

Desertification, Drought, and Surface Vegetation: An Example from the West African Sahel



S. E. Nicholson,* C. J. Tucker,+ and M. B. Ba*#

ABSTRACT

Many assumptions have been made about the nature and character of desertification in West Africa. This paper examines the history of this issue, reviews the current state of our knowledge concerning the meteorological aspects of desertification, and presents the results of a select group of analyses related to this question. The common notion of desertification is of an advancing “desert,” a generally irreversible anthropogenic process. This process has been linked to increased surface albedo, increased dust generation, and reduced productivity of the land. This study demonstrates that there has been no progressive change of either the Saharan boundary or vegetation cover in the Sahel during the last 16 years, nor has there been a systematic reduction of “productivity” as assessed by the water-use efficiency of the vegetation cover. While it also showed little change in surface albedo during the years analyzed, this study suggests that a change in albedo of up to 0.10% since the 1950s is conceivable.

1. Introduction

The highly populated West African Sahel has historically been prone to long and severe droughts. The most recent began in 1968 and relatively dry conditions have persisted since then. Commensurate with this drought arose the idea that the region was undergoing a process of desertification that may have exacerbated or even caused the drought and at least enhanced its impact. For example, in a now classic paper, Charney (1975) speculated that albedo changes related to overgrazing and denuding of the highly reflective soil produced a decline in rainfall in the region.

The term desertification evokes an image of the “advancing desert,” a living environment becoming sterile and barren. But this is not an accurate picture (Nicholson 1994a). Desertification is a process of land degradation that reduces its productivity, and its impact may be confined to relatively small scales. It has been most severe in arid and semiarid regions, and most of such regions are at risk if not properly managed. However, the extent of affected lands has been exaggerated and the issue of desertification has become a controversial one, suffering from a dearth of data and rigorous scientific study (Mainguet 1991; Graetz 1991; Verstraete 1986; Hellden 1991; Thomas and Middleton 1994). Moreover, the “advances” of the desert during recent years closely mimic fluctuations of rainfall in the Sahel zone (Tucker et al. 1991).

In view of the abrupt increase of rainfall in the Sahel in 1994 (Nicholson et al. 1996), the recent U.N. Conference on Desertification (Pugdefabregas 1995), papers challenging the concept, and the improved monitoring capability afforded by remote sensing, revisiting the issue of desertification in the Sahel is timely. In this article, we briefly summarize the history of the problem and its meteorological aspects. We then examine the common scenario of desertification, particularly the questions of the advancing desert, of

*Department of Meteorology, The Florida State University, Tallahassee, Florida.

+NASA, Laboratory for Terrestrial Physics, Goddard Space Flight Center, Greenbelt, Maryland.

#Current affiliation: National Oceanic and Atmospheric Administration-National Environmental Satellite, Data and Information Service, Washington, D.C.

Corresponding author address: Prof. S. E. Nicholson, Department of Meteorology, The Florida State University, Tallahassee, FL 32306-3034.

In final form 6 February 1998.

©1998 American Meteorological Society

accompanying changes in surface albedo, and of a decline in productivity.

2. Background

Nearly two decades ago the United Nations (1980) announced that desertification had affected some 35 million km² of land globally and that overall 35% of the earth's land surface was at risk of undergoing similar changes. The official U.N. definition was

diminution or destruction of the biological potential of the land [which] can lead ultimately to desert-like conditions.

Other definitions abound, with most ignoring the relationship to climate; thus, most definitions encapsule the idea that desertification is

the expansion of desert-like conditions and landscapes to areas where they should not occur climatically (Graetz 1991).

Mainguet (1991) proposes a more encompassing definition:

Desertification, revealed by drought, is caused by human activities in which the carrying capacity of land is exceeded; it proceeds by exacerbated natural or man-induced mechanisms, and is made manifest by intricate steps of vegetation and soil deterioration which result, in human terms, in an irreversible decrease or de-

struction of the biological potential of the land and its ability to support population.

More recently, the United Nations changed its definition to read

land degradation in arid, semiarid and dry sub-humid areas resulting from various factors, including climate variations and human activities (Puigdefabregas 1995, Warren 1996).

A trigger for the surge of interest in desertification was the drought that ravaged the Sahel in the early 1970s. Reportedly, a million people starved, 40% to 50% of the population of domestic stock perished, and millions of people took refuge in camps and urban areas and became dependent on external food aid (Graetz 1991). At the same time satellite and photos showed evidence that human activities can impact land on a large scale. International borders separating grazed and ungrazed land, such as in the Sinai and Negev, were vividly seen from space, and heavily grazed areas appeared as brighter spots on satellite images.

Many general causes of desertification have been identified (Warren 1996). Its roots lie in societal changes like increasing population, sedentarization of indigenous nomadic peoples, breakdown of traditional market and livelihood systems, introduction of new and inappropriate technology in the affected regions, and, in general, bad strategies of land management. Associated with these changes are growing livestock numbers, overcultivation, intensive irrigation, and deforestation (Fig. 1). Animals cluster around the few



FIG. 1. (a) Grazing animals in the Sahel contribute to the desertification problem. (b) Selling of firewood along roadway in Botswana; gathering of fuelwood contributes to desertification.

(c)



(d)



(e)



(f)



(g)



(h)



FIG. 1. *Continued.* (c) Millet cultivation in a desertified landscape in West Africa near Niamey, Niger. (d) Highly reflective soils in agriculture field in Botswana. (e) Agricultural burning in the savanna of Botswana. (f) Grazing animals around a well in Morocco; desertification often begins as a result of the grazing pressure around such isolated wells. (g) Desertified landscape in central Australia, near Alice Springs. (h) Atmospheric dust loading is increased as a result of soil erosion, a process of desertification. Increased dustiness also accompanied the increasing aridity in the Sahel (N'Tchayi Mbourou et al. 1997).

available wells, overgrazing the surrounding land; trees and shrubs are removed to produce fuel wood, charcoal, or agricultural land; the land becomes increasingly impacted by wind and water erosion.

This alters the land's topography, vegetation, and soils. The topsoil is eroded and tracts of land are washed away, producing huge gullies. The finer soil materials increase the atmospheric dust loading. The soil's texture, organic matter, and nutrient contents are changed in ways that reduce its fertility. Poor irrigation and management practices lead to salinization and waterlogging of the soil. The land cover may become more barren or diverse, and nutrient-rich species are replaced by vegetation of poorer quality. The carrying capacity of the land is reduced.

The concept of good lands becoming deserts has resurged from time to time since the beginning of the twentieth century. With the claims of Charney (1975) and others that the 1970s Sahel drought was a result of desertification and the U.N. proclamation that some 35 million km² of land had already been lost, this topic became the focus of much scientific, political, and institutional attention. Nevertheless, we still do not have any true understanding of the process nor any accurate assessment of the extent and degree of desertification globally. Unfortunately, most of the evidence of desertification is from locations and time periods that were simultaneously affected by drought or long-term declines in rainfall. Consequently, there is disagreement concerning the causes and processes of degradation, the extent to which the changes are natural or man-made, the amount of land affected or at risk, and the reversibility of desertification.

3. The controversy surrounding desertification

From the onset of interest in desertification in the 1970s, the issue has caused considerable controversy. A major point of dissention was the relative roles of climate and people in the process. The nature and impacts of desertification were also disputed. Much of the controversy resulted from the lack of scientific rigor in the studies of the 1970s and the information disseminated by the United Nations.

An abundance of reports were produced, documenting case studies from around the world, but in them was a vir-

tual absence of ecological detail. Attention was paid to higher levels of ecosystem function, for example, numbers of livestock and harvest quality rather than manifestations of desertification on soils and vegetation (Graetz 1991). Sweeping conclusions were drawn from miscellaneous observations with no measurements or systematic assessments of the actual changes. The U.N. Environmental Programme (UNEP) produced, for example, a map of desertification severity that was largely extrapolated from risk factors in the environment; de facto, it was a map of vegetation and climate and contained virtually no information on desertification status. Consequentially, the extent and severity of desertification was largely exaggerated.

At the heart of the problem was the intentional elimination of climate as a possible cause of desertification. This was unfortunate because nearly all of the few actual assessments extended over periods of drought or rainfall decline. Thus, while desertification itself was defined as anthropogenic, the evidence used to assess it could equally have been a product of climatic variability. A good example is the pivotal work of Lamprey (1975), who quantified desert encroachment in the Sahel using maps from the 1950s and aerial surveys from 1975. He concluded that between 1958 and 1975 the desert had advanced southward in the western Sudan by 90–100 km. During this same period, rainfall in the Sahel declined by nearly 50% (Fig. 2) with a somewhat lesser reduction in the western Sudan (Nicholson 1990).

Other aspects of the desertification issue were also challenged. Scientists at Lund University in Sweden did extensive studies in the Sudan to test some of the tenets of desertification (Hellden 1984; Olsson 1985; Ahlcrona 1988). They showed through a combination of field work and analysis of satellite photos that there was neither a systematic advance of the desert or other vegetation zones, nor a reduction in vegetation cover, although degradation and replacement of forage with woody species was apparent. There was no evidence of a systematic spread of desertified land around vil-

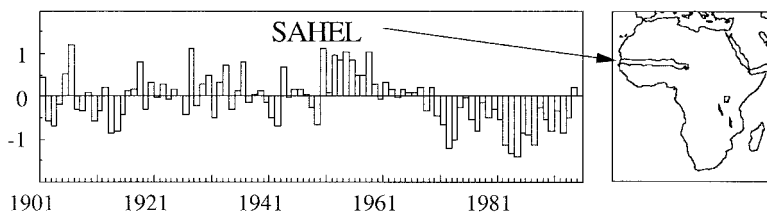


FIG. 2. Long-term rainfall fluctuations in the Sahel, expressed as a percent standard departure from the long-term mean.

lages and waterholes or of reduced crop yield due to cultivation of marginal or vulnerable areas. On the other hand, they clearly demonstrated that changes took place in response to drought, with full recovery of the land productivity at the end of the drought, a conclusion reached by Tucker et al. (1991) for the Sahel as a whole.

None of the studies challenging earlier ideas claim that desertification is not a problem. Land degradation has affected many regions, including the Sahel. This degradation is of concern because global ecosystems are stabilized by a series of feedbacks between man, animals, soil, vegetation, and climate (Graetz 1991; Schlesinger et al. 1990). In the undisturbed arid environment in equilibrium, the feedback loops tend to be negative, hence preserving the status quo. The disturbances induced by desertification turn some of the feedback loops to positive, allowing the disturbance to be amplified. In other words, the desertification becomes self-accelerating (see also Schlesinger et al. 1990). Droughts can further promote the process.

4. Meteorological aspects of desertification

Rainfall variability in marginal regions like the Sahel is inherently large and the natural vegetation is well adapted to the vagaries of rainfall (Nicholson 1997). When humans alter the landscape, as they do with cropping or ranching, the system may become more vulnerable to climatic variability, particularly droughts. This section examines two questions concerning the interrelationship between desertification and climate: to what extent can desertification influence climate and might land surface effects attributed to desertification in fact be climatically induced?

a. Examples of desiccation and land degradation versus climate

There have been a number of modern cases of arid or semiarid regions becoming increasingly desiccated or degraded. Just after the turn of the century, it was commonly believed that the Kalahari of southern Africa was drying up. A proposed solution was a grandiose flooding scheme, the creation of Lake Kalahari, to bring back the waning rains (Schwarz 1920). The concept of the Sahara encroaching into the Sahel also goes well back in time, to papers noting the desiccation of the Senegal River and nearby wells (Bovill 1921) and the decline of forests in parts of Mali, Niger,

and Nigeria (Stebbing 1935). At the time, these events were attributed to human activities. Landscape degradation also affected huge regions of Australia at the end of the last century. The number of sheep in New South Wales declined from 13 million in 1890 to 4–5 million in 1900 (Graetz 1991).

These situations in Australia and Africa have two commonalities: all were roughly contemporaneous and the observed trends paralleled a climatic desiccation that affected nearly the global Tropics (Kraus 1955). The decline of the waters and forests in the Sahel, as well as the “drying up” of the Kalahari, followed a two-decade decline in rainfall. Thus landscape degradation was contemporaneous with climatic perturbations. Likewise, the Dust Bowl days of the 1930s in the Great Plains, when farmland was ruined and soil was eroded, occurred during a record drought. This tandem of events occurred again with the Sahel drought of the 1970s. These examples illustrate that it is virtually impossible to separate the impact of drought from that of desertification and that the two processes often work together.

b. The impact of desertification on climate

In an address to the Royal Meteorological Society, Charney (1975) suggested that desertification may have caused the Sahel drought to occur. His mechanism was based on the exposure of highly reflective soil as a result of overgrazing, a hypothesis also put forth by Otterman (1974). Using a simple dynamic model, Charney showed that such an increase in surface albedo would increase radiative losses over the Sahara, thereby enhancing the negative net radiation balance of the desert and adjacent Sahel. The increased cooling enhanced subsidence and the local Hadley circulation. These results suggested a positive feedback mechanism by which droughts could be self-accelerating, or could perhaps even be produced. This paper was followed up by GCM experiments (Charney et al. 1975; Charney et al. 1977) in which albedo was increased from 03.14 to 03.35 over several semiarid regions, including the Sahel. The result was a significant reduction in rainfall and a southward shift of the ITCZ.

Chervin (1979), Sud and Fennessy (1982, 1984), Sud and Smith (1985), and Sud and Molod (1988) performed additional experiments on the roles of albedo, transpiration, and roughness. These studies generally concluded that a positive feedback exists, with such changes reducing rainfall and thereby further altering the vegetation and soil and promoting desertification (see review in Nicholson 1988).

These earlier papers used crude representations of the biosphere and somewhat unrealistic changes of surface conditions. More recently, Xue and Shukla (1993) performed a numerical simulation of desertification in the Sahel using a GCM with a detailed land-surface process scheme and more modest changes. In the desertification case, vegetation type over the Sahel was altered from one with surface albedo of 0.20 to one having a surface albedo of 0.30. They found that desertification reduced both moisture flux convergence and rainfall in that region and further south, and produced circulation changes and rainfall anomaly patterns consistent with those observed during drought years. Dirmeyer and Shukla (1994a, 1996) likewise found that doubling the global extent of deserts had a dramatic effect on rainfall, particularly over the Sahel. The same model was used to study the effect of albedo perturbations on climate, a factor closely tied into desertification (Dirmeyer and Shukla 1994b). The simulations suggested that an increase in albedo over the Amazon as low as 0.03, as a consequence of deforestation, would suffice to reduce rainfall over the region. Simulations by Lofgren (1995a,b) likewise demonstrate the potential importance of surface albedo-climate feedbacks via vegetation.

Recent modeling studies have considered other impacts of desertification: soil erosion and dust generation. Using the Goddard Institute for Space Studies general circulation model with an aerosol tracer and “natural” conditions of soil and vegetation over the Sahel, Tegen and Fung (1994) could not simulate the source and seasonal shift of the West African dust plume. When the model allowed for “disturbed” soils in the Sahel, a result of the protracted drought and changes in land management practices, a more realistic, seasonally migrating plume resulted (Tegen and Fung 1995). The study concluded that “disturbed” sources resulting from climate variability, cultivation, deforestation, and wind erosion contribute some 30%–50% of the total atmospheric dust loading.

The mineral dust has considerable influence on the atmospheric radiation balance (Fouquart et al. 1987). It effectively absorbs longwave radiation, possibly in sufficient degree to evoke a greenhouse-type warming of the atmosphere at least locally and thereby modify atmospheric dynamics (Andreae 1996; Tegen et al. 1996). The dust both scatters and absorbs solar radiation, but the scattering effect dominates in the visible portion of the spectrum (Li et al. 1996; Tegen et al. 1996). However, it must be noted that, while the dust might result from desertification, the dust load-

ing over the Sahel has clearly followed the trends in rainfall (Fig. 3).

Observational evidence of climatic impacts of desertification is more difficult to obtain because it is nearly impossible to separate natural variability from changes induced by desertification. For this reason there is little evidence to indicate that desertification modifies larger-scale phenomena such as rainfall. In view of this difficulty, most studies have examined its effects on surface parameters of relevance to climate. Significant impacts on albedo have been noted, but effects on temperature are less clear. Three case studies with field measurements are worth noting: a study of “protected” and “unprotected” grazing areas in Tunisia and studies that surveyed grazed and ungrazed sides of international borders in the Sinai–Negev and the Sonoran Desert of the United States and Mexico.

Satellite photos (Otterman 1977, 1981) indicate that the soil in the overgrazed Sinai has an albedo of 0.4 in the visible and 0.53 in the infrared; in the protected area of the Negev, the visible and infrared albedos were 0.12 and 0.24, respectively, but in most of the region the albedo averaged about 0.25. In Tunisia the albedo of protected versus unprotected sites was 0.35 versus 0.39 in one case and 0.26 versus 0.36 in another, while oases had albedos on the order of 0.10 to 0.23 (Wendler and Eaton 1983). These changes are of the same order of magnitude as the albedo changes in the Charney models.

Other differences between grazed and ungrazed land are more controversial. In the Sinai, where the soil albedo is higher, radiometric ground temperatures of

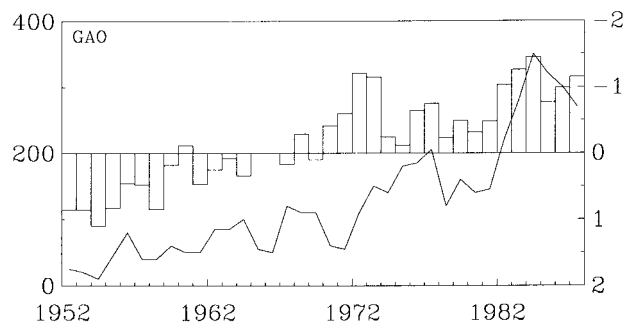


FIG. 3. Frequency of dust occurrence from 1957 to 1987 at Gao (solid line, left vertical axis), compared to rainfall anomalies (bar graph, right vertical axis) for the Sahelian region as a whole (from N'Tchayi Mbourou et al. 1997). Rainfall is expressed as a regionally averaged, standardized departure (departure from the long-term mean divided by the standard departure), but the axis of the rainfall graph is inverted to facilitate comparison with dust occurrence. Dust is represented by the number of days with dust haze.

about 40°C were measured, compared to 45°C on the darker Negev side (Otterman and Tucker 1985). This apparent contradiction might reflect differences in emissivity and not real surface temperatures, but geometric arguments for a warmer surface where the vegetation cover is denser can be made. In contrast, surface temperatures in the Sonora were generally 2° to 4°C higher on the brighter, more heavily grazed Mexican side of the border than on the U.S. side (Balling 1988; Bryant et al. 1990).

In the case of the Sonora, the temperature differences on the grazed and protected sides of the border were shown to have an impact on soil moisture and cloudiness, but no changes in precipitation were apparent (Balling 1988; Bryant et al. 1990; Barnston and Schickedanz 1984). On the other hand, studies of the effect of vegetation patterns and irrigation on meso-scale circulation indirectly support the idea that desertification can at least potentially have an influence on weather and climate (e.g., Anthes 1984; Avissar and Pielke 1989). Also, both observational and theoretical studies of the characteristics of drought in arid and semiarid regions strongly underscore the importance of land-surface-atmosphere feedback in the persistence of anomalously dry conditions (e.g., Karl 1983; Diaz 1983; Entekhabi et al. 1992; Brubaker et al. 1993). This conclusion, supported by modeling studies of Charney et al. (1975), Charney et al. (1977), Lare and Nicholson (1994), and others, implies that if desertification is extreme enough, it could similarly evoke such feedback.

5. Evaluation of the common desertification scenario in the Sahel

a. Methodology

The purpose of this analysis is to examine the common scenario of desertification in the Sahel: an advancing desert, increasing albedo, and a decline in biological productivity. If this scenario is valid and the process is still ongoing, a systematic increase in desert area and southward shift in its boundary should be apparent and the relationship between vegetation cover and rainfall should change. Here the extent of the Sahara over the period 1980–95 is monitored using the normalized difference vegetation index (NDVI) obtained from advanced very high-resolution radiometer data from the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellite (Tucker et al. 1994). These data are compared with rainfall.

Both indicators are compared with surface albedo, as estimated from METEOSAT, using data derived by M. Ba et al. (1998, manuscript submitted to *J. Climate*).

NDVI is a simple ratio between the red and near-infrared reflectance bands. In arid and semiarid regions it correlates well with percent vegetation cover, biomass, and biological productivity (Nicholson 1994b). For this reason, it can be used to roughly distinguish the desert from the semiarid grassland and determine if a systematic decline in productivity has occurred. However, NDVI in itself is not an adequate indicator of land degradation per se since this involves changes of species composition, soil texture and fertility, etc. (Graetz 1991). Hence, our results as described below should not be interpreted as evidence that there has been no systematic degradation of the land.

Ideally, one would examine the aforementioned “desertification” scenario over a longer period, extending at least through the decline in rainfall between the wet 1950s and the drought of the 1970s (Fig. 2). Unfortunately, satellite data are limited to more recent years, a time period when generally subnormal conditions of rainfall have prevailed. Nonetheless, the analysis does depict the fluctuations of the desert and Sahel during nearly two decades and serves to underscore the close link between these fluctuations and rainfall.

This study represents an update of Tucker et al. (1991), and essentially the same methodology is utilized but with several modifications. For one, rainfall is assessed using both conventional station data, as in Tucker et al., and gridded, satellite-derived estimates. Because of the low spatial autocorrelation of rainfall, the latter provide a spatial average more directly comparable to the vegetation estimates. A second modification is that the current study is confined to the central and western Sahel, a region more homogeneous with respect to climate and vegetation than that previously analyzed. The study region extends from approximately 15° to 17°N, from the Atlantic coast eastward to 15°E.

Five analyses are carried out. The first is mapping of the boundary, as defined by NDVI and by rainfall. The second is a quantification of the extent of the Sahara, based both on NDVI and on rainfall. The third is an estimate of annually integrated NDVI and annual rainfall in the semiarid Sahel zone just south of the desert where mean annual rainfall ranges from approximately 200 to 400 mm. The fourth is calculation of the ratio of NDVI to rainfall. The fifth is determination of regionally averaged surface albedo for the central and western Sahel and evaluation of its interannual variability.

As in Tucker et al. (1991), mean annual rainfall of 200 mm is used to “climatically” delineate the Saharan boundary. Malo and Nicholson (1990) found that this corresponds to an annually integrated NDVI of 1. Revisions in the NDVI dataset, such as soil corrections, have altered the NDVI–rainfall relationships, particularly in the driest areas. For this reason, a seasonally averaged value of NDVI is used to predict the position of the 200 isohyet using the NDVI–rainfall regression derived by C. Tucker and S. Nicholson (1998, manuscript submitted to *Science*). It is recognized that these values actually represent the Sahelo-Saharan–Sahel transition, but in the drier regions use of NDVI is impractical and satellite estimates of rainfall become less accurate. The extent of the Sahara is calculated with respect to the latitude of 20°N; calculated values essentially represent the area of desert south of that latitude.

b. Data

NDVI has proved useful in numerous monitoring studies of vegetation and drought (e.g., Prince and Astle 1986; Justice et al. 1985; Kogan 1995; Nicholson et al. 1990; Nicholson and Farrar 1994). It is calculated as the normalized difference in reflectances between channels 1 (0.55–0.68 μm) and 2 (0.73–1.1 μm). The data are calculated from global-area coverage data with a resolution of 4 km and are mapped to an equal-area projection with a grid cell of approximately 7.6 km (Tucker et al. 1991). A cloud mask is applied based on channel 5 (11.5–12.5 μm). For the period 1 July 1991 to March 1993, a correction is applied for the stratospheric aerosols due to the Mt. Pinatubo eruption (Vermote and El Saleous 1994). A soil background correction (see Tucker et al. 1994) is applied in areas where the annual amplitude of NDVI is less than about 0.4, that is, roughly corresponding to areas where mean annual rainfall is less than 200 mm. Daily values of NDVI are formed into monthly composite images by using for each pixel the maximum NDVI within the compositing period (Holben 1986).

Use of maximum values minimizes the influence of varying solar zenith angles and surface topography on the index. There nonetheless exist interannual variations in NDVI that result from such factors as satellite calibrations, changes in satellite orbits, and tropospheric aerosols (Gutman et al. 1995). Corrections have been made for this (Tucker et al. 1994; Los 1993), but the margin of error is still about 0.01 NDVI units. This residual error is evident via analysis of the year-to-year variation of NDVI over absolute desert locations.

Using the year 1986 as a reference point, the time series of NDVI over the western desert just north of the Sahel is used to correct the Sahelian NDVI values, thereby minimizing spurious influences on the apparent interannual variability. Corrections were made by subtracting the value over the desert zone centered on 21°N from the NDVI averaged for the whole Sahel to 15°E.

NDVI is considered to be a “greenness” index. In arid and semiarid regions it is well correlated with such parameters as leaf area index, greenleaf biomass, vegetation cover, etc. (see Nicholson 1994b). However, strictly speaking it is a measure of photosynthetic activity. For a biophysical interpretation of NDVI, one is referred to Asrar et al. (1984), Tucker and Sellers (1986), and Prince (1991).

Rainfall is assessed from the 141 stations indicated in Fig. 4. These are part of a continental rainfall archive assembled by Nicholson (1986, 1993). Rainfall is also assessed from METEOSAT data, using a technique applied by Ba et al. (1995) and Nicholson et al. (1996) and based on mean infrared radiances. The satellite estimates explain 89% of the rainfall variance in most of the region, but the method tends to systematically overestimate rainfall in the driest northern sector and an additional step in the regression is used to estimate rain in this area. Calculations are for the rainy season, defined as July through October.

Data used in this study are extracted from a surface albedo dataset produced by M. Ba et al. (1998, manuscript submitted to *J. Climate*). In that study, surface albedo is calculated from METEOSAT B2 data [i.e., International Satellite Cloud Climatology Project (ISCCP) data] with a resolution of 30 km. The data consist of three-hourly, eight-bit digitized images in three spectral bands: 0.4–1.1 μm (visible channel), 10.5–12.5 μm (thermal infrared channel), and 5.7–

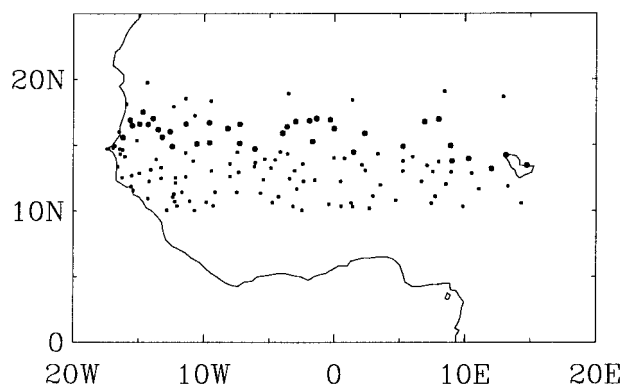


FIG. 4. Rainfall stations used in the current study. Larger dots indicate those stations lying within the region defined as Sahel.

7.7 μm (water vapor channel). Initially, global solar irradiance in the visible band is calculated using the physically based model of Dedieu et al. (1987). Then a top-of-atmosphere bidirectional reflectance factor, defined as the ratio of the actual flux to the flux that would be reflected by an ideal Lambertian surface, is calculated. To this, atmospheric corrections and a cloud and aerosol screening procedure are applied in order to obtain surface albedo (M. Ba et al. 1998, manuscript submitted to *J. Climate*). The calibration initially relies upon ISCCP calibration coefficients (Brest and Rossow 1992; Desormeaux et al. 1993). Using as a fixed target a Libyan desert test site, adjustments are made to minimize errors due to calibration uncertainties. Finally, directional effects on surface albedo due to seasonal variation in the solar zenith angle are corrected using a linear function of the cosine of that angle.

6. Results

a. The extent of the desert

Figure 5 shows the position of the 200-mm isohyet over West Africa each year from 1980 to 1995. That on the right is based on rainfall, that on the left is approximated from NDVI using an NDVI–rainfall regression. Both variables show a progressive southward movement of the boundary of the desert from 1982 to 1984, a rapid northward retreat in 1985, and continued retreat until 1989. The northward displacement since 1984, when the boundary was situated between approximately 12° and 14°N, was about 3° latitude. In 1990, the desert boundary again moved southward as rainfall decreased, reaching a limit close to that in the early 1980s. It retreated in 1991 and 1992, advanced markedly in 1993, and then in 1994 retreated to its northernmost position since 1980.

These fluctuations are quantified in Table 1, which gives the areal extent of the Sahara up to a latitude of 20°N and eastward to 15°E, based on the NDVI–rainfall regression. Within the period 1980 to 1990, desert extent varied from about $256 \times 10^4 \text{ km}^2$ to $305 \times 10^4 \text{ km}^2$. In Fig. 6 these estimates are compared with those based on rainfall, using the 200-mm rainfall isohyet to represent the Sahara’s southern boundary. One set of estimates is based on station precipitation, the other on satellite assessments of rainfall, as in Ba et al. (1995) and Nicholson et al. (1996).

There is considerable agreement between estimates based on rainfall and those based on NDVI, as well as

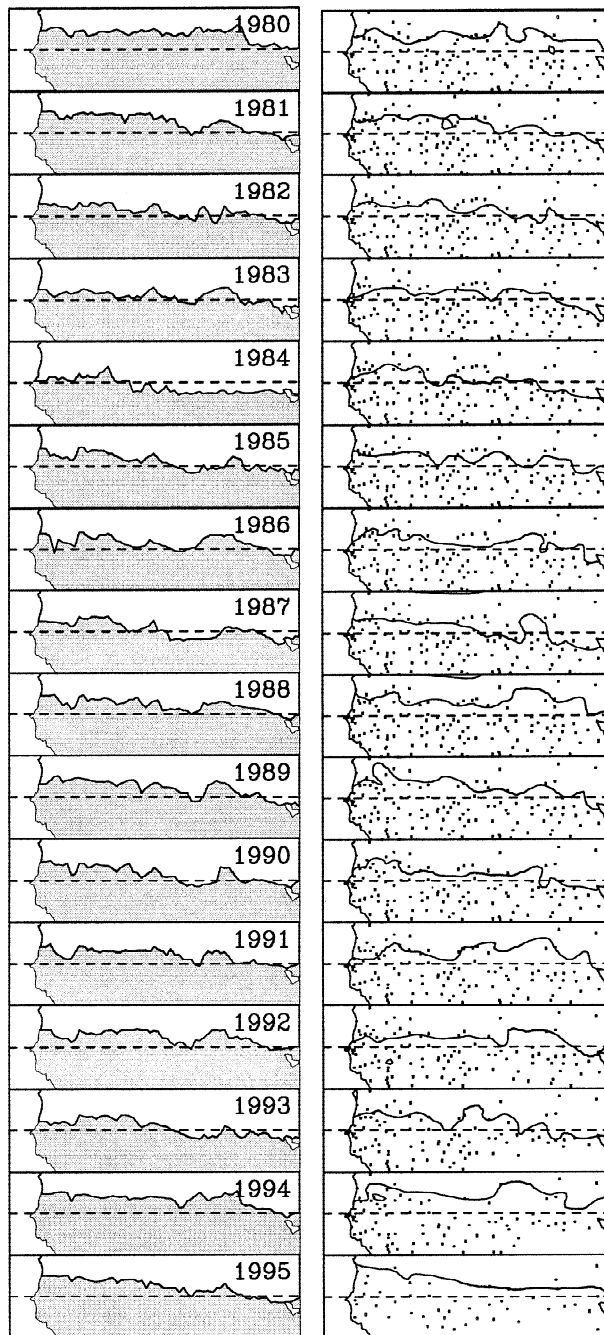


FIG. 5. An approximation of the 200-mm isohyet as an indicator of the Saharan boundary in the years 1980–1995: (right) on the basis of station rainfall, (left) on the basis of NDVI as a proxy indicator of the 200-mm isohyet. Dashed line indicates 15°N.

excellent agreement between the two sets of rainfall calculations. The few discrepancies all occur in conjunction with relatively wet years, 1985, 1988, and 1991. In each case, the desert “extent” calculated from rainfall is smaller than that calculated from NDVI, but the NDVI-based estimates catch up to those based on rainfall 1 yr later. This suggests that the vegetation

TABLE 1. Year to year fluctuations in the extent of the Sahara (in 10^4 km^2) lying south of 20°N and west of 15°E .

1980	257	1988	278
1981	270	1989	276
1982	292	1990	285
1983	295	1991	281
1984	305	1992	275
1985	290	1993	293
1986	286	1994	260
1987	296	1995	276

does not fully recover from a dry episode until a year after better conditions of rainfall return.

Overall, the results of this analysis indicate that there is no progressive “march” of the desert over West Africa. Rather, the interannual fluctuations of the desert boundary, as assessed from NDVI, mimic to a large degree that of rainfall.

b. The relationship between desert extent, NDVI, and rainfall

The above analysis shows that shifts in the desert boundary, as evidenced by surface vegetation, closely parallel shifts in rainfall patterns. This conclusion is

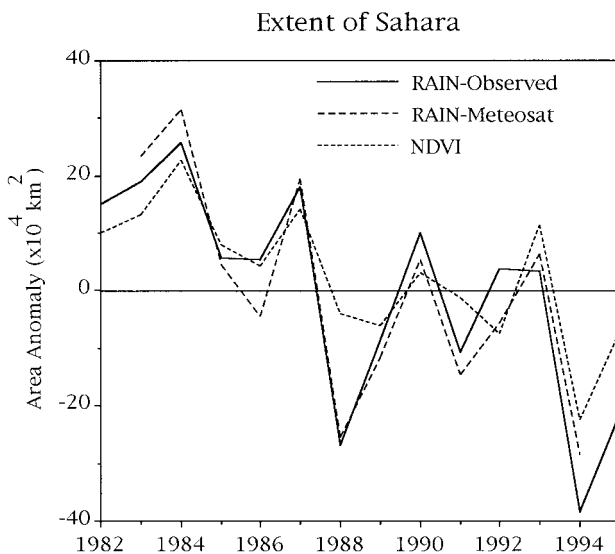


FIG. 6. The extent of the Sahara Desert, calculated as the area between the 200-mm isohyet and 25°N : solid line—as assessed from rainfall stations; dashed line—as assessed from Meteosat data; dotted line—as assessed from NDVI. Area, in 10^4 km^2 , is calculated with respect to the mean area during the period 1980–95.

further underscored through examination of NDVI and rainfall for the 200–400-mm zone as a whole. Figure 7 shows for each year the value of NDVI integrated for the wet season of July to October and compares it with rainfall in the zone during the same years.

NDVI is lowest in 1984, highest in 1988 and 1989, and drops dramatically in the years 1987 and 1990 (Fig. 7). The trend of rainfall is strikingly similar: rainfall is likewise lowest in 1984, highest in 1988 and 1992. The relative decline in NDVI in 1984 is, however, much stronger than the decline in rainfall. There are small discrepancies between the series in the early 1990s, but the magnitude of variation of both series was small in these years. The correlation between NDVI and rainfall is 0.9, a value that is significant at the 1% significance level. One apparent anomaly is the increase in NDVI in 1992. A similar discrepancy in 1992 was noted over the Kalahari of southern Africa (Grist et al. 1996). This could be a spurious consequence of a switch, late in 1991, from *NOAA-11* with a near-noon overpass, to *NOAA-12*, with a morning overpass.

c. Rain-use efficiency

The net annual increase of biomass, or net primary production, is a measure of the productivity of an ecosystem. This quantity bears a direct relationship to photosynthesis and NDVI is strongly correlated with both, particularly in arid lands. Noy-Meir (1985) suggests that the ratio of primary production to rainfall, P/R, (rain-use-efficiency) is a better parameter for characterizing arid and semiarid regions like the Sahel. Clearly, a decrease in this ratio over time would imply a decline in biological productivity due to factors other than drought.

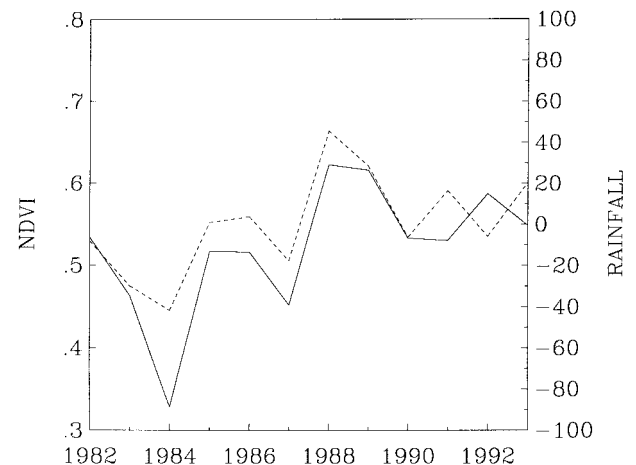


FIG. 7. Seasonal (June–October) rainfall (dashed line) and NDVI (solid line) in the West African Sahel, 1980–95. Rainfall is expressed as a percent departure from the long-term mean

The ratio of NDVI to rainfall provides a useful proxy for rain-use efficiency (Malo and Nicholson 1990; Nicholson et al. 1990; Nicholson and Farrar 1994). This parameter, averaged year-by-year over the whole Sahel, is shown in Fig. 8. The solid line is calculated from station data within the sector shown in Fig. 4. The dashed line is calculated from gridded $1^\circ \times 1^\circ$ satellite estimates of rainfall within this area, as calculated by M. Ba and S. Nicholson (1998, manuscript submitted to *J. Climate*), and corresponding spatial averages of NDVI.

The clearest results are that there is little interannual variability of the NDVI/rainfall ratio and that no decline in the ratio has occurred during the 13 yr of analysis. A large, temporary increase occurs in the ratio in 1984, the driest year, but this appears to be related to a few, localized occurrences of exceedingly dry conditions. Our results are in complete agreement with those of Prince et al. (1998), who likewise evaluated rain-use efficiency in the Sahel using station rainfall data and NDVI.

d. Interannual variability of surface albedo in the Sahel

Figure 9 shows the surface albedo for January and July averaged for the Sahel zone to 15°E , using data for the period 1983–88 produced by M. Ba and



FIG. 8. The ratio of seasonal rainfall (mm) to NDVI for the years 1982–93 (values are multiplied by 1000 to facilitate presentation). The solid line represents an average over all stations in the Sahelian sector indicated in Fig. 6. The dashed line is calculated from gridded $1^\circ \times 1^\circ$ satellite estimates of rainfall within this area, as calculated by M. Ba and S. Nicholson (1998, manuscript submitted to *J. Climate*), and corresponding spatial averages of NDVI.

S. Nicholson (1998, manuscript submitted to *J. Climate*). The total year-to-year variation within this period is on the order of 0.02 to 0.03, compared to wet–dry season differences on the order of 0.04–0.06, and it shows little relationship to fluctuations in rainfall or NDVI. This may be a result of the relatively small fluctuations of rainfall and NDVI within this period, compared with the long-term trends (Fig. 2). Albedo was noticeably lower in 1988, a wet year and the only year with markedly different rainfall conditions. Much of the apparent variability of surface albedo during 1983–88 is probably within the margin of error of satellite assessments.

Thus, surface albedo in the Sahel has shown relatively small year-to-year changes during these seven years. Within the same period, the latitude of the Saharan boundary shifted by about 1° of latitude. If this were a true displacement of the Sahara, the latitudinal albedo gradient (Fig. 10) suggests that this would correspond to a change of albedo of nearly 0.08. Thus, within the albeit brief period between 1983 and 1988 there is no systematic increase that would be symptomatic of “desertification.” Observational studies of Courel et al. (1984) found somewhat greater year-to-year variations of albedo, about 0.01 to 0.15 within the period 1967–79. They also demonstrated that the fluctuations bore a general relationship to rainfall conditions, the variation of which was greater during 1967–79 than during the 1983–88 period.

Moreover, surface albedo within the period 1983–88 is constrained by the overall vegetation character,

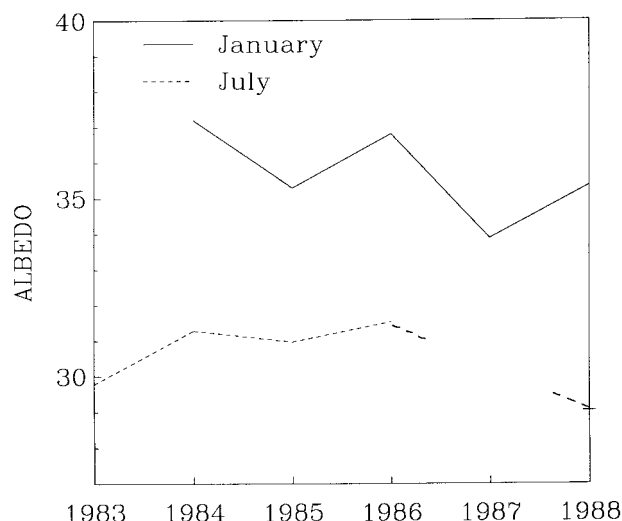


FIG. 9. Surface albedo over the Sahelian zone (see Fig. 2) for January and July for the years 1983–88 (based on M. Ba and S. Nicholson 1998, manuscript submitted to *J. Climate*).

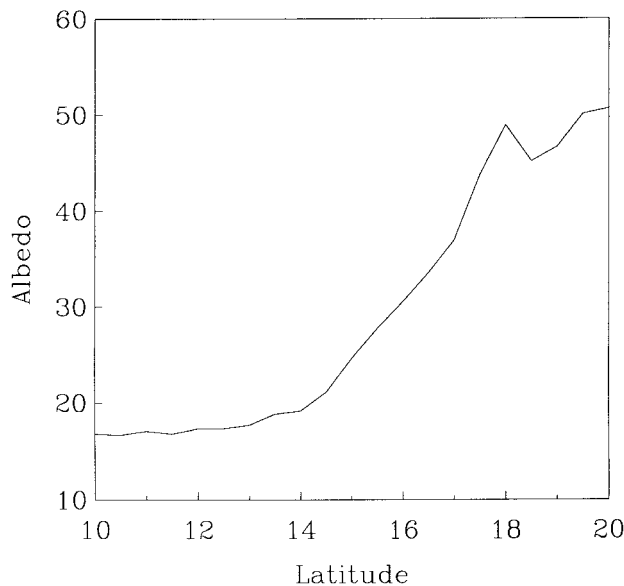


FIG. 10. Surface albedo at 10°W as a function of latitude. This transect represents the albedo in a band from 11° to 9°W. The data are extracted from a gridded surface albedo dataset produced by M. Ba et al. (1998, manuscript submitted to *J. Climate*).

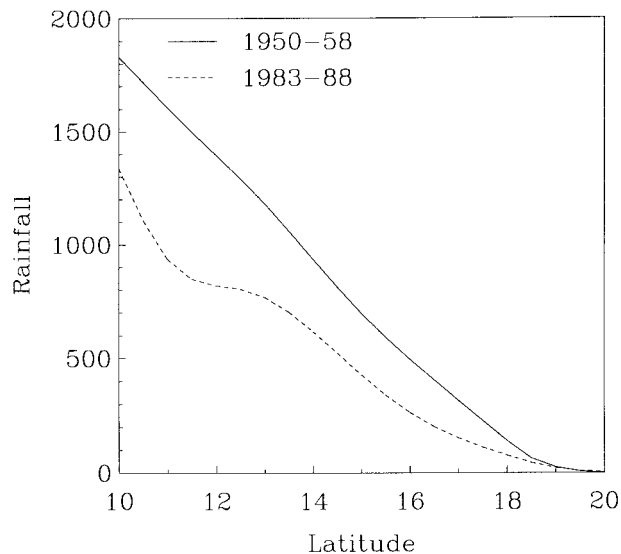


FIG. 11. Mean annual rainfall (mm) as a function of latitude at 10°W for the period 1950–59 and 1983–88.

including the presence or absence of boreal elements and their density. This does not change on timescales of years, but there is considerable evidence that it has changed over timescales of decades (e.g., Akhtar-Schuster 1995). Numerous West African residents describe a much different vegetation regime in the 1950s and early 1960s, before the onset of the multidecadal drought (Nicholson 1993). Thus, the question arises as to corresponding changes in surface albedo (see also Gornitz 1985).

Some estimate can be made from the latitudinal gradients of rainfall and albedo (Figs. 10 and 11); the former is a consequence of latitudinal gradients in the vegetation cover and soil moisture, which in turn reflect the rainfall gradient. For this reason, a strong,

inverse correlation exists between mean surface albedo and mean annual rainfall over West Africa (Fig. 12). At 15°N (roughly the southern boundary of the Sahel), where surface albedo is about 0.30 (Fig. 10), mean rainfall for 1983–88 was about 450 mm (Fig. 11). At 17°N (roughly the Sahel’s northern boundary), where surface albedo is 0.43, mean rainfall for the same period was about 200 mm. For the 1950s, rainfall at these same latitudes was about 750 and 350 mm (Fig. 11). Similar changes in rainfall conditions occurred throughout West Africa (Table 2). If the vegetation and soil characteristics of the 1950s were similar to those now in equilibrium with these rainfall conditions, the corresponding surface albedos would be about 0.20 and 0.32, respectively (Fig. 12). Hence surface albedo

TABLE 2. Difference in mean annual rainfall (mm) between 1950–58 and 1983–88 at latitudes and longitudes indicated, respectively, as columns and rows in the table.

lat \ long	-10	-8	-6	-4	-2	0	2	4	6	8	10
10	569	336	504	608	323	375	235	243	169	174	147
12	648	326	361	275	291	414	204	209	227	243	250
14	331	284	248	247	271	244	228	260	243	231	221
16	238	216	232	178	208	190	162	149	153	166	157
18	57	40	106	69	53	57	83	89	91	86	68
20	0	0	0	0	-3	13	47	61	51	29	11

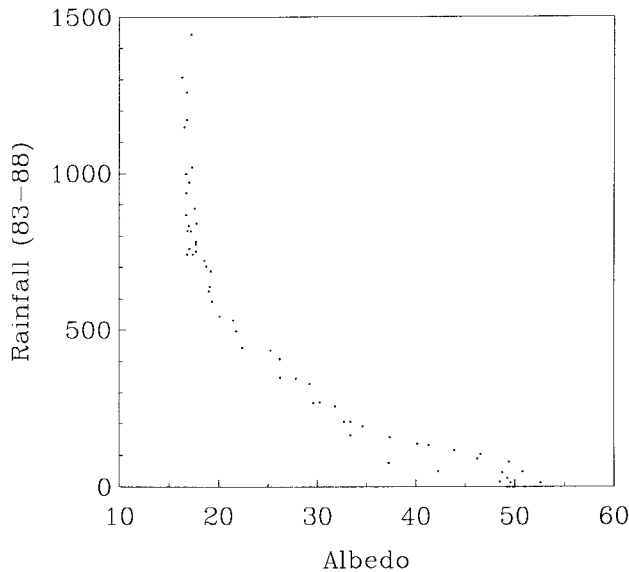


FIG. 12. Surface albedo vs mean annual rainfall (mm) at 10°W. The indicated correlation reflects the fact that large latitudinal gradients of both parameters exist over West Africa.

in the Sahel may have been about 0.10 lower during the 1950s than today.

7. Summary and conclusions

Our analyses have clearly demonstrated that the extent of the Sahara and the vegetation cover within the Sahelian zone fluctuate from year to year in accordance with the interannual variability of rainfall. No progressive change in either the desert boundary or the vegetation cover in the Sahel is evident during the 1980–95 analysis period. Neither has there been a change in the “productivity” of the land, as assessed by the ratio of NDVI to rainfall.

During this period, interannual variations in surface albedo have been on the order of 0.02–0.03. These are small in comparison to the albedo changes prescribed by Charney et al. (1975), Charney et al. (1977), and other modeling studies. Our results do not rule out a significant change since the time that wetter conditions prevailed earlier in the century, prior to the protracted period of relatively dry conditions and drought since the late 1960s. On the contrary, it can be argued that a change in albedo of 0.10 between the 1950s and the 1980s is conceivable. This is comparable to the change from 0.20 to 0.30 used by Xue and Shukla (1993) to simulate desertification. In general, however, albedo is a complex problem and a reduction of vegetation cover does not always result in higher albedo

(M. Ba and S. Nicholson 1998, manuscript submitted to *J. Climate*).

This study does not imply that significant changes in the extent of the Sahara have not taken place over longer time periods. Neither does it attempt to contest the climatic importance of interactions between the land surface and the atmosphere. It demonstrates mainly that during the 16-yr study period human impacts have neither produced a progressive southward march of the Sahara nor a large-scale exposure of barren, less productive, and highly reflective land in the Sahel.

The complexity of causes and effects of desertification and its relationship to rainfall variability and drought is underscored by the extensive field work and analysis of Akhtar-Schuster (1995), Graetz (1991), and others. It is difficult to distinguish between human-induced and climatically induced changes of the land surface, that is, between drought and desertification. Sometimes desertification takes the form of incomplete recovery of the land during wetter years or changes in the individual elements of the vegetation cover. Examples are desirable species for animal foraging being replaced by less palatable ones and by species more resistant to the vagaries of rainfall, hence resulting in a reduction of the interannual variability of the vegetation cover.

It is of critical importance that such ideas as a monolithic encroachment of the desert on the savanna, a reduction in total vegetation cover, and exposure of bare soil be replaced by a view of desertification recognizing this complexity. Only then can the true extent of the problem and its relationship to meteorological factors be evaluated.

References

- Ahlcrona, E., 1988: *The Impact of Climate and Man of Land Transformation in Central Sudan*. Lund University Press, 140 pp.
- Akhtar-Schuster, M., 1995: *Degradationsprozesse und Desertifikation im semiariden randtropischen Gebiet der Butana/Rep. Sudan*. Goettinger Beitrage zur Land- und Forstwirtschaft in den Tropen und Subtropen, Vol. 105, Universität Goettingen, 166 pp.
- Andreae, M. O., 1996: Raising dust in the greenhouse. *Nature*, **380**, 389–390.
- Anthes, R., 1984: Enhancement of convective precipitation by mesoscale variations in vegetative covering in semiarid regions. *J. Climate Appl. Meteor.*, **23**, 541–554.
- Asrar, G., M. Fuchs, E. T. Kanemasu, and J. L. Hatfield, 1984: Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat. *Agron. J.*, **76**, 300–306.

- Avisar, R., and R. A. Pielke, 1989: A parameterization of heterogeneous land surface for atmospheric numerical models and its impact on regional meteorology. *Mon. Wea. Rev.*, **117**, 2113–2136.
- Ba, M. B., R. Frouin, and S. E. Nicholson, 1995: Satellite-derived interannual variability of West African rainfall during 1983–1988. *J. Appl. Meteor.*, **34**, 411–431.
- Balling, R. C., Jr., 1988: The climatic impact of Sonoran vegetation discontinuity. *Climate Change*, **13**, 99–109.
- Barnston, A. G., and P. T. Schickedanz, 1984: The effect of irrigation on warm season precipitation in the southern Great Plains. *J. Climate Appl. Meteor.*, **23**, 865–888.
- Bovill, E. W., 1921: The encroachment of the Sahara on the Sudan. *J. African Soc.*
- Brest, C. L., and W. B. Rossow, 1992: Radiometric calibration and monitoring of NOAA/AVHRR data for ISCCP. *Int. J. Remote Sens.*, **13**, 235–273.
- Brubaker, K., D. Entekhabi, and P. Eagleson, 1993: Estimation of continental precipitation recycling. *J. Climate*, **6**, 1077–1089.
- Bryant, N. A., L. F. Johnson, A. J. Brazel, R. C. Balling, C. F. Hutchinson, and L. R. Beck, 1990: Measuring the effect of overgrazing in the Sonoran Desert. *Climate Change*, **17**, 243–264.
- Charney, J. G., 1975: Dynamics of deserts and drought in Sahel. *Quart. J. Roy. Meteor. Soc.*, **101**, 193–202.
- , P. H. Stone, and W. J. Quirk, 1975: Drought in the Sahara: A biogeophysical feedback mechanism. *Science*, **187**, 434–435.
- , W. J. Quirk, S. H. Chow, and J. Kornfield, 1977: A comparative study of the effects of albedo change on drought in semi-arid regions. *J. Atmos. Sci.*, **34**, 1366–1385.
- Chervin, R. M., 1979: Response of the NCAR general circulation model to changed land surface albedo. *Report of the JOC Study Conference on Climate Models: Performance, Intercomparison and Sensitivity Studies*, GARP Publication Series No. 22, Vol. 1, 563–581.
- Courel, M., R. Kandel, and S. Rasool, 1984: Surface albedo and the Sahel drought. *Nature*, **307**, 528–538.
- Dedieu, G., P. Y. Deschamps, and Y. H. Kerr, 1987: Satellite estimation of solar irradiance at the surface of the earth and of surface albedo using a physical model applied to Meteosat. *J. Climate Appl. Meteor.*, **26**, 79–87.
- Desormeaux, Y., W. B. Rossow, C. L. Brest, and G. G. Campbell, 1993: Normalization and calibration of geostationary satellite radiances for the International Satellite Cloud Climatology Project. *J. Atmos. Oceanic Technol.*, **10**, 304–325.
- Diaz, H., 1983: Some aspects of major dry and wet periods in the contiguous United States, 1895–1981. *J. Climate Appl. Meteor.*, **22**, 3–16.
- Dirmeyer, P. A., and J. Shukla, 1994: The response of climate to subtropical desertification in a GCM with idealized topography. *Proc. Sixth Conf. on Climate Variations*, Nashville, TN, Amer. Meteor. Soc., 37–40.
- , and —, 1994b: Albedo as a modulator of climate response to tropical deforestation. *J. Geophys. Res.*, **99**, 20 863–20 877.
- , and —, 1996: The effect on regional and global climate of expansion of the world's deserts. *Quart. J. Roy. Meteor. Soc.*, **122**, 451–482.
- Entekhabi, D., I. Rodriguez-Iturbe, and R. Bras, 1992: Variability in large-scale water balance with a land surface–atmosphere interaction. *J. Climate*, **5**, 798–813.
- Fouquart, Y., B. Bonnell, G. Brogniez, J. C. Buriez, L. Smith, J. J. Morcrette, and A. Cerf, 1987: Observations of Saharan aerosols: Results of ECLATS field experiment. Part II. Broadband radiative characteristics of the aerosols and vertical radiative flux divergence. *J. Climate Appl. Meteor.*, **26**, 38–52.
- Gornitz, V., 1985: A survey of anthropogenic vegetation changes in West Africa during the last century—Climatic implications. *Climate Change*, **7**, 285–325.
- Graetz, R. D., 1991: Desertification: A tale of two feedbacks. *Ecosystem Experiments*, H. A. Mooney et al., Eds., Wiley, 59–87.
- Grist, J., S. E. Nicholson, and A. Mpolokang, 1996: On the use of NDVI for estimating rainfall fields in the Kalahari of Botswana. *J. Arid Environ.*, **35**, 195–214.
- Gutman, G., D. Tarpley, A. Ignatov, and S. Olson, 1995: The enhanced NOAA global land dataset from the Advanced Very High Resolution Radiometer. *Bull. Amer. Meteor. Soc.*, **76**, 1141–1156.
- Hellden, U., 1984: *Drought Impact Monitoring: A Remote Sensing Study of Desertification in Kordofan, Sudan*. Lunds Universitets Naturgeografiska Institution, 61 pp.
- , 1991: Desertification—Time for an assessment? *Ambio*, **20**, 372–383.
- Holben, B. N., 1986: Characteristics of maximum-value composite images from temporal AVHRR data. *Int. J. Remote Sens.*, **7**, 1395–1416.
- Justice, C. O., J. R. G. Townshend, B. N. Holben, and C. J. Tucker, 1985: Analysis of the phenology of global vegetation using meteorological satellite data. *Int. J. Remote Sens.*, **6**, 1271–1318.
- Karl, T., 1983: Some spatial characteristics of drought in the United States. *J. Climate Appl. Meteor.*, **22**, 1356–1366.
- Kogan, F., 1995: Drought of the late 1980s in the United States as derived from NOAA polar orbiting satellite data. *Bull. Amer. Meteor. Soc.*, **76**, 655–668.
- Kraus, E. B., 1955: Secular changes of tropical rainfall regimes. *Quart. J. Roy. Meteor. Soc.*, **81**, 138–210.
- Lamprey, H., 1975: Report on the Desert Encroachment Reconnaissance in Northern Sudan, Khartoum. National Council for Research/Ministry of Agriculture, Food and Natural Resources, 16 pp.
- Lare, A. R., and S. E. Nicholson, 1994: Contrasting conditions of surface water balance in wet years and dry years as a possible land surface–atmosphere feedback mechanism in the West African Sahel. *J. Climate*, **7**, 653–668.
- Li, X., H. Maring, D. Savoie, K. Voss, and J. J. Prospero, 1996: Dominance of mineral dust in aerosol light scattering in the North Atlantic trade winds. *Nature*, **380**, 416–419.
- Lofgren, B. M., 1995a: Sensitivity of land–ocean circulations, precipitation, and soil moisture to perturbed land surface albedo. *J. Climate*, **8**, 2521–2542.
- , 1995b: Surface albedo–climate feedback simulated using two-way coupling. *J. Climate*, **8**, 2543–2562.
- Los, S. O., 1993: Calibration adjustment of the NOAA-AVHRR normalized difference vegetation index without recourse to channel 1 and 2 data. *Int. J. Remote Sens.*, **14**, 1907–1917.
- Mainguet, M., 1991: *Desertification, Natural Background and Human Mismanagement*. Springer-Verlag, 306 pp.
- Malo, A. R., and S. E. Nicholson, 1990: A study of rainfall and vegetation dynamics in the African Sahel using normalized difference vegetation index. *J. Arid Environ.*, **19**, 1–24.

- Nicholson, S. E., 1986: The spatial coherence of African rainfall anomalies: Interhemispheric teleconnections. *J. Climate Appl. Meteor.*, **25**, 1365–1381.
- , 1988: Land surface–atmosphere interaction: Physical processes and surface changes and their impact. *Progr. Phys. Geogr.*, **12**, 36–65.
- , 1990: The need for a reappraisal of the question of large-scale desertification: Some arguments based on consideration of rainfall fluctuations. Report of the SAREC-Lund International Meeting on Desertification, December 1990, Lund, Sweden, 14 pp.
- , 1993: An overview of African rainfall fluctuations of the last decade. *J. Climate*, **6**, 1463–1466.
- , 1994a: Desertification. *Encyclopedia of Climate and Weather*, S. H. Schneider, Ed., Simon and Schuster, 239–242.
- , 1994b: On the use of the normalized difference vegetation index as an indicator of rainfall. *Global Precipitations and Climate Change*, NATO ASI Series I, Vol. 26, Springer, 293–306.
- , 1997: The physical-biotic interface in arid and semi-arid systems. *Arid Lands Management—Towards Ecological Sustainability*, T. W. Hoekstra and M. Shachak, Eds., University of Illinois Press, in press.
- , and T. J. Farrar, 1994: The influence of soil type on the response between NDVI, rainfall and soil moisture in semi-arid Botswana. Part I. Response to rainfall. *Remote Sens. Environ.*, **50**, 107–120.
- , M. L. Davenport, and A. R. Malo, 1990: A comparison of the vegetation response to rainfall in the Sahel and East Africa, using Normalized Difference Vegetation Index from NOAA AVHRR. *Climate Change*, **17**, 209–241.
- , M. B. Ba, and J. Y. Kim, 1996: Rainfall in the Sahel during 1994. *J. Climate*, **9**, 1673–1676.
- Noy-Meir, I., 1985: Desert ecosystem structure and function. *Hot Deserts and Arid Shrublands*, M. Evenari, I. Noy-Meir, and D. W. Goodall, Eds., *Ecosystems of the World*, Vol. 12A, Elsevier, 93–103.
- N’Tchayi Mbourou, G., J. J. Bertrand, and S. E. Nicholson, 1997: The diurnal and seasonal cycles of desert dust over Africa north of the equator. *J. Appl. Meteor.*, **36**, 868–882.
- Olsson, L., 1985: An integrated study of desertification. Lunds Universitets Geografiska Institution Avhandlingar, XCVIII.
- Otterman, J., 1974: Baring high-albedo soils by overgrazing: A hypothesized desertification mechanism. *Science*, **186**, 531–533.
- , 1977: Anthropogenic impact on the albedo of the Earth. *Climate Change*, **1**, 137–157.
- , 1981: Satellite and field studies of man’s impact on the surface in arid regions. *Tellus*, **33**, 68–77.
- , and C. J. Tucker, 1985: Satellite measurements of surface albedo and temperatures in semi-desert. *J. Climate Appl. Meteor.*, **24**, 228–234.
- Prince, S. D., 1991: A model of regional primary production for use with coarse resolution satellite data. *Int. J. Remote Sens.*, **12**, 1313–1330.
- , and W. L. Astle, 1986: Satellite remote sensing of rangelands in Botswana. II. Landsat MSS and herbaceous vegetation. *Int. J. Remote Sens.*, **7**, 1533–1553.
- , E. Brown de Colstoun, and L. L. Kravitz, 1998: Desertification of the Sahel? Evidence from remotely sensed rain-use efficiencies. *Global Change Biol.*, in press.
- Puigdefabregas, J., 1995: Desertification: Stress beyond resilience, exploring a unifying process structure. *Ambio*, **24**, 311–313.
- Schlesinger, W. H., J. F. Reynolds, G. L. Cunningham, L. F. Huenneke, W. M. Jerrell, R. A. Virginia, and W. G. Whitford, 1990: Biological feedbacks in global desertification. *Science*, **247**, 1043–1048.
- Schwarz, E. H. L., 1920: *The Kalahari or Thirstland Redemption*. T. Maskew Miller.
- Stebbing, E. P., 1935: The encroaching Sahara. *Geogr. J.*, **86**, 509–510.
- Sud, Y. C., and M. J. Fennessy, 1982: A study of the influence of surface albedo on July circulation in semiarid regions using the GLASS GCM. *J. Climatol.*, **2**, 105–125.
- , and ———, 1984: A numerical study of the influence of evaporation in semiarid regions on the July circulation. *J. Climatol.*, **4**, 383–398.
- , and W. E. Smith, 1985: Influence of local land-surface processes on the Indian monsoon: A numerical study. *J. Climate Appl. Meteor.*, **24**, 1015–1036.
- , and A. Molod, 1988: A GCM simulation study of the influence of Saharan evapotranspiration and surface-albedo anomalies on July circulation and rainfall. *Mon. Wea. Rev.*, **116**, 2388–2400.
- Tegen, I., and I. Fung, 1994: Modeling of mineral dust in the atmosphere: Sources, transport, and optical thickness. *J. Geophys. Res.*, **99**, 22 897–22 914.
- , and ———, 1995: Contribution to the atmospheric mineral aerosol load from land surface modification. *J. Geophys. Res.*, **100**, 18 707–18 726.
- , A. A. Lacis, and I. Fung, 1996: The influence of mineral aerosols from disturbed soils on the global radiation budget. *Nature*, **380**, 419–422.
- Thomas, D. S. G., and N. J. Middleton, 1994: *Desertification: Exploding the Myth*. Wiley, 194 pp.
- Tucker, C. J., and P. J. Sellers, 1986: Satellite remote sensing of primary production. *Int. J. Remote Sens.*, **7**, 1395–1416.
- , and S. E. Nicholson, 1997: Large-scale Saharan-Saharan vegetation variations from 1980 to 1996 derived from ground precipitation and NOAA satellite data. *Science*, submitted.
- , H. E. Dregne, and W. W. Newcomb, 1991: Expansion and contraction of the Sahara desert from 1980 to 1990. *Science*, **253**, 299–301.
- , W. W. Newcomb, and H. C. Dregne, 1994: AVHRR data sets for determination of desert spatial extent. *Int. J. Remote Sens.*, **15**, 3547–3566.
- United Nations, 1980: *Desertification*, M. K. Biswas and A. K. Biswas, Eds., Pergamon Press.
- Vermote, E. F., and N. Z. El Saleous, 1994: Stratospheric aerosol perturbing effect on remote sensing of vegetation: Operational method for the correction of AVHRR composite NDVI. *SPIE Atmospheric Sens. and Modeling*, **2311**, 19–29.
- Verstraete, M. M. 1986: Defining desertification: A review. *Climate Change*, **9**, 5–18.
- Warren, A., 1996: Desertification. *The Physical Geography of Africa*, W. M. Adams, A. S. Goudie, and A. R. Orme, Eds., Oxford University Press, 342–355.
- Wendler, G., and F. Eaton, 1983: On the desertification in the Sahel zone. Part I. Ground observations. *Climate Change*, **5**, 365–380.
- Xue, Y., and J. Shukla, 1993: The influence of land surface properties on Sahel climate: Part I. Desertification. *J. Climate*, **6**, 2232–2245.