ELSEVIER
Journal of Arid Environments 63 (2005) 596–614
Journal of Arid Environments
www.elsevier.com/locate/jnlabr/yjare

Analysis of Sahelian vegetation dynamics using NOAA-AVHRR NDVI data from 1981–2003

A. Anyamba[a,b,*], C.J. Tucker[b]

[a]*Goddard Earth Sciences Technology Centre, University of Maryland Baltimore County, USA*
[b]*NASA/Goddard Space Flight Center, Biospheric Sciences Branch, Code 614.4, Greenbelt, MD 20771, USA*

Abstract

Remotely sensed measurements from NOAA-AVHRR expressed as normalized difference vegetation index (NDVI) have generated a 23-year time series appropriate for long-term studies of Sahel region. The close coupling between Sahelian rainfall and the growth of vegetation has made it possible to utilize NDVI data as proxy for the land surface response to precipitation variability. Examination of this time series reveals two periods; (a) 1982–1993 marked by below average NDVI and persistence of drought with a *signature* large-scale drought during the 1982–1985 period; and (b) 1994–2003, marked by a trend towards 'wetter' conditions with region-wide above normal NDVI conditions with maxima in 1994 and 1999. These patterns agree with recent region-wide trends in Sahel rainfall. However taken in the context of long-term Sahelian climate history, these conditions are still far below the wetter conditions that prevailed in the region from 1930 to 1965. These trend patterns can therefore only be considered to be a gradual recovery from extreme drought conditions that peaked during the 1983–1985 period. Systematic studies of changes on the landscape using high spatial resolution satellite data sets such as those from LANDSAT, SPOT and MODIS will provide a detailed spatial quantification and description of the recovery patterns at local scale.

Keywords: NOAA-AVHRR; NDVI time series; Sahel; Drought

*Corresponding author. NASA/Goddard Space Flight Center, Biospheric Sciences Branch, Code 614.4, Greenbelt, MD 20771, USA. Tel.: +1 301 614 6001; fax: +1 301 614 6015.
E-mail addresses: assaf@ltpmail.gsfc.nasa.gov (A. Anyamba), compton@ltpmailx.gsfc.nasa.gov (C.J. Tucker).

0140-1963/$ - see front matter
doi:10.1016/j.jaridenv.2005.03.007

1. Introduction

The Sahel is a semi-rid region stretching approximately 5000 km across northern Africa from the Atlantic Ocean in the west to near the Red Sea in the east and extending roughly from 12°N to 18°N. This region forms an ecological transition between the Sahara desert to the north and the humid tropical savanna to the south (Le Houerou, 1980). The characteristic vegetation types constitute mixtures of grasslands, shrubs and thorny trees. In general, the precise geographic location of the Sahel is difficult to distinguish because these physical characteristics change over time and space (Le Houerou, 1980; Monod, 1986). Generally, the northern limit is defined by the 100–200 mm/year rainfall contour and the southern limit by the 400–600 mm/year as shown in Fig. 1a. The rainfall regime in the region is characterized large variations from year to year compounded by persistent long-term drought since the early 1970s. Since the mid 1960s this region has experienced a systematic decrease in rainfall and wide spread droughts affecting the larger area of Sub-Saharan Africa (Tanaka et al., 1975; Bunting et al., 1976; Nicholson, 1979; Lamb, 1982). These large variations and trends in rainfall have attendant impacts on vegetation dynamics and availability of food and fiber for the people of the region. The peak of the cumulative decreasing rainfall trend resulted in a large-scale drought during the 1982–1985 period resulting in large-scale food shortages and famine (Olsson, 1993; Glantz, 1994). The development and prosperity of the region has therefore been largely dependent on fluctuations in rainfall through the historical times. Over the last several years, the region has experienced an increase in rainfall compared to the amounts in the late 1960s, prior to the onset of the prolonged drought in the 1970s (Bell et al., 2000; Hulme et al., 2001; Nicholson, 2001). In this paper, we utilize time series satellite vegetation measurements from National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) sensor to examine the variability and trends of land surface conditions in the Sahel as represented by vegetation index data from July 1981 to December 2003.

2. Data and analysis methods

Analysis of seasonal and interannual vegetation dynamics and trends of Sahel region is based the normalized difference vegetation index (NDVI) data derived from measurements made by the AVHRR sensor aboard NOAA polar orbiting satellite series (NOAA-7, 9, 11, 14, 16). This index is calculated from AVHRR measurements in the visible and infrared bands as

$$NDVI = (\rho_{\mathrm{nir}} - \rho_{\mathrm{r}})/(\rho_{\mathrm{nir}} + \rho_{\mathrm{r}}), \tag{1}$$

where ρ_{r} and ρ_{nir} are the surface reflectances 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 is based on a large body of research in the 1980s in a wide range of arid land regions

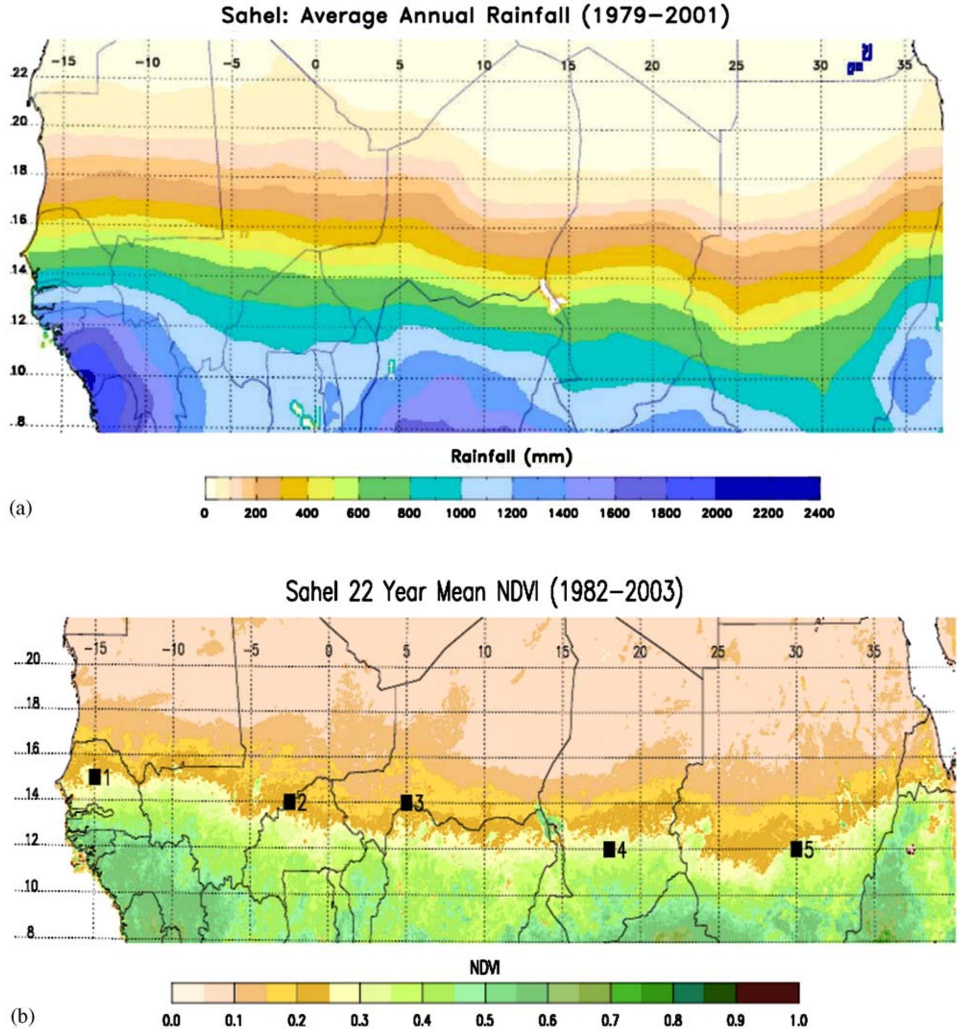

Fig. 1. Average annual rainfall for the Sahel region (1979–2001) derived from a blend of satellite measurements and rain gauge network (a—top). Long-term mean NDVI for the Sahel region (1982–2003) showing the transition from wet savanna with values of 0.5 to dry savanna with values 0.2 close to the Sahara desert (b—bottom). The numbered locations indicate sites where NDVI data were extracted to examine the temporal variations and trends in NDVI from 1981 to 2003.

demonstrating the close relationship between NDVI and rainfall variations on seasonal to interannual time scales (Gray and Tapley, 1985; Tucker et al., 1985; Justice and Hiernaux, 1986; Townshend and Justice, 1986; Nicholson et al., 1990; Tucker et al., 1991; Tucker and Nicholson, 1999; Rasmusson, 1998). 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 (Henricksen and Durkin, 1986; Hielkema et al., 1986; Tucker et al., 1986; Hutchinson, 1991). Although, seasonal variations in atmospheric water vapor (Justice et al., 1991), atmospheric aerosol content (Vermote et al., 1997) and large areas of bare soil in arid and semi-arid areas may cause significant variations in NDVI not associated with actual vegetation cover (Huete, 1985; Huete and Tucker, 1991), this index has been shown to be a good indicator of various vegetation parameters, including green leaf area index (LAI), biomass, percent green cover, green biomass production and the fraction of absorbed photosynthetically active radiation (Tucker, 1979; Asrar et al., 1984; Sellers, 1985). The compiled 23-year time series is now exploited to examine the linkages between climate variations and ecosystem dynamics especially those associated with El Nino/Southern Oscillation phenomenon (Anyamba and Eastman, 1996; Myneni et al., 1996; Anyamba et al., 2002; Lotsch et al., 2003) and more recently to study long-term trends in vegetation (Eklundh and Olsson, 2003; Slayback et al., 2003; Nemani et al., 2003).

Data used in this study were processed by the GIMMS group at NASA's Goddard Space Flight Center, as described by Tucker et al. (1994, 2005). For this research, NDVI monthly data at 8 km spatial resolution were generated from already processed 15-day NDVI composites using the maximum value compositing procedure to minimize effects of cloud contamination, varying solar zenith angles and surface topography (Holben, 1986). In addition calibration based on invariant desert targets has been applied to the original data to minimize the effects of sensor degradation (Los, 1993). Stratospheric aerosol corrections were applied to remove the effects of the eruptions of El Chichon from 1982–1984 and Mt. Pinatubo from 1991 to 1993 (Vermote and El Saleous, 1994). For this study, we subset the Sahel region covering the domain 20°W–40°E and 8°N–22°N, from the continental data set for the period July 1981–December 2003. Fig. 1b shows an example of the average of all data for complete years from 1982 to 2003 showing the long-term mean for the region. Since the evolution of NDVI in the Sahel region is closely related to rainfall seasonality, we concentrated our analysis in this paper only on NDVI patterns during the growing season. The growing season was defined by examining the long-term mean patterns of both rainfall and NDVI shown in Fig. 2a and b, respectively, and with reference to long-term patterns of annual average rainfall distribution (Lamb, 1980). The months of July through October, referred to here as JASO, were selected to represent the average start and end of the growing season, even though the start of the growing season may vary across the region from year to year. In order to reduce the amount of data to be examined, we created a long-term NDVI climatology (1981–2003) by averaging data for all cloud-free pixels for July–October months from 1981–2003. The year to year variability in the NDVI patterns was examined by calculating yearly JASO anomalies as follows:

$$NDVI\sigma = [((NDVI\alpha)/(NDVI\mu) - 1)100], \quad (2)$$

where $NDVI\sigma$ are the respective JASO percent anomalies, $NDVI\alpha$ are individual seasonal JASO means and $NDVI\mu$ is the long-term JASO mean (shown in Fig. 2c). All means and anomalies were calculated taking into account cloud and other

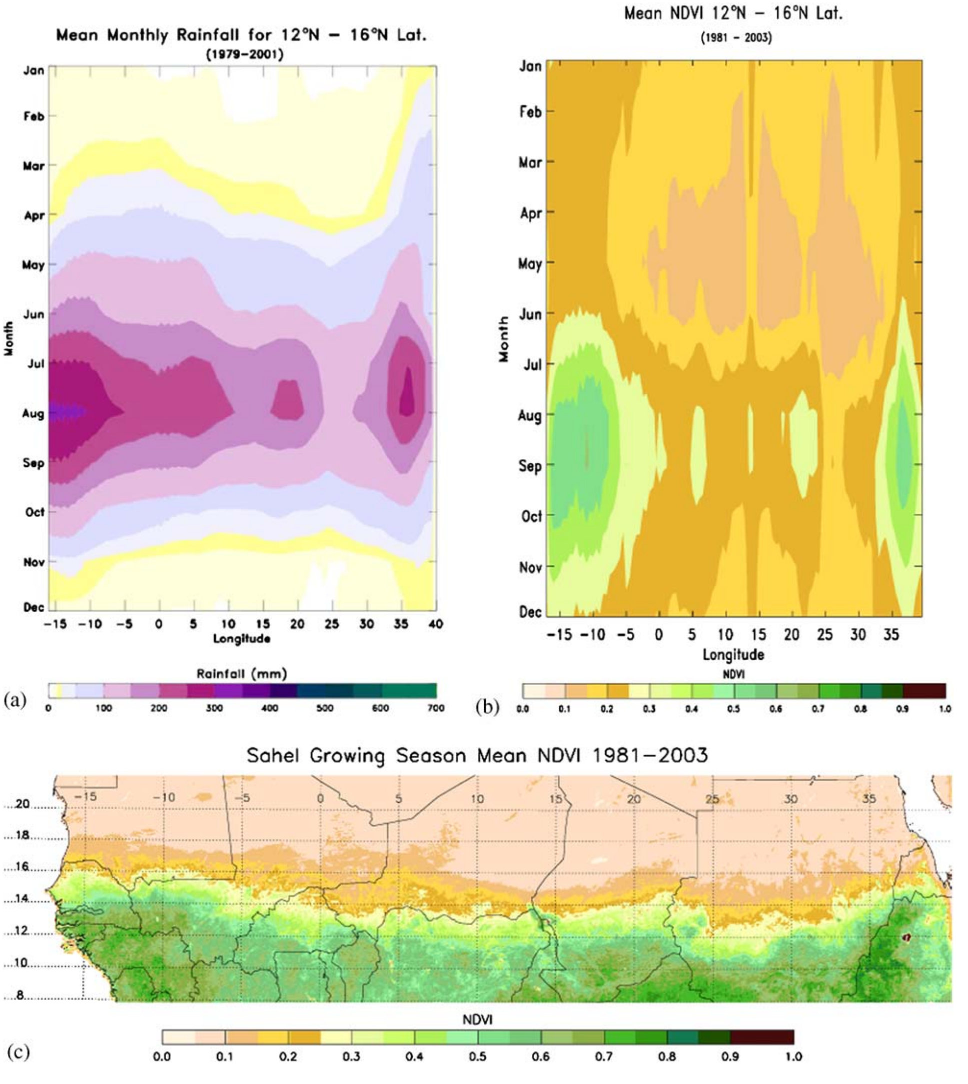

Fig. 2. Hovmoller diagrams of climatological monthly rainfall for the Sahel region averaged between 12°N and 16°N from 15°W to 40°E showing a uni-modal rainfall distribution pattern. The rainfall occurs from July to October; the rest of the year is dry (a). Corresponding monthly climatology for NDVI for the same spatial domain is shown in (b). Note the close correspondence between rainfall and NDVI during the growing season from July to October. In (c) long-term mean NDVI for the Sahel growing season created by averaging all July, August, September, October (JASO) data from 1981 to 2003 shows the gradient of decreasing NDVI values from wet savannah environment in the south to arid savanna bordering the Sahara desert in the north.

quality control flags. Hovmoller (time longitude) diagrams were generated to summarize and examine the space–time features of seasonal evolution and the anomaly patterns for the entire monthly time series from 1981 to 2003.

In addition time series data were extracted for 5 locations across the Sahel shown in Fig. 1b by averaging pixels in a 100×100 km block centered on each location to examine the specific temporal variation and trends for the period 1981–2003. An index of historical rainfall anomalies for the region (20°W–35°E, 10°N–20°N) was derived from the Global Historical Climatology Network (GHCN) (1930–2000) for comparison with NDVI time series data and to place the current patterns of vegetation variability within the long historical context of the region. A regional trend surface map was derived by fitting linear trend to annual average data to characterize the magnitude of changes in NDVI over this time period (Slayback et al., 2003).

3. Results and discussion

3.1. Annual mean rainfall and NDVI patterns

Fig. 2a and b show the mean annual evolution of rainfall and NDVI, respectively. The rainfall data is based on Global Precipitation Climatology Project (GPCP) data which blends satellite rainfall estimate with gauge network data (Huffman et al., 1995). Data shown here is averaged for the latitude band range from 12°N to 16°N spanning the entire width of the region from 15°W to 40°E. This illustration provides a generalized overview of the annual evolution of the Sahel rainy season, showing that the region has one rainy season which corresponds to the annual march of rains northwards across Africa with the movement of the Intertropical Convergence Zone (ITCZ) during the summer months.

On average most of the rainfall (200–300 mm/month) occurs between July and October, with a maxima 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. Both western and eastern parts of region receive higher rainfall than the central region, indicating the influence of Atlantic maritime conditions on the rainfall to west and combined Indian Ocean maritime and orographic influences to the east from the Ethiopian highlands. These rainfall patterns correspond well with the NDVI annual cycle shown in Fig. 2b. Both rainfall and NDVI show a maximum in August–September, with the highest values recorded at the western and eastern extremes of the region. Both rainfall and NDVI contours narrow inland to the central part of the region indicating a much drier environment at the heart of the Sahel region.

3.2. Monthly time series patterns 1981–2003

The monthly time series for the region are presented as a hovmoller diagram from July 1981 to December 2003 as shown in Fig. 3a. Vegetation seasonality is shown by the extent of the 0.2–0.3 NDVI values across the region throughout the series. The flush of green vegetation with values greater than 0.2 NDVI corresponds well with the Sahel rainy season from June to October. This pattern shows the green up of

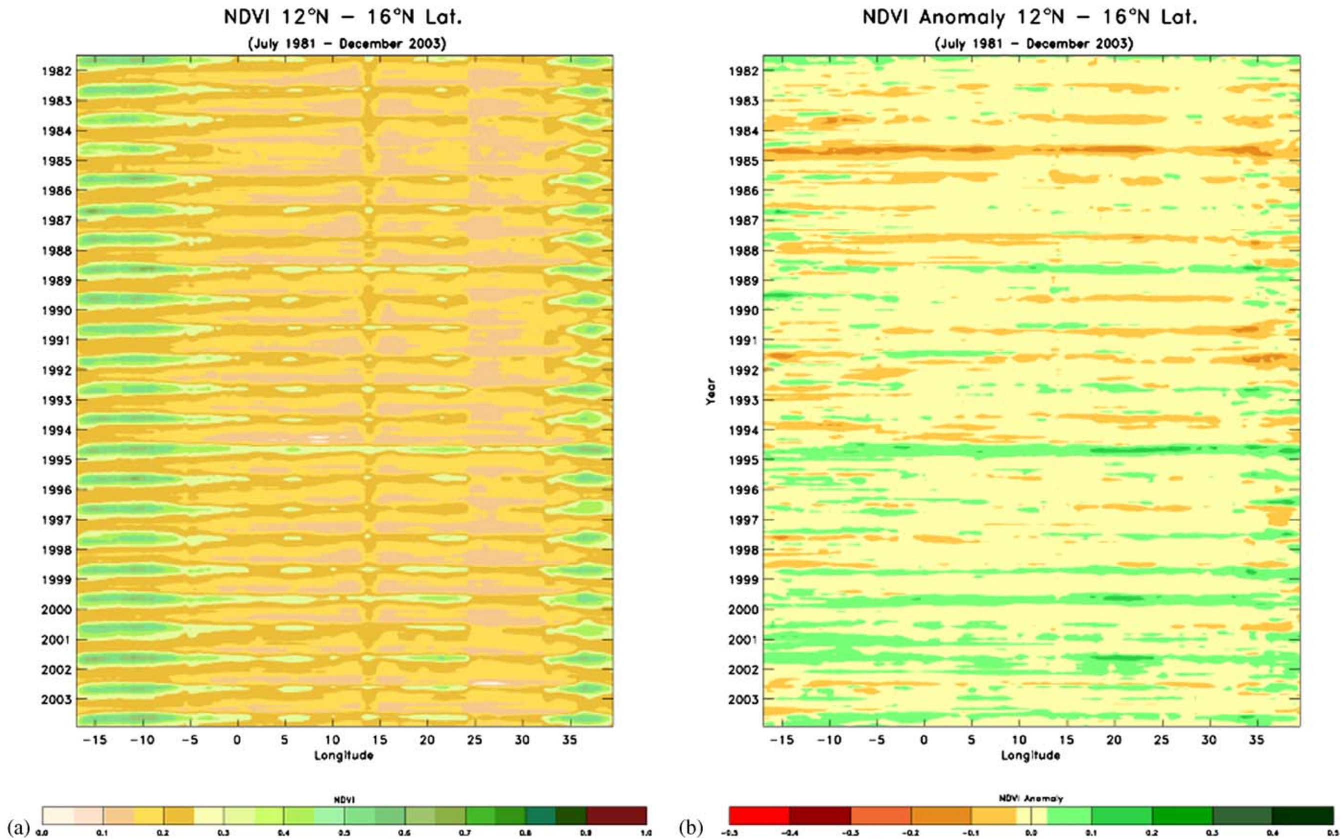

Fig. 3. Time-longitude section of monthly NDVI from July 1981 to December 2003 averaged between 12°N–16°N from 15°W to 40°E in (a) showing the monthly evolution of NDVI and in (b) the corresponding NDVI anomalies showing dry conditions in the 1980s and greener than normal conditions from mid-1990s to 2003.

vegetation corresponds well with rainfall patterns previously shown in Fig. 2a, which is associated with the annual excursions of the ITCZ into this region. These high NDVI values persist towards the end of the 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. During the growing seasons from 1983 to 1985, the "green wave" indicated here by 0.3 extend only as far as 5°W and to 35°E from the eastern side. Most of the region from Senegal to eastern Sudan shows less than 0.2 NDVI values indicating the prevalence of drought conditions. These low NDVI values persist thorough out the region between ~3°W and ~33°E from 1983 to 1987. From the 1988 growing season to 2003 the 0.2 to 0.3 NDVI values extend across most of the region during each of the growing seasons except for the region between ~23°E and ~30°E covering central Chad to central Sudan which has values less than 0.2 NDVI from 1990–1992 and from 2001–2002. This region-wide extent of the 0.2 NDVI values across the region since 1988 indicates slight improvement in vegetation conditions across the region. The extent and duration of these NDVI values can thus be used as an indicator of the strength and duration of the rainfall producing mechanisms associated with the ITCZ since vegetation growth in the region is primarily controlled by rainfall, although other factors including potential evaporation influence the fluctuating boundary towards the Sahara (Milich and Weiss, 2000).

Further examination of vegetation conditions in the Sahel is illustrated by the time-longitude section of NDVI anomalies in Fig. 3b and provides clear evidence of these patterns. The anomalies show departures from the long-term monthly means (1982–1999) by month for the whole satellite record period from July 1981 to December 2003. The significant anomaly patterns during this period indicate above normal NDVI during the 1981 period predominantly over western half of the region suggesting that rainfall was higher in 1981 compared to 1982–84 period, although still below the historical long-term average (Nicholson, 1985). Since 1982 to 1987 most of region shows below normal NDVI, with the most severe conditions from late 1983 to late 1985 covering the whole region with NDVI anomaly values ranging from -0.1 to -0.3 indicating persistent and widespread drought conditions. The regional extent of this drought patterns is reflective of the continental scale nature of this drought that affected all countries in the Sahel region extending as far as east Africa. During the 1988 growing season there is an easing of these severe drought conditions with above normal NDVI especially over the central Sahel region from 5°E to 35°E, following a good rainy season in the region. From 1990 to 1993 most of the region shows near normal conditions except for the eastern part of the Sahel which shows below normal NDVI from late 1990 to early 1993. This dry eastern sector is a western extension of the drought that affected eastern Africa in 1991–1992. The last period from 1994 to 2003 is dominated by normal to above normal NDVI with the highest values during the growing seasons of 1994, 1999–2001. The above normal conditions extend across the whole region perhaps suggesting that the causal mechanisms of severe drought as in 1984 and greener conditions as in 1994 are large scale in nature affecting the continental extent of the

Sahel region (Giannini et al., 2003). During the recent years only 2002 shows below normal conditions mainly over the western portion of the region with a return to above a normal conditions during the 2003 growing season.

3.3. Spatial patterns and trends

The spatial NDVI anomaly patterns for Sahel region are shown in Fig. 4. These series of images show the JASO percent NDVI anomaly patterns for selected growing seasons during the 1981–2003 period. In 1981, most of the region shows above normal vegetation conditions with anomalies ranging between 10 to 60% roughly extending 12°N to 16°N across the entire region, with most of the pronounced greenness concentrated in the western half of region (Fig. 4a). In contrast 1983 shows a patchy pattern of below normal NDVI showing the prevalence of drought conditions across the region particularly in Senegal, Mauritania, Chad and eastern Sudan (Fig. 4b). This pattern is enhanced in 1984 with the whole region between 5°N and 17°N showing below normal conditions with the most extreme negative departures reaching 80% below normal concentrated in a band between 13°N to 16°N across the region (Fig. 4c). These magnitudes of negative departures agree with rainfall departure patterns for the region shown by Nicholson (1985) with most pronounced negative anomalies from central to eastern Sahel. There is an easing of these conditions in 1985 although most of the area especially from Burkina Fasso eastwards to Chad still shows negative departures in NDVI ranging between 10% and 30% (Fig. 4d). Region-wide drought conditions return during the 1987 growing season with negative departures in NDVI on the order of 20–40% concentrated in Mali and Niger, although most of the area between 8°N and 10°N shows normal to above normal vegetation conditions (Fig. 4e). 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 (Walker and Rowntree, 1977; Nicholson, 1979; Lamb, 1982; Rasmusson, 1988).

During the period 1994–2003 vegetation anomalies show patterns largely opposite of the 1981–1987 series. During the 1994 growing season, the whole region except some areas south of 10°N show above normal vegetation conditions with positive anomalies ranging between 20% and 80% especially the region between 12°N and 17°N (Fig. 4f). The above normal greening during this period was associated with positive rainfall anomalies during the months of August, September and October (LeCompte et al., 1994; Nicholson et al., 1996). The zonal coherence of positive NDVI anomalies across region suggests that the ITCZ during this period maintained a persistent northward position throughout the growing season. Although this was the wettest year for the whole region since 1969 (LeCompte et al., 1994), it was still below the mean compared to the 1950–1965 period (Nicholson et al., 1996). Our analysis using NDVI data is only based on an 23-year reference average from 1981–2003, which may not be representative of the typical 30-year averages used in computing rainfall anomalies in historical climatological studies. The patterns in 1994 are similarly observed across the whole region during the 1999 growing season (Fig. 4g),

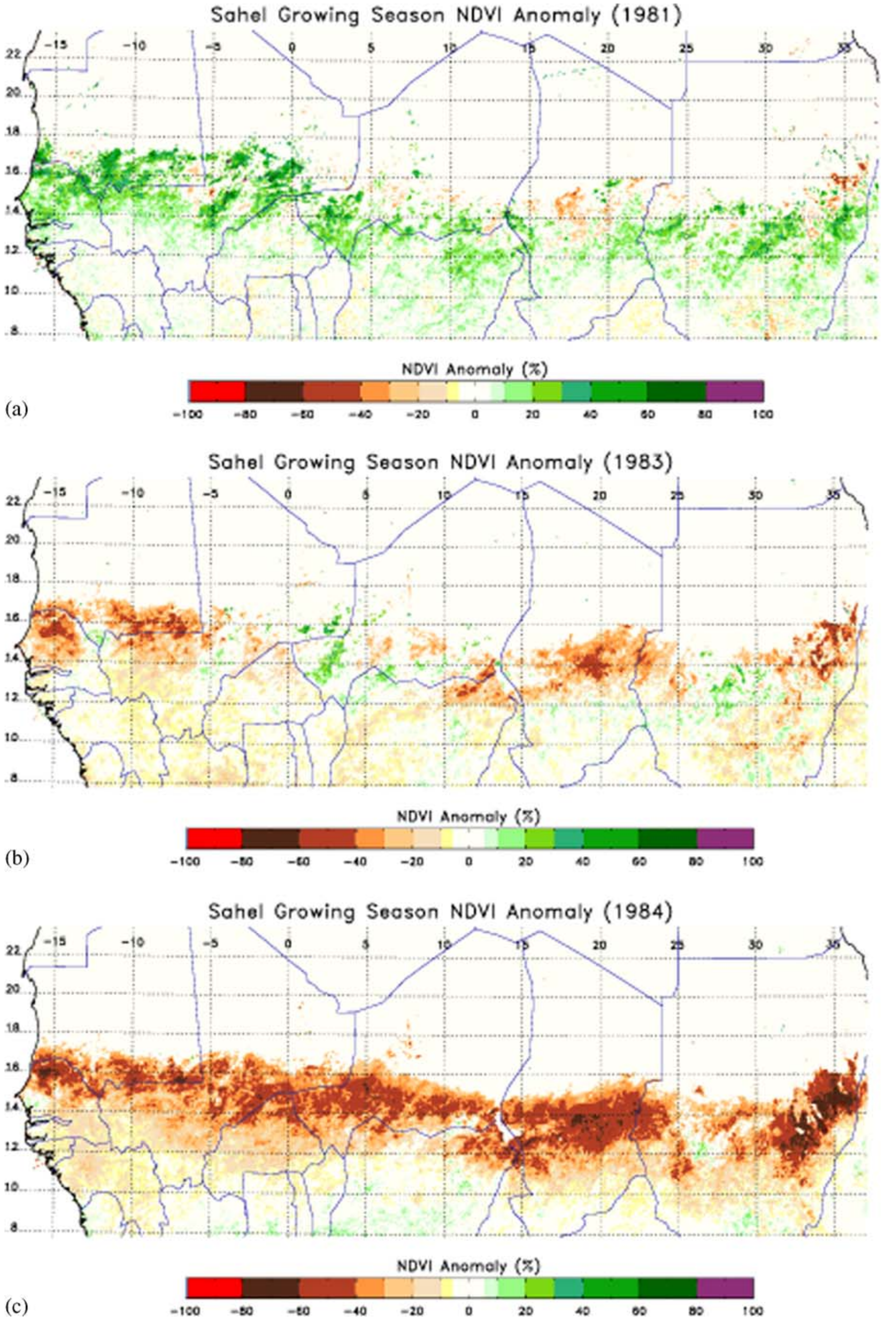

Fig. 4. Growing season (JASO) NDVI anomaly patterns for selected years during the 1981–2003 period. The spatial patterns show persistent drought conditions between 1983 and 1987 (b–e) and a contrasting pattern of greener than normal conditions between 1994 and 2003 (f–j).

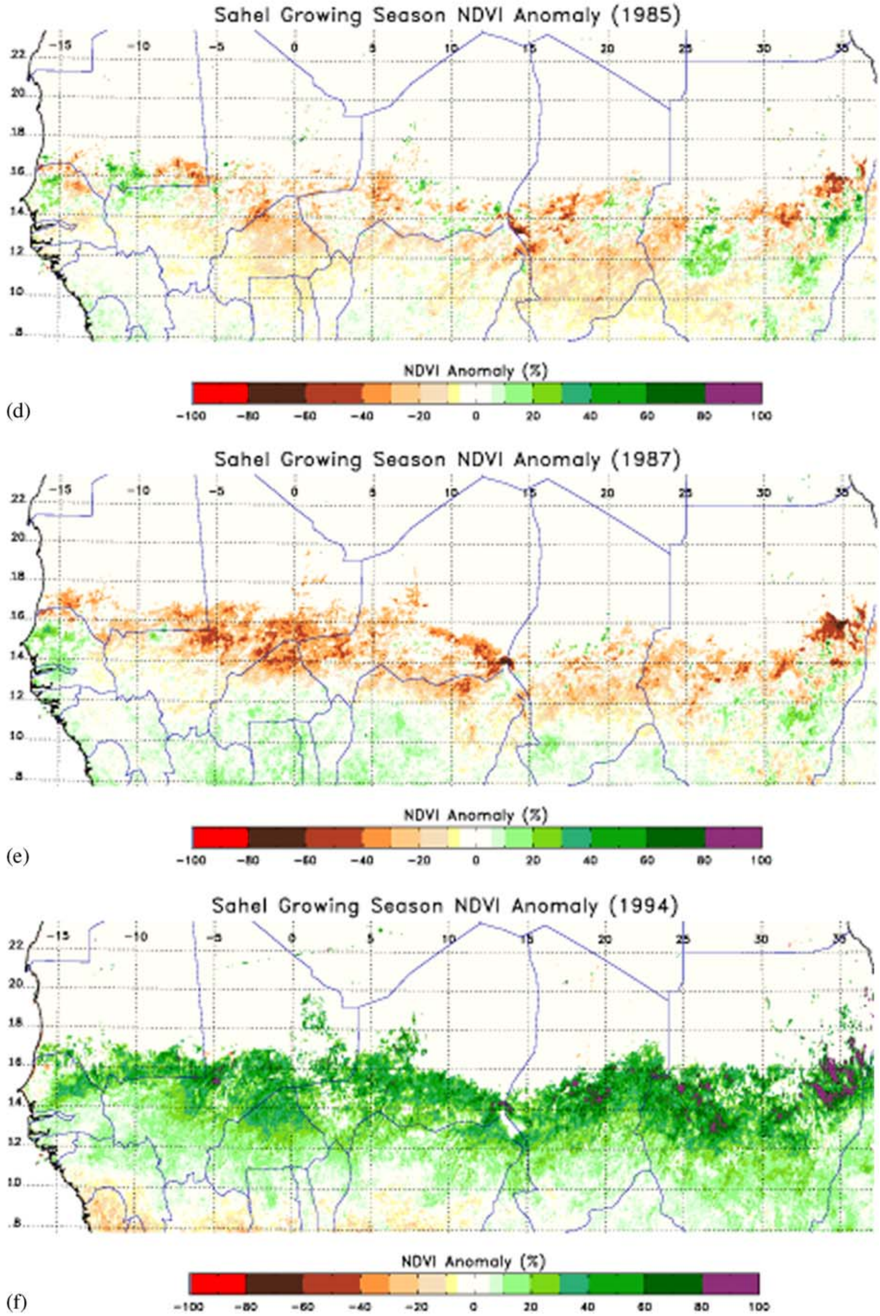

Fig. 4. (*Continued*)

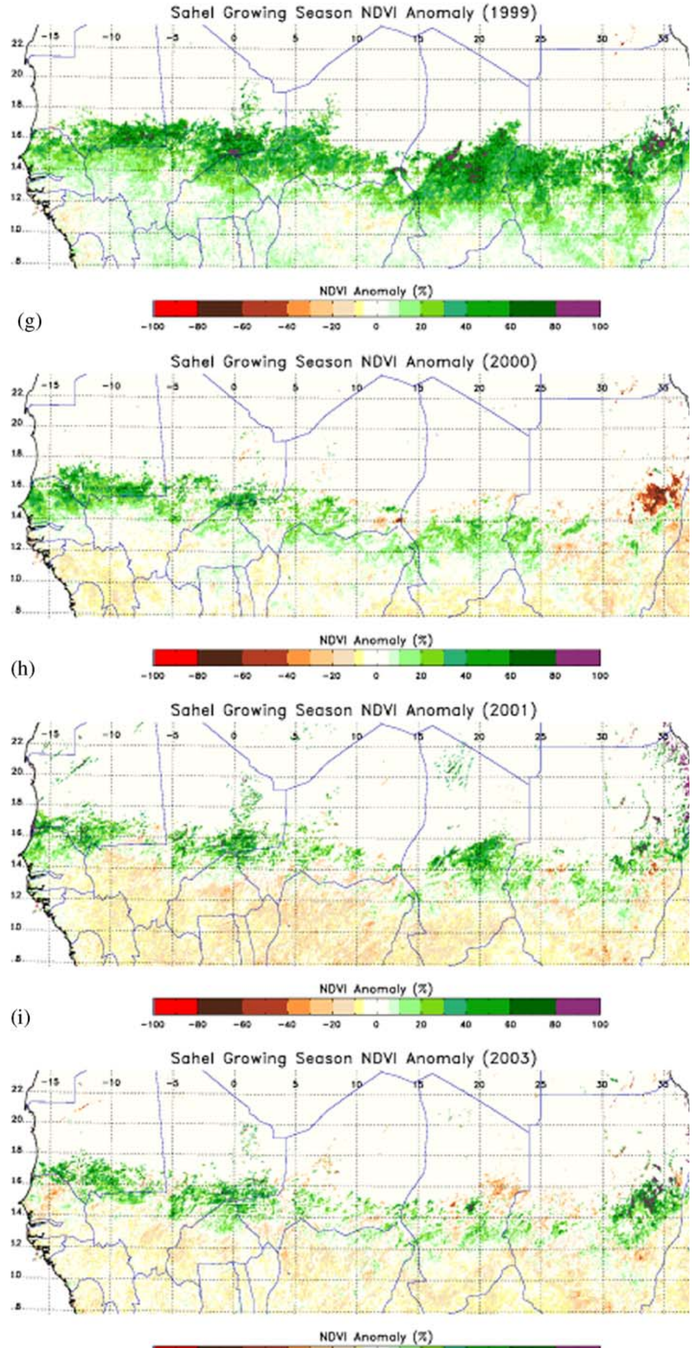

Fig. 4. (*Continued*)

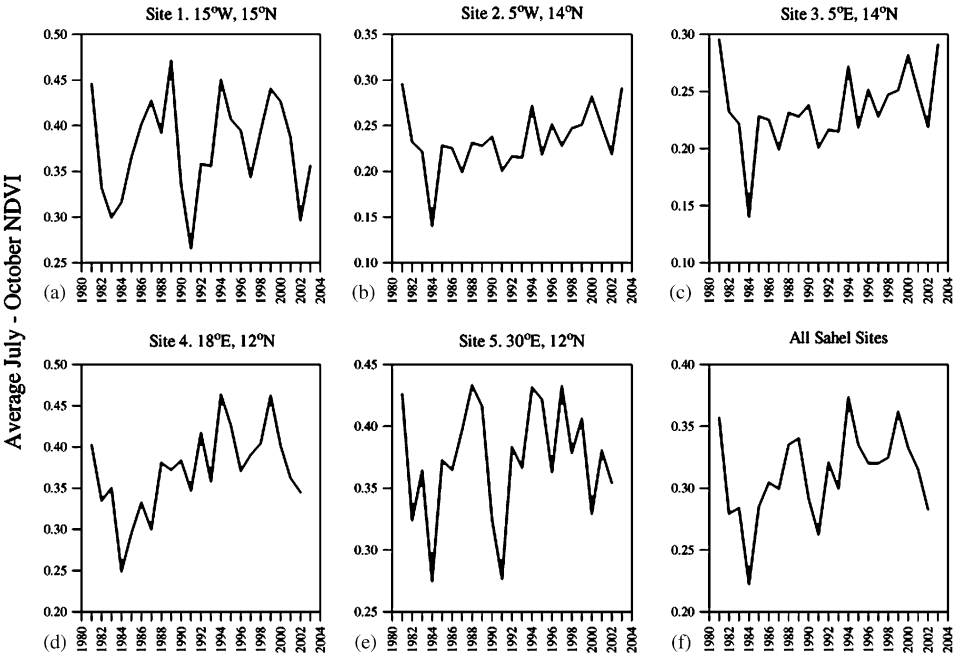

Fig. 5. Time series of average July–October NDVI for selected sites across the Sahel (a–e) and average NDVI for the five sites shown in (f). All sites show an overall trend of increasing NDVI through time particularly the central Sahel sites (b, c and d).

though the area of the strongest positive anomalies is reduced to between 14°N and 16°N in western Sahel and 12°N to 16°N in the eastern Sahel. The region experienced an exceptionally wet rainy season during 1999 with area-averaged totals reaching the highest levels since 1967, except for some areas in the southwestern part of the region (Bell et al., 2000). This pattern of positive NDVI anomalies persists throughout the growing seasons of 2000, 2001 and recently in 2003, although the magnitudes of the anomalies are reduced through the subsequent years since 1994. In 2000, 2001 and 2003 some areas of the Sahel particularly the zone south of 12°N shows below normal NDVI patterns on the order of −10% to −20%, as opposed to the zone to the north (Fig. 4, h, i, j). It has been observed that, in some years there is a tendency for rainfall anomalies to be of opposite sign north and south of the 10°N (Nicholson, 1981). This pattern is evident in the NDVI anomaly patterns for 1987, 2000, 2001 and 2003 (Fig. 4 e, i, j). This different anomaly patterns are associated with an earlier northward excursion of the ITCZ which produces a longer rainy season at latitudes north of 10°N, leaving the southern region dry (Griffiths, 1972; Motha et al., 1980).

Time series of NDVI for selected locations across the Sahel for the period 1981–2003 are shown in Fig. 5. The sites were selected randomly across the Sahel to examine point specific trends in NDVI during the 23-year period; one site in the western Sahel, three in central Sahel and one in eastern Sahel. The data presented here are average NDVI values for the growing season (JASO) at each location. All

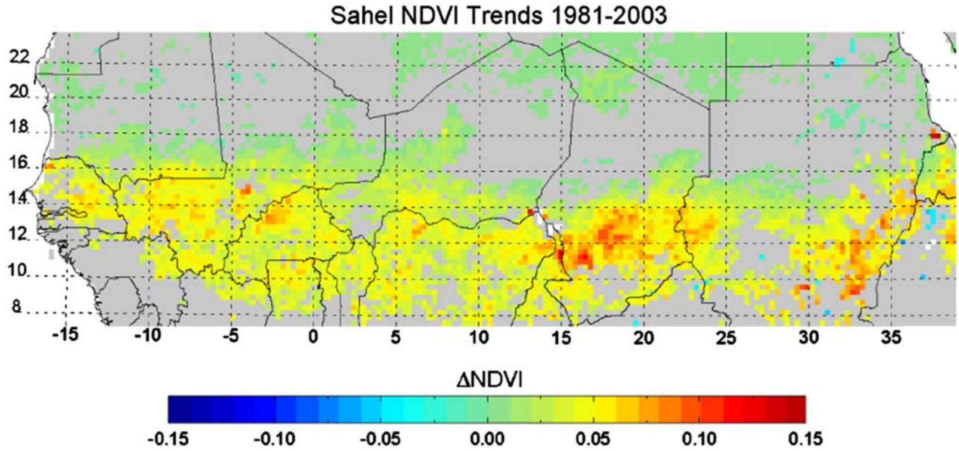

Fig. 6. Summary trend map of changes in Sahel NDVI from 1981–2003. Yellow to red colors indicate areas of significant change at 90% confidence, and gray areas show no significant trend.

the sites show positive trends in NDVI through the time series. The most pronounced trends are for the three sites in central Sahel which show a systematic positive trend with NDVI values increasing consistently from the lowest values in 1984 at the height of the long-term Sahelian drought to a peak in 1994 and 1999 (Fig. 5b, c and d). All the sites show the persistence of the drought in the early to mid 1980s with a dramatic decrease in NDVI values beginning in 1981, reaching a minimum in 1984 and increasing gradually to 1981 levels by 1988 (Fig. 5a–e).

The western and eastern sites in Senegal and Sudan, respectively (Fig. 5a and e), show pronounced interannual variability which may in part be an indicator of maritime influence from the adjacent oceans, the Atlantic to the west and Indian Ocean to the east, respectively. The two sites show a drop in NDVI values in 1984–85 and 1991–92, during El Niño/Southern Oscillation (ENSO) cold and warm years, respectively, and peak in NDVI in 1988–89 and 1999–2000 during ENSO cold event years and peaks in 1994–1995, ENSO warm event year. Teleconnection linkages between ENSO and Sahel rainfall variability is not straight forward relationship and is subject of continued research and disagreement (Ropelewski and Halpert, 1987; Semazzi et al., 1988; Janicot et al., 2001). If there is any influence on Sahel rainfall, it is likely to be indirect as the Sahel rainfall season is out of phase with the peak phase of ENSO events (Nicholson and Palao, 1993) and the impacts on rainfall may vary from event to event as illustrated by the NDVI anomalies in this paper. Furthermore, rainfall in the Sahel exhibits variability on a much longer time scale than the typical ENSO frequency (Nicholson and Entekhabi, 1986). The averaged time series for all the five Sahel sites is shown in Fig. 5f and summarizes the interannual variability and trend pattern of the time series. In general it shows the pronounced and persistent drought event from 1982 to 1985, and peaks in NDVI values in 1988 and 1994 and 1999 during periods of above normal rainfall in the last 23 years. The positive trend in NDVI is shown with a minimum in 1984 and maxima in 1994. Overall the surface trend analysis across the whole region shown in Fig. 6 illustrates that there is a significant increase in NDVI from 1981 to 2003 across the region. Most of the increase is concentrated in a band between 12°N and 14°N. The most significant increase are in central Sahel region, particularly in Chad with increases of between 0.1 and 0.15 NDVI units and in western Sahel (Mali) with increases between 0.05 and 0.1 NDVI units. The patchy nature of these patterns shows the underlying patterns of vegetation formation which tends to vary in structure across the region.

4. Summary and conclusions

Satellite measurements of Sahelian vegetation dynamics during the last 23 years have provided a comprehensive picture of the patterns of land surface interannual variation and trends. 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 across the region during this time period. The prevalence of greener than normal conditions during the 1990s to 2003, follows a similar increase in rainfall over the region during the last decade (Nicholson, 2005). In general, the time series trends in NDVI indicate a greening pattern across the region with the most systematic pronounced increases in the central Sahel region. The period 1981–1990 is dominated by below normal conditions with 80% of the years showing below normal NDVI conditions with severest departures in NDVI in 1984 (2.5 standard deviations below the mean) persisting for 6 years between 1982 and 1987, with exception of 1981, 1988 and 1989. These patterns are summarized in Table 1 and Fig. 7. Between 1991 and 2003, 76% of the years show above normal vegetation conditions with 1994 and 1999 showing ~1.5 standard deviations above the long-term mean with only 1991, 1993 and 2002 showing below normal conditions (Fig. 7). The persistent nature of these two different patterns in NDVI between 1981–1990 and 1991–2003 is in agreement with the historical patterns of rainfall anomalies in the region (Nicholson, 2001). In the context of the long-term changes in the Sahel region, the conditions in the last two decades are still far below rainfall conditions that prevailed across the region between 1930 and 1965 (Fig. 7).

What the NDVI time series data indicates is that there is a gradual and slow but persistent recovery from the peak drought conditions that affected the region in the early to mid-1980s. This is corroborated by the decrease in the magnitudes of negative rainfall departures from 1984 to 2000 (Fig. 7). The correlation between the NDVI and rainfall anomaly time series for the 1981–2000 period is positive and significant ($r = 0.78$, $p < 0.01000$) 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 1994, a difference of 10 years might suggest some large-scale climatic influence on Sahelian vegetation dynamics. 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

Table 1
NDVI anomaly scores (−/+) showing persistence patterns of below normal or above normal vegetation conditions

Year	81	82	83	84	85	86	87	88	89	90
Anomaly (+/−)	+	−	−	−	−	−	−	+	+	−
Year	91	92	93	94	95	96	97	98	99	00
Anomaly (+/−)	−	+	−	+	+	+	+	+	+	+
Year	01	02	03							
Anomaly (+/−)	+	−	+							

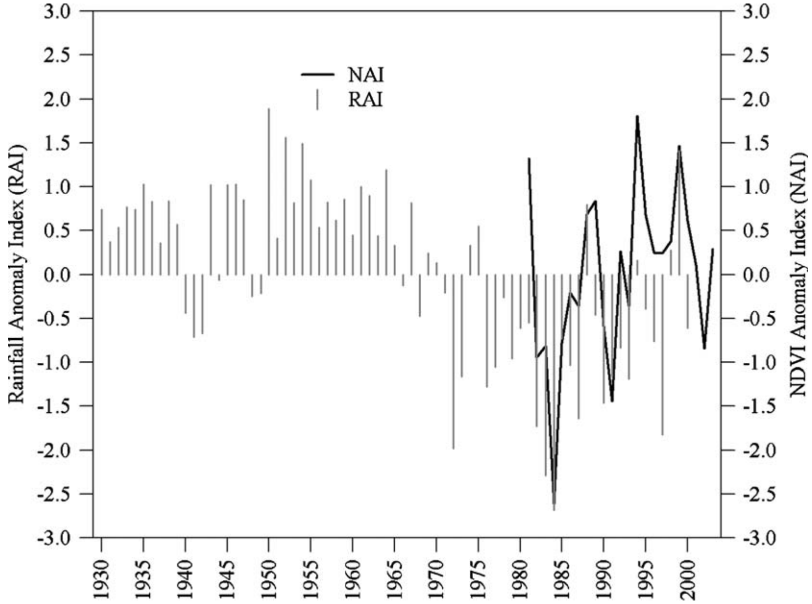

Fig. 7. Comparison between Sahel rainfall anomaly index (RAI: 1930–2000) and NDVI anomaly index (NAI: 1981–2003).

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.

Acknowledgements

This work was funded in part through GEST under NASA/GSFC Cooperative Agreement with University of Maryland, Baltimore County, NCC5-494 and is part a contribution to interagency program in support of United States Agency for International Development/Famine Early Warning System (USAID/FEWS) on

Food Security and Environmental Monitoring. Robert Mahoney and Jennifer Small assisted with the programming and the contributions of Dan Slayback are acknowledged.

References

Anyamba, A., Eastman, J.R., 1996. Interannual variability of NDVI over Africa and its relationship to El Niño/Southern Oscillation. International Journal of Remote Sensing 17, 2533–2548.

Anyamba, A., Tucker, C.J., Mahoney, R., 2002. From El Niño to La Niña: vegetation response patterns over east and Southern Africa during the 1997–2000 period. Journal of Climate 15, 3096–3103.

Asrar, G., Fuchs, M., Kanemasu, E.T., Hatfield, J.L., 1984. Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat. Agronomy Journal 76, 300–306.

Bell, G.D., Halpert, M.S., Schnell, R.C., Wayne Higgins, R., Lawrimore, J., Kousky, V.E., Tinker, R., Thiaw, W., Chelliah, M., Artusa., A., 2000. Climate Assessment for 1999. Bulletin of the American Metrological Society 81 (6), 1328.

Bunting, A.H., Dennet, M.D., Elston, J., Milford, J.R., 1976. Rainfall trends in the West African Sahel. Quarterly Journal of the Royal Meteorological Society 102, 59–64.

Eklundh, L., Olsson, L., 2003. Vegetation index trends for the African Sahel 1982–1999. Geophysical Research Letters 30, 1430.

Giannini, A., Saravanan, R., Chang, P., 2003. Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales. Science 302, 1027–1030.

Glantz, M.H., 1994. Drought, desertification, and food production. In: Glantz, M.H. (Ed.), Drought Follows the Plow. Cambridge University Press, Cambridge, pp. 9–30.

Gray, T.I., Tapley, D.B., 1985. Vegetation health: natures climate monitor. Advances in Space Research 5, 371–377.

Griffiths, J.F., 1972. Climates of Africa, World Survey of Climatology, vol. 10. Elsevier, Amsterdam, pp. 604.

Henricksen, B.L., Durkin, J.W., 1986. Growing period and drought early warning in Africa using satellite data. International Journal of Remote Sensing 7, 1583–1603.

Hielkema, J.U., Prince, S.D., Astle, W.L., 1986. Rainfall and vegetation monitoring in the Savanna Zone of the Democratic Republic of Sudan using the NOAA advanced very high resolution radiometer. International Journal of Remote Sensing 7, 1499–1513.

Holben, B.N., 1986. Characteristics of maximum-value composite images for temporal AVHRR data. International Journal of Remote Sensing 7, 1417–1434.

Huete, A.R., 1985. Spectral response of a plant canopy with different soil backgrounds. Remote Sensing of Environment 17, 37–53.

Huete, A.R., Tucker, C.J., 1991. Investigation of soil influences in AVHRR red and near-infrared vegetation index imagery. International Journal of Remote Sensing 12, 1223–1242.

Huffman, G.J., Adler, R.F., Rudolf, B., Schneider, U., Keehn, P.R., 1995. Global precipitation estimates based on a technique for combining satellite-based estimates, rain gauge analysis, and NWP model precipitation information. Journal of Climate 8, 1284–1295.

Hulme, M., Doherty, R., Ngara, T., New, M., Lister, D., 2001. African climate change: 1990–2100. Climate Research 17, 145–168.

Hutchinson, C.F., 1991. Use of satellite data for famine early warming in sub-Saharan Africa. International Journal of Remote Sensing 12, 1405–1421.

Janicot, S., Trzaska, S., Poccard, I., 2001. Summer Sahel-ENSO teleconnection and decadal time scale SST variations. Climate Dynamics 18, 302–320.

Justice, C.O., Hiernaux, P.H.Y., 1986. Monitoring the grasslands of the Sahel using NOAA AVHRR data: Niger 1983. International Journal of Remote Sensing 17, 1475–1497.

Justice, C.O., Eck, T.F., Tanre, D., Holben, B.N., 1991. The effect of water vapor on normalized difference vegetation index derived for the Sahelian region from NOAA AVHRR data. International Journal of Remote Sensing 12, 1165–1187.

Lamb, P.J., 1980. Sahelian Drought. New Zealand Journal of Geography 68, 12–16.

Lamb, P.J., 1982. Persistence of Sub-Saharan drought. Nature 299, 46–48.

LeCompte, D., Tinker, R., Dione, J., Halpert, M., Thiao, W., 1994. Wettest rainy season in 30 years across African Sahel. Special Climate Summary 94/2, 5. NOAA, Washington, DC.

Le Houerou, H.N., 1980. The rangelands of the Sahel. Journal of Range Management 33, 41–46.

Los, S.O., 1993. Calibration adjustment of the NOAA AVHRR normalized difference vegetation index without recourse to channel 1 and 2 data. International Journal of Remote Sensing 14, 1907–1917.

Lotsch, A., Friedl, M.A., Anderson, B.T., 2003. Coupled vegetation-precipitation variability observed from satellite and climate records. Geophysical Research Letters 30, 1774.

Milich, L., Weiss, E., 2000. GAC NDVI interannual coefficient of variation images: Ground-truth sampling in the Sahel along north-south transects. International Journal of Remote Sensing 21 (2), 235–260.

Monod, T., 1986. The Sahel zone north of the equator. In: Evenari, M., Noy-Meir, I., Goodall, D.W. (Eds.), Ecosystems of the World, Hot Deserts and Arid Shrublands. Elsevier, New York, pp. 203–243.

Motha, R.P., Leduc, S.K., Stayaert, L.T., Sakamoto, C.M., Strommen, N.D., 1980. Precipitation patterns in West Africa. Monthly Weather Review 109, 1567–1578.

Myneni, R.B., Los, S.O., Tucker, C.J., 1996. Satellite-based identification of linked vegetation index and sea surface temperature anomaly areas from 1982–1990 for Africa, Australia and South America. Geophysical Research Letters 23, 729–732.

Nemani, R.R., Keeling, C.D., Hashimoto, H., Jolly, W.M., Piper, S.C., Tucker, C.J., Myneni, R.B., Running, S.W., 2003. Climate-driven increases in global terrestrial net primary production from 1982 to 1999. Science 300, 1560–1563.

Nicholson, S.E., 1979. Revised rainfall series for the West African subtropics. Monthly Weather Review 107, 473–487.

Nicholson, S.E., 1981. Rainfall and atmospheric circulation during drought periods and wetter years in West Africa. Monthly Weather Review 109, 2191–2208.

Nicholson, S.E., 1985. Sub-Saharan Rainfall 1981–84. Journal of Climate and Applied Meterology 24, 1388–1391.

Nicholson, S.E., 2005. On the question of the "recovery" of the rains in the West African Sahel. Journal of Arid Environments, in press, doi:10.1016/j.jaridenv.2005.03.004.

Nicholson, S.E., Ba, M.B., Kim, J.Y., 1996. Rainfall in the Sahel during 1994. Journal of Climate 9, 1673–1676.

Nicholson, S.E., Davenport, M.L., Malo, A.R., 1990. A comparison of vegetation response to rainfall in the Sahel and East Africa using normalized difference vegetation index from NOAA-AVHRR. Climate Change 17, 209–241.

Nicholson, S.E., Entekhabi, D., 1986. The quasi-periodic behavior of rainfall variability in Africa and its relationship to the Southern Oscillation. Archive Fur Meteorologie Geophysik und Bioklimatologie A 34, 311–348.

Nicholson, S.E., Palao, J.M., 1993. A re-evaluation of rainfall variability in the Sahel, Part I. Characteristics of rainfall fluctuations. Journal of Climatology 13, 371–389.

Nicholson, S.N., 2001. Climate and environmental change in Africa during the last two centuries. Climate Research 14, 123–144.

Olsson, L., 1993. On the causes of famine: drought, desertification and market failure in the Sudan. Ambio 22, 395–403.

Rasmusson, E.M., 1988. Global climate change and variability: effects on drought and desertification in Africa. In: Glantz, G.H. (Ed.), Drought and Hunger in Africa. Cambridge University Press, New York, pp. 4–36.

Ropelewski, C.F., Halpert, M.S., 1987. Global and regional scale precipitation patterns associated with El Niño/Southern Oscillation. Monthly Weather Review 115, 1606–1626.

Sellers, P.J., 1985. Canopy reflectance, photosynthesis and transpiration. International Journal of Remote Sensing 8, 1335–1372.

Semazzi, F.H., Mehta, V., Sud, Y.C., 1988. An investigation of the relationship between sub-Saharan rainfall and global sea surface temperatures. Atmosphere-Ocean 26, 118–138.

Slayback, D.A., Pinzon, J.E., Los, S.O., Tucker, C.J., 2003. Northern hemisphere photosynthetic trends 1982–1999. Global Change Biology 9, 1–15.

Tanaka, M., Weare, B.C., Navato, A.R., Newell, R.E., 1975. Recent African rainfall patterns. Nature 255, 201–203.

Townshend, J.R.G., Justice, C.O., 1986. Analysis of the dynamics of African vegetation using the normalized difference vegetation index. International Journal of Remote Sensing 7, 1435–1445.

Tucker, C.J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sensing of Environment 8, 127–150.

Tucker, C.J., Justice, C.O., Prince, S.D., 1986. Monitoring the grasslands of the Sahel 1984–1985. International Journal of Remote Sensing 7, 1571–1581.

Tucker, C.J., Newcomb, W.W., Dregne, H.E., 1994. AVHRR data sets for determination of desert spatial extent. International Journal of Remote Sensing 17, 3547–3565.

Tucker, C.J., Newcomb, W.W., Los, S.O., Prince, S.D., 1991. Mean and inter-annual variation of growing-season normalized difference vegetation index for the Sahel 1981–1989. International Journal of Remote Sensing 12, 1133–1135.

Tucker, C.J., Nicholson, S.E., 1999. Variations in the size of the Sahara Desert from 1980 to 1997. Ambio 28, 587–591.

Tucker, C.J, Pinzon J.E., Brown, M.E, Slayback, D., Pak E., Mahoney R, Vermote E, El Saleous, N., 2005. An Extended AVHRR 8-km NDVI Data Set Compatible with MODIS and SPOT Vegetation NDVI Data. International Journal of Remote Sensing, in press.

Tucker, C.J., Vanpreat, C.L., Sharman, M.J., Van Ittersum, G., 1985. Satellite remote sensing of total herbaceous biomass production in the Senegalese Sahel: 1980–1984. International Journal of Remote Sensing 7, 233–249.

Vermote, E.F., El Saleous, N.Z., 1994, Stratospheric aerosol perturbing effect on remote sensing of vegetation: operational method for the correction of AVHRR composite NDVI, Atmospheric Sensing and Modeling, Rome, Italy, September 29–30, SPIE Proceedings, 2311, 19–29.

Vermote, E.F., El Saleous, N.Z., Justice, C.O., Kaufman, Y.J., Privette, J., Remer, L., Roger, J.C., Tanre, D., 1997. Atmospheric correction of visible to middle infrared EOS-MODIS data over land surface, background, operational algorithm and validation. Journal of Geophysical Research 14, 17131–17141.

Walker, J., Rowntree, P.R., 1977. The effect of soil moisture on circulation and rainfall in a tropical model. Qurterly Journal of the Royal Meteorological Society 103, 29–46.