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Analysis of Sudan Vegetation Dynamics Using NOAA-AVHRR NDVI Data from 1982-1993

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Abstract: Long term observation of space-borne remote sensing data provides a means to explore temporal variation on the Earth's surface. This improved understanding of variability is required by numerous global change studies to explain annual and inter-annual trends and to separate those from individual events. This knowledge also can be included into budgeting and modeling for global change studies. The study employs daily 8 km NOAA-AVHRR data of the Pathfinder program to study changes in the annual variability of vegetation in Sudan, during the time period from 1982 to 1993. The daily data were processed to improve 15 day composites using an iterative approach including metadata and robust statistical techniques. This study employs GIS to examine the relationship between rainfall and the Normalized Difference Vegetation Index (NDVI) in the context of the Sudan and the value of NDVI is taken as a tool for drought monitoring. The relationship between rainfall and NDVI during 1982 and 1993 in Sudan is examined using spatial analysis methods and a strong positive correlation is found. The correlation is strongest during years of heaviest rainfall, indicating that the relationship between rainfall and NDVI is not a simple linear one. However it is argued that the input data accuracy has affected the quality of the GIS output and the shortcomings of the data are highlighted. The study stresses the need for the use of remote sensing to provide real time data for forecasting. Whilst most countries in the Sahel including Sudan lack the resources (financial, technical and human) to establish the information systems necessary for drought monitoring, this study concludes that remote sensing is the only feasible data source to fill such a gap. NDVI is a valuable first cut indicator for such systems, although analyzing and interpreting its relationship to rainfall is complex and must be based on detailed analysis of its relationship to ecological zone, vegetation type and season.

Key words: NOAA-AVHRR, NDVI time series, drought, rainfall, Sudan

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INTRODUCTION

The majority of Sudan is characterized as semi-arid region and thus susceptible to degradation or even desertification; semi-arid regions are subject to regular seasonal dryness and large inter-annual variability in precipitation. This results in variable vegetation cover on annual and inter-annual timescales, as both natural ecosystems and non-irrigated crops rely on soil moisture derived from seasonal rains or springtime snow melt (Evans and Geerken, 2004; Weiss *et al*., 2004). Figure 1a shows average annual rainfall in Sudan (1982-1993).

Climate-induced variability in semi-arid vegetation is a matter of both ecological interest and economic concern, as strong sensitivity to climate can result in rapid land use change (Vanacker *et al*., 2005) and vulnerability to human-induced degradation (Evans and Geerken, 2004). Climate is one of

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the most important factors affecting vegetation condition. Therefore, evaluation of the quantitative relationship between vegetation patterns and climate is an important object of applications of remote sensing at regional and global scales. The Normalized Difference Vegetation Index (NDVI) is established to be highly correlated to green-leaf density and can be viewed as a proxy for above-ground biomass (Tucker and Sellers, 1986).

The causes of variance of relationship between NDVI and its explanatory variables are known to be spatial variations in properties such as vegetation type, soil type, soil moisture (Ji and Peters, 2004; Foody, 2005). Vegetation cover processes play a crucial role in the water balance over a wide range of spatio-temporal scales (Betts *et al*., 1996). Unfortunately, vegetation dynamics and their interaction with climate are still largely unexplored. Under this framework, satellite data have proved to be very useful for collecting realistic data about land use change and vegetation trends from local to global scale (IGBP-IHDP, 1999). In particular, NOAA-AVHRR (Advanced Very High Resolution Radiometer, onboard National Oceanic and Atmospheric Administration satellites) data can provide useful information on such changes over climatic spatio-temporal scales. The long time series of observations can be very useful for studying vegetation dynamics over inter-annual scales.

Vegetation is one of the most important parameters for human environment assessment and monitoring due to their specific role in geo-sphere, biosphere and atmosphere interactions and plays an important role in global climate change. The vegetation amount controls the partitioning of incoming solar energy in the sensible and latent heat fluxes and consequently changes in vegetation amount will result in long term changes in the global and local climate, which will in turn affect the vegetation growth as a feedback. Vegetation has special characteristics due to its distinct annual and seasonal changes it is a sensitive indicator on the study of global and local environment change caused by climate or human activities. Thus it comes as no surprise that the detection and quantitative assessment of green vegetation is one of the major applications of remote sensing.

In this decade, human beings consequently realized the significance of global change monitoring, several international organizations such as IGBP, HDP and WCP, have lunched very important programs, among which land cover and vegetation change monitoring is a key project. The method for studying land use and vegetation change is developed very quickly as the progress of remote sensing technique in the world.

This study aim to employ GIS to examine the relationship between rainfall and the normalized difference vegetation Index (NDVI) in Sudan, during the time period from 1982 to 1993 and the value of NDVI is taken as a tool for drought monitoring. The objective of this work is to examine whether there is a relationship between rainfall and NDVI in Sudan. Once a positive relationship is established, the work analyses the use of NDVI as a proxy indicator for the occurrence of meteorological drought, that is, when precipitation is significantly below what is normally required by vegetation. This is done by integrating multi-source geo-referenced datasets in a GIS platform in order to facilitate analysis and the generation of cartographic, statistical and modeling products. The final output comprises the spatial analysis products and aims to be useful in the decision making process for drought monitoring and to avert its consequences on lives and livelihoods.

DATA AND ANALYSIS METHODS

The AVHRR satellite, with its 12 year data record (1982-1993) and reasonably spatial resolution (8 km), provides an excellent tool for the analysis of regional vegetation. AVHRR 15 day composites of surface reflectance and maximum NDVI were downloaded from World Meteorological Organization (WMO) website in this study.

We removed noisy pixel areas characterized by exceptionally low NDVI values relatively to their pixel neighborhood. This pixels represented large cloud areas and were replaced by a mean value

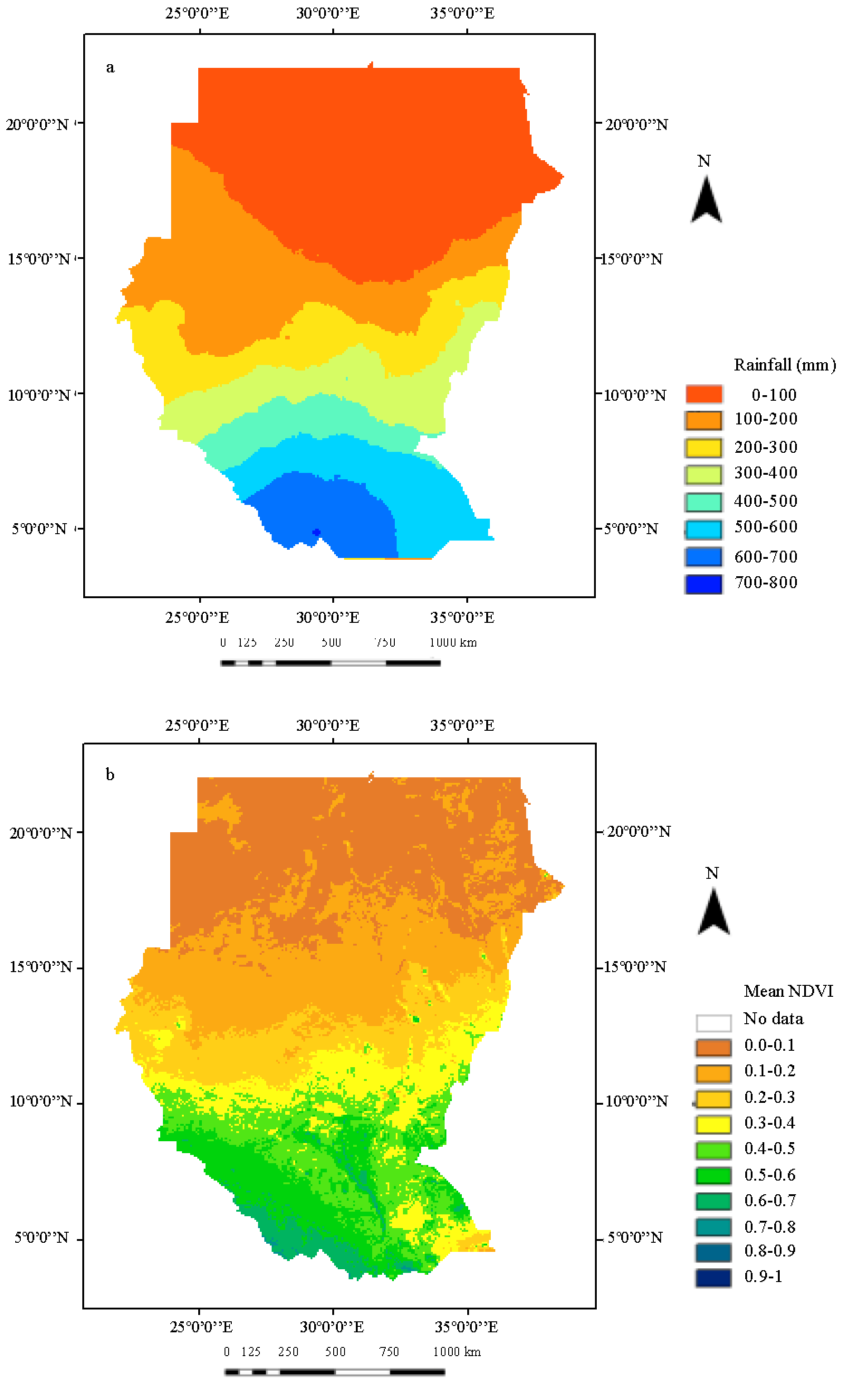


Fig. 1: (a) Average annual rainfall in Sudan (1982-1993) and (b) mean NDVI in Sudan (1982-993)

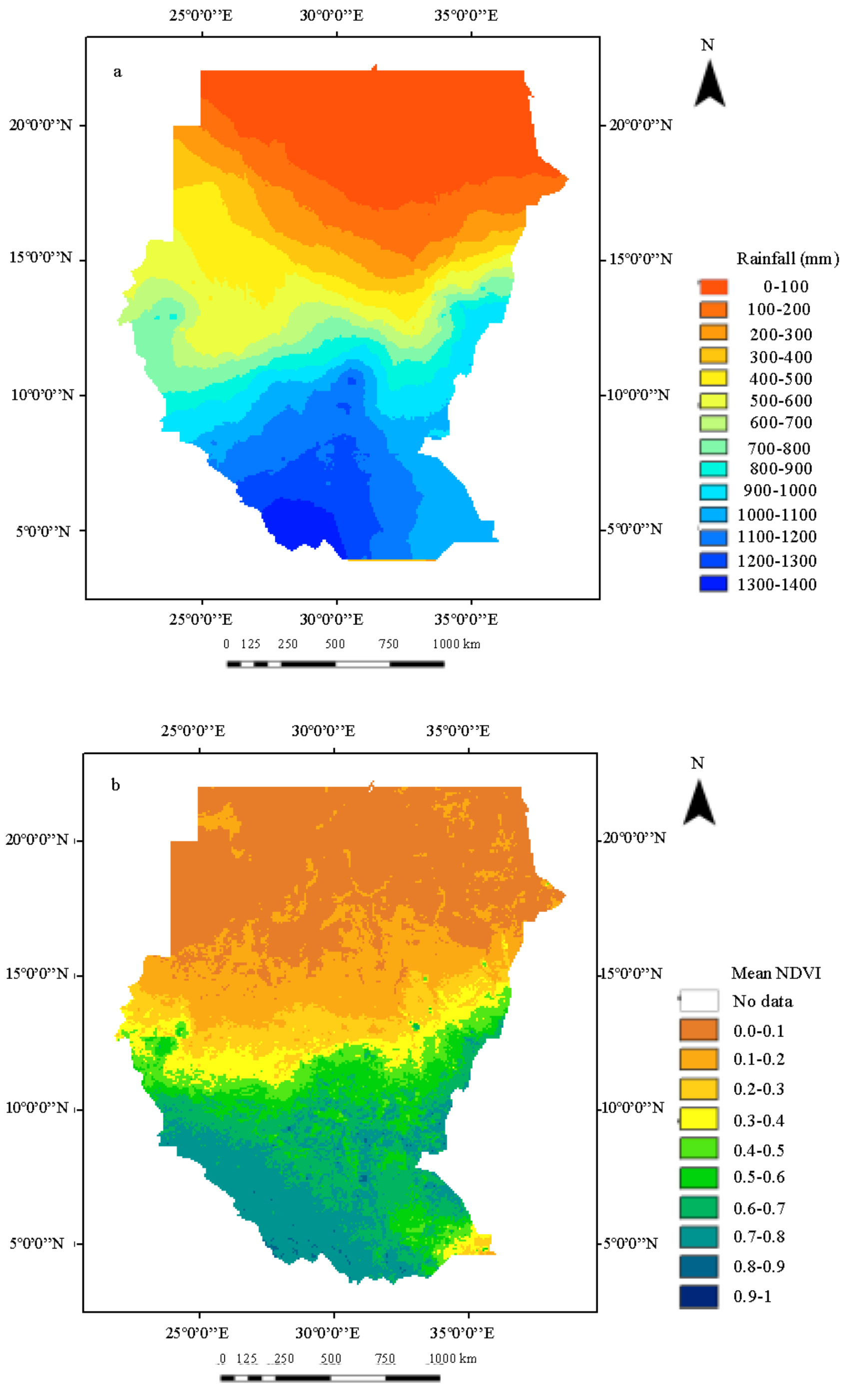


Fig. 2: (a) Average annual rainfall in growing season (JASO) in Sudan (1982-1993) (b) mean NDVI in growing season (JASO) in Sudan (1982-1993)

calculated from the temporal neighboring NDVI layers. The 15 day NDVI composites were integrated to mean monthly and then to mean growing season values for each of the analysis years.

Analysis of seasonal and inter-annual vegetation dynamics and trends of Sudan region is based the normalized difference vegetation index (NDVI). This index is calculated from AVHRR measurements in the visible and infrared bands as follows:

$$\mathrm{NDVI} = (\rho_{nir}-\rho_r)/(\rho_{nir}+\rho_r)$$

Where, ρ_r and ρ_{nir} are the surface reflectance's in the 550-700 nm (visible) and 730-1000 nm (infrared) regions of the electromagnetic spectrum, respectively.

The foundation for using NDVI data in monitoring arid and semi-arid lands was based on a large body of research in 1980s in a wide range of arid land regions, which demonstrated a close relationship between NDVI and rainfall variations on seasonal to inter-annual time scales (Tucker and Nicholson, 1999). This relationship between NDVI and rainfall provided the basis for using time series NDVI data for drought monitoring and development of famine early warning systems in regions with sparse terrestrial rainfall networks (Hutchinson, 1991). The compiled 12 year time series is now exploited to examine the linkages between climate variations and ecosystem dynamics (Lotsch *et al*., 2003) and more recently to study long-term trends in vegetation (Eklundh and Olsson, 2003; Slayback *et al*., 2003). For this study we subset the Sudan country from the continental data set for the period 1982-1993. Figure 1b shows an example of the average of all data for complete years from 1982 to 1993 showing the long-term mean in Sudan. Since the evolution of NDVI in Sudan is closely related to rainfall seasonality, the analysis in this paper only focuses on NDVI patterns during the growing season. The growing season was defined by examining the long-term mean patterns of NDVI. The months of July through October, referred to here as JASO, were selected to represent the average start and end of the growing season. In order to reduce the amount of data to be examined, we created a long-term NDVI climatology by averaging data for all cloud free pixels for July-October months from 1982-1993. The year to year variability in the NDVI patterns was examined by calculating yearly JASO anomalies as follows:

$$\mathrm{NDVI}_\sigma = [((\mathrm{NDVI}_\alpha)/(\mathrm{NDVI}_\mu)-1)100]$$

Where:

NDVI_σ = The respective JASO percent anomalies.

NDVI_α = Individual seasonal JASO means.

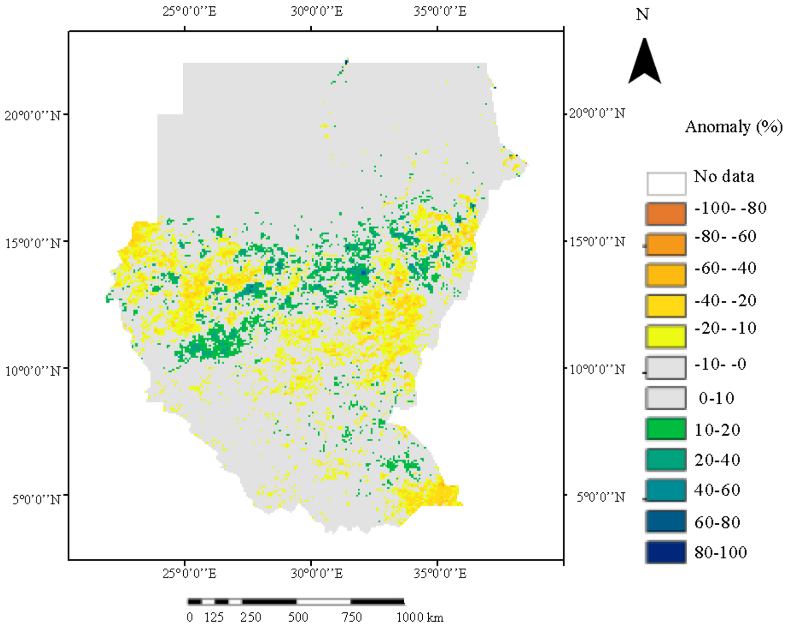
NDVI_μ = The long-term JASO mean (Fig. 2b) and Fig. 2a shows Average Annual Rainfall in Growing Season (JASO) in Sudan in the time period of 1982-1993.

RESULTS AND DISCUSSION

Spatial Patterns

The spatial NDVI anomaly patterns in Sudan are shown in Fig. 3. These series of images show the JASO percent NDVI anomaly patterns for selected growing seasons during the 1982-1993 periods. These series of NDVI anomalies shows the spatial coherence and temporal persistence of drought conditions during the 1980s, a noted feature of the persistence in rainfall departures throughout the recorded climate history of the region (Rasmusson, 1988). In 1982 and 1983, a patchy pattern of below normal NDVI showed the prevalence of drought conditions across the country, especially in the western and eastern areas and most of the pronounced greenness was concentrated in the middle of Sudan. This pattern was enhanced in 1984, 1990 and 1991 and the whole region showed a low NDVI

NDVI Anomaly in growing season (JASO) in Sudan (1982)



NDVI Anomaly in growing season (JASO) in Sudan (1983)

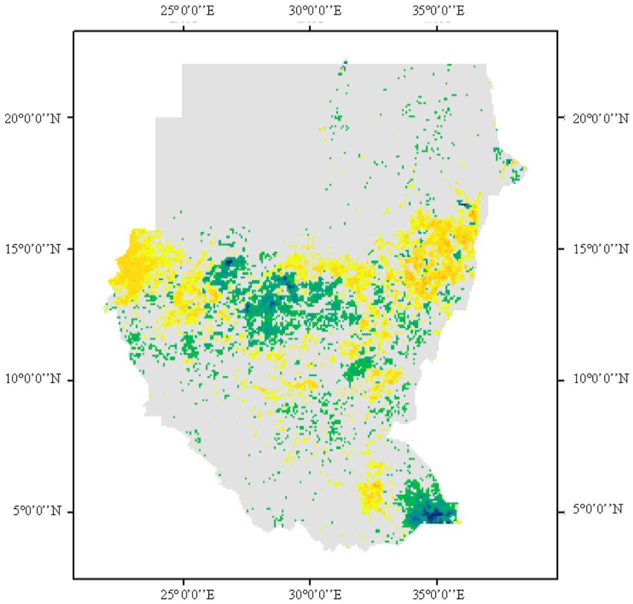
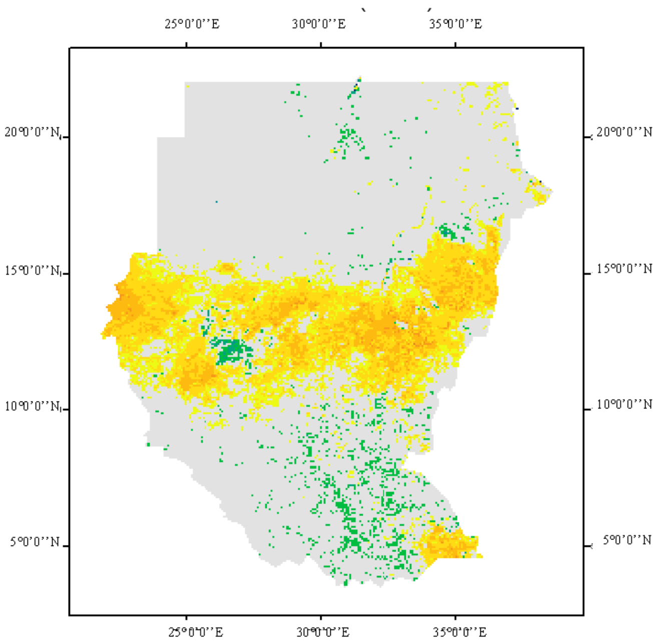


Fig. 3: Continued

NDVI Anomaly in growing season (JASO) in Sudan (1984)



NDVI Anomaly in growing season (JASO) in Sudan (1985)

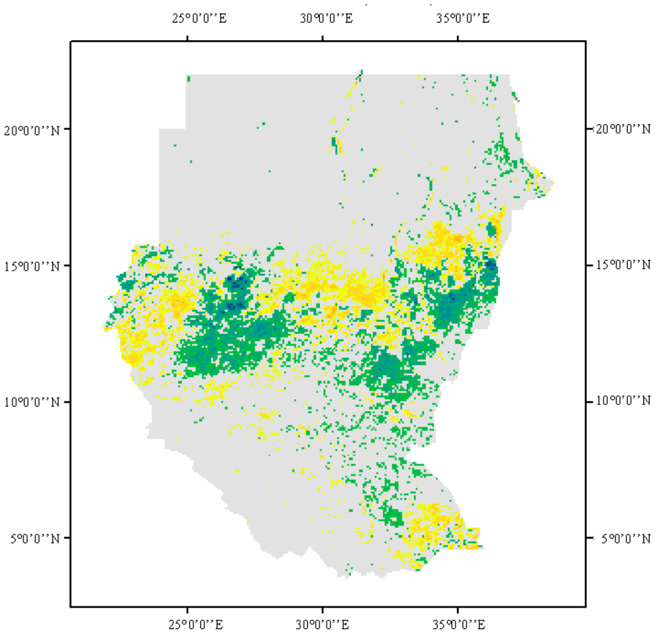
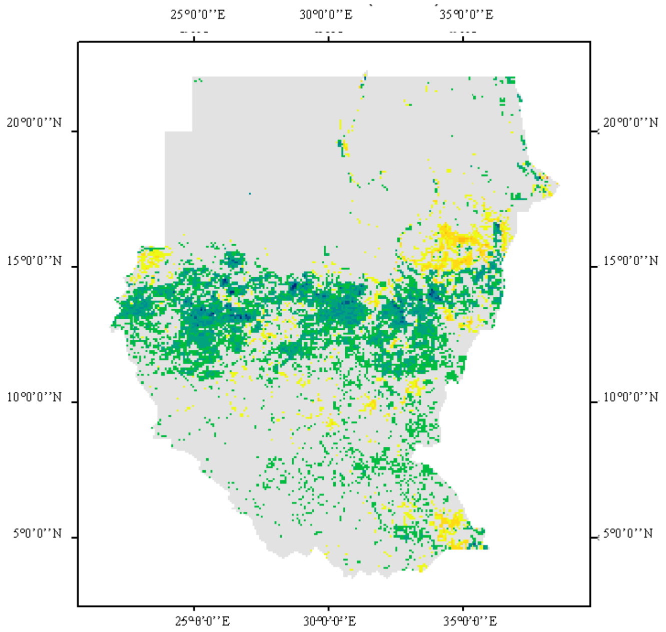


Fig. 3: Continued

NDVI Anomaly in growing season (JASO) in Sudan (1986)



NDVI Anomaly in growing season (JASO) in Sudan (1987)

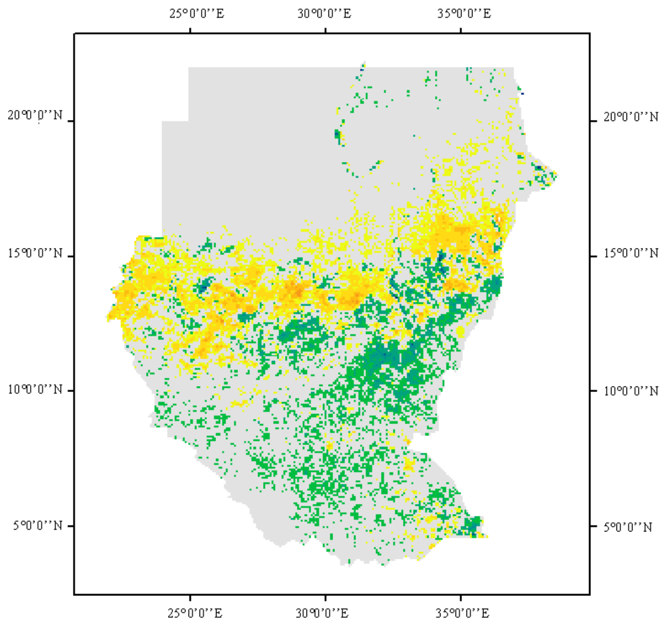
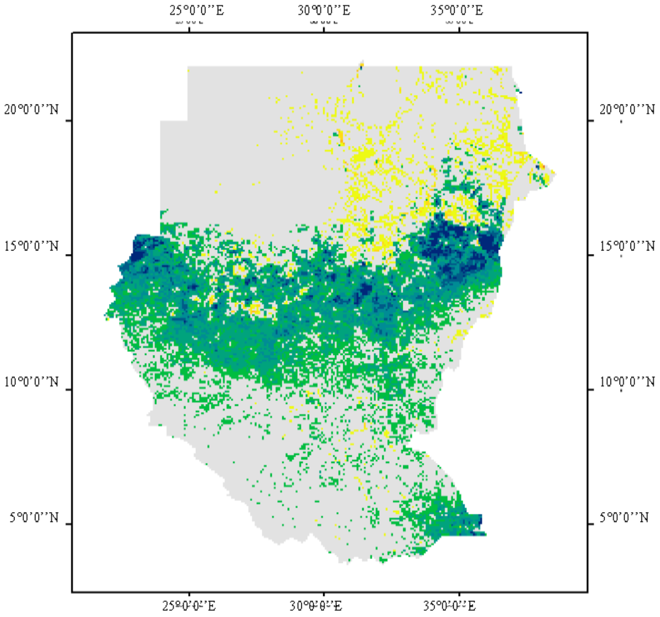


Fig. 3: Continued

NDVI Anomaly in growing season (JASO) in Sudan (1988)



NDVI Anomaly in growing season (JASO) in Sudan (1989)

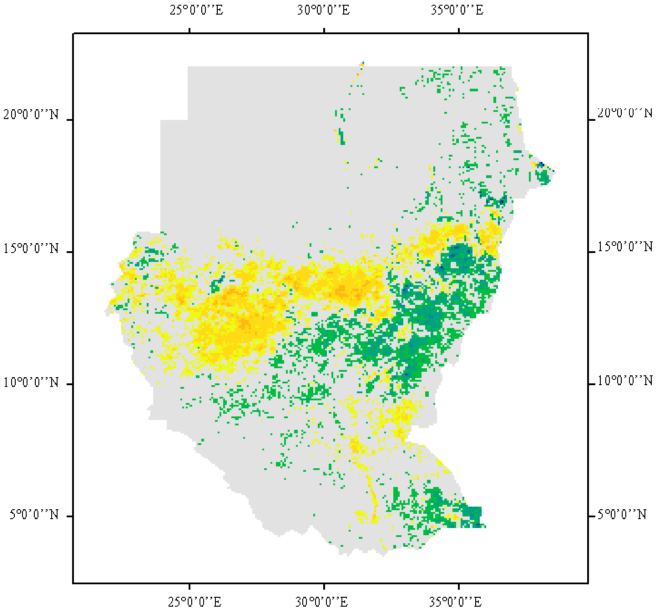
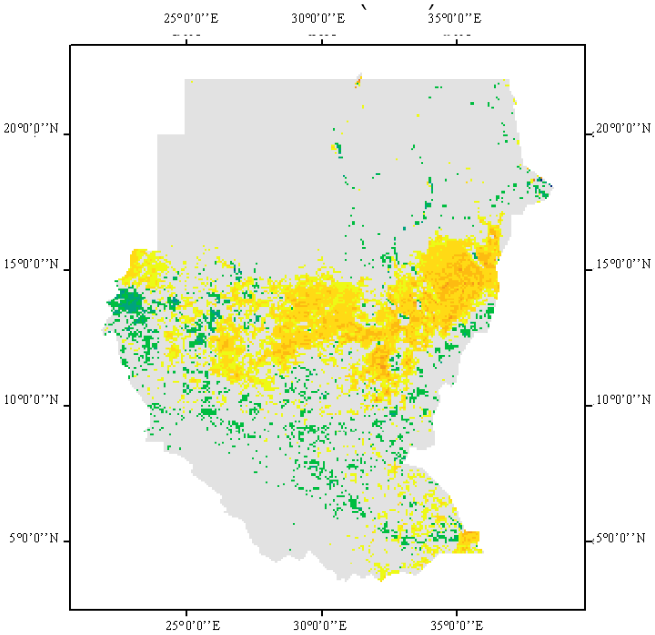


Fig. 3: Continued

NDVI Anomaly in growing season (JASO) in Sudan (1990)



NDVI Anomaly in growing season (JASO) in Sudan (1991)

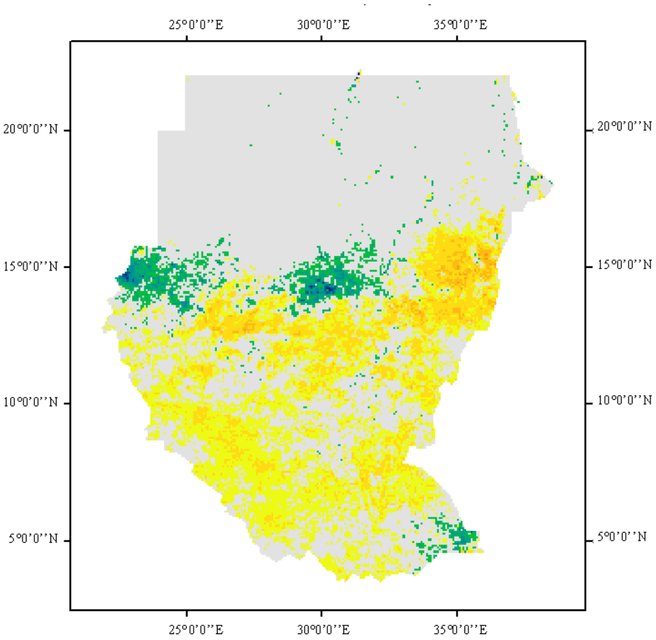
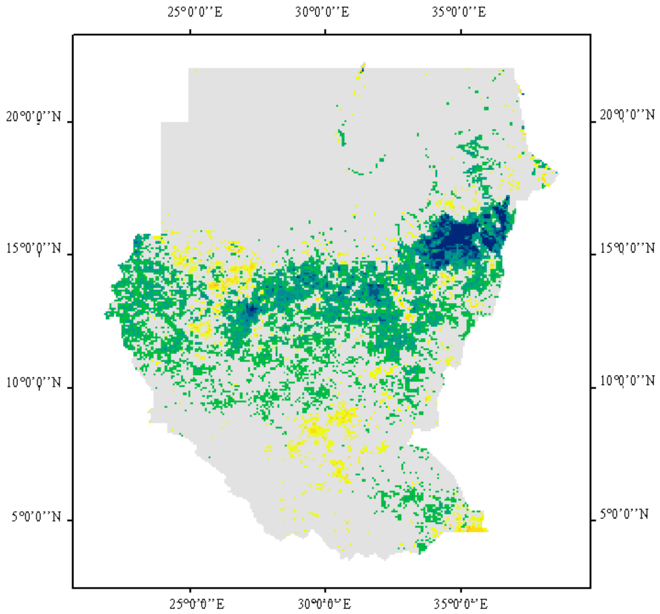


Fig. 3: Continued


NDVI Anomaly in growing season (JASO) in Sudan (1992)

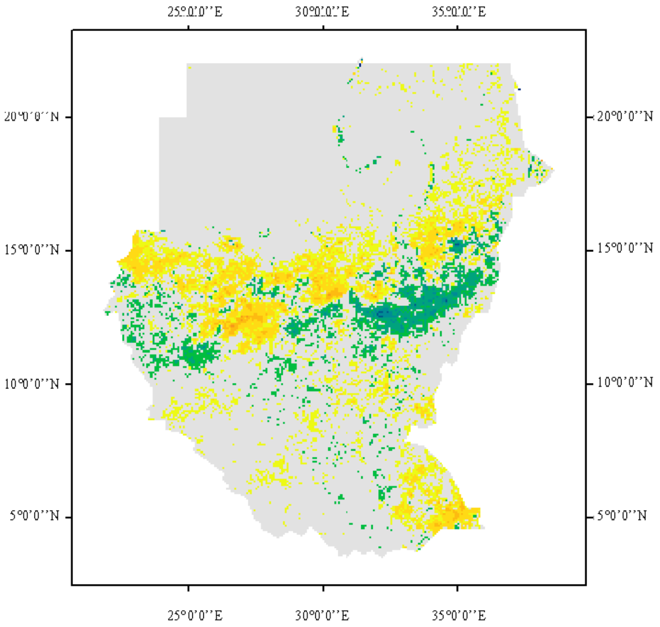

NDVI Anomaly in growing season (JASO) in Sudan (1993)

Fig. 3: NDVI anomaly patterns in the growing season (JASO) during the time period of 1982-1993

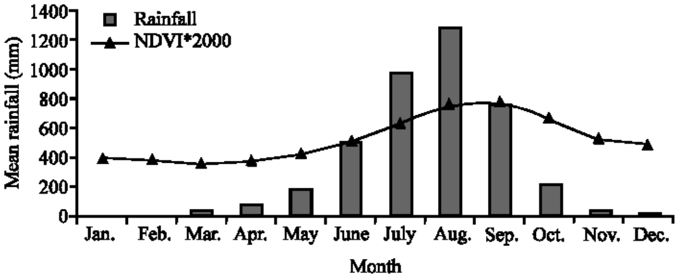


Fig. 4: Mean monthly NDVI and monthly rainfall in Sudan during (1988)

level of below normal conditions and the most extreme negative departures reached 80% lower than the normal conditions. These magnitudes of negative departures agreed with rainfall departure patterns for the region shown by Nicholson (1985). In 1985, it still showed negative departures in NDVI ranging between 10 and 40%. Region-wide drought conditions returned in the growing season in 1987 and the negative departures in NDVI were on the order of 10-60%, which were concentrated from the east to the west in the central Sudan, although it showed normal to above normal vegetation conditions in the most part of south-east Sudan. During the growing season in 1988 and 1992, the whole region showed a high NDVI level of above normal vegetation conditions and had positive anomalies ranging between 20 and 100%. The above normal greening in 1988 was associated with positive rainfall anomalies during the months of August, September and October (Nicholson *et al*., 1996). Presented in Fig. 4 Monthly NDVI and mean monthly rainfall in Sudan in 1988.

Monthly Time Series Patterns in the Time Period from 1982 to 1993

The monthly time series of NDVI and rainfall from 1982 to 1993 in Sudan are shown in Fig. 5 and 6. On average most of the rainfall occurs between July and October, with a maximum in August. Approximately 83% of the annual rainfall falls between the July and October (Lamb, 1980), so averaging NDVI data for these months fairly represents the growing season for the region. From Fig. 7, monthly relationship of rainfall and NDVI for that time series in Sudan showed that the NDVI values had a correlation (0.598) as a linear relation to the rainfall,, Both rainfall and NDVI show a maximum in August-September.

Mean monthly NDVI ranged from 0.2 to 0.35 across the country throughout the time series in Fig. 8 and the NDVI values greater than 0.2 corresponded well with the rainy season from July to October. These high NDVI values persisted towards the end of year in November and December indicating the lagged response of vegetation to rainfall in this region (Nicholson *et al*., 1990). The extent of these values across the region is an indicator of rainfall conditions.

The low NDVI values lower than 0.3 were distributed from the east to the west in the central Sudan in 1984, 1990 and 1991, indicating the prevalence of drought conditions. The extent and duration of these NDVI values can be used as an indicator of the strength and duration of the rainfall to produce mechanisms associated with the ITCZ (Intertropical Convergence Zone) since vegetation growth in the region is primarily controlled by rainfall, although other factors including potential evaporation influence the fluctuating boundary (Milich and Weiss, 2000).

During the growing season in 1988 there was an easing of the severe drought conditions with above normal NDVI, following a good rainy season in Sudan. From 1989 to 1993 it showed low NDVI values of below normal NDVI except 1992. This is a western extension of the drought that affected eastern Africa in 1991-1993.

The persistence and spatial coherence of drought conditions during the 1980s is well represented by the NDVI anomaly patterns and corresponds with the documented rainfall anomalies in Sudan during the time period from 1982 to 1991. The time series was dominated by low NDVI values of

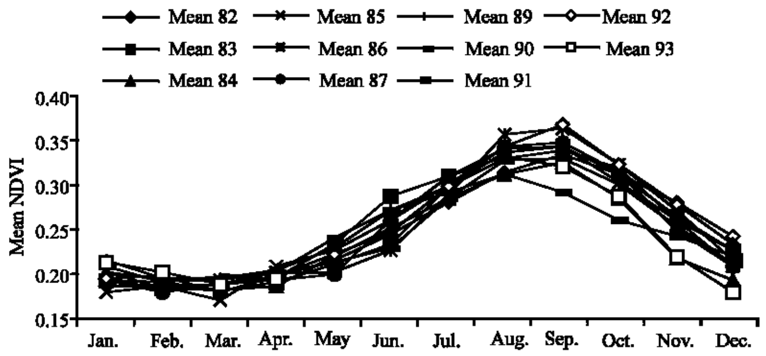


Fig. 5: Mean monthly NDVI in Sudan (1982-1993)

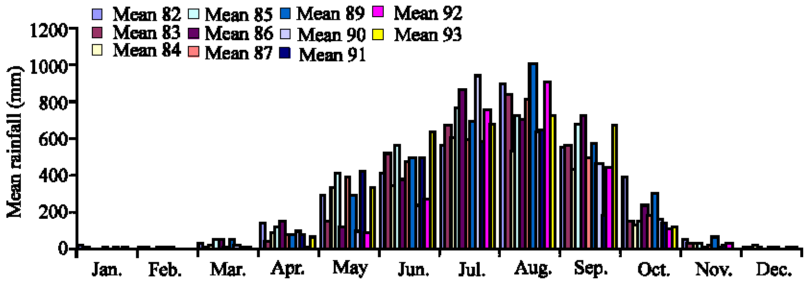


Fig. 6: Mean monthly rainfall in Sudan (1982-1993)

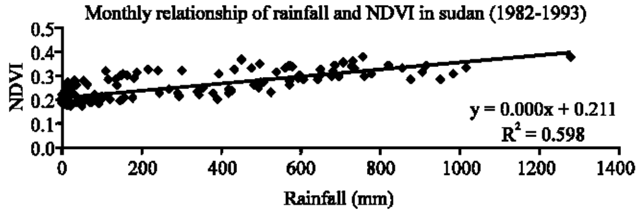


Fig. 7: Scatter plot of the rainfall and NDVI in Sudan (1982-1993)

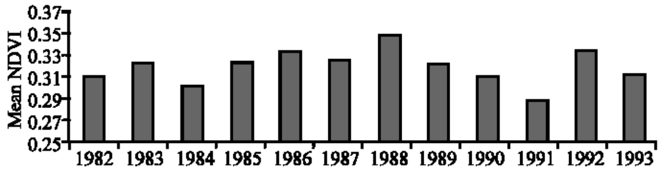


Fig. 8: Average NDVI in the time period of July-October in Sudan (1982-1993)

below normal conditions, with 60% of the years showing below normal NDVI conditions and the severest departures in NDVI occurred in 1984, which situation persisted for 6 years in the time series, with exceptions in years of 1983, 1985, 1986 and 1988. These patterns are shown in Table 1 and Fig. 9. Between 1987 and 1993, 71% of the years showed low NDVI values of below normal vegetation conditions, but it showed high NDVI values of above the long-term mean in 1988 and 1992 (Fig. 9).

Table 1: NDVI anomaly scores (+/-) showing persistence patterns of above normal or below normal vegetation condition

Year	82	83	84	85	86	87	88	89	90	91	92	93
Anomaly (+/-)	-	+	-	+	+	-	+	-	-	-	+	-

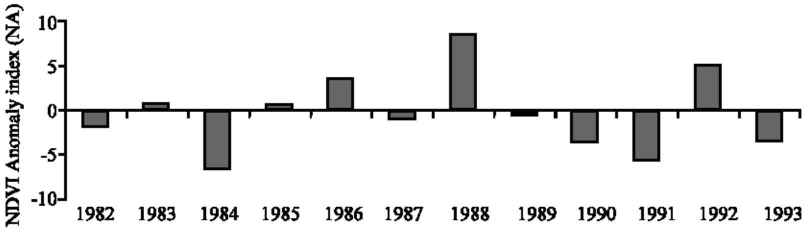


Fig. 9: NDVI Anomaly index (NAI) in Sudan (1982-1993)

CONCLUSIONS

The persistent nature of these patterns in NDVI in the time series of 1982-1991 is in agreement with the historical patterns of rainfall anomalies in the region. The NDVI time series data indicated that there was a gradual and slow but persistent recovery from the peak drought conditions that affected the region in the early to mid-1980s. It was corroborated by the decrease in the magnitudes of negative rainfall departures from 1984 to 2000 (Nicholson, 2001). The correlation between the NDVI and rainfall anomaly time series for the 1981-2000 period is positive and significant (R = 0.78) indicating the close coupling between rainfall and land surface response patterns over the region. The large scale and coherent changes in anomaly patterns between 1984 and 1993, a difference of 10 years might suggest some large-scale climatic influence on Sudan vegetation dynamics. In the process it has been demonstrated that in regions such as Sahelian Africa, where there is a dearth of digital data from which useful monitoring and management information can be drawn, GIS using remotely sensed data obtained from satellites is technically feasible. Furthermore, it is a relatively low cost system, as it uses free data for input and can be run on an ordinary desktop computer. The training required for running the system is also limited since once set, it uses pre-processed data inputs. The analysis has shown that NDVI is a complex indicator, difficult to interpret, as well as being a delayed outcome indicator. NDVI is a crude indicator of drought risk and needs to be related to other socio-economic and bio-physical data in order to be useful. The precision of NDVI as a vegetation index also needs to be strengthened through establishing its relationship to the growing season, for each specific climatic zone, on the basis of local vegetation and crop types. The GIS can help in understanding and analyzing complex environmental situations, such as the Sudan, even where data is relatively scarce and there is a limited knowledge base. The GIS tools used, however, have highlighted the shortcomings of the data sets and the method. For any system for monitoring environmental change, the objectives need to be specific. In particular, it should be clear whether the aim is to monitor environmental change across years, in which case a long time-series data is required, or whether it is to monitor vegetation and crop changes within seasons for purposes of drought warning. An effective drought warning system using NDVI should take advantage of remote sensing sources in using real time data, in order to facilitate timely decision making. If this were to be done, NDVI can be a valuable first cut indicator and provide a key input for cost-effective, reliable and timely drought monitoring systems. The patchy nature of the increase in NDVI will require the use of higher spatial resolution data from LANDSAT, SPOT and MODIS in order to determine the driving factors of change at the landscape scale. Further studies examining combined climate data including rainfall and sea surface temperature patterns and continued gathering of long-term satellite data sets will help in understanding the long-term changes in the climate and land surface conditions of this sensitive semi-arid environment.

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