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Meteorological Drought and Crop Yield in Sub-Saharan Sudan

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Abstract: The paper presents regional time series of the standardized precipitation index (SPI) for the arid and semi-arid areas of Sudan during the period 1941-2010. Accordingly, the regional drought events are detected and evaluated for their severity based on two time scales, 3-running months and 12 months. Probability curves of the SPIs have been compared between two periods, wet (1941-1970) and dry (1971-2010). The vulnerability of agriculture to drought is assessed by the relationship between the inter-annual variability in both the crop yield (CY) and the SPI over the time span 1961-2009. Sorghum and millet were chosen as major food crops grown in the region. It has been found that (1) the so-called rainfall recovery period of 1991-2010, though wetter than 1971-1990, has far less wet conditions compared to the pre-drought period, (2) the 2000s have seen at least 2-4 drought years of mild and moderate severities, (3) the drought can occur on seasonal basis with 44-47% probability (return period of ~2 years) based on the dry-period data compared to only 24-32% (return period of ~3-4 years) for the wet period and (4) there is a highly significant relationship between the drought SPIs and CY during the early-to-mid growing calendar. The above results could be useful for issuing drought and agricultural policies for food security based on early warning.

Key words: Standardized Precipitation Index · Drought frequency · Crop yield prediction Sahel · Sudan

INTRODUCTION

The drought phenomena are believed to be brought about by admixtures of causes, including those climatic, hydrological, environmental, socioeconomic and cultural in nature [1]. Rainfall is by far the primary indicator of water availability [2] and hence meteorological drought. In spite of the complexity of the sequence of events leading to famine in Sudan [3-6], the role of drought in stretching the limits of famine should not be counted out [7]. Analysis of the most recent famine disasters in Sudan shows that the links between vegetation greenness/food availability and good rainfalls are relatively strong [8-11]. This is particularly true in view of the fact that the majority of the country's grain supply comes from the rainfed areas of eastern and western Sudan [12]. During the period of escalating population numbers and intensifying drought, the complex relationship between rainfall and crop yield in the Sahel region of Sudan revealed that the yields had tended to decline gradually [9, 13]. Since the rainfall in the region falls during the summer months and since the wet season is already short, low rainfall amounts aggravate the situation of restricted crop growth [14], particularly if the decreased rainfall coincided with the sensitive stages of growth due to reduced water supply [15].

Since rainfall has proved to be a process governing the susceptibility of a community to drought hazard in terms of food production, this study assesses (1) the vulnerability of the arid and semi-arid parts of Sudan, where rainfed grains are produced, to the hazard of meteorological drought and (2) the predictability of an index of rainfall deficiency for the major food crops grown in the region.

MATERIALS AND METHODS

The meteorological data used in this study consist of monthly rainfall observed by Sudan Meteorological Authority during the period 1941-2010 at 13 stations

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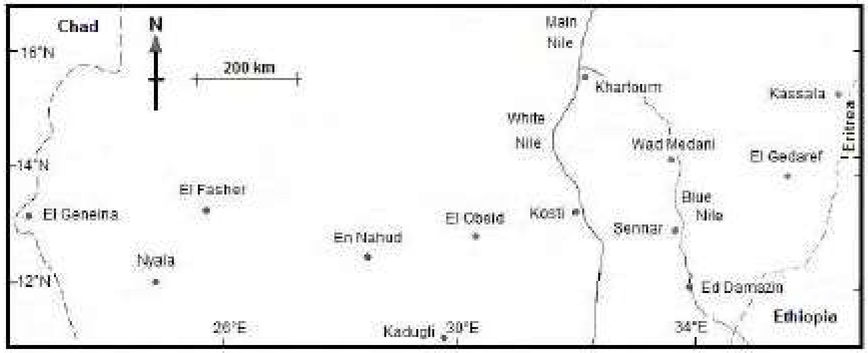

Fig. 1: Map of the study area and location of the stations

spread over the arid and semi-arid region (Fig. 1), which is encompassed by latitudes 10 °N and 16 °N. Each station was taken to represent a state of the region. In order to obtain a regional dataset, the area weighted average was found. Sorghum and millet yield data were obtained from the Food and Agriculture Organization (FAO) [16] for the period 1961 to 2009. In this work, the meteorological drought is assessed by the standardized precipitation index (SPI), using the SPI classes proposed by [17]. Despite the limitations of SPI in relation to the length of precipitation record and nature of probability distribution that play an important role for calculating SPI [18], thus strongly necessitates the standardization of the index computational procedures [19], the SPI is widely used to monitor the drought phenomena [1, 18, 20-23]. Moreover, monitoring and quantifying the wetness/dryness of the African Sahel rainy season is usually based on this index despite its dependence on the reference period selected for the computation. In fact, Ntale and Gan [24] identified this index to be more appropriate for investigating the drought characteristics in East Africa.

The index has been calculated on two time scales, running three-monthly and annual, since SPI data of longer time scales have been shown to exhibit relatively better performance in describing the drought characteristics in contrast to one-month values [19]. It is suggested that short-term droughts of 3 months may relate to agricultural drought occurring at a critical stages of the growing season while long-term droughts of 12 months may represent hydrological droughts [25]. The wet season, was considered to be May to October. Since the rainfall series include a few extreme events, thus generally approximating to a log-normal distribution, they are normalized by taking natural logarithms or prior to calculation of the mean, as suggested by many researchers [26-29]. After the logarithmic transformation of the dataset, the corresponding mean and standard deviation of rainfall values were computed for the normal period 1981-2010. Then, the deviations from the mean were found and standardized by dividing by the standard deviation. For the crop yield data, the skewness was found relatively small so no logarithmic transformation was needed. The last 30-year period (1980-2009) was used to standardize these yield data.

Probability curves for all the SPI datasets were developed for two periods, wet (1941-1970) and dry (1971-2010) to study the changing probability of occurrence of the drought classes between the two time eras. Frequency analysis was also carried out for three periods, namely wet as before, 1971-1990 and 1991 onwards. There was an underlying rationale for the sub-division of the dry period that some investigators have pointed out a limited recovery of the Africa Sahel rainfall during 1990-2007 from the long lasting drought post the 1980s [30-32], although earlier studies refute the recovery until 2000 [33, 34]. Results by West *et al*. [35] from interviews with farmers and by Elagib and Elhag [36] using major climate indicators also show no return to the pre-drought conditions.

To assess the vulnerability of agricultural yield to the regional drought, the relationship between the yields of two major crops grown in the region, viz. sorghum and millet and the SPI values have been investigated: (1) to examine the predictability of the SPI index for the crop yield and (2) in search for the most influencing drought class(s).

RESULTS AND DISCUSSION

Historical Pattern: Fig. 2 shows the time series of SPI on seasonal (3-month) and annual bases. Overall, the period 1941-1970 saw wet conditions with several years lying in the extremely and severely wet classes. Very few cases of mild drought were recorded. The SPIs for the 1970s were a mixture of below-and above-normal values, but with the former characterize the first half of the decade while

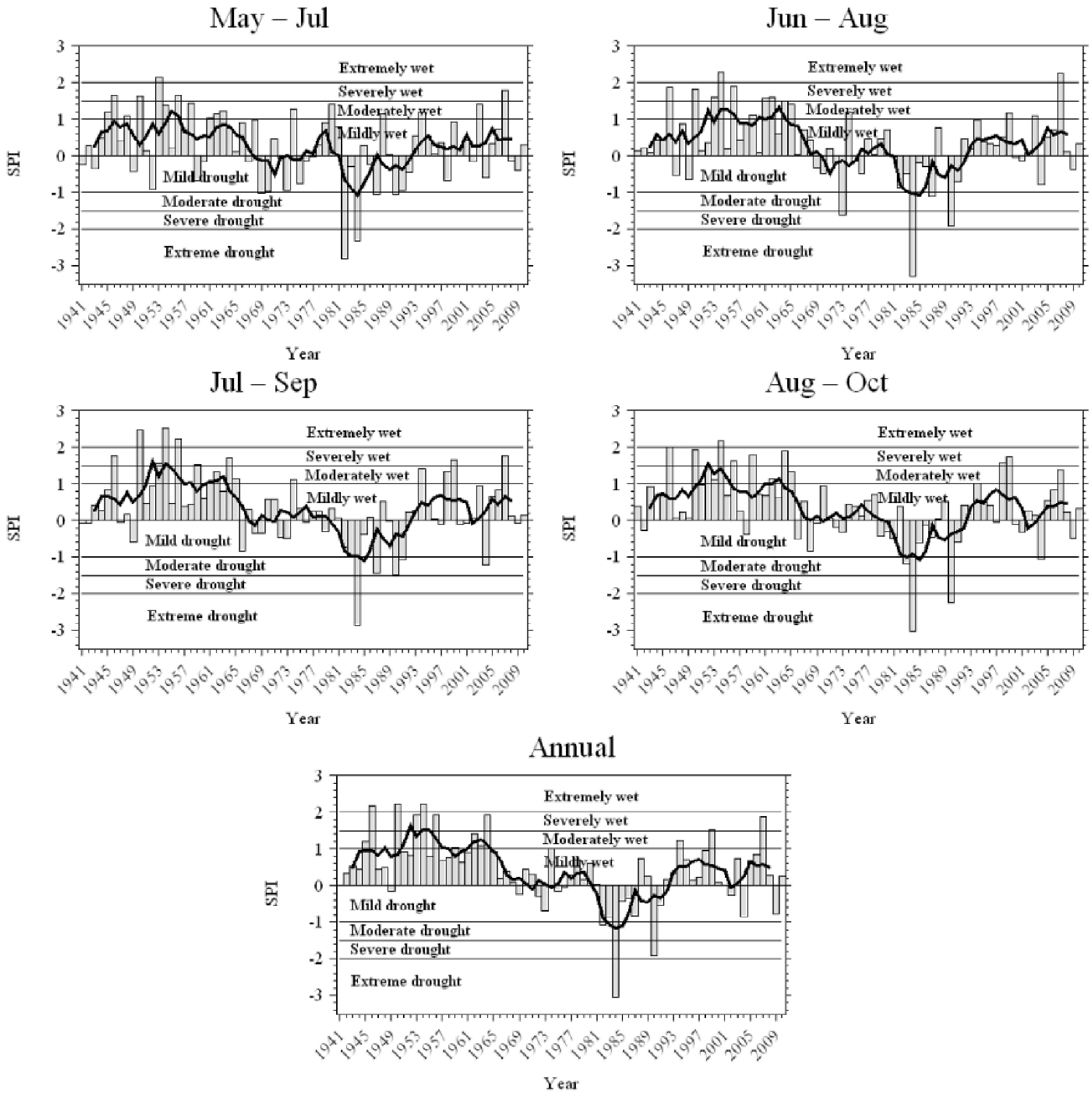

Fig. 2: Time series of SPI for short-and long-term scales

the latter are indicated during the second half. Most of the drought cases were mild and only one case was severe, as shown in the time series for June-August. On the other hand, the wet cases were overwhelmingly mild and very rarely moderate. By the 1980s, the drought conditions had persistent nature until the end of the decade. This period was the driest throughout the study period with the 1984 revealing the worst single drought on record of extreme drought condition. The year 1980/1981 and 1988 were exceptionally mildly to moderately wet. Dry conditions continued until 1991. Thereafter, slight rainfall enhancement was prominent, with the year 1999 appeared to be the wettest within the decade. Again, lower-than-normal rainfall was characteristic in the very early 21st century. The 2000s registered many positive SPI values, with 2007 being the wettest year of moderately to extremely wet conditions, depending on the series under consideration. Mild and moderate drought characterized the year 2004, which was the driest during this decade, while the 2009 was also a dry year noticeable from all the time series. In comparison to the mid-1980s and early 1990s droughts, a study conducted by Sulieman and Elagib [37] for eastern Sudan has shown that 2009 had lesser rain days, higher concentration of rainfall and as late wet season. Ali and Lebel [38] found that SPI of = -0.5 computed on the scale of the whole Sahel defines the year as significantly dry. This criterion describes well the situation in 2004 (all series) and 2009 (annual series).

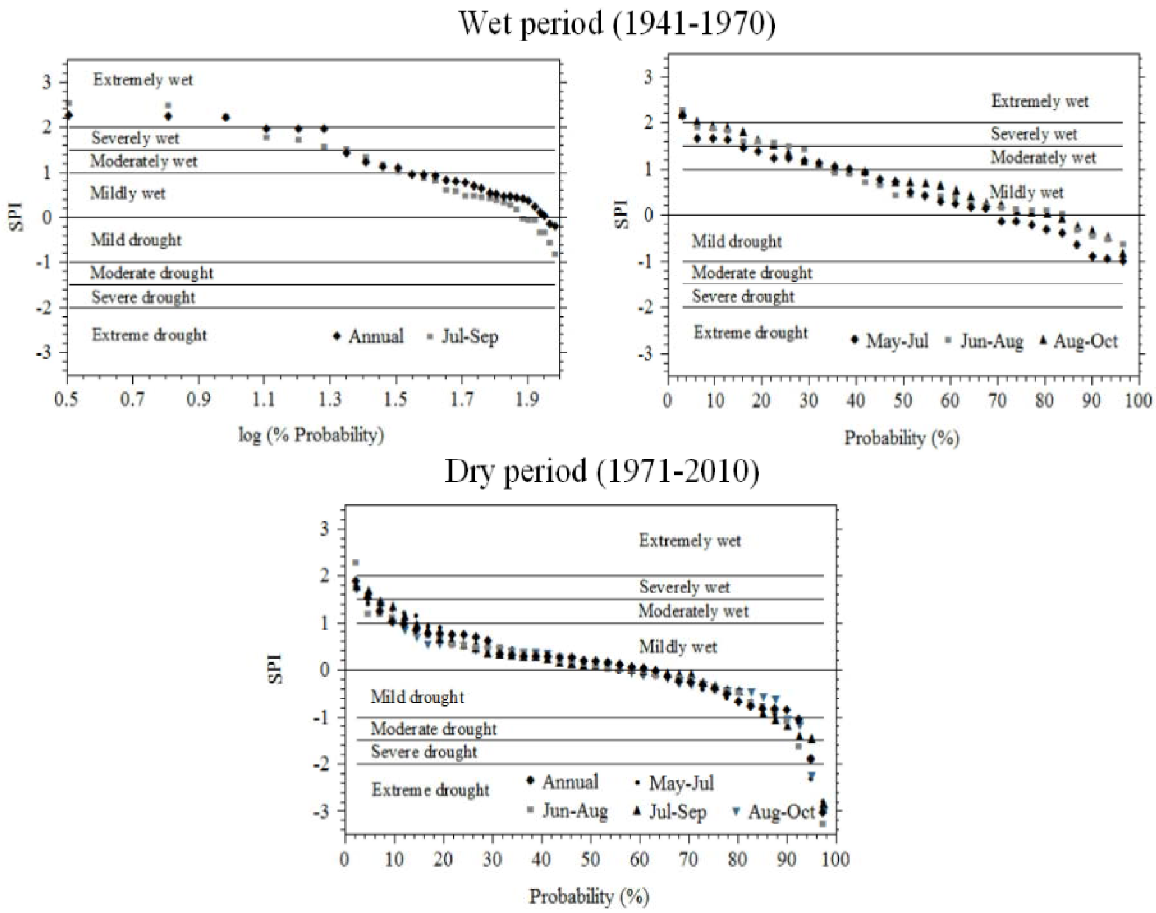

Fig. 3: Scatter plot of SPI probability curves for the wet and dry periods

The partial rainfall recovery noticed in the arid and semi-arid areas in Sudan compare well with discussions of anterior studies for the west African Sahel [30-35]. Despite this recovery, one can still notice the high year-to-year variability of rainfall since the outset of the drought era in the late 1960s/early1970s, thus matching the conclusions by Ali and Lebel [38] for the western Sahel. In their study, they [38] also regard a year with SPI of > 0.5 as significantly wet. Using this criterion to assess the average situation for the 2000s decade and for the whole period post-1990, the so-called recovery period, it has been found that none of the series qualifies for significantly wet condition. Average SPI values for the most recent decade of 2000-2010 ranges from 0.16 to 0.36 while those for 1991-2010 have the range of 0.15-0.37. Moreover, the average SPI values for the latter period were only 40.6% to 53.6% relative to those for the wet period of 1941-1970. On yearly basis, the regional time series reveal 5-7 years during the recovery period with SPI > 0.5; however, the years with SPI values less than this threshold were sufficiently enough to outweigh their effect. These results point out the fact that the region has not yet escaped even the near-normal wet conditions despite the so-called recovery, thus confirming the conclusion drawn recently by Elagib and Elhag [36].

Drought Frequency: A comparison of the SPI probability curves between the wet and dry period is shown in Fig. 3. During the dry period of 1971-2010, the probability of occurrence of a negative SPI value, i.e. dry condition, is 44% (annual, Jun-Aug and Aug-Oct), 47% (May-Jul) and 46% (Jul-Sep). For the wet period of 1941-1970, on the other hand, the probabilities are 32% (May-Jul), 28% (Jun-Aug), 26% (Jul-Sep), 24% (Aug-Oct) and 7.5% (annual). These figures clearly identify the changes between the two periods in terms of increased chances of drought recurrence during the recent period. For the purpose of estimating the drought probability of occurrence for future planning and management, the corresponding curve-fit equations are given in Table 1 for the recent data period.

Table 1: Probability (%) curve equations for SPI during 1971-2010 of the form SPI = A + B × Probability + C × Probability^2

Series	R^2	∝	A	B	C
Annual	0.864	0.000	1.1869	-0.01092	-0.00018
May-Jul	0.902	0.000	1.3485	-0.01500	-0.00020
Jun-Aug	0.831	0.000	1.1365	-0.00875	-0.00021
Jul-Sep	0.867	0.000	1.2976	-0.01746	-0.00012
Aug-Oct	0.824	0.000	1.0930	-0.00910	-0.00019

Table 2: Kendall-tau test results of the relationship of standardized anomalies of crop yield and SPI. ∝ is the significance level

Crop	Test statistics	Annual	May-Jul	Jun-Aug	Jul-Sep	Aug-Oct
Sorghum	tau	0.241	0.179	0.238	0.276	0.162
	∝	0.007	0.035	0.008	0.003	0.051
Millet	tau	0.315	0.207	0.298	0.281	0.235
	∝	0.0007	0.018	0.001	0.002	0.009

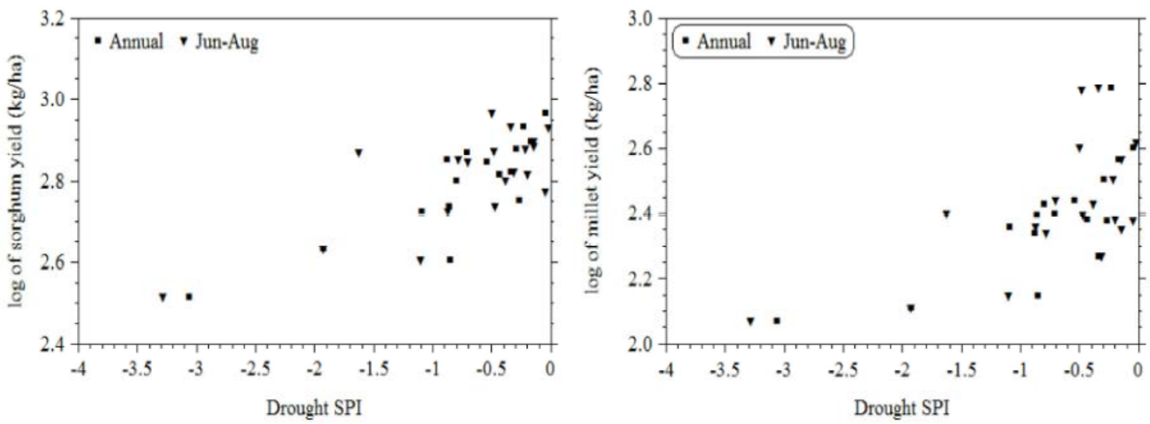

Fig. 4: Scatter plot of crop yield versus drought SPI

Predictability of SPI for Crop Yield: Table 2 gives the Kendall tau test (one-tailed) results of the correlation between standardized anomalies of sorghum and millet yields and SPI values over the period 1961-2009. Higher predictability of SPI for millet yield than for sorghum yield is indicated by the tau values and the significance levels. For millet, the running seasonal SPIs calculated over May to October give significant correlation with yield, with Jun-Aug SPI series showing the most possibility for predication. The results for sorghum indicate chances for yield prediction using seasonal values of SPI calculated over May through September, with best results obtained using Jul-Sep data. It can be seen also that the overall rainfall condition plays an appreciable role in the determination of the yield.

To examine further the role of rainfall anomalies, the crop yield is plotted against negative SPIs, as shown in Fig. 4, for the annual SPI data and for the strongest relationship with seasonal data (Jun-Aug). The high dependence of crop yield on the drought categories indicates clearly that drought is a major yield loss factor for sorghum and millet in this region of Sudan. The relationship is quadratic for the annual SPI data and prominently exponential for seasonal SPI data. It is higher in the case of sorghum compared to millet, expressing respectively 71.8 and 61.7% of the variation in CY using the annual SPI and 55.4 and 42.2% for Jun-Aug SPI data. In mathematical form, the best fits to the relationships are as follows:

Sorghum

Annual: $\log CY = 2.9244+0.2138SPI+0.0268SPI^2$ ($R^2 = 0.718$; ∝ $= 0.0003$)

Jun-Aug: $\log CY = 2.8856\exp(0.0401SPI)$ ($R^2 = 0.554$; ∝ $= 0.0003$)

Millet

Annual: $\log CY = 2.5984+0.3715SPI+0.0648SPI^2$ ($R^2 = 0.619$; ∝ $= 0.0020$)

Jun-Aug: $\log CY=2.5231\exp(0.0658SPI)$ ($R^2 = 0.422$; ∝ $= 0.0026$)

The above equations demonstrate that just a mild drought of the order of $-1.0 < SPI < 0$ is capable of causing a drastic loss of yield. Based on the seasonal equation for sorghum above, for instance, the yield drops from 769 kg/ha at SPI = 0 to as low as 593 kg/ha at SPI = -1.0. Under extreme drought conditions (SPI ≅ -3.0) such as those prevailed in 1984, one could expect sorghum yield to be as low as 360 kg/ha. From the impact point of view on agriculture, these results go in line with the statement made by Hope [39] that "*climate change is expected to considerably reduce cereal production in Sudan*". Elsewhere in East African highland, drought stress is found to induce yield loss under rainfed agricultural conditions [40]. Furthermore, these results support the calculations made by Ali and Lebel [38] that a year with SPI of = -0.5 is considered significantly dry.

CONCLUSIONS

This study attempted to describe how the drought has evolved and how its impact looks like on the yield of two major crops grown in the arid and semi-arid region of Sudan. It has been shown that drought has become more probable during the recent four decades, i.e. it recurs at shorter time intervals. The drought probability curves presented herein allow the estimation of the frequency of occurrence of the different drought severity classes. It has been found that the SPI could provide a useful tool for predicting the crop yield at an early stage of the crop calendar data. Using June-to-August seasonal data of SPI, the good relationship between CY and negative SPIs provides more accurate assessment of the crop yield under drought conditions. This would mean that the impact of drought conditions is more important than of the wet conditions. Furthermore, this suggests that crop yield loss is more likely to occur if the drought is experienced during the early to mid stages of the crop growth period. Drought is one of the most important factors which can cause tremendous economic losses and famine in Sudan due to its direct impact on agriculture. Crop yield declines exponentially with increasing drought. Such information provides a platform for identifying and/or predicting the underlying causes of drought-related impacts on agriculture. The emerging results can be crucial for early warning of disasters associated with rainfall anomalies over the region. Given the formidable threats posed by drought to the region, early assessment system of crop yield can undoubtedly reduce the potential damage at least in relation to food security.

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