Relations between Soil Moisture and Satellite Vegetation Indices in the U.S. Corn Belt

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ABSTRACT

Satellite-derived vegetation indices extracted over locations representative of midwestern U.S. cropland and forest for the period 1990–94 are analyzed to determine the sensitivity of the indices to neutron probe soil moisture measurements of the Illinois Climate Network (ICN). The deseasoned (i.e., departures from multiyear mean annual cycle) soil moisture measurements are shown to be weakly correlated with the deseasoned full resolution (1 km × 1 km) normalized difference vegetation index (NDVI) and fractional vegetation cover (FVC) data over both land cover types. The association, measured by the Pearson-moment-correlation coefficient, is stronger over forest than over cropland during the growing season (April–September). The correlations improve successively when the NDVI and FVC pixel data are aggregated to 3 km × 3 km, 5 km × 5 km, and 7 km × 7 km areas. The improved correlations are partly explained by the reduction in satellite navigation errors as spatial aggregation occurs, as well as the apparent scale dependence of the NDVI–soil moisture association. Similarly, stronger relations are obtained with soil moisture data that are lagged by up to 8 weeks with respect to the vegetation indices, implying that soil moisture may be a useful predictor of warm season satellite-derived vegetation conditions. This study suggests that a ''long-term'' memory of several weeks is present in the near-surface hydrological characteristics, especially soil water content, of the Midwest Corn Belt. The memory is integrated into the satellite vegetation indices and may be useful for predicting crop yield estimates and surface temperature anomalies.

1. Introduction

Satellite sensors capture many of the physiognomic characteristics of vegetation (e.g., photosynthetic activity, plant moisture content) through spectral radiance measurements (Tucker et al. 1985). Several methods based on the band-ratioing of vegetation sensitivity in the near-infrared (NIR) and visible (VIS) spectral bands, have been developed to convert the radiance measurements into vegetation indices. The most widely used of these vegetation indices is the normalized difference vegetation index (NDVI), computed from the VIS and NIR channels of the Advanced Very High Resolution Radiometer (AVHRR) deployed on the polar-orbiting meteorological satellites operated by the National Oceanic and Atmospheric Administration (NOAA). The NDVI is defined as the ratio of the difference between the NIR reflectances in the 725–1100-nm wavelength band, or AVHRR channel 2, and the VIS reflectances in the 580–680-nm wavelength band (channel 1), to the sum of the two. Other satellite-derived indices include the simple difference vegetation index (DVI) and the fractional vegetation cover (FVC). The DVI is obtained by taking the difference between the first two channels of the AVHRR, instead of the normalized difference (Gutman 1991), and the FVC is derived from NDVI using a procedure that reduces the biases in NDVI pixel values introduced by the background (i.e., soil and bare ground) reflectance (Carlson et al. 1994). The latter is important when comparing measurements of the early with peak-growing season. Compared to NDVI and DVI, FVC is more sensitive to vegetation photosynthetic activity within a given pixel because it strictly indicates the fraction of a pixel covered by vegetation and, therefore, minimizes the background contamination problem of those indices (Carlson et al. 1994; Gillies and Carlson 1995).

Although NDVI has proven very useful for assessing vegetation phenology, and estimating net primary production in a variety of land cover situations over large areas, the exact interpretation of the observed variations in NDVI is not easily made because of poorly documented interactions among the vegetation, climate, and soil hydrological properties represented in the satellite-measured radiances. As an integrated indicator of vegetation activity, NDVI responds to variables such as canopy density, photosynthesis, and surface moisture

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differently according to land cover type (Kogan 1990; Srivastava et al. 1997). Moreover, it is not always clear to what variable(s) the NDVI is responding most at any given time or averaging period for a particular site. Numerous studies have linked the spatial and temporal patterns of NDVI with climate, including temperature and precipitation regimes (Schultz and Halpert 1993; Myneni et al. 1996), plant evapotranspiration (Cihlar et al. 1991), soil physical properties (Lozano-Garcia et al. 1995; Gillies et al. 1997), and large-scale climate teleconnection patterns such as ENSO (Anyamba and Eastman 1996; Bounoua et al. 2000). In other studies where NDVI has been used to monitor regional drought conditions, the index has been associated closely with eco-climatological variables such as potential evapotranspiration, growing degree days, and soil hydrologic properties (Hayes and Decker 1996; Yang et al. 1997).

The above-mentioned studies have focused on the relations between NDVI and particular hydroclimate variables, often over limited time periods such as one or two growing seasons. Thus, it is not clear that the conclusions drawn from those studies can be extended beyond the years or regions investigated. Research is needed to better characterize satellite vegetation index–climate relations in the longer term, and to determine whether similar relationships exist during periods other than the previously studied years, particularly during climate anomalies like floods or droughts.

Of particular interest is the role of soil moisture in surface climate by its influence on partitioning the available surface energy into sensible and latent heat fluxes (Shuttleworth 1991). Previous investigations for the Midwest (Carleton et al. 1994; Carleton and O'Neal 1995) suggest that the summer (i.e., June–August) NDVI of the region is primarily an indicator of land cover type, although it also shows sensitivity to short-term surface moisture fluctuations, as proxied by antecedent precipitation occurrence. Moreover, soil moisture has been shown (Kunkel 1990) to affect crop status and crop yield potential more directly than the purely climatological variables of precipitation and temperature. Accordingly, the present study investigates the correspondence between warm season (April–September) satellite-derived vegetation indices and soil moisture for Illinois over the time period 1990–94. This was a period of marked interannual variability in Midwestern climate for the growing season (Lozano-Garcia et al. 1995).

We use contemporaneous measurements of AVHRR-derived vegetation indices (NDVI and FVC), and neutron probe soil moisture measurements obtained for two stations representative of very different land covers (i.e., cropland, forest) in the Illinois Climate Network (ICN). Statistical relationships between these two hydroclimate variables are derived for a recent 5-yr period (1990–94) for which we were able to obtain the full-resolution (1.1 km $\times$ 1.1 km) AVHRR data. Two ICN stations (Bondville: BVL and Carbondale: SIU) are used to represent the croplands and forests (Fig. 1a). NDVI and FVC–soil moisture relations are examined over the entire warm season (April–September) for concurrent and lagged datasets. The analysis is limited to these two stations because the spatial averaging of soil moisture measurements is inadvisable given the large spatial inhomogeneity that soil moisture exhibits.

2. Data and methods

a. Soil moisture data

Neutron probe measurements of soil moisture are made biweekly at most of the 17 ICN stations currently operated by the Illinois State Water Survey. Although this Illinois data record is barely 20 years long (1981–2000), it comprises the most comprehensive set of continuous soil moisture measurements available for any area in the Midwest. The dataset has proven invaluable for studies attempting to validate satellite measurements of vegetation and surface moisture conditions with the regional climate and soil moisture obtained from conventional data (Brown and Arnold 1998; Vinnikov et al. 1999). Soil moisture measurements are taken within 11 soil layers to a depth of 2 m (m): the first in the top 0.1 m of the profile, and then at intervals of 0.2 m to a depth of 1.9 m. The lowest measurement is taken in the layer between 1.9 and 2.0 m (Hollinger and Isard 1994). On average, less than 5% of the soil moisture change from winter to summer occurs below 1 m (Hollinger and Isard 1994); hence, for the analyses reported here, we use only measurements of the top layer (10–30 cm) to capture shorter timescale soil moisture fluctuations, and also profile-averaged moisture values for the upper 1 m of soil. Figure 2 shows the time series of these soil moisture values for April–September (1990–94) superimposed on the full-resolution NDVI data extracted over the two ICN stations included in this study.

b. USGS land use/land cover (LU/LC) digital data

Land use/land cover (LU/LC) information at and around the two ICN stations was included in the analyses to assess the possible effects of land cover differences (i.e., forest, cropland) on the NDVI–soil moisture relations. A previous study suggests that Midwest land surfaces (forest, cropland) may influence convective cloud development differently (Carleton et al. 2001), hence the decision to explicitly examine the influence of land cover differentiation on satellite vegetation index–soil moisture associations. For the present study, LU/LC information for the Midwest was obtained from the U.S. Geological Survey (USGS) LU/LC digital database of the continental United States. The assignment of land cover classes in this database is based upon the Anderson classification scheme (Anderson et al. 1976), which includes several broad land cover categories including urban or builtup land, cropland, rangeland, forest land, water, wetland, and barren land.

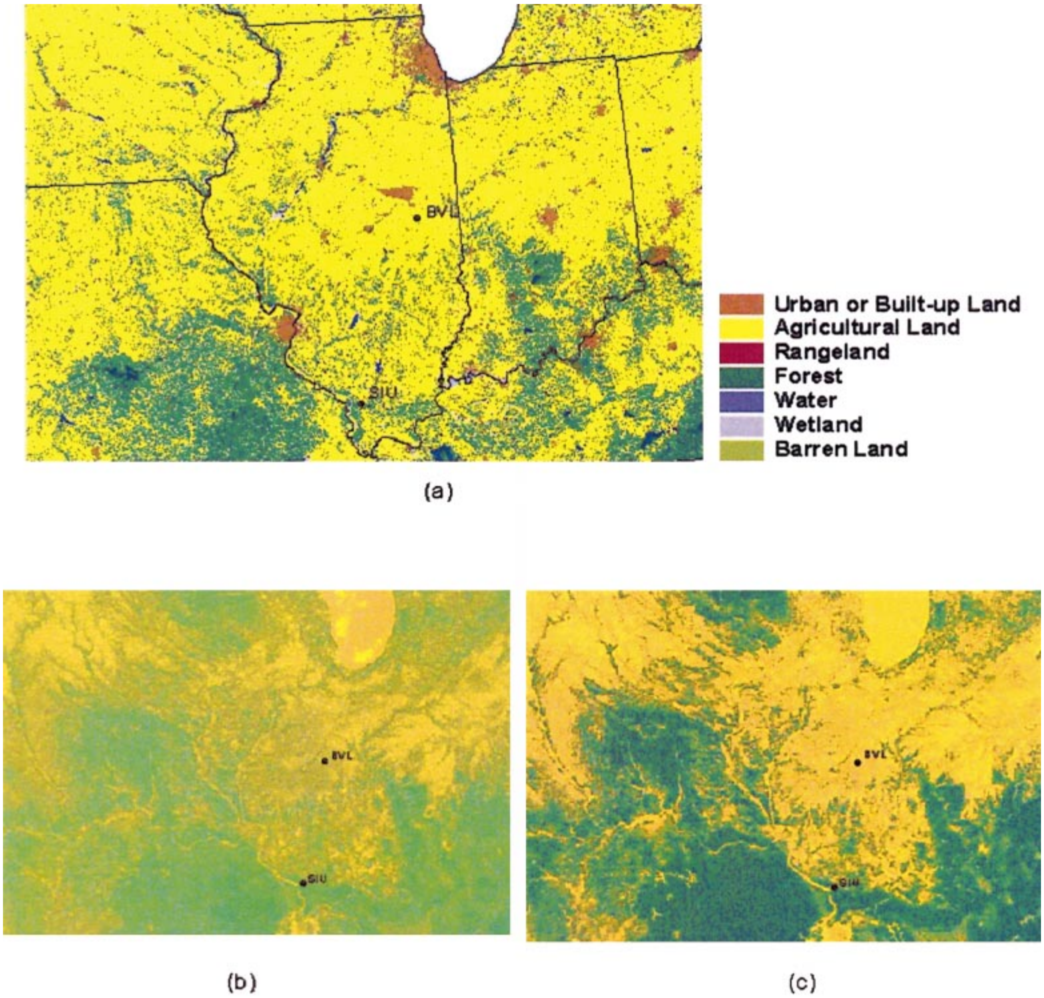

FIG. 1. (a) Map of central Midwest Corn Belt LU/LC, (b) the composite 1–10 Jun 1992 NDVI, and (c) FVC for the same region. Each image shows the location of the ICN soil moisture stations representative of cropland (BVL) and forest (SIU) areas used in the study.

The USGS provides the digital LU/LC data in the geographic information retrieval and analysis (GIRAS) format. We converted the data into ARC/INFO export format and subsequently processed the data using the ARC/INFO Geographic Information System software package. Vector data-layer processing routines were used to edge-match and combine the quadrangles to produce a georeferenced digital LU/LC map of the Midwest. Detailed information on the procedures used in the construction of the Midwest LU/LC map is given in Adegoke and Carleton (2000).

To facilitate comparisons of the station soil moisture observations with the LU/LC area-averaged satellite pixel data, a georeferenced digital map of the location of the ICN stations was developed using the ARC/INFO software. Overlay and spatial analysis routines link the LU/LC map to the ICN stations exact locations, and create circular buffer zones of 5.5 km in diameter around each ICN station. The size of the buffer zones was chosen to correspond with the area of the NDVI maximum-aggregation level of 7 km × 7 km. The dominant land cover type in each buffer zone was determined based on a 70% dominance criterion at and in the vicinity of the ICN stations. The 70% dominance threshold is considered appropriate for regional-scale studies (Belward and Loveland 1996).

c. *NDVI and fractional vegetation cover (FVC) data*

The NDVI data used in this study is the full-resolution (1 km × 1 km) local area coverage (LAC) AVHRR product from the ''afternoon'' passes of NOAA operational meteorological satellite *NOAA-11*. The USGS at its Earth Resources Observation Systems (EROS) Data Center (EDC) in Sioux Falls, South Dakota, developed this 1 km × 1 km resolution AVHRR time series for the conterminous United States, Alaska, and Eurasia under a special arrangement with NOAA. As part of

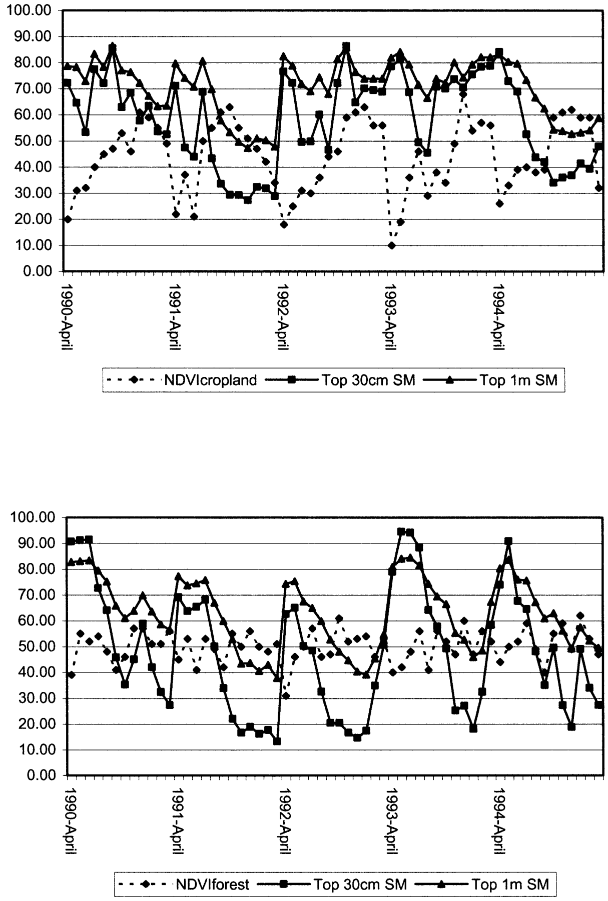

FIG. 2. Apr–Sep 1990–94 time series of full-resolution NDVI ($\times$ 100) and profile-averaged soil moisture (top 30 cm, top 1 m) for (a) cropland and (b) forest sites.

this arrangement, a comprehensive series of calibrated, georegistered, daily observations and biweekly full-resolution NDVI composites have been produced annually since 1989, and published on CD-ROM. Though complete coverage of the global land surface is possible daily with the AVHRR sensors, the daily data can be of poor quality because of atmospheric transient conditions including clouds and aerosols. These tend to decrease the magnitude of NDVI (Holben 1986). Other factors affecting the daily NDVI product include satellite navigation errors, the degradation of the AVHRR sensor with time (i.e., ''sensor drift''), variations in the viewing and solar zenith angles, the surface bidirectional reflectance distribution functions, and variations in soil background texture and color (Los et al. 1994). To help accommodate these effects, several methods such as temporal compositing of multiday images, and selection of pixels close to the subsatellite track are used to reduce the likelihood of unrepresentative samples in the NDVI dataset.

The USGS uses a biweekly compositing period with screening for possible influences of subpixel clouds on the NDVI radiances; thus only images that provide a clear observation of ground areas at reasonable nadir-viewing angles were included in the composites (Eidenshink 1992). The procedures used to generate the composites encompass several steps including radiometric calibration of the AVHRR visible and near-infrared channels (channels 1 and 2) using time-dependent calibration coefficients based on measurements of desert targets (Holben et al. 1990). This procedure was developed to specifically account for the effects of post-launch AVHRR sensor degradation. In addition to the radiometric calibration, the solar illumination variability, which occurs in the north–south direction within an orbit, was corrected using the cosine of the solar angle. Satellite sensor drift, which causes the satellite overpass time to occur progressively later in the day, became an issue for *NOAA-11* beginning in 1993. Although the effects of orbital drift are greater for bare ground, significant effects are also found for certain vegetation classes (Gutman 1999). However, a recent study (Kaufmman et al. 2000) of the effect of changes in solar zenith angle and sensor changes on reflectances in channel 1, channel 2, and NDVI from AVHRR Pathfinder land data for 1981–94 showed that the data are not contaminated by trends introduced by sensor drift and that NDVI can be used to analyze interannual variability of vegetation activity. The USGS LAC data have not been specifically adjusted for orbital sensor drift.

The FVC is a measure of the fraction of a pixel covered (i.e., shaded) by vegetation. The biweekly fractional vegetation data used in this analysis were derived from the full-resolution NDVI biweekly composites. NDVI values range from -1.0 to $+1.0$ with areas having NDVI < 0 rarely containing any vegetation, and NDVI considerably larger than 0 normally having vegetation that is photosynthesizing. Above a lower threshold slightly greater than 0, the FVC increases approximately as the square of NDVI, and reaches 100% at an upper threshold of the NDVI that is considerably less than 1.0 (Gillies and Carlson 1995). This gives the formulas:

$$\begin{aligned}
&\mathrm{N} \le \mathrm{T}_1: \\
&\mathrm{FVC} = 0.0,\ \mathrm{T}_1 < \mathrm{N} < \mathrm{T}_2: \\
&\mathrm{FVC} = [(\mathrm{N} - \mathrm{T}_1)/(\mathrm{T}_2 - \mathrm{T}_1)] \\
&\qquad \times [(\mathrm{N} - \mathrm{T}_1)/(\mathrm{T}_2 - \mathrm{T}_1)],\ \mathrm{N} \ge \mathrm{T}_2: \\
&\mathrm{FVC} = 1.0,
\end{aligned}$$

where FVC is the fractional vegetation cover, N is the NDVI values, T_1 the lower threshold, and T_2 the upper threshold.

Compared to the NDVI, FVC is less sensitive to the background soil and bare ground reflectance. It therefore captures growing season phenological changes of the vegetation more accurately. The FVC composites used in this study were developed by Joe Santanello (2000, personal communication) using an inversion procedure

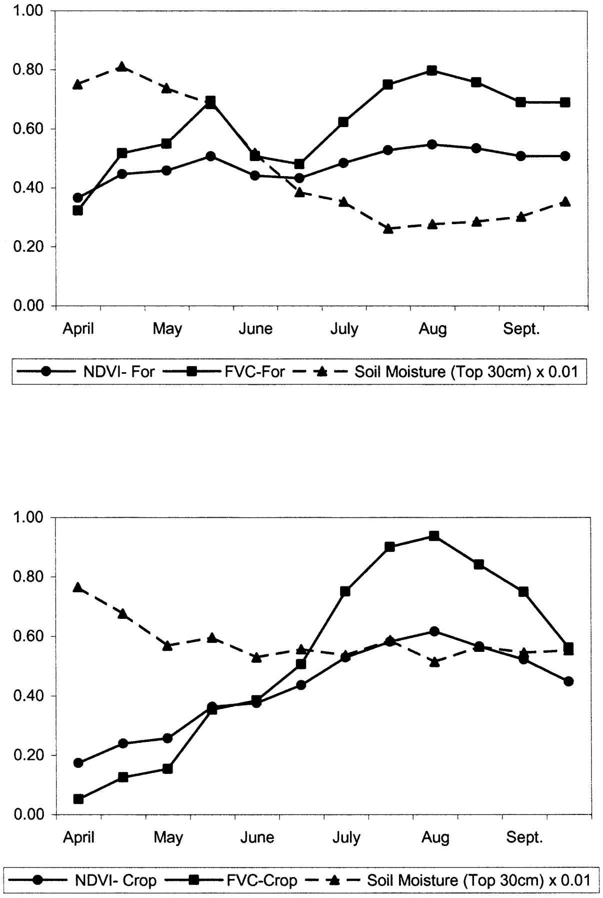

FIG. 3. Mean annual cycle of $NDVI_7$, FVC_7, and soil moisture data at (a) forest and (b) cropland sites: Apr–Sep 1990–94.

documented in Gillies and Carlson (1995) and are part of the hydrology and land cover data archive of the Pennsylvania State University's Environment Institute. The FVC dataset was successfully validated with field measurements in the United States from two intensive measurement programs—the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) and Monsoon '90 (Gillies et al. 1997).

To reduce the uncertainty associated with satellite-to-surface collocation errors in the LAC data and to assess the impact of changing the spatial scale of the satellite indices and their relationship to soil moisture, we aggregate the biweekly full-resolution [i.e., $NDVI_1$ and FVC_1, where the subscript refers to the pixel resolution (km)] datasets. The aggregation routine passes a window of a predetermined size over the entire matrix of pixel values, and generates a new dataset by averaging the data within the window. Three window sizes, 3 km $\times$ 3 km, 5 km $\times$ 5 km, and 7 km $\times$ 7 km, are used in this study to generate new satellite data composites (i.e., $NDVI_3$, FVC_3; $NDVI_5$, FVC_5; $NDVI_7$, FVC_7) at these pixel resolutions. Finally, each NDVI and FVC satellite image composite (e.g., Figs. 1b and 1c) is registered to the same map base as the LU/LC map and ICN point coverage, and pixel values of the vegetation indices centered on the two ICN stations are extracted.

To evaluate the sensitivity of NDVI and FVC to the neutron probe soil moisture values at BVL and SIU, integrated over the same biweekly period, Pearson-product-moment correlation coefficients were calculated between the deseasoned vegetation index (full resolution and aggregated) and soil moisture data pairs. The deseasoned data are defined as departures of the satellite vegetation indices and soil moisture data from their respective multiyear mean annual cycle, calculated thus:

$$\mathrm{NDVI}'(c) = \mathrm{NDVI}(c) - \langle \mathrm{NDVI}(c) \rangle,$$

$$\mathrm{FVC}'(c) = \mathrm{FVC}(c) - \langle \mathrm{FVC}(c) \rangle,$$

$$\mathrm{SM}'(c) = \mathrm{SM}(c) - \langle \mathrm{SM}(c) \rangle,$$

where SM is soil moisture, c is the compositing period (i.e., biweekly) from April to September, the angle brackets designate the 5-yr-averaged value of the relevant biweekly variable, and NDVI$'$, FVC$'$, and SM$'$ are the deseasoned variables. Figure 3 shows the mean annual cycle of the satellite indices ($NDVI_7$ and FVC_7) superimposed on the corresponding mean annual cycle of soil moisture for each of the two sites. Both figures show that simultaneous soil moisture and vegetation index are correlated negatively (i.e., high soil moisture and low vegetation index in early spring and vice versa in late summer) and sufficiently lagged soil moisture and vegetation index are correlated positively (i.e., high vegetation index in summer and high moisture values during the prior spring). Direct correlations between these variables will produce inflated r values, which would be artifacts of seasonal effects as both satellite vegetation indices and soil moisture follow a general annual course, albeit with phase lagged by a few months. By using deseasoned time series to compute statistical associations between these variables, we minimize the seasonal dependence of these variables. Figures 4 and 5 show the deseasoned $NDVI_7$, FVC_7, and soil moisture data for the forest and cropland sites.

One of our main objectives in this study is to determine the extent to which antecedent soil moisture data can be used to predict summer NDVI and FVC. In order to do this, soil moisture measurements were reconstructed for 2- to 8-week periods prior to the NDVI and FVC time period and these were then used to determine the sensitivity of the satellite vegetation indices to lagged soil moisture data. For each time lag, correlation coefficients were computed for pairs of deseasoned soil moisture and vegetation index data. An n-week lag means that the starting date for integrating the 2-week soil moisture data was n weeks prior to the date when the biweekly NDVI or FVC was composited.

3. Results and discussion

a. Growing season soil moisture, NDVI, and FVC contemporaneous associations

The full growing season period varies across the Midwest according to crop type and farming practices. However, it generally extends from April through late September/early October; hence, the April–September base period used in this analysis. The concurrent correlation between a 5-yr (1990–94) series of full-resolution biweekly data ($NDVI_1$) and top 30-cm soil moisture for the growing season is very weak over both the cropland (0.13) and forest (0.17) sites (Fig. 6a). When computed using the spatially aggregated $NDVI_3$, $NDVI_5$, and $NDVI_7$ data, the correlations improve slightly (Fig. 6a). Only the correlations for the forest location (0.24, 0.24, and 0.26, respectively) are significant at the 0.05 level of significance [sample size (N) = 60]. The larger correlations for the forest site is somewhat surprising as one would expect crops to show a higher susceptibility to the shorter timescale soil moisture fluctuations that characterize the upper 30-cm soil layer. A possible explanation for the lower correlations at the crop site is that crop greenness is also quite susceptible to air temperature stress compared to forest canopies. We calculated correlations between maximum air temperature and $NDVI_7$ at both sites but found no evidence of temperature-related crop stress, as the correlations were similar for both the forest (0.21) and crop (0.19) sites. Differences in hydrological and ecological characteristics of the two locations are also possible contributing factors. For example, typically there is less runoff at a forest location and trees have higher stomatal resistance compared to agricultural crops (Jones 1992). Therefore, the integrated effect of soil moisture availability on plant matter should be more evident over forest locations, and this could be reflected in the slightly higher correlations obtained there.

With soil moisture data averaged over a deeper (top 1 m) soil profile, we obtained slightly larger correlations between soil moisture and aggregated NDVI (0.24, 0.27, and 0.28 for $NDVI_3$, $NDVI_5$, and $NDVI_7$) data over cropland (Fig. 6b). These are comparable to the correlations obtained for the forest site, suggesting that the root system of crop canopies at the Bondville site is fairly deep and can draw water from over a root zone much deeper than the top 30 cm of the soil. This is not surprising because corn, which is the dominant crop cultivated in Illinois in summer, is a relatively deep-rooted crop. Typically, in deep soils, corn roots grow laterally 0.3 to 0.5 m from the stalk and downward to a depth of 1.2 m or more.

Because the FVC relates more closely to the amount of green matter within a given pixel, the contemporaneous correlations between this index and soil moisture at the crop and forest locations should be larger than those between NDVI and soil moisture. This is indeed found to be the case. The computed correlations at full resolution (FVC_1) and for the aggregated (FVC_3, FVC_5, and FVC_7) datasets are 0.23, 0.24, 0.26, and 0.28 over cropland, and 0.25, 0.28, 0.28, and 0.32 over the forest location (Fig. 7). The FVC–soil moisture correlations over both cropland and forest are significant at the 0.05 confidence level (N = 60), and, as with the NDVI–soil moisture correlations, progressively increase with higher levels of FVC aggregation. However, the differences between the correlations for full-resolution and aggregated datasets are not statistically significant. Although the improved correlation at higher levels of aggregation hints at the possibility that the satellite vegetation index–soil moisture relationship is somewhat scale dependent, it is equally likely that the improved correlations result from reduction in satellite navigation errors as the spatial scale of aggregation increased.

We also addressed concerns about possible contamination of AVHRR data in 1993 and 1994 due to satellite orbital drift by computing correlations using just 1990–92 data. The results are similar to those obtained using the full 5-yr datasets. For example, the FVC–soil moisture correlations for full-resolution and aggregated datasets for 1990–92 (Fig. 8) is quite similar to the 1990–94 correlations (Fig. 7). It is therefore very unlikely that satellite orbital drift negatively affects the NDVI data used in this study.

b. Lag correlations between soil moisture, NDVI, and FVC

During nondrought years, the soil moisture drawdown by crops and plants tend to peak during the summer season when plant transpiration and seasonal values of vegetation indices peak. In Illinois, mid-July normally coincides with the lowest seasonal soil moisture levels (Hollinger and Isard 1994). Given this occurrence, lag correlations between the satellite-derived vegetation indices (the dependent variable) and soil moisture (the leading variable) should be stronger than the concurrent correlations between the two. This hypothesis is tested by computing a series of correlation coefficients between NDVI, FVC, and soil moisture at variable time lags of 2–10 weeks. The vegetation index is assumed to be the dependent variable in all cases.

In the case of lag 1, the NDVI for a given 2-week period is correlated with the top 1-m profile averaged soil moisture measurements for the 2-week period immediately preceding the period for which NDVI is composited. We show the results for $NDVI_7$ and FVC_7 in Figs. 9a and 9b, respectively. It is immediately obvious from these figures that the soil moisture–satellite vegetation associations over cropland improve when the data are lagged. In both cases, the calculated r values for the 2-week shifted data (0.42 and 0.48) are statistically significant at the 0.01 significance level (N = 55), the difference between these r values and the con-

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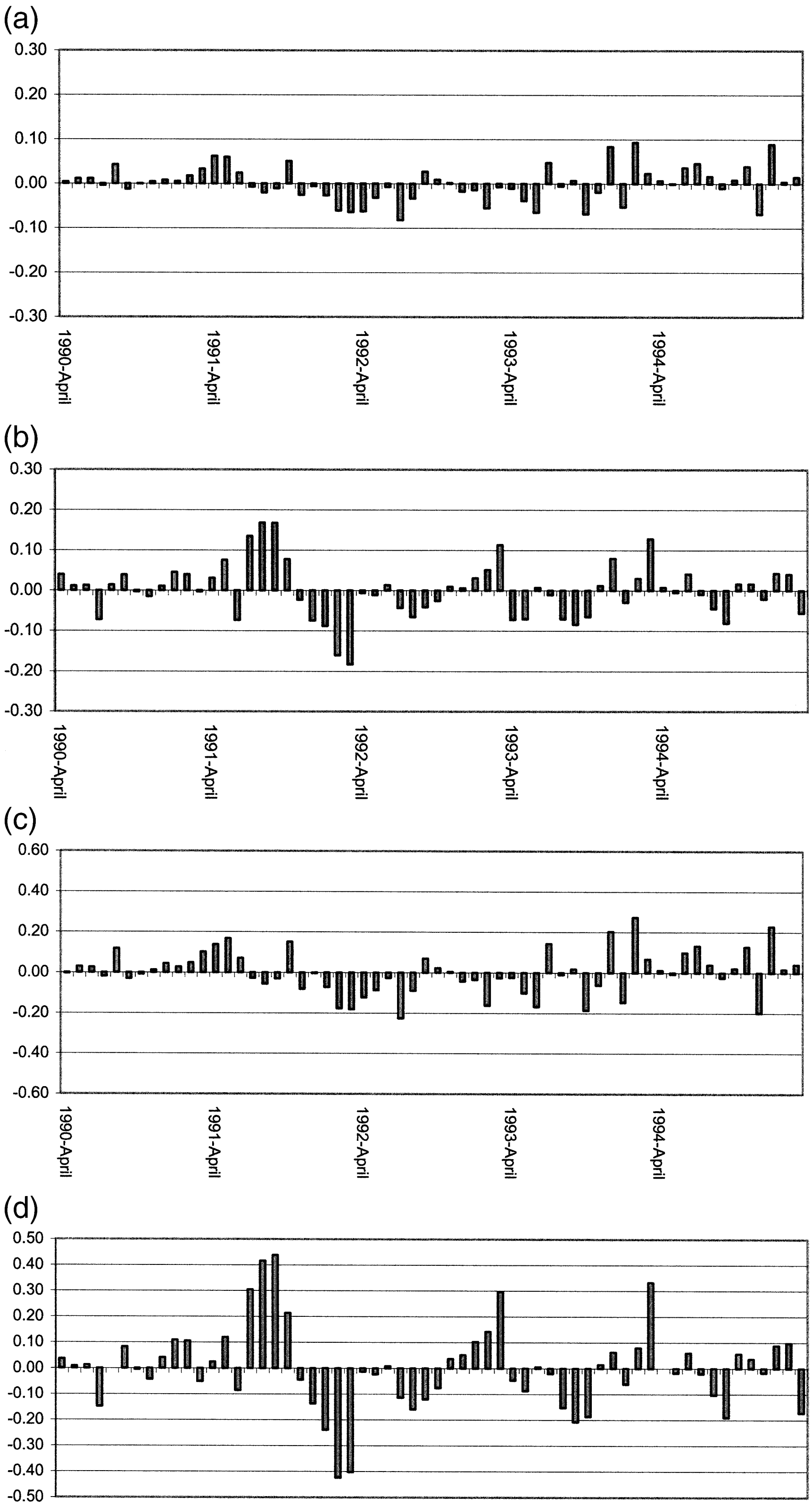
FIG. 4. Deseasoned $NDVI_7$: (a) forest and (b) cropland. Deseasoned FVC_7: (c) forest and (d) cropland. Apr–Sep 1990–94.


(a)
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
1990-April
1991-April
1992-April
1993-April
1994-April
(b)
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
1990-April
1991-April
1992-April
1993-April
1994-April
(c)
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
1990-April
1991-April
1992-April
1993-April
1994-April
(d)
0.50
0.40
0.30
0.20
0.10
0.00
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-0.50
1990-April
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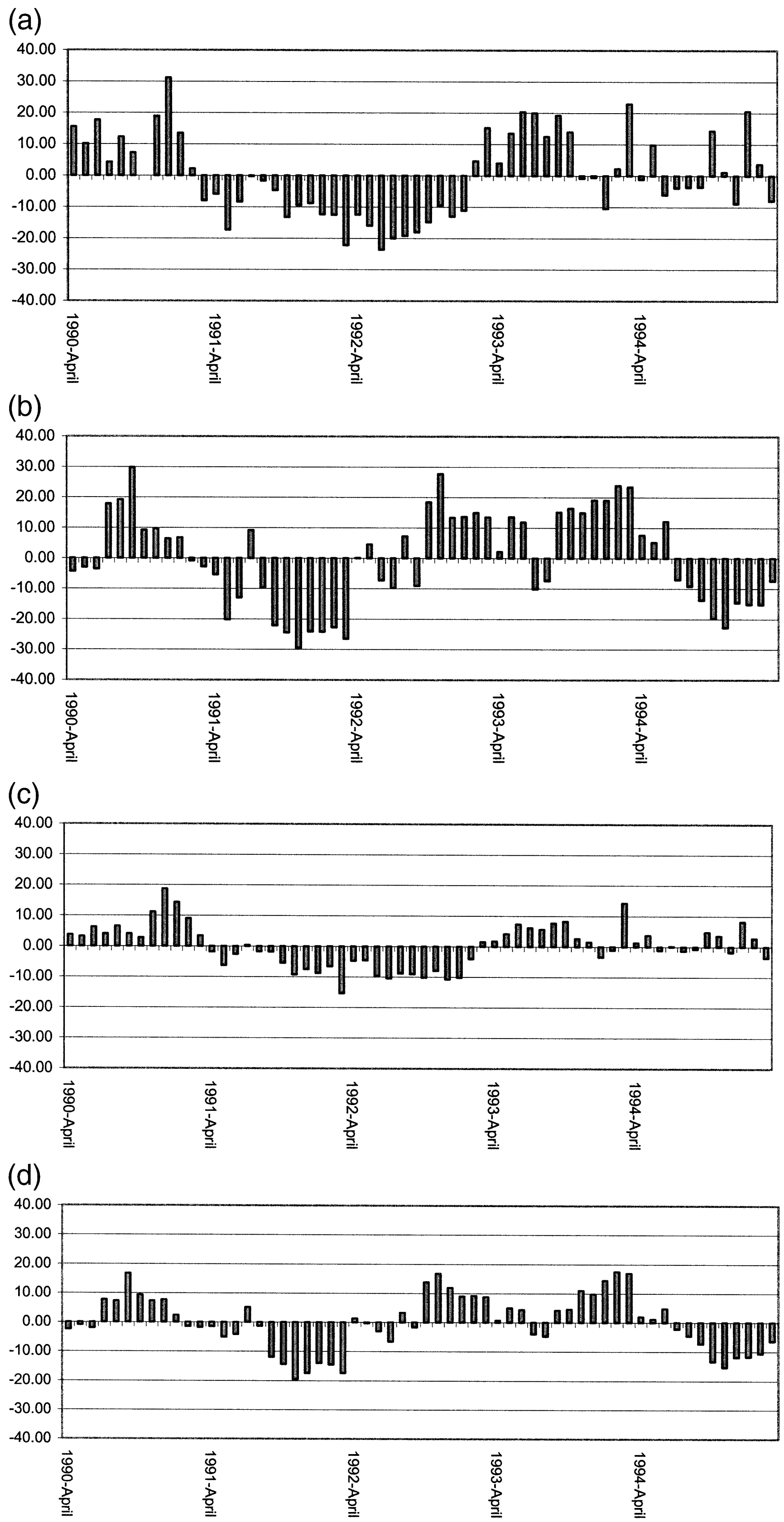
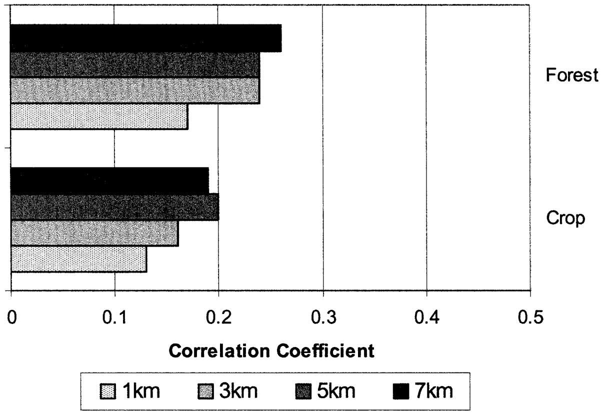

(a)
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
-40.00
1990-April
1991-April
1992-April
1993-April
1994-April
(b)
(c)
(d)

current correlations (0.28 and 0.29, respectively) is also statistically significant ($N = 55$; $p < 0.1$). Additionally, that the satellite vegetation index–soil moisture correlations remain moderately high for up to 8 weeks over cropland, although less so over the forest site. These results indicate a delayed vegetation response to soil moisture conditions over cropland, suggesting that soil moisture values may be useful for predicting satellite-derived vegetation conditions in the summer. By extension, it should be possible to more reliably predict crop yields by incorporating late spring/early summer soil moisture data into crop prediction models.



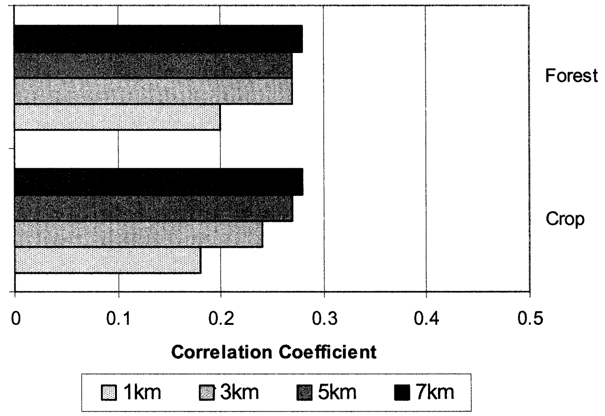


FIG. 6. Correlations between full-resolution and aggregated NDVI and (a) top 30-cm and (b) top 1-m profile averaged soil moisture data for forest and cropland sites: Apr–Sep 1990–94.

4. Conclusions

Contemporaneous measurements of AVHRR-derived vegetation indices (NDVI and FVC) and neutron probe soil moisture measurements for two sites in Illinois located in very different vegetated land covers, are used to investigate the correspondence between the satellite indices and soil moisture during the growing season. While several studies have investigated the relationship between satellite-derived vegetation indices and surface climate moisture variables for parts of the central United States, little attempt has been made to relate the satellite signal to actual measurements of surface hydrological variables such as soil moisture. The present study attempts to bridge this gap by focusing on the sensitivity of satellite vegetation indices to current and antecedent soil moisture conditions. The analysis procedures and results of this study are as follows:

1) Neutron probe measurements of soil moisture taken at forest and cropland sites are weakly associated with the full-resolution NDVI and FVC data for pixels centered over the stations. The association, measured by the Pearson-moment-correlation coefficient, is stronger over forest than cropland. The correlations computed using FVC are also larger than those obtained using NDVI values, because of the reduced background ‘‘contamination’’ in the FVC pixel values.
2) At both locations (i.e., cropland and forest), the strength of the satellite index–soil moisture associations increases slightly when pixel-aggregated NDVI and FVC data are used instead of the full-resolution dataset. Similarly, better relations are obtained when soil moisture data are time lagged with respect to the satellite vegetation indices. Moderately high correlation coefficients between NDVI, FVC, and soil moisture are realized at lag periods of up to 8 weeks. These results imply that the soil moisture–satellite vegetation index relationship is somewhat scale dependent, though not markedly so, and that a fairly ‘‘long-term’’ memory of up to 2 months is present in the near-surface hydrological characteristics, especially soil water content. This is integrated into the satellite vegetation indices (NDVI and FVC).

The results reported here are more robust than those obtained previously based on only one or two growing seasons; our analyses are based on data for five sequential, climatologically different growing seasons that include two very wet years (1990 and 1993) and a relatively dry year (1994). By also identifying pertinent spatial and temporal characteristics of satellite vegetation indices–soil moisture relations over the central Midwest Corn Belt, this study extends previous work in, and should contribute to a better understanding of, surface climate relations and their associated scale depen-

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FIG. 5. Deseasoned top 30-cm soil moisture for (a) forest and (b) cropland. Top 1-m soil moisture profile for (c) forest and (d) cropland. Apr–Sep 1990–94.

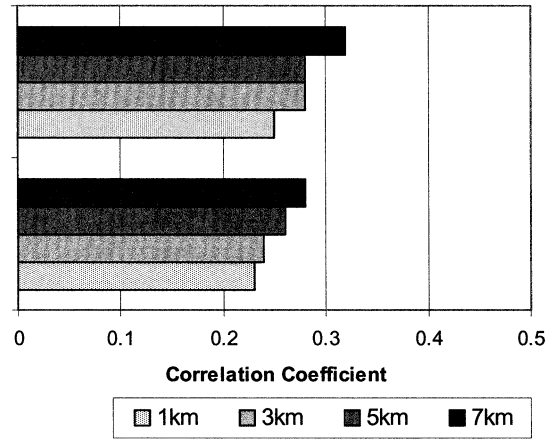

FIG. 7. Correlations between full resolution and aggregated NDVI and top 1-m profile averaged soil moisture for forest and cropland sites: Apr–Sep 1990–94.

dencies. In our continuing work, which incorporates additional surface climate variables and soil data, we hope to determine how the satellite indices–soil moisture associations established in this study are affected by variations in soil reflectance, phenology, and other ecoclimatological factors. Furthermore, newer satellite products from sensors that are better calibrated [e.g., the Moderate Resolution Imaging Spectroradiometer (MODIS)] are now becoming available. We envisage that these new data sources will permit a more detailed investigation of the kinds of relationships explored in this study.

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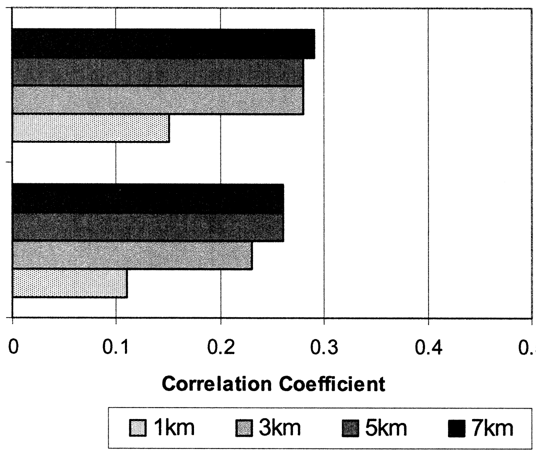

FIG. 8. Correlations between full-resolution and aggregated FVC and top 1-m profile averaged soil moisture for forest and cropland sites: Apr–Sep 1990–92.

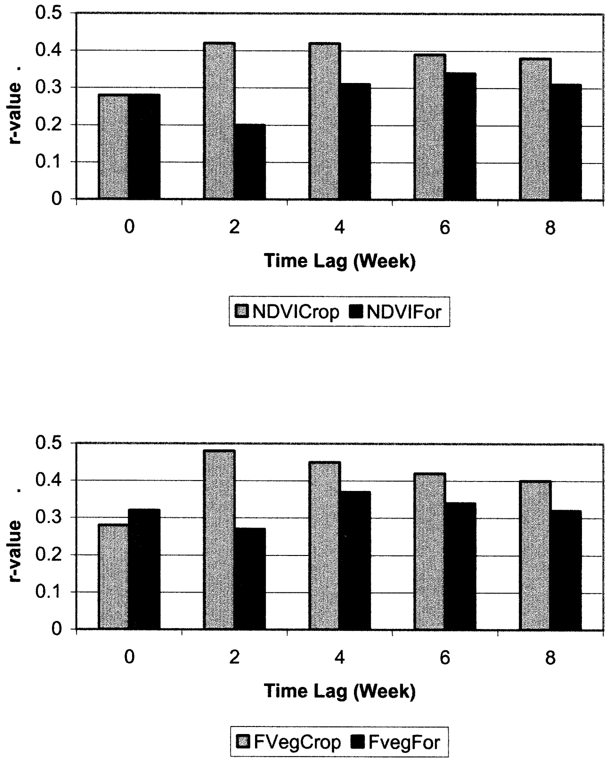

FIG. 9. Lag correlations between top 1-m profile averaged soil moisture and (a) $NDVI_7$ and (b) FVC_7 at the forest and cropland sites: Apr–Sep 1990–94.

REFERENCES

Adegoke, J. O., and A. M. Carleton, 2000: Warm season land surface–climate interactions in the United States Midwest from mesoscale observations. *Linking Climate to Land Surface Change,* S. McLaren and D. Kniveton, Eds., Kluwer Academic, 83–97.

Anderson, J. R., E. E. Hardy, J. T. Roach, and R. E. Witmer, 1976: A land use and land cover classification system for use with remote sensing data. U.S. Geological Survey Professional Paper 964, 28 pp.

Anyamba, A., and J. R. Eastman, 1996: Interannual variability of NDVI over Africa and its relation to El Nino/Southern Oscillation. *Int. J. Remote Sens.,* **17,** 2533–2548.

Belward, A., and T. Loveland, 1996: The DIS 1 km land cover data set. *Global Change Newslett.,* **27,** 7–9.

Bounoua, L., G. J. Collatz, S. O. Los, P. J. Sellers, D. A. Dazlich, C. J. Tucker, and D. A. Randall, 2000: Sensitivity of climate to changes in NDVI. *J. Climate,* **13,** 2277–2290.

Brown, M. E., and D. L. Arnold, 1998: Land surface–atmosphere interactions associated with deep convection in Illinois. *Int. J. Climatol.,* **18,** 1637–1653.

Carleton, A. M., and M. O'Neal, 1995: Satellite-derived land surface climate "signal" for the Midwest U.S.A. *Int. J. Remote Sens.,* **16,** 3195–3202.

——, D. Jelinski, D. Travis, D. Arnold, R. Brinegar, and D. Easterling, 1994: Climatic-scale vegetation–cloud interactions during drought using satellite data. *Int. J. Climatol.,* **14,** 593–623.

——, J. O. Adegoke, J. Allard, D. Arnold, and D. Travis, 2001: Summer season land cover–convective cloud associations for the Midwest U.S. ''Corn Belt.'' *Geophys. Res. Lett.,* **28,** 1679–1682.

Carlson, T. N., R. R. Gillies, and E. M. Perry, 1994: A method to make use of thermal infrared temperature and NDVI measurements to infer surface water content and fractional vegetation cover. *Remote Sens. Rev.,* **9,** 161–173.

Cihlar, J., L. St. Laurent, and J. A. Dyer, 1991: Relation between rainfall and the normalized difference vegetation index and ecological variables. *Remote Sens. Environ.,* **35,** 279–298.

Eidenshink, J. E., 1992: The 1990 conterminous U.S. AVHRR data set. *Photogramm. Eng. Remote Sens.,* **58,** 809–813.

Gillies, R. R., and T. N. Carlson, 1995: Thermal remote sensing of the surface soil water content with partial vegetation cover for incorporation into climate models. *J. Appl. Meteor.,* **34,** 745–756.

——, T. N. Carlson, J. Cui, W. P. Kustas, and K. S. Humes, 1997: A verification of the ''triangle'' method for obtaining surface soil water content and energy fluxes from remote measurements of the NDVI and surface radiant temperature. *Int. J. Remote Sens.,* **18,** 3145–3166.

Gutman, G., 1991: Vegetation indices from AVHRR: An update and future prospects. *Remote Sens. Environ.,* **29,** 121–135.

——, 1999: On the monitoring of land surface temperatures with the NOAA/AVHRR: Removing the effect of satellite orbital drift. *Int. J. Remote Sens.,* **20,** 3407–3413.

Hayes, M. J., and W. L. Decker, 1996: Using NOAA AVHRR data to estimate maize production in the United States Corn Belt. *Int. J. Remote Sens.,* **17,** 3189–3200.

Holben, B. N., 1986: Characteristics of maximum-value composite images from temporal AVHRR data. *Int. J. Remote Sens.,* **7,** 1417–1434.

——, Y. J. Kaufman, and J. D. Kendall, 1990: *NOAA-11* AVHRR visible and near-IR inflight calibration. *Int. J. Remote Sens.,* **7,** 1417–1434.

Hollinger, S. E., and S. A. Isard, 1994: A soil moisture climatology of Illinois. *J. Climate,* **7,** 822–833.

Jones, H. G., 1992: *Plants and Microclimate: A Quantitative Approach to Environmental Plant Physiology.* 2d ed. Cambridge University Press, 428 pp.

Kaufmann, R. K., L. Zhao, Y. Knyazikhin, N. V. Shabanov, R. B. Myneni, and C. J. Tucker, 2000: Effect of orbital drift and sensor changes on the time series of AVHRR vegetation index data. *IEEE Trans. Geosci. Remote Sens.,* **38,** 2584–2597.

Kogan, F. N., 1990: Remote sensing of weather impacts on vegetation in non-homogeneous areas. *Int. J. Remote Sens.,* **11,** 1404–1419.

Kunkel, K. E., 1990: Operational soil moisture estimation for the Midwestern United States. *J. Appl. Meteor.,* **29,** 1158–1166.

Los, S. O., C. O. Justice, and C. J. Tucker, 1994: A global 1×1 NDVI data set for climate studies derived from the GIMMS continental NDVI data. *Int. J. Remote Sens.,* **15,** 3493–3518.

Lozano-Garcia, D. F., R. N. Fernandez, K. P. Gallo, and C. J. Johannsen, 1995: Monitoring the 1988 severe drought in Indiana, U.S.A. using AVHRR. *Int. J. Remote Sens.,* **16,** 1327–1340.

Myneni, R. B., S. O. Los, and C. J. Tucker, 1996: Satellite-based identification of linked vegetation index and sea surface temperature anomaly area from 1982–1990 for Africa, Australia and South America. *Geophys. Res. Lett.,* **23,** 729–732.

Schultz, P. A., and M. S. Halpert, 1993: Global correlation of temperature, NDVI and precipitation. *Adv. Space Res.,* **13,** 1335–1372.

Shuttleworth, W. J., 1991: Insight from large-scale observational studies of land/atmosphere interactions. *Land Surface–Atmosphere Interactions for Climate Modeling: Observations, Models and Analysis,* E. F. Wood, Ed., Kluwer, 3–20.

Srivastava, S. K., V. Jayaraman, P. P. Nageswara, B. Manikiam, and M. G. Chandrasekhar, 1997: Interlinkages of NOAA/AVHRR derived integrated NDVI to seasonal precipitation and transpiration in dryland Tropics. *Int. J. Remote Sens.,* **18,** 2931–2952.

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

Vinnikov, K. Y., A. Robock, S. Qiu, J. K. Entin, M. Owe, B. J. Choudhury, S. E. Hollinger, and E. G. Njoku, 1999: Satellite remote sensing of soil moisture in Illinois, United States. *J. Geophys. Res.,* **104,** 4145–4168.

Yang, W., L. Yang, and J. W. Merchant, 1997: An assessment of AVHRR/NDVI–ecoclimatological relations in Nebraska, U.S.A. *Int. J. Remote Sens.,* **10,** 2161–2180.