Drought monitoring with NDVI-based Standardized Vegetation Index

Article *in* Photogrammetric Engineering and Remote Sensing · January 2002

Drought Monitoring with NDVI-Based Standardized Vegetation Index

Albert J. Peters, Elizabeth A. Walter-Shea, Lei Ji, Andrés Viña, Michael Hayes, and Mark D. Svoboda

Abstract

Drought is one of the major natural hazards affecting the environment and economy of countries worldwide. Reliance on weather data alone is not sufficient to monitor areas of drought, particularly when these data can be untimely, sparse, and incomplete. Augmenting weather data with satellite images to identify the location and severity of droughts is a must for complete, up-to-date, and comprehensive coverage of current drought conditions. The objective of this research was to standardize, by time of year, the Normalized Difference Vegetation Index (NDVI) to augment drought-monitoring techniques. The Standardized Vegetation Index (SVI) describes the probability of vegetation condition deviation from "normal," based on calculations from weekly NDVI values. The study was conducted with 12 years (1989–2000) of Advanced Very High-Resolution Radiometer (AVHRR) satellite images. Z-scores of the NDVI distribution are used to estimate the probability of occurrence of the present vegetation condition at a given location relative to the possible range of vegetative vigor, historically. The SVI can be interpreted as vegetation condition based on the fact that vegetation is an efficient integrator of climatic and anthropogenic impacts in the boundary layer of the atmosphere. It thereby provides a spatially and temporally continuous short-term indicator of climatic conditions. Findings indicate that the SVI, along with other drought monitoring tools, is useful for assessing the extent and severity of drought at a spatial resolution of 1 km. The SVI is capable of providing a near-real-time indicator of vegetation condition within drought regions, and more specifically areas of varying drought conditions.

Introduction

Accurately monitoring drought has always been a challenge. One explanation for this is that droughts are a slow-onset, or "creeping," natural disaster, developing over months and years, and frequently they exist before it is realized that a drought is occurring. Secondly, a drought's severity varies by it's precipitation deficit, spatial extent, and duration, making it difficult to compare one drought to another. Finally, the impacts of drought are based on the range of economic, environmental, and social resources within a region. The challenge is to develop an operational drought index that can aid in making appropriate and timely decisions in response to drought.

In August 1999, the United States Department of Agriculture, the National Oceanic and Atmospheric Administration, and the National Drought Mitigation Center launched a joint drought-monitoring project. This project, called the Drought Monitor (DM), now produces a weekly map of general drought conditions around the United States. The DM has nine authors that utilize a series of climate and water-resource products and a network of local experts to assess the current drought situation in the United States (http://enso.unl.edu/monitor/monitor.html). A variety of products to monitor drought go into generating the map, including precipitation indices, stream flow levels, soil moisture models, snow pack levels, and satellite vegetation index data. Spatially and temporally continuous coverage offered by satellite data enhances the value of these drought-monitoring products.

The value of meteorological satellite imagery for the investigation of vegetation vigor and phenology has been demonstrated (Goward *et al.*, 1985; Tucker *et al.*, 1985; Peters *et al.*, 1997). Vegetation condition is closely related to short-term atmospheric dynamics in the boundary layer and is an important element in global vegetation monitoring (Justice *et al.*, 1985; Gallo, 1990).

At present the Advanced Very High Resolution Radiometer (AVHRR) on board the National Oceanic and Atmospheric Administration's (NOAA's) polar-orbiting satellites is the instrument of choice for collecting coarse-resolution imagery worldwide due to its twice-daily coverage and synoptic view (Batista *et al.*, 1997; Unganai and Kogan, 1998). The Normalized Difference Vegetation Index (NDVI), derived from AVHRR data, has been extensively used for vegetation monitoring, crop yield assessment, and drought detection (Benedetti and Rossini, 1993; Moulin *et al.*, 1998). The NDVI is calculated as (NIR − RED)/(NIR + RED), where NIR is the reflectance radiated in the near-infrared waveband and RED is the reflectance radiated in the visible red waveband of the satellite radiometer (Justice *et al.*, 1985). Higher NDVI indicates a greater level of photosynthetic activity (Sellers, 1985; Tucker *et al.*, 1991). It has been demonstrated that multitemporal NDVI derived from AVHRR data is useful for monitoring vegetation dynamics on a regional and continental scale (Goward *et al.*, 1985; Justice *et al.*, 1985; Tucker *et al.*, 1985; Tucker and Choudhury, 1987; Eidenshink and Haas, 1992).

While the NDVI has proven useful for timely estimation of vegetation condition, as a normalized ratio, it does not allow for relative comparison at a pixel location or time period (Burgan and Hartford, 1993; Kogan, 1995). The ability to compare pixel values this way would be useful for removing seasonal vegetation changes, facilitating interpretation through the historical record and between different vegetation cover.

Satellite NDVI data have been used in classifying vegetation condition. Kogan (1990) suggested an approach to vegetation

A.J. Peters, Lei Ji, and A. Viña are with the Center for Advanced Land Management Information Technologies.

E.A. Walter-Shea is with the School of Natural Resources Sciences, and M. Hayes and M.D. Svoboda are with the National Drought Mitigation Center, all at the University of Nebraska-Lincoln, Lincoln, NE 68588-0517 (apeters@calmit.unl.edu).

Photogrammetric Engineering & Remote Sensing
Vol. 68, No. 1, January 2002, pp. 71–75.
0099-1112/02/6800–071$3.00/0

condition monitoring based on minimum and maximum NDVI values compiled per pixel over time. Kogan (1990) states that available moisture and natural resources determine the NDVI minimum while other values, including the historical maximum, are determined by the weather. Kogan (1990) used this NDVI statistical range to develop the "Vegetation Condition Index (VCI)," an indicator of environmental stress. The VCI is NDVI normalized for each pixel on the basis of the maximum statistical range over the historical record of available imagery.

Burgan and Hartford (1993) introduced the concept of "relative greenness," a percentage value that expresses how green each pixel is in relation to the average greenness over the historical record for a pixel location at a given time. For relative greenness, the range of possible values is determined by the ratio of current NDVI to the mean NDVI for a time period for each pixel. The actual mean value was determined for every pixel location in the United States, and will change as new image data are added each year. Biweekly AVHRR NDVI data at a 1-km resolution were used. Maps produced using the relative greenness technique are quite useful for comparing the present greenness to the historical record. The VCI and relative greenness techniques have been used successfully to monitor drought conditions and crop yields in various parts of the world (Kogan, 1995; Burgan *et al.*, 1996; Hayes and Decker, 1998; Unganai and Kogan, 1998).

This study was based on transforming a probability of an observed greenness amount into an index using AVHRR 1-km NDVI biweekly data to monitor areas of drought/vegetation condition called the "Standardized Vegetation Index" (SVI). The SVI allows visualization of relative vegetation greenness in terms of "greenness probability" at each 1-km^2-pixel location through the use of a probability estimate, which suggests comparison over time periods that are longer than the archival imagery.

Methodology

This research began with the 14-day (biweekly) maximum-value NDVI composite images for the conterminous United States, produced by the U.S. Geological Survey Earth Resources Observation System (EROS) Data Center since 1989 (Eidenshink, 1992). The maximum-value composite procedure is based on a time series where the daily NDVI for each pixel is examined during the 14-day period and only the highest value is retained. Holben (1986) found that, by compositing AVHRR data over short-time periods, spatially continuous cloud-free images of large areas could be produced. A linear interpolation method was used to derive weekly NDVI composite images. The procedure resulted in a weekly maximum-value composite data set for the growing seasons of 1989 through 1999. Since January 2000, weekly maximum-value composite AVHRR imagery of the central portion of the U.S. have been collected from the University of Nebraska-Lincoln (UNL) ground receiving station, thus extending the data set for an additional 52 weeks, for the year 2000.

The SVI is based on calculation of a z score for each AVHRR pixel location in the Great Plains of the United States (2020 columns by 2674 rows). The z score is a deviation from the mean in units of the standard deviation, calculated from the NDVI values for each pixel location for each week for each year, during the 12-years 1989–2000 as

$$z_{ijk} = \frac{\mathrm{NDVI}_{ijk} - \overline{\mathrm{NDVI}}_{ij}}{\sigma_{ij}}$$

where z_{ijk} is the z-value for pixel i during week j for year k, NDVI_{ijk} is the weekly NDVI value for pixel i during week j for year k, $\overline{\mathrm{NDVI}}_{ij}$ is the mean NDVI for pixel i during week j over n years, and σ_{ij} is the standard deviation of pixel i during week j over n years.

The z_{ijk} was assumed to fit a standard normal distribution, which has mean of zero and standard deviation of 1, denoted as $z_{ijk} \sim N(0, 1)$. To test the assumption of normality, 100 pixels from the 1989 through 2000 growing seasons were randomly selected. Of those, 80.3 percent were found to be normally distributed based on Shapiro and Wilk's W-test (Royston, 1995) at the $\alpha = 0.01$ level. Thus, the probability density function of z_{ijk} is given by

$$\mathrm{SVI} = \mathrm{P}\ (Z < z_{ijk}).$$

This per-pixel probability, expressed as the Standardized Vegetation Index (SVI), is an estimate of the "probability of occurrence" of the present vegetation condition. The values of the SVI range between greater than zero to less than one ($0 < \mathrm{SVI} < 1$). Zero is the baseline condition in which a pixel NDVI value is lower than all possible NDVI values for that week in other years. One is the baseline condition in which the pixel NDVI value for the respective week is higher than all the NDVI values of the same week in the other years. Subsequently, for mapping purposes, SVI values were grouped into five classes, each of which comprises different and consecutive ranges of values. These classes were termed very poor (0 to 0.05), poor (0.05 to 0.25), average (0.25 to 0.75), good (0.75 to 0.95), and very good (0.95 to 1). The distribution of vegetation conditions into these classes was intended to mimic a normal probability density function. For instance, a pixel that is classified as "very poor" indicates that its NDVI value is lower than the average during the same week of the year relative to that in other years of the study. A pixel classified as very good indicates that its NDVI value is higher than average, or that vegetation is in very good relative condition. The discussion comparing the SVI and DM are based upon climatic information derived from the Weekly Weather and Crop Bulletin (NOAA/USDA, Joint Agricultural Weather Facility).

Results and Discussion

Figure 1 is a map of the study area focused on the Great Plains states from North Dakota to Texas. Plate 1 shows the SVI and corresponding DM maps (http://enso.unl.edu/monitor/monitor.html) for six time periods during the 2000 growing season. The purpose for the comparison is to show how the SVI can be a valuable tool when used in conjunction with the DM maps. In some cases, the DM maps verify the SVI maps showing drought where vegetation conditions are poor. In other cases, there is not a clear match between the two products. This can happen for several reasons: (1) because the SVI reflects short-term vegetative response to weather conditions and the DM maps show both short term and longer-term drought conditions, the SVI map will show areas of relatively good or poor vegetation status and will show changes more quickly than the DM maps; (2) relatively poor vegetation condition may be caused by other factors besides drought (e.g., flooding, unseasonable coolness that can put vegetation behind phenologically, or crop rotation); and (3) the DM maps are a mix of objective and subjective determinations of drought conditions and may not be in themselves completely accurate. Like any tool, the SVI needs to be used carefully and one must know when and how to use the SVI, as well as understand its strengths and weaknesses.

Plate 1 illustrates why the understanding of local information is essential for comparing and analyzing the two drought products. In early May 2000, drought seen in the DM map was centered on the western Corn Belt (between Nebraska and Illinois) following a very dry fall, winter, and spring. Because of favorable early season growing conditions, Corn Belt crop development was ahead of normal. Very poor to poor SVI conditions in southeastern Nebraska, much

Figure 1. Study area covering the central part of the United States, focusing on the Great Plains.

of Iowa, central Missouri, and northwestern Illinois correspond to the drought stages on the DM map for this same period. The extreme drought in western Texas had a definite impact on the SVI values in this particular area.

By early June, the Corn Belt, as measured by the SVI, had greened considerably compared to one month earlier, even though extreme and severe drought was indicated in places on the DM map. This is likely a combination of two factors. First, eastern portions of the Corn Belt had received beneficial rains during May. Second, the dry conditions along with above-normal temperatures throughout the spring had allowed farmers within the Corn Belt to plant earlier than usual, thus resulting in more vigorous growth than that which occurs normally. The greenness in the western Corn Belt is attributed to immature crops developing more rapidly than normal while taking advantage of available root-zone moisture and favorable temperatures. Note the appearance of poor and very poor SVI conditions for this period appearing in southwestern Nebraska and northwestern Kansas, providing a forewarning of developing drought conditions. In addition, both the SVI and the DM maps for early June provide an indication of the severity of drought taking place in western Texas and southern New Mexico. Central Montana also shows a good correspondence between the SVI and the DM map.

By the first week in July, considerable precipitation had fallen across the entire Corn Belt region, improving growing conditions (see the 04 July 2000 DM map). Larger areas of "average" conditions in July as compared to June are shown by the SVI, which can be attributed to a return to normal crop development due to adequate precipitation. However, some agricultural areas experienced retarded growth due to localized-excessive precipitation, particularly across southern Minnesota, northern Iowa, and Wisconsin. Early monsoonal moisture occurring in late June in western Texas and eastern New Mexico resulted in a decrease in drought severity in both the SVI and DM maps. The cause of the large groupings of very-poor class pixels ranging from Mexico north through the Rockies on the SVI is due to intensifying drought, as confirmed by the numerous forest fires in the area (NIFC, 2000). Very poor to poor vegetative conditions in Arkansas and Louisiana are captured by the early July SVI map but are located in a more restricted area centered around New Orleans on the DM map. This is an additional case of the SVI showing early drought development as vegetative conditions generally remained in the very poor to poor category in subsequent time periods, while drought progressed across the same region in the DM maps.

By late July, the areas to notice within the SVI map include (1) pockets of very poor to poor vegetation condition in the western Corn Belt, particularly in western Iowa and in parts of South Dakota, Nebraska, and Kansas; (2) a strong decrease in vegetation condition across the eastern half of Texas that is likely related to the development of drought there; and (3) very poor to poor SVI-class levels across the Rockies, indicating vegetation conditions primed for wildfires (i.e., 2000 did approach the recent record for the number of acres burned in the United States set in 1988).

The most notable change in the early September maps is the rapid intensification of drought across the southern Plains reflected in both the SVI and DM maps (the term to describe this development was "flash drought" because of the combination of no precipitation and very high temperatures, particularly during August). Recall that vegetation conditions in Texas, Arkansas, and Louisiana were starting to indicate drought development back in July. Vegetation in early September is in relatively poor condition compared to that indicated on the DM maps, and depicts the severity and extent of the dryness across the southern Plains and in the Rockies.

Finally, very poor to poor vegetation condition appears during the first week of October in nearly the entire central United States (see the SVI map). This is likely caused by the deepening drought across most of the region as seen on the DM map for early October. This particular SVI map provides a good vegetation condition indicator for many locations, except in cropland in some parts of the north where the growing season is over and most crops are ready for harvest if not already harvested. At this time the SVI is no longer a valid tool for drought detection because of fall vegetation senescence. Many drought-measurement tools applied by the DM are insensitive to the season (e.g., the Crop Moisture Index, snow pack levels), whereas it has been demonstrated that the SVI is very effective during the growing season.

Conclusions

Our evaluation of SVI maps for the 2000 growing season demonstrates that the SVI is a good indicator of vegetation response to short-term weather conditions. Some of the advantages of the SVI as compared to the DM maps are its high spatial resolution (1 km) and potential for near-real-time evaluation of actual vegetation conditions. Care needs to be taken in local areas when evaluating the SVI because climatic conditions other than drought can cause reduced vegetation vigor.

It can be concluded that the SVI is a useful tool and is capable of providing a near-real-time indicator of the onset, extent, intensity, and duration of vegetation stress. When used along with traditional drought indices and other weather and ancillary information, the SVI could make a contribution toward the development of an operational drought index that can aid in

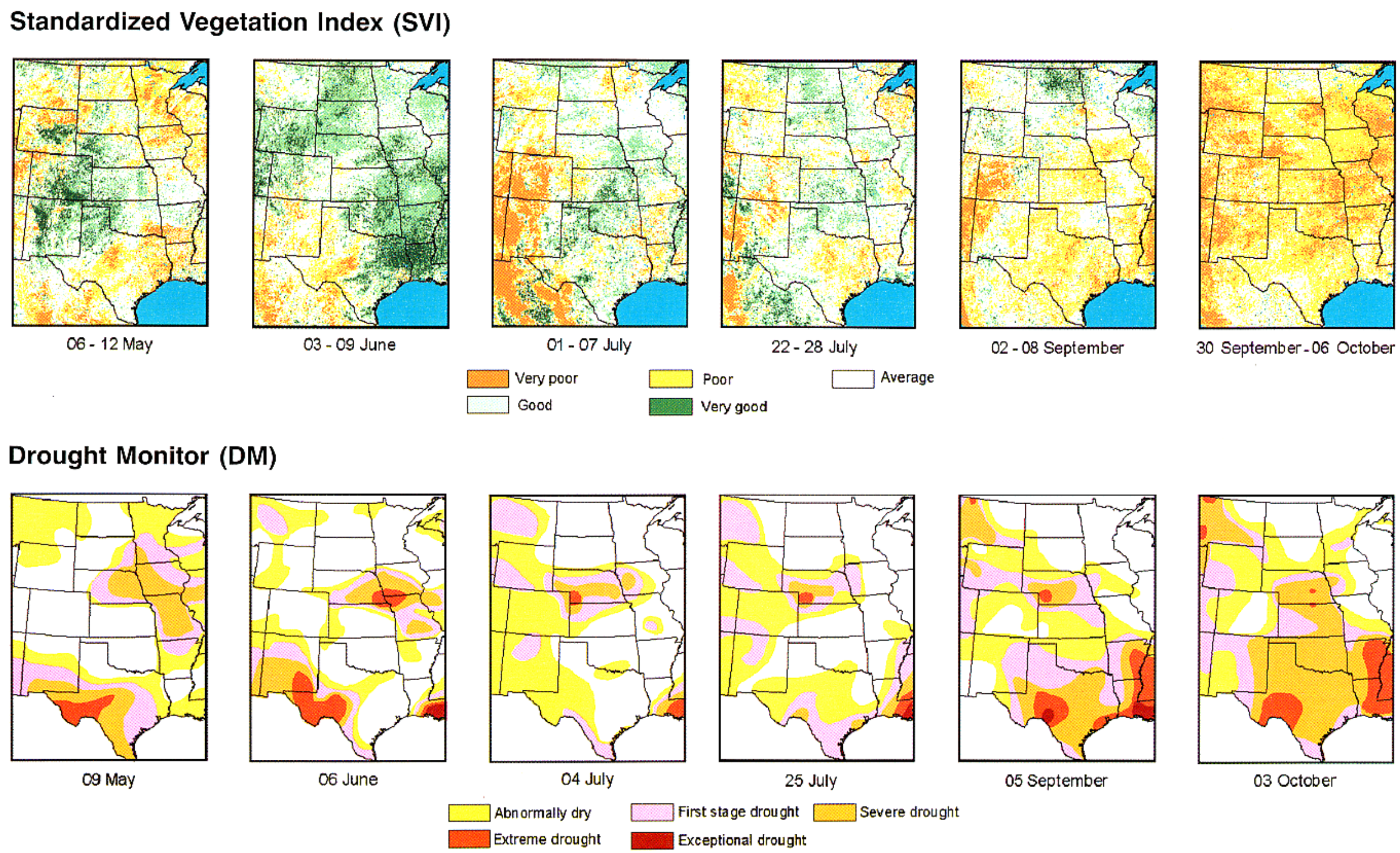

Plate 1. Selected Standardized Vegetation Index (SVI) and Drought Monitor (DM) maps for the year 2000 growing season for the Great Plains (http://enso.unl.edu/monitor/monitor.html).

making appropriate and timely decisions in response to drought.

Acknowledgments

We wish to acknowledge funding from the National Aeronautical and Space Administration under Research Announcement 95-MTPE-03, which supports a project through the National Center for Atmospheric Research (NCAR), Climate and Global Dynamics Division, Climate Change Research Section, from which the SVI was developed. We also received a contribution of the University of Nebraska Agricultural Research Division, Lincoln, NE 68583. Journal Series No. 12567.

References

Batista, T.T., Y.E. Shimabukuro, and W.T. Lawrence, 1997. The long-term monitoring of vegetation cover in the Amazonian region of northern Brazil using NOAA-AVHRR data *International Journal of Remote Sensing*, 18:3195–3210.

Benedetti, R., and P. Rossini, 1993. On the use of NDVI profiles as a tool for agricultural statistics: The case study of wheat yield estimate and forecast in Emilia Romagna, *Remote Sensing of Environment*, 45:311–326.

Burgan, R.E., and R.A. Hartford, 1993. *Monitoring Vegetation Greenness with Satellite Data*, Gen. Tech. Rep. INT-297, U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, Utah, 13 p.

Burgan, R.E., R.A. Hartford, and J.C. Eidenshink, 1996. *Using NDVI to Assess Departure from Average Greenness and Its Relation to Fire Business*, Gen. Tech. Rep. INT-GTR-333, U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, Utah, 8 p.

Eidenshink, J.C., 1992. The 1990 Conterminous U.S. AVHRR data set, *Photogrammetric Engineering & Remote Sensing*, 58:809–813.

Eidenshink, J.C., and R.H. Hass, 1992. Analyzing vegetation dynamics of land systems with satellite data, *GeoCarto International*, 1:53–61.

Gallo, K.P., 1990. Satellite derived vegetation indices: A new climatic variable? *Proceedings of the Symposium on Global Change Systems, Special Sessions on Climate Variations and Hydrology*, 05–09 February, Anaheim, California, Amer. Meteor. Soc., pp. 133–137.

Goward, S.A., C.J. Tucker, and D. Dye, 1985. North American vegetation patterns observed with the NOAA-7 advanced very high resolution radiometer, *Vegetatio*, 64:3–14.

Hayes, M.J., and W.L. Decker, 1998. Using satellite and real-time weather data to predict maize production, *International Journal of Biometeorology*, 42(1):10–15.

Holben, B.N., 1986. Characteristics of maximum-value composite images from temporal AVHRR data, *International Journal of Remote Sensing*, 23:1417–1434.

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, *International Journal of Remote Sensing*, 6:1271–1318.

Kogan, F.N., 1990. Remote sensing of weather impacts on vegetation, *International Journal of Remote Sensing*, 11:1405–1419.

———, 1995. Droughts of the late 1980s in the United States as derived from NOAA polar-orbiting satellite data, *Bulletin of the American Meteorological Society*, 76:655–668.

Moulin, S.A., A. Bondeau, and R. Delecolle, 1998. Combining agricultural crop models and satellite observations: From field to regional scales, *International Journal of Remote Sensing*, 19:1021–1036.

National Interagency Fire Center, 2000. *Incident Management Situation Report, Tuesday, July 4, 2000*, National Interagency Fire Center, Boise, Idaho [available at http://stone.cidi.org/wildfire/0007/0003.html].

NOAA/USDA, Joint Agricultural Weather Facility, 2000. *Weekly Weather and Crop Bulletin Volume 87*, NOAA/NWS/NCEP/CPC, Camp Springs, Maryland (published weekly).

———, 2001. *Weekly Weather and Crop Bulletin Volume 88*, NOAA/NWS/NCEP/CPC, Camp Springs, Maryland (published weekly).

Peters, A.J., M.D. Eve, E.H. Holt, and W.G. Whitford, 1997. Analysis of desert plant community growth patterns with high temporal resolution satellite spectra, *Journal of Applied Ecology*, 34:418–432.

Royston, J.P., 1995. A remark on algorithm AS181: The W-test for normality, *Applied Statistics*, 44:547–551.

Sellers, P.J., 1985. Canopy reflectance, photosynthesis and transpiration, *International Journal of Remote Sensing*, 6:1335–1372.

Tucker, C.J., J.R.G. Townshend, and T.E. Goff, 1985. African land-cover classification using satellite data, *Science*, 227:369–375.

Tucker, C.J., and B.J. Choudhury, 1987. Satellite remote sensing of drought conditions, *Remote Sensing of Environment*, 23:243–251.

Tucker, C.J., H.E. Dregne, and W.W. Newcomb, 1991. Expansion and contraction of the Sahara Desert from 1980 to 1990, *Science*, 253:299–301.

Unganai, L.S., and F.N. Kogan, 1998. Drought monitoring and corn yield estimation in southern Africa from AVHRR data, *Remote Sensing of Environment*, 63:219–232.

(Received 03 May 2001; accepted 27 June 2001; revised 27 August 2001)