ABSTRACT

Recent climatic changes are posing great threat to natural resources and biodiversity worldwide and the threat is particularly eminent in Sub-Saharan Africa, urging for better adaptation interventions. In turn, in this study, we explored the drought pattern in Sudan and South Sudan for the period between 1961 and 2013. Consistent with several recent studies those characterized drought patterns; we used the Standardized Precipitation-Evapotranspiration Index (SPEI) of drought to explore possible drought events in two countries Sudan and South Sudan over the last 53 years. Our analysis documented results about drought in these two countries. While in Sudan temperature is increasing, precipitation is dramatically decreasing. In south Sudan, we saw opposite scenario where temperature is generally has a declining trend and precipitation is increasing. Also, the recurrence last drought periods for the most times was moderate except the fact that in 1984, 1991, and 2000 most of Sudan and South Sudan has witnessed extreme and severe drought periods. There is a wide seasonal and spatial variability in drought intensity, as some areas became drier in summer and wetter in autumn and winter. Overall, we provide evidence that the drought is persistently occurring in Sudan with a prolonged periods. This information is of high value for setting up adaptation and mitigation strategies related to forest and natural resources. Furthermore, we caution that our study has no intention to predict the future of drought in both countries as this is beyond our objectives.

INTRODUCTION

Drought is considered a major environmental problem facing humanity, as about one-third of the world's countries located in arid and semi-arid areas including Sub-Saharan Africa (Zhang J. et al 2012). Recent climate change reports have classified Sub-Saharan Africa as one of the most susceptible, sensitive and vulnerable regions of the world to the impacts of drought events as more severe and longer drought periods have been observed since the1970s in these areas (IPCC, 2007).

A plausible warmer world with longer and harsher droughts could lead to a rapid collapse in tropical forest communities converting them from a net carbon sink into a large carbon source with cascading effects on global climate-vegetation feedbacks (Lewis, 2006). The recent findings of the Intergovernmental Panel on Climate Change (IPCC) (e.g. IPCC 2007 and 2013), showed that climate change is already having clear impacts on natural resources and subsequently affecting livelihoods of millions of people around the world. Not only these current noticeable heat waves and destructive drought events but also similar climatic change-related crises have been predicted to continue increasing in frequency and severity over the next few decades and specifically in arid zones. Perhaps such increase in frequency of drought in these fragile arid ecosystems such as sub-Saharan Africa, for example, will have severe consequences on natural forest and biodiversity (Siddig, 2014).

***Corresponding author: Yousif Elnour Yagoub**
[1]State Key Laboratory of Cryospheric Sciences/Tian Shan Glaciological Station, Northwest Institute of Eco-Environment and Resources, CAS, 320 Donggang West Road, Lanzhou, 730000, China
[2]University of Khartoum, Faculty of Forestry, Department of Forest Protection and Conservation, Code 13314, Shambat, Sudan
[3]Northwest Normal University, College of Geography and Environmental Science, Anning Road, Lanzhou 730000, P. R. China

Examples of these ecological consequences on arid-land's forests may include; failure of trees natural regeneration, species-range shift, changes in community structure and composition, reduction in species abundance, reduction in forest products as well as spread of fires and diseases. Sudan is one of the driest but also the most variable countries in Africa in terms of rainfall. Extreme years (either good or bad) are more common than average years (Zakieldeen, 2007). While the drought of 1968 was very severe and persisted throughout the early 1970s, the second wave was limited to the year 1982 only, but harsher and was considered the third driest year in the period of 1940-1982. Also the year 1982 appears to have received substantially less rainfall than the drought years of the 1940s.

Despite these drought impacts in Sudan, the knowledge on measuring the occurrence, frequency, and severity is limited. Furthermore, there is limited information about the future scenarios and their possible impacts on natural resources at the country scale. This obviously makes the need for more in-depth studies and analysis to understand how crucial is this phenomenon. For instance, questions like how severe the drought can get every year and where (i.e. in which part of the country) is of deep concern. Also what does the recurrence interval of the drought and what are the determinants of this is very important question as well as how long each drought period takes (i.e. how many years). Fortunately, drought indices provide reasonable answers to many of these questions. According to the definition of drought by Mawdsley et al. (1994), there are two types of drought indicators: (a) environmental indicators, which measure the direct effect on the hydrological cycle, including among others, rainfall, temperature, evapotranspiration, river flow, etc., and (b) water resources indicators, which measure the severity in terms of the impact on the use of water, e.g. water supply for domestic or agricultural use, fisheries or recreation. Although these both types of drought indicators are useful tools and easy to construct based on historical hydro-meteorological data, however, they can only reflect drought conditions (e.g. intensity) with no ability to quantify the economic losses or destruction level (Mishra and Singh, 2010).

Drought indices are very important tools for environmental research and management in arid zones. Their values not only for measuring the spatiotemporal extent of drought events but also are useful tools for guiding decision making to declare drought state of emergency, for example, and designing drought-mitigation plans (Quiring, 2009 and Piara, 2014). Moreover, environmental indices in general including drought indices are significant communication tool between environmental scientists and public. Intuitively, these indices enable scientists to describe and quantify the state and trend of the environment to ordinary people in a simple and understandable numbers. Among the earliest efforts and developments in drought indices, Thornthwaite (1948) has proposed a simple drought index which based on the value of precipitation in a certain point of time minus evapotranspiration at the same period. Although Thornthwaite's index was very simple but had provided an important foundation for later research by other drought scientists. Almost two decades later Palmer (1965) proposed a new drought index i.e. the Palmer Drought Severity Index (PDSI), considering a number of elements. In addition to precipitation and evapotranspiration values, PDSI consider temperature and soil moisture information. Despite decades since the emergence of these drought indices, PDSI has been recognized as a milestone in the history of drought indices and now being widely used in the United States and around the world. The Standardized Precipitation-Evapotranspiration Index (SPEI) is the most recent and famous drought index, proposed by Vicente-Serrano et al. (2010). The SPEI is based on precipitation and potential evapotranspiration (PET), and it combines the sensitivity of PDSI to changes in evaporative demand with the multiscalar nature of the SPEI. Details of the method used to calculate the SPEI can be found in Vicente-Serrano et al., (2010) and Beguería et al., (2014). SPEI applied the Thornthwaite procedure (Thornthwaite, 1948) to estimate the PET, which has the advantage of requiring limited data of monthly mean temperature. The drought intensity grading based on the SPEI's values is presented below in table 1 and readers are referred to Liu et al. (2013) and Wang et al (2015) for the full description of SPEI grading.

Table 1. Classification of drought intensity based on SPEI drought index

	Drought category	SPEI
1	No drought	< -0.5
2	Mild drought	-0.5 to -1
3	Moderate drought	-1 to -1.5
4	Severe drought	-1.5 to -2
5	Extreme drought	> -2

During the last decade, temperature trends in some African regions have been the subject of a number of assessments and monitoring projects. Findings showed that eastern Africa has dominated cool daytime and warm nighttime but no warm time was found in the Mozambique Channel region (King'uyu et al. 2000). The devastating Sahelian desiccation over the last fifty years of the 20th century has motivated many scientists to monitor the changes in drought conditions in Sudan (Eldredge et al., 1988; Hulme, 1990; Hulme, 2001). Several studies showed that Sudan is suffering from land degradation as a result of highly variable rainfall and recurrent droughts (e.g. Ayoub, 1998). While South Sudan is generally cooler and wetter, Sudan has a dry and harsher climate due to the dominant variable precipitation and temperature as well as high frequency of drought periods.

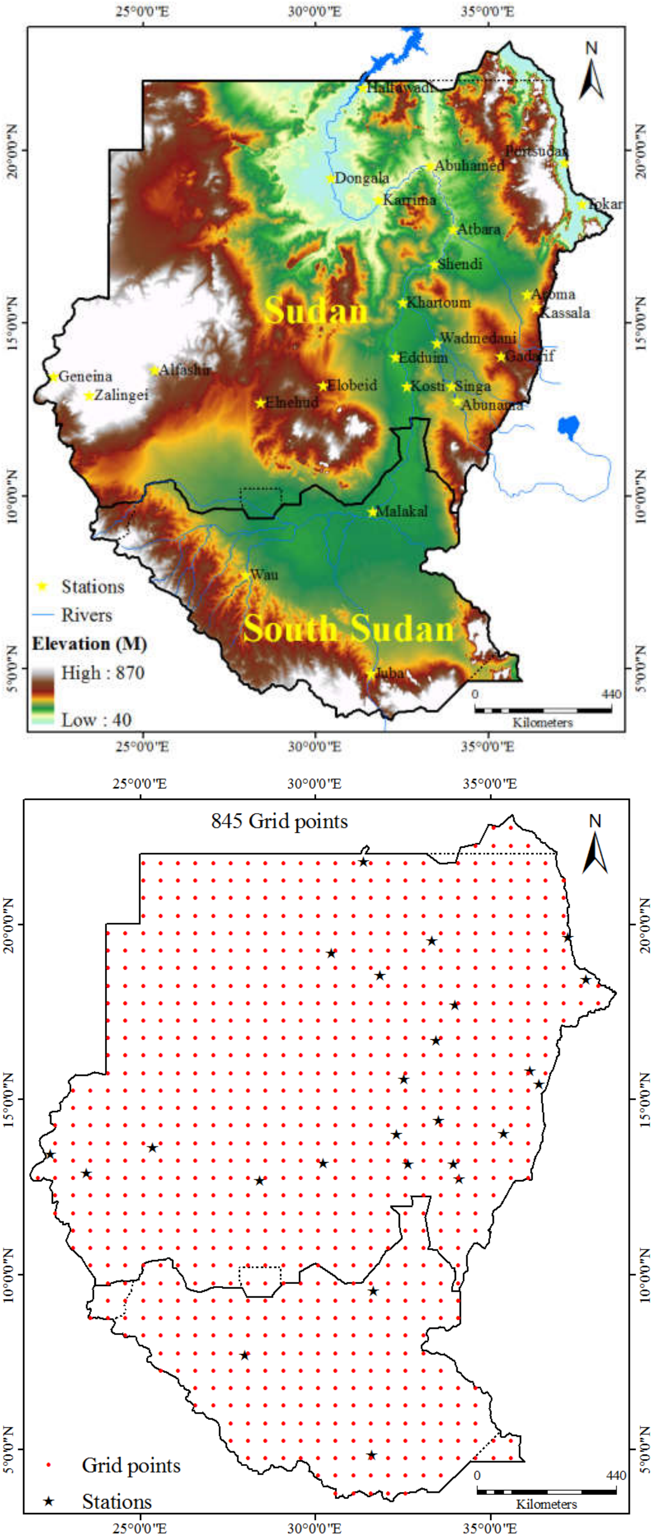
Apparently, drought is one of the most important natural disasters in Sudan not only for its substantial impacts on agricultural production, food security, livestock, but also it causes significant disturbances to the forest ecosystems. Recent observations showed that Sahara desert is encroaching southwards at alarming rate due to vegetation cover degradation in semi-arid zones as a result of the drought. Additionally, drought can lead to increase in natural resources-related conflicts and civil wars, expand shifting cultivation areas, and insecurity in land tenure (Sivakumar et al., 2007). Of course, these are reasonable causes of concern to environmental scientists in both countries to address these issues by knowing more about drought patterns and consequences. Although there were several attempts to study drought in Sudan and South Sudan, still there is absence of recent analysis of drought pattern and trends. In the current study, based on precipitation and temperature data from 25 weather stations from both countries over the period 1961 -

2013, we aim to; (a) explore the spatial and temporal variation pattern in precipitation and temperature, (b) and detect the occurrence of drought periods and their geographic extent based on SPEI.

MATERIALS AND METHODS

Study area

This study focused on Sudan and South Sudan, which are located in the northeastern to central part of Africa (Fig. 1). Both countries together cover an area of 2501010 km^2, extending from latitude of 2° 40' - 22° 30' N and from longitude 21° 50 ' - 38° 50' E. While Sudan is drier as its northern half is entirely desert forming the southeast borders for Sahara desert, South Sudan is wetter and greener given its location near to equator line. In the mountainous areas of the western Sudan, the winter is considered mild with mean temperature slightly less than 20 C°. Excluding South Sudan, there is a wide range of difference in temperature between the monthly minimum and maximum temperature. During the hot summer, the maximum temperature exceeds 40 C°.



* Source of DEM data: (http://srtm.csi.cgiar.org/), resolution = 90 m × 90m

Fig. 1. The distribution of meteorological stations and grid points of climate data in two study areas

As many other Sahelian African countries, Sudan is a drought prone area (Elagib, 2009). Despite these harsh conditions, Sudan is one of the wealthiest countries in Africa for its natural resources. With less than 4% of the continent's population, it has 7% of the continent's cropland, 13% of its pasture land, and 10% of its livestock population (WRI/UNEP/WB/UNDP, 1996). Table 2 shows the longitude and latitude, altitude and annual precipitation of meteorological stations used in this study.

Table 2 The Longitude and latitude, altitude and annual precipitation of meteorological stations in Sudan

	Stations	Longitude	Latitude	Altitude (m)	Precipitation (mm)
1	Abuhamed	33°44′	19°51′	313	12.5
2	Abunama	34°06′	12°65′	434	632.0
3	Alfashir	25°31′	13°58′	738	170.5
4	Aroma	35°94′	15°77′	445	234.8
5	Atbara	33°75′	17°64′	385	42.9
6	Dongola	30°63′	19°20′	249	7.0
7	Edduim	32°19′	13°89′	385	230.5
8	Elnehud	28°44′	12°65′	573	438.8
9	Elobeid	30°31′	13°27′	610	357.3
10	Gadarif	35°31′	14°21′	571	521.0
11	Geneina	22°50′	13°27′	845	748.1
12	Halfawadi	31°25′	21°08′	320	3.8
13	Juba	31°56′	4°84′	598	735.1
14	Karrima	31°88′	18°58′	242	13.5
15	Kassala	36°25′	15°46′	490	341.0
16	Khartoum	32°50′	15°46′	383	133.3
17	Kosti	32°81′	12°96′	362	362.7
18	Malakal	31°56′	9°84′	392	719.8
19	Portsudan	37°19′	19°83′	41	35.6
20	Shendi	33°44′	16°70′	378	62.0
21	Singa	34°06′	12°96′	426	536.7
22	Tokar	37°81′	18°89′	256	171.8
23	Wadmedani	33°44′	14°52′	407	216.9
24	Wau	28°13′	7°65′	440	912.7
25	Zalingei	23°44′	12°96′	862	549.3

SPEI

The SPEI development requires information about monthly temperature and precipitation records for all the area within the study focus. We gathered the monthly temperature and precipitation data from Sudan Meteorological authority for 25 weather stations across Sudan and South Sudan for the period of 1961-2013 (Fig. 1).

Mann-Kendall test (M-K)

We applied the Mann-Kendall test, developed by Mann, (1945) and Kendall, (1975) in order to detect the significant trends in SPEI time series. The rank-based Mann-Kendall (M-K) test is the most widely used nonparametric method for trend detection. We particularly used this method due to sensitivity and nature of meteorological data to alternative parametric tests those assume specific probability distribution. Temperature and precipitation data that we used to construct SPEI have no exception and are likely to be not normally distributed and usually having outliers.

RESULTS AND DISCUSSION

Pattern of temperature and annual precipitation

Precipitation anomaly shows great fluctuations all over Sudan and South Sudan. Alternating positive and negative anomalies fluctuations, the most negative anomalies periods have been recorded, for example, in 1966, 1972, 1984, 1991 and 2000 (Fig. 2a). On the other hand, wet years are also noticed, for example, in 1969, 1979, 1988 and 2011. Likewise precipitation, temperature has shown fluctuations around the average with a generally increasing trend (Fig. 2a - bottom). On the basis of analysis of precipitation and temperature data for the twenty-two stations of Sudan, a steep decreasing trend in annual precipitation and increasing trend in temperature were found (Fig 2b, respectively). Oppositely, and from a similar subset analysis for the three stations of South Sudan only, we found that there are rapidly increasing trend in precipitation (Fig 2c).

Drought pattern based on SPEI

SPEI provided useful information about drought patterns i.e. occurrence, intensity and extent throughout the study area during the 53-year window. While our SPEI results were calculated at time scales of 1, 4, 12, 24, 36, and 48-month, here we only present a result for 12-month time step which showed occurrence of highest number of drought periods (i.e. drought frequency). As in Fig. 3, SPEI 12-month shows high number drought occurrences (i.e. periods) that were happened in 1973 - 1975, 1981, 1991 - 1992, 2000 - 2001, 2003 - 2006 and 2008-2011. Also, we noted that the 2000s witnessed three drought periods with recurrence interval of 2.5 years on average.

According to the drought intensity classes, there are four categories include mild, moderate, severe and extreme drought. SPEI index showed that mild drought is the most dominant drought level in Sudan on the annual as well as the seasonal basis. Table 3 shows the percentages of different drought intensities that detected in Sudan and South Sudan annually and across seasons. Also, SPEI trend analysis by Mann-Kendall (M-K) test showed significant increasing trend in the seasonal drought patterns in towns such as Wadmedani, Tokar, Portsudan, Kassala, Gadarif, Dongala, Aroma and Abuhamed ($P = 0.00$), while significant (i.e. $P = 0.00$) decreasing trends in all three stations of South Sudan (i.e. became more humid). Table 4 presents the results of the seasonal drought trends as computed by M-K test.

Correlation of the SPEI drought index with precipitation and temperature

SPEI calculated from Juba station's data presenting South Sudan and from Elobied, Geneina, Kasala and Wadi-Halfa stations for Sudan were correlated with same stations precipitation and temperature data. While precipitation in Juba showed weak and negative correlation with SPEI, but there was a clear significant negative association between temperature and SPEI (Table 5). For Sudan's stations, SPEI for Kassala and Wadi-Halfa showed strong correlation with both precipitation and temperature, but drought in Elobied and Geneina indicated no significant correlation with precipitation, although they were highly correlated with temperature. Table 5 showed the association between drought index and precipitation and temperature in five towns in Sudan and South Sudan.

Spatial distribution of drought intensity

Drought appears to occur in many locations in the study area with different levels of intensities. In general, Portsudan, Karrima, Abuhamed, Atbara, Elobeid, Malakal and Wau

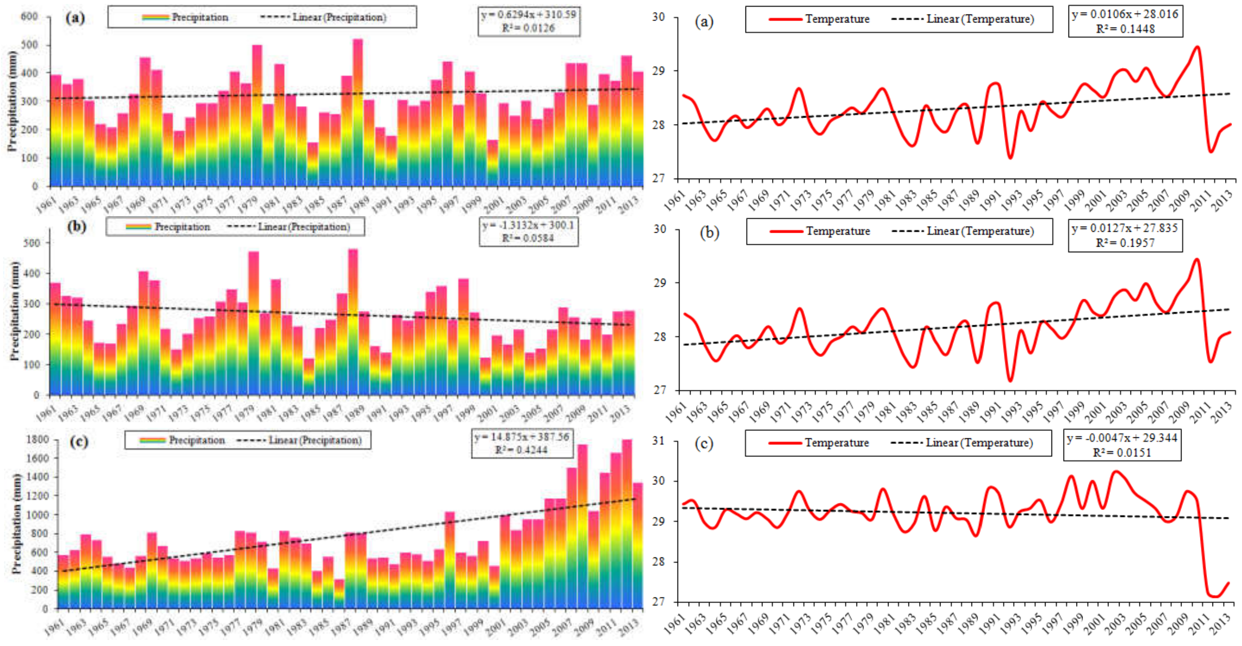


Fig. 2 (a-c) Mean annual precipitation and temperature trend in Sudan and South Sudan during 1961 to 2013. (a) Results for all 25 stations of the study area (i.e. both Sudan and South Sudan). (b) Results from only twenty two station of Sudan. (c) Results from only three station of South Sudan

Table 3. Percentage of SPEI-drought intensities occurred in the whole year as well as winter, summer and autumn seasons in Sudan and South Sudan during 1961 - 2013

	Drought category	SPEI %			
		winter	summer	autumn	annual
1	No drought	52.69	51.85	51.25	52.00
2	Mild drought	27.15	25.51	29.13	25.51
3	Moderate drought	10.69	13.89	10.19	11.85
4	Severe drought	06.00	05.89	06.79	08.60
5	Extreme drought	03.46	02.87	02.64	02.04
	Total drought	47.31	48.15	48.75	48.00

Table 4 Results of SPEI-seasonal trend analysis in Sudan and South Sudan during 1961 - 2013.

	Stations	winter		summer		autumn	
		Z value	P value	Z value	P value	Z value	P value
1	Abuhamed	*-3.27*	0.00	*-2.83*	0.00	*-2.83*	0.00
2	Abunama	*-2.39*	0.01	-0.91	0.18	-1.56	0.06
3	Alfashir	-1.37	0.09	-1.50	0.07	-0.8	0.21
4	Aroma	*-2.68*	0.00	-1.43	0.08	*-3.00*	0.00
5	Atbara	*-2.70*	0.00	*-2.88*	0.00	*-2.22*	0.01
6	Dongola	*-2.94*	0.00	-1.20	0.11	*-2.66*	0.00
7	Edduim	*-2.39*	0.01	*-2.12*	0.02	*-2.06*	0.02
8	Elnehud	-0.73	0.23	*-2.14*	0.02	-1.6	0.05
9	Elobeid	*-1.93*	0.03	*-2.54*	0.01	-1.42	0.08
10	Gadarif	*-2.96*	0.00	*-1.94*	0.03	*-2.74*	0.00
11	Geneina	-1.35	0.09	*-2.17*	0.01	-0.68	0.25
12	Halfawadi	*-2.45*	0.01	-0.39	0.35	-1.94	0.03
13	Juba	3.57	0.00	1.93	0.10	2.34	1.00
14	Karrima	*-2.60*	0.00	-1.27	0.10	*-1.96*	0.03
15	Kassala	*-2.71*	0.00	-1.30	0.10	*-4.40*	0.00
16	Khartoum	*-2.56*	0.01	-1.48	0.07	*-1.85*	0.03
17	Kosti	*-1.71*	0.04	-1.52	0.06	-1.02	0.15
18	Malakal	1.20	0.10	-0.33	0.37	2.92	0.00
19	Portsudan	*-2.63*	0.00	*-1.60*	0.05	*-3.70*	0.00
20	Shendi	*-2.50*	0.01	*-2.19*	0.01	-2.22	0.01
21	Singa	*-2.32*	0.01	-1.20	0.11	*-1.63*	0.05
22	Tokar	*-1.90*	0.03	*-3.86*	0.00	*-4.47*	0.00
23	Wadmedani	*-2.19*	0.01	-1.70	0.05	*-2.85*	0.00
24	Wau	2.52	0.01	0.370	0.23	1.43	0.92
25	Zalingei	-0.29	0.38	*-2.16*	0.02	-0.43	0.33

Note: The bold and italic values are indicating drought, while the underlined values are indicating trends towards humid conditions.

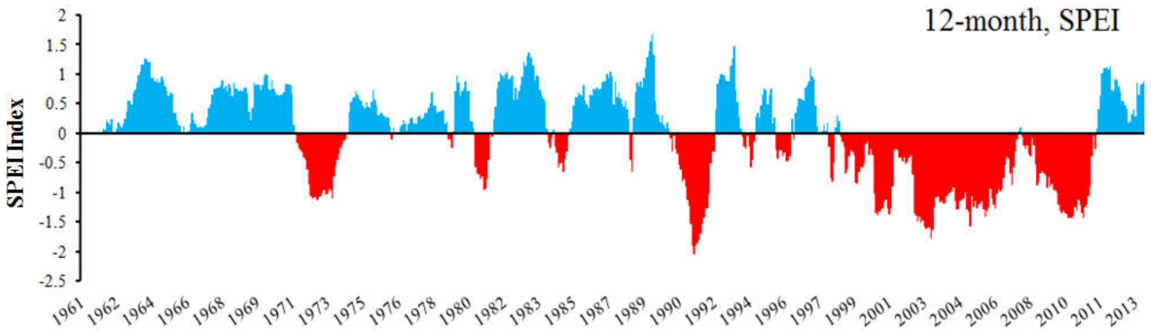


Fig. 3 SPEI drought index values in Sudan and South Sudan during 1961 - 2013, based on the 12-month time scale

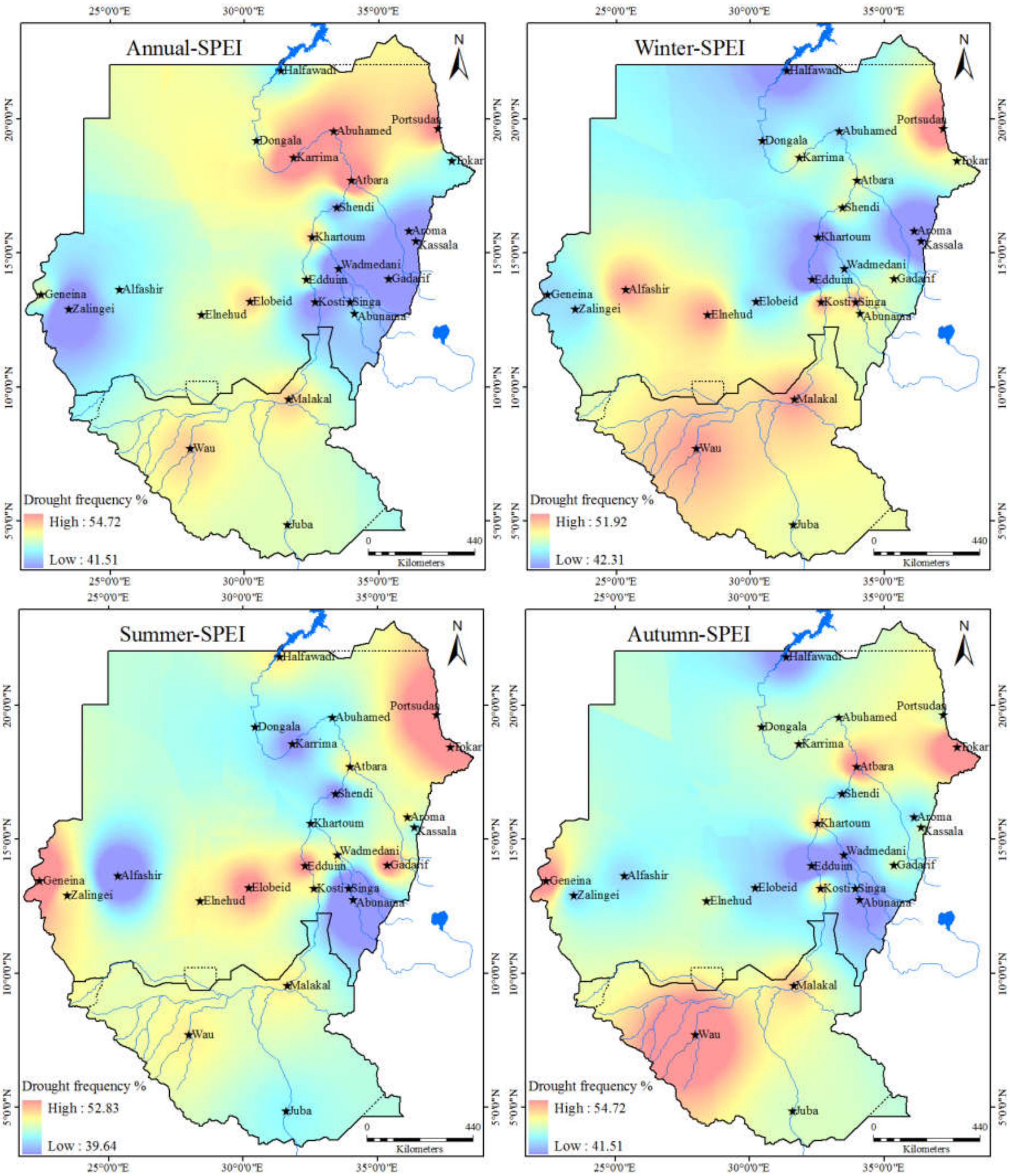


Fig. 4 The distribution of an annual and seasonal SPEI drought index of total drought intensity in Sudan and South Sudan during 1961 - 2013

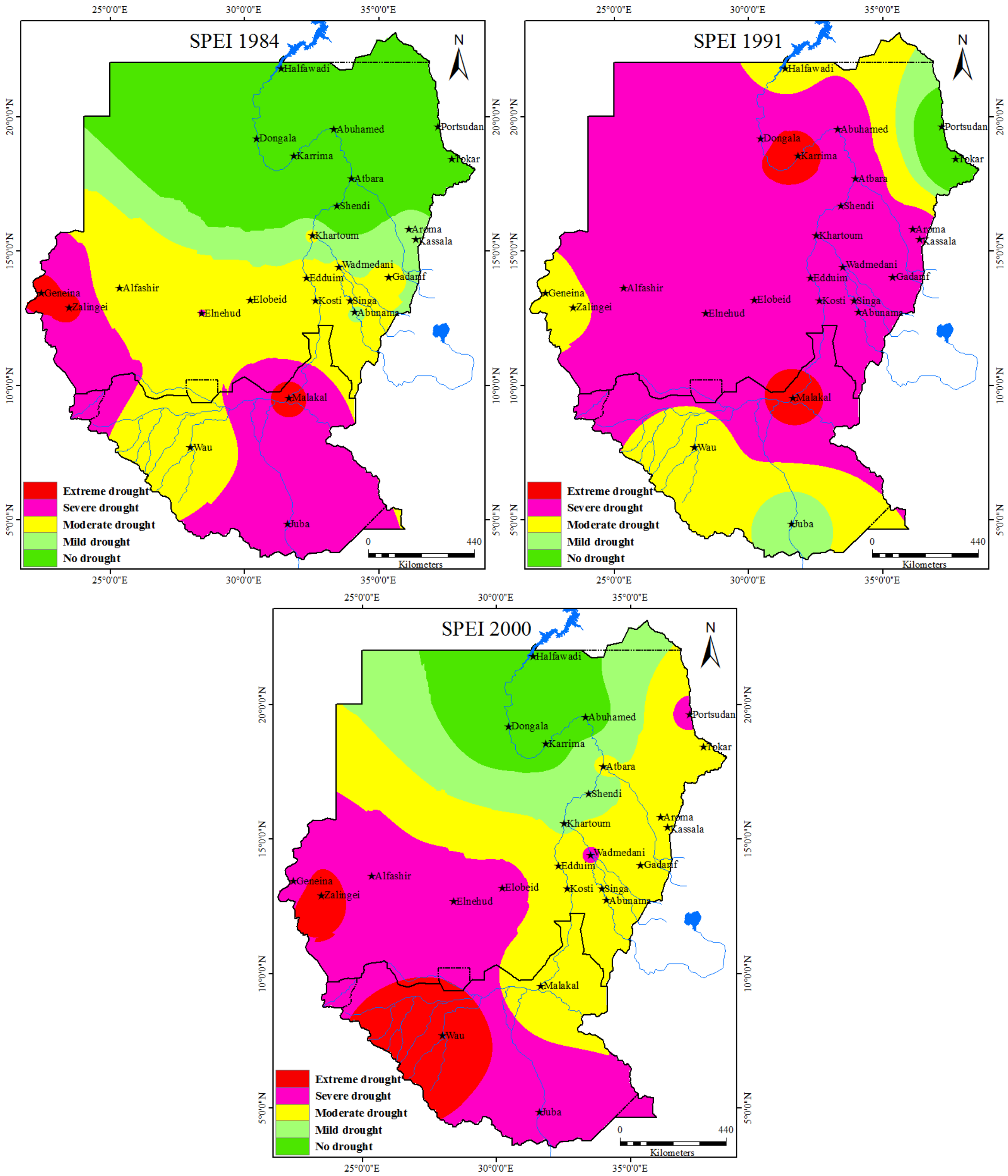


Fig. 5 changes in drought intensity in Sudan in the top-three highest drought periods (1984, 1991 and 2000).

Table 5 Correlation between SPEI drought index and precipitation and temperature based on five weather stations in Sudan and South Sudan

Station	SPEI with Precipitation		SPEI with Temperature	
	Pearson correlation	P value, Sig.	Pearson correlation	P value, Sig.
Elobeid	0.265	0.055	-.646**	0.000
Geneina	0.077	0.583	-0.580**	0.000
Juba	-0.191	0.170	-.638**	0.000
Kassala	.529**	0.000	-.856**	0.000
Halfawadi	.343*	0.012	-.925**	0.000

**Correlation is significant at the 0.01 level (2-tailed)
*Correlation is significant at the 0.05 level (2-tailed)

showed high level of drought, whereas towns like Kosti, Singa, Abunama, Kassala, Gadaref exhibited low levels of drought (Fig. 4). More details about the seasonal variability in drought intensity can be found in Fig. 4.

A comparison of intensity in the top-three driest periods

Finally, according to SPEI drought index, we presented a comparison of the intensity and distribution of drought in Sudan for the top three drought periods observed during the study window in Sudan and South Sudan (Fig. 5). These noticeable years with highest drought intensity were 1984, 1991 and 2000. For the year 1984, SPEI indicated that the majority of Sudan witnessed a mild to moderate drought except Geneina and Zalingei have extreme drought. For the same year, South Sudan was dominated by severe drought in Juba and Malakal, but Wau with mild drought (Fig. 5). The year 1991 marked the harshest drought as much of Sudan has witnessed severe drought except western Darfur and red sea coast regions where conditions were moderate (Fig. 5). In 1991, South Sudan, in general, was wet except Malakal which was characterized by extreme drought conditions (Fig. 5). Finally, the year 2000 indicated that there were extreme drought events in the western region of Sudan and most parts of South Sudan except Malakal. All other parts of the country showed mild to moderate effects of drought at that year (Fig. 5).

Conclusion

The increasingly-intensified desertification and recent climatic change have stimulated detailed studies of precipitation and temperature records in many areas of the world including Sudan and South Sudan. In this study, we showed that temperature is increasing and precipitation is substantially decreasing in Sudan, though South Sudan is getting cooler and wetter. Moreover, drought has increased dramatically in the last two decades consistent with the increased temperature and reduced precipitation that we just observed. Not only these conclusions, but also we argue that these conditions may dramatically degrade natural vegetation cover, crops production, and livestock production consistent with the currently observed losses in many areas of Sudan. Most drought studies focus on quantifying drought and its impacts at the regional or global scale, but this generalization can obscure localized effects. Therefore, this study has focused on the country scale to characterize drought occurrence, severity, and duration in a relatively small scale. Indeed these findings can inform policy making and adaptation strategies. We believe that our findings may be of great value to sectors such as agriculture, forestry, animal and livestock, and water resources in their efforts to minimize the impacts of drought. For example, our study confirmed that losses in agricultural production occurred in Sudan in 1984, 1991 and 2000 those were the years of heist drought intensity. Based on our analysis and increased frequency of drought, we also suggest that livelihood sector should adopt drought-adaptation options in grazing and animal movement and seasonality in order to mitigate any losses due to anticipated drought years. This particularly will be helpful if it happens in concert with local nomadic communities' involvement in designing policies and projects for effective adaptation strategies. SPEI drought index has proven to be excellent tool to get information about the history of drought spread and intensity in a cost-effective way. With reliance only on temperature and precipitation data that readily available nowadays, we suggest that all natural resources sectors (e.g. grassland, wildlife, and forestry) must develop this index for monitoring the drought patterns and its potential impacts on arid-land ecosystems and habitats in regular and long-term periods.

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