1991

Estimation of Shortwave Hemispherical Reflectance (Albedo) from Bidirectionally Reflected Radiance Data

Elizabeth A. Walter-Shea
University of Nebraska - Lincoln, ewalter-shea1@unl.edu

Blaine L. Blad
University of Nebraska - Lincoln

REMOTE SENS. ENVIRON. 38:123–134 (1991)

RS-437

Estimation of Shortwave Hemispherical Reflectance (Albedo) from Bidirectionally Reflected Radiance Data*

Patrick J. Starks, John M. Norman,[†] *Blaine L. Blad,*[‡] *Elizabeth A. Walter-Shea,*[‡] *and Charles L. Walthall*[§]

Department of Agricultural Meteorology, University of Nebraska, Lincoln

Albedo is the ratio of reflected solar radiation from a surface to that incident upon it. Due to the spatial and temporal resolution of satellite remote sensing instruments, many formulations have been developed to convert remotely sensed data into estmates of albedo. Most of these equations depend upon the assumption of isotropic reflection and, therefore, use only nadir measurements; only in recent years have investigators attempted to model the anisotropic nature of terrestrial surfaces. A Barnes Modular Multiband Radiometer (MMR) was used to collect remotely sensed data from prairie vegetation at seven view zenith angles in the solar principal plane. An equation to estimate albedo from bidirectional reflectance data is proposed and evaluated in this paper. The estimates of albedo were greater than values obtained with simultaneous pyranometer measurements: a more conventional approach. The overestimation was systematic. Potential sources of error are discussed and include: 1) extrapolation of the bidirectional reflectance data out to a view zenith angle of 90°; 2) use of inappropriate weighting coefficients in the numerator of the albedo equation; 3) surface shadowing caused by the A-frame instrumentation used to measure the incoming and outgoing radiation fluxes; 4) errors in estimates of the denominator of the proposed albedo equation (i.e., incoming shortwave radiation); and 5) a "hot spot" contribution in bidirectional data measured by the MMR.

INTRODUCTION

Albedo, also referred to as shortwave hemispherical reflectance, is defined as the ratio of reflected solar radiation from a surface to that incident upon that surface. As an element of the radiation balance, albedo is of distinct significance (Charney et al., 1977; Mintz, 1984) and of prime importance to the overall goals of a NASA sponsored experiment known as FIFE (First ISLSCP Field Experiment; see Sellers et al., 1988).

Reflected and incident solar radiation are typi-

*Published as Paper No. 9413, Journal Series, Nebraska Agricultural Research Division. The work reported here was conducted under Nebraska Agricultural Research Division Project 27-004.

†Department of Soil Science, University of Wisconsin, Madison, Wisconsin.

‡Department of Agricultural Meteorology, University of Nebraska, Lincoln.

§Global Remote Sensing Systems Laboratory, Department of Geography, University of Maryland, College Park.

Address correspondence to Patrick J. Starks, Post Doctoral Fellow, Cooperative Institute for Applied Meteorology, University of Missouri, Federal Building, Room 200, 608 East Cherry Street, Columbia, MO 65201.

Received 7 December 1990; revised 10 June 1991.

0034-4257/91/$3.50

655 Avenue of the Americas, New York, NY 10010

cally measured with downward-facing and upward-facing pyranometers, respectively. Point measurements of albedo may be extended to represent homogeneous surfaces. Most areas, especially large regions, rarely exhibit homogeneity either in topography or vegetative characteristics, thereby limiting the utility of point measurements. Additionally, the expense of procuring the required number of pyranometers, and attendant data logging equipment, to adequately describe large nonhomogeneous areas, becomes quite prohibitive.

Data from various remote sensing systems have been evaluated to estimate albedo over large areas since the early 1970s (Pease and Pease, 1972; Pease and Nichols, 1976; Pease et al., 1976; Gillespie and Kahle, 1977; Kriebel, 1979; Robinove et al., 1981; Brest, 1987; Brest and Goward, 1987). Remote sensing systems utilized by these investigators include aerial photography, airborne electro-optical scanners, and satellite systems. Various formulations and equations convert remotely sensed data into estimates of albedo (Pease and Pease, 1972; Gillespie and Kahle, 1977; Kriebel, 1979; Robinove et al., 1981; Brest, 1987). Except for the work of Kriebel (1979), it was assumed that terrestrial surfaces behaved as Lambertian reflectors. This assumption was necessary because the various remote sensing instruments used by the investigators were nadir-viewing only.

Most natural surfaces, such as vegetation and soil, are anisotropic diffusers of incident solar radiation. Anisotropic reflectance is influenced by many factors, so that a nadir view does not present enough information to effectively quantify some important surface characteristics. Thus, there are errors involved in assuming that a surface behaves as an isotropic reflector (See Salamonson and Marlatt, 1971; Kriebel, 1976; 1978; Eaton and Dirmhirn, 1979; Kimes et al., 1980; 1984; 1987; Kimes and Sellers, 1985; Norman et al., 1985). The anisotropy of natural surfaces can be characterized by the angle of incidence of the solar beam and the view angle. These two angles give rise to the term bidirectional reflectance; further elabortion is found in Nicodemus et al. (1977), Swain and Davis (1978), and Slater (1980). Kriebel (1979), Walthall et al. (1985), Kimes et al. (1987), and Irons et al. (1988) examined ways of producing estimates of albedo using bidirectional data obtained from remote sensing instruments.

The research reported herein was conducted as part of FIFE during the growing seasons of 1987 and 1988, detailed by Starks (1990). This

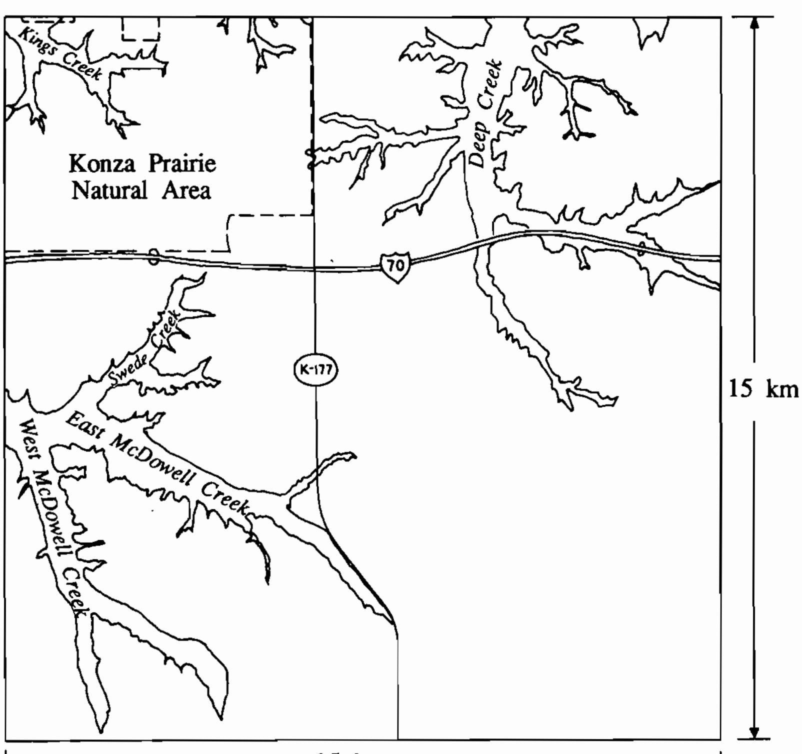


Figure 1. The FIFE study site located south of Manhattan, Kansas in the Flint Hills region of Northeastern Kansas. The Konza Prairie natural research area is located in the northwest portion of the FIFE study site. [Adapted from Sellers and Hall (1987).]

article reports on one of the first attempts to compare independently measured values of albedo with albedos estimated from models utilizing bidirectional reflectance data obtained at numerous view zenith angles.

SITE DESCRIPTION

The FIFE study site was located south of Manhattan in the Flint Hills of northeastern Kansas. The study area, 225 km^2 (15 km × 15 km) in size, was predominantly grazed, spring-burned, privately owned pasture land. The Konza Prairie, a 3487-ha long-term ecological research (LTER) site, is located in the northwest corner of the FIFE study site (Fig. 1).

Vegetation of the FIFE study site is predominately *Andropogon gerardii* Vitman (Big bluestem), *Sorghastrum nutans* (L.) Nash (Indiangrass), *Panicum virgatum* L. (Switchgrass), and *Schizachyrium scoparium* (Michx.) Nash (Little bluestem). Stands of trees are found along water courses, and shrubs and forbs are intermixed among the prairie grasses, depending upon the topography, soil type, water availability, and grazing and burning practices.

EXPERIMENTAL METHOD

FIFE was initiated in the late spring/early summer of 1987. During 1987, four intensive field measurement and data collection periods were established based upon vegetative phenology. These intensive field campaigns (IFCs) represented the "green up," "peak greenness," "dry down," and "senescence" periods of vegetative growth (Sellers et al., 1988). We also collected data between the 1987 IFCs. Additional data were acquired during May, July, and August of 1988.

A calibrated, eight-channel Barnes Modular Multiband Radiometer (MMR) Model 12-1000 (Robinson et al., 1982) was used to collect bidirectional reflectance data from the prairie vegetation. The seven channels in the visible, near-infrared, and midinfrared portion of the electromagnetic spectrum were used in this study (Table 1).

A specially designed portable mast held the MMR approximately 3 m above the soil surface. The MMR, with a field-of-view of 15°, produced a circular view spot with a diameter of approximately 0.8 m when pointed at nadir. Norman and Walthall (1985) suggested that most bidirectional information on vegetated and soil surfaces is found in the principal plane of the sun and within viewing angles approximately 50° either side of nadir. Measurements were made from seven view zenith angles, nadir and 20°, 35°, and 50° to either side of nadir, located in or near the solar principal plane. Voltage responses of the MMR were converted into units of spectral radiance (W m^{-2} μm^{-1} sr^{-1}) after Markham et al. (1988).

During 1987, a portable A-frame was fitted with a net radiometer and an Eppley precision spectral pyranometer (PSP) to measure reflected solar radiation. The same PSP was rotated to the upright position to record the incoming solar radiation. In 1988, two PSPs, one to measure incoming solar radiation and the other to measure reflected solar radiation, and two net radiometers were mounted on the A-frame. Measurements of incoming and outgoing shortwave radiation were

Table 1. Actual and Extended Bandpass Limits for the MMR Channels (Bands) Used in the Study[a]

Channel #	*Bandpass Limits* (μm)	W_j'	*Extended Bandpass Limits* (μm)	W_j
1	0.4569–0.5190	0.104	0.3000–0.5200	0.251
2	0.5344–0.6087	0.116	0.5200–0.6150	0.149
3	0.6402–0.6921	0.070	0.6150–0.7250	0.134
4	0.7509–0.8877	0.132	0.7250–1.0000	0.222
5	1.1724–1.3062	0.054	1.0000–1.3600	0.144
6	1.5677–1.7985	0.042	1.3600–1.8000	0.065
7	2.0678–2.3267	0.018	1.8000–4.0000	0.036

[a] Unextended (W_j') and extended (W_j) weighting coefficients are given for each channel.

made nearly simultaneously with the MMR measurements.

Nadir-viewed MMR measurements were made over a calibrated barium sulfate ($BaSO_4$) field reference panel in 1987 and a halon (Schutt et al., 1981) reference panel in 1988 every 20–25 min. The $BaSO_4$ and halon reference panels were calibrated according to Jackson et al. (1987). Data collected over the panel were used to estimate the incident radiation at the time of the collection of reflectance data. Reflected radiation from the target divided by that reflected in the nadir direction from the reference panel (by band) yields a reflectance factor (RF).

Computational Method

The defining equation for albedo as measured from a hemispherical sensor, such as a pyranometer, may be written as:

$$\rho(\theta_i) = \int_{\lambda L}^{\lambda U} E(\lambda, \theta_i) \int_0^{2\pi} \int_0^{\pi/2} \rho(\lambda;\theta_i, \theta_V, \phi_V) \times \cos\theta_V \sin\theta_V \, d\theta_V d\phi_V d\lambda \times \left[\int_{\lambda L}^{\lambda U} E(\lambda, \theta_i) \int_0^{2\pi} \int_0^{\pi/2} \cos\theta_V \sin\theta_V \, d\theta_V d\phi_V d\lambda \right]^{-1}, \quad (1)$$

where

$\rho(\theta_i)$ = hemispherical reflectance as a function of the source incidence angle (θ_i),
λ_L = lower wavelength of instrument sensitivity,
λ_U = upper wavelength of instrument sensitivity,
$\rho(\lambda;\theta_i,\theta_V,\phi_V)$ = reflected radiation as a function of view zenith angle (θ_V), view azimuth angle (ϕ_V), source incidence angle (θ_i), and wavelength (λ),
$E(\lambda, \theta_i)$ = spectral flux density of incident solar radiation as a function of wavelength and source incidence angle ($W\ m^{-2}\ \mu m^{-1}$).

Technically, Eq. (1) is for directional-hemispherical reflectance and assumes that the solar direct beam dominates over the incident sky diffuse irradiance. For near clear-sky conditions when satellite observations are possible, this is a good approximation.

From Eq. (1), albedo is the ratio of reflected solar radiation, integrated over the shortwave spectrum and hemisphere of view (numerator) to that incident upon the surface identically integrated (denominator). Performing integration over limits of θ_v and ϕ_v yields

$$\rho(\theta_i) = \frac{\int_{\lambda L}^{\lambda U} \rho_H(\lambda, \theta_i) E(\lambda, \theta_i) \, d\lambda}{\int_{\lambda L}^{\lambda U} E(\lambda, \theta_i) \, d\lambda}, \quad (2)$$

which defines albedo in terms of directional-hemispherical spectral reflectance, or $\rho_H(\lambda,\theta_i)$, and total incident radiation.

Equation (2) can be written as

$$\rho(\theta_i) = \int_{\lambda L}^{\lambda U} \rho_H(\lambda, \theta_i) \left[\frac{E(\lambda, \theta_i)}{\int_{\lambda L}^{\lambda U} E(\lambda, \theta_i) \, d\lambda} \right] d\lambda. \quad (3)$$

Assuming $\rho_H(\lambda,\theta_i)$ is constant over discrete waveband intervals (e.g., the seven channels of the MMR), Eq. (3) can be written as

$$\rho_{BB}(\theta_i) = \sum_{j=1}^{7} (\rho_{Hj})(W_j), \quad (4a)$$

where

$\rho_{BB}(\theta_i)$ = albedo calculated from the broad-band MMR radiometric data,
ρ_{Hj} = directional-hemispherical spectral reflectance in waveband j,
j = waveband number (i.e., 1,2,3, . . ., 7),
L_j = lower wavelength for MMR waveband j (μm),
U_j = upper wavelength for MMR waveband j (μm),
W_j = weighting coefficient calculated from

$$W_j = \int_{Lj}^{Uj} E(\lambda, \theta_i) \, d\lambda \Big/ \int_{0.3}^{4.0} E(\lambda, \theta_i) \, d\lambda. \quad (4b)$$

Values of 0.3 and 4.0 are the approximate lower and upper wavelengths of the solar spectrum, respectively. Thus, albedo can be estimated if both ρ_{Hj} and W_j can be reasonably approximated.

Directional-hemispherical spectral reflectances in Eq. (4) can be approximated by directional-hemispherical spectral reflectance factors (RF_{Hj}) to give

$$\rho_{BB}(\theta_i) = \sum_{j=1}^{7} (RF_{Hj})(W_j). \quad (5)$$

Although RFs are conveniently obtained in field settings and Holm et al. (1989) have calculated them for Thematic Mapper data, satellite digital numbers are more readily converted into units of radiances than into RFs. Additionally, as part of our FIFE research objectives, both the incoming and reflected shortwave radiation streams were to be directly calculated from the MMR data. Thus Eq. (6) was developed:

$$\rho_{BB}(\theta_i) = \frac{\sum_{j=1}^{7}[RD_{Hj}(\theta_i)][\Delta\lambda_j][W_j / W_j']}{\pi \sum_{j=1}^{7}[Ref_j(\theta_i)][\Delta\lambda_j][W_j / W_j']}, \qquad (6)$$

where

RD_{Hj} = directional-hemispherical spectral irradiance in units of $W\ m^{-2}\ \mu m^{-1}$,

Ref_j = field reference panel spectral radiance in units of $W\ m^{-2}\ \mu m^{-1}\ sr^{-1}$, corrected for non-Lambertion characteristics according to Jackson et al. (1987).

W_j, W_j' = weighting coefficients,

$\Delta\lambda_j$ = actual bandwidth of MMR channel j in units of μm.

Equations (5) and (6) yield approximately the same results (Fig. 7). Estimations of directional-hemispherical spectral radiances and weighting coefficients are described below.

Calculation of $RD_{Hj}(\theta_i)$

Walthall et al. (1985) developed a simple multiple regression technique whereby bidirectional reflectance factors (RFs), obtained at three or more view zenith angles, could be used to simulate hemispherical reflectance:

$$RF = a\theta_V^2 + b\theta_V \cos(\phi_V - \phi_S) + c, \qquad (7)$$

where θ_V and ϕ_V are measured in radians, ϕ_S is the solar azimuth angle in radians, and *a, b,* and *c* are coefficients derived from the multiple regression procedure. Integration over the hemisphere yields the directional-hemispherical spectral reflectance factor (RF_{Hj})

$$RF_{Hj} = 2.305a / \pi + c. \qquad (8)$$

We used the MMR radiances in Eq. (7) instead of the RFs to give directional spectral radiance (RD_{Hj}) so that Eq. (8) is written as

$$RD_{Hj} = \pi RF_{Hj} = 2.305a + \pi c, \qquad (9)$$

the units of which are $W\ m^{-2}\ \mu m^{-1}$. Using this approach; the MMR measurements made at the various view zenith angles were converted into approximated hemispherically-viewed values on a band-by-band basis.

Calculation of Weighting Coefficients

Knowledge of the spectral distribution of the global solar radiation at the earth's surface must be adequately known to determine the weighting coefficients. Bird and Riordan (1984) developed a model, SPCTRAL2, which produces a spectral solar distribution given certain input parameters. This model adjusts the spectral distribution of the incident solar radiation at the top of the atmosphere for absorption due to ozone and water vapor, accounts for the solar beam path length, and takes into account Mie and Rayleigh scattering based upon atmospheric turbidity.

Rather than producing a separate solar irradiance curve for each time plot data were collected, we used input parameters to reflect "average conditions" (Iqbal, 1983) for the entire period (experimental season) over which data were obtained. Using these "average condition" parameters, the solar zenith angle was varied from 0° to 70° in 10° increments, thereby yielding eight separate solar irradiance curves for calculation of the weighting coefficients.

Figure 2 is an example of a solar irradiance curve produced by the SPCTRAL2 model. The nominal waveband limits of the MMR (Table 1) are depicted as the cross-hatched boxes in the lower portion of the figure. The entire solar spectrum must be accounted for in the definition of shortwave albedo. Because the MMR samples the solar spectrum in discrete, noncontiguous wavebands, it must be "forced" to sample the whole spectrum. The upper and lower waveband limits are extended to form seven contiguous wavebands. The upper and lower wavelengths of these extended wavebands (Table 1 and Fig. 2) are based, in part, upon the distribution of reflected solar radiation from a vegetated surface.

Integration of the area under the curve for each extended and unextended MMR waveband was performed for each of the eight SPCTRAL2 simulations from which average radiance values for each waveband was computed. Following Eq. (4b), weighting coefficients for extended and un-

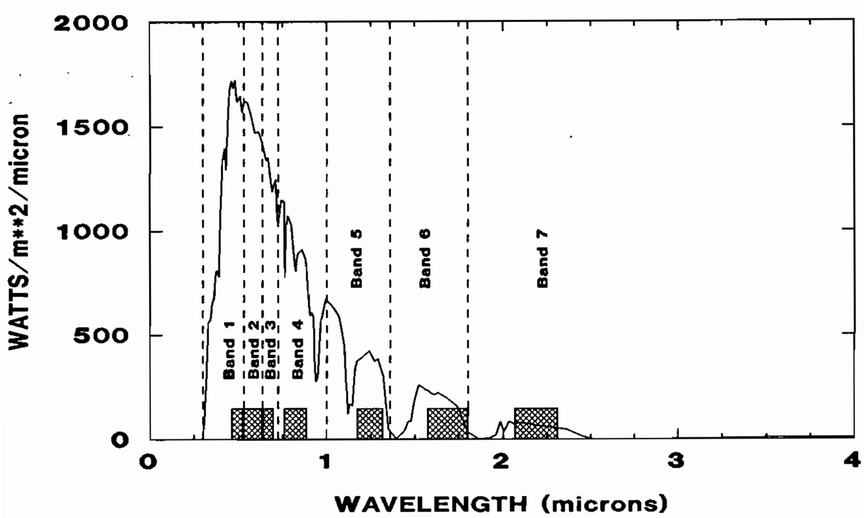


Figure 2. Distribution of global solar energy at the surface of the earth. Actual MMR bandwidths are indicated by the cross-hatched boxes; extended bandwidths indicated by the dashed lines.

extended wavebands were computed (W_j and W_j', respectively). When summed, the seven unextended weighting coefficients yield a value similar to the P/T ratio (partial spectrum / total spectrum) of Jackson (1984).

Equation (6) was used to calculate albedo from the MMR bidirectional reflectance data acquired during 1987 and 1988. The 1987 data set represents 27 days of data collection for a total of 522 cases where albedo estimates can be compared to the near-simultaneously acquired pyranometer measurements. These 522 cases represent variations in plot topography, vegetative characteristics, and diurnal and seasonal effects. During 1988, seven days of bidirectional reflectance data were acquired at a single site. There are 64 cases where comparisons can be made.

Statistical Methods

Willmott and Wicks (1980) and Willmott (1981; 1982) raised concerns about the exclusive use of r and r^2 in the context of model performance evaluation. Willmott (1981) noted that very dissimilar values of estimates and measurements can produce an r very near one. Moreover, small differences between measured and estimated quantities can produce a low or even negative r (Willmott and Wicks, 1980). A relatively new statistical parameter, the "d" index of model agreement, was proposed by Willmott (1982). Used in conjunction with other common statistical measures, d aids in evaluating the accuracy of models. A $d=1$ indicates complete agreement between modeled and measured values; a $d=0$ indicates complete disagreement.

Mean bias errors (MBEs) describe the average deviation of the predicted values from the measured values. Root mean square errors (RMSEs) describe the average total error in the estimating procedure and can be partitioned into a random or unsystematic component (E_u) and a systematic component (E_s).

Unsystematic errors may occur because of unobserved intermittent instrument problems, inconsistent data collection techniques, or random variations in the phenomena being observed. These random errors can be visualized as a measure of clustering about a regression line drawn through a cloud of points. Large random errors would occur if data points were greatly dispersed and small random errors if points were tightly clustered about the regression line.

Systematic errors may arise due to consistent error in experimental procedure, instrument calibration error, or error in the predicting equation. These errors may be thought of as the distance from the one-to-one line to the regression line. If the distance is large, there is a large systematic error, whereas a small error indicates the two lines are in close proximity.

Mean relative error (MRE) is the average percentage that the estimates over- or underpredict relative to the measured values.

RESULTS

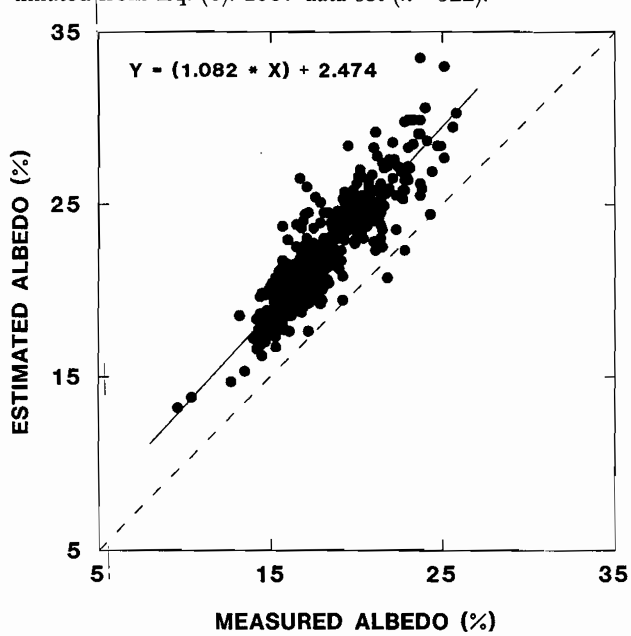
Graphical comparisons of estimated and measured albedos for 1987 and 1988 are shown in Figures 3 and 4, respectively. Albedos estimated with Eq. (6) were higher than measured values during both years.

The nature and magnitude of the discrepancy between the estimated and measured albedo values were statistically analyzed (Table 2). Correlation coefficients (r) are 0.89 and 0.84 for the 1987 and 1988 data sets, respectively (Table 2). Coefficients of determination (r^2) indicate that 80% of the variation in the measured value is accounted for in the estimated quantity for the 1987 data set and approximately 70% for the 1988 data set.

The d index was higher for the 1987 data than for the 1988 data, but modeled estimates for both data sets did not agree as well with the measured values as r and r^2 values might suggest. Modeled albedo values are approximately four units higher than measured albedos for both years. That is, if the measured albedo was found to be 17.0%, the modeled value would be 21.0%, as also indicated by the MBE and the RMSE.

E_s is large compared to E_u (Figs. 3 and 4 and Table 2) and makes up the largest part of the average total error (RMSE). This large systematic error gives rise to an MRE of approximately 22% and 28% for the 1987 and 1988 data sets, respectively.

Figure 3. Comparison of measured albedo with albedo estimated from Eq. (6): 1987 data set ($n = 522$).



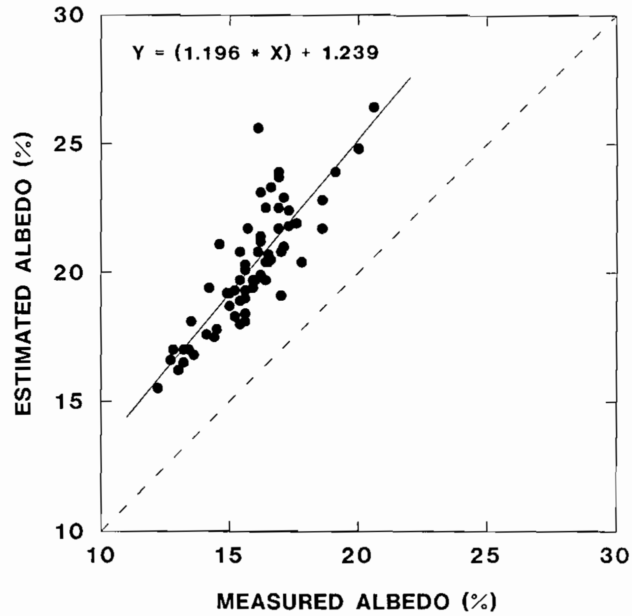


Figure 4. Comparison of measured albedo with albedo estimated from Eq. (6): 1988 data set ($n = 64$).

DISCUSSION

Willmott (1982) indicated that differences described by E_s can be explained by a linear function, so that it is possible to reduce E_s by modifying the estimating algorithm. E_u can be interpreted as a measure of potential accuracy. Equation (6) should produce estimates of albedo to within 1% (absolute) of the measured value if the systematic error can be reduced or eliminated.

Systematic errors in Eq. (6) are likely to arise in: 1) calculation of hemispherical irradiance (RD_{Hj}) from the Walthall model and 2) determination of the weighting coefficients (W_j and W_j'). The Walthall equation, which is a three-parameter fit to the bidirectional reflectance factor distribution, could have extrapolation errors when the second-order equation is extrapolated from 50° (highest view angle measurement) to 90°. Only the first term in the Walthall equation [Eq. (8)] can cause extrapolation errors. This error can be estimated by integrating the Walthall equation from nadir to only 60°, and then integrating from 60° to 90° by substituting a fixed angle of 60° in for the view

Table 2. Statistical Analysis of Albedo Estimates Produced from Eq. (6) Compared to Simultaneously Measured Values[a]

	d	r	r^2	MBE ($W\ m^{-2}$)	MRE (%)	X ($W\ m^{-2}$)	s ($W\ m^{-2}$)	RMSE ($W\ m^{-2}$)	E_u ($W\ m^{-2}$)	E_s ($W\ m^{-2}$)
1987 Data Set										
Modeled	0.66	0.89	0.80	3.9	22.3	21.8	3.0	4.2	1.4	3.9
Measured						17.8	2.5			
1988 Data Set										
Modeled	0.47	0.84	0.71	4.4	27.6	20.2	2.4	4.5	1.3	4.4
Measured						15.8	1.7			

[a] $d = 1 - [\Sigma(E_i - M_i)^2 / \Sigma(|E_i - M| + |M_i - M|)^2]$, E_i = estimated albedo at time i, M_i = measured albedo at time i, M = mean measured albedo for the data set, RMSE $= \{[N^{-1}\Sigma(P_{ri} - M_i)^2] + [N^{-1}\Sigma(P_{ri} - E_i)^2]\}^{1/2}$, $E_s = [N^{-1}\Sigma(P_{ri} - M_i)^2]^{1/2}$, $E_u = [N^{-1}\Sigma(P_{ri} - E_i)^2]^{1/2}$, P_{ri} = predicted albedo using values derived from least squares regression of estimated and measured albedo, $P_{ri} = mM_i + b$, m = slope, b = intercept, MBE $= N^{-1}\Sigma(E_i - M_i)$, MRE $= N^{-1}[\Sigma(E_i - M_i)/M_i][100]$, $s = [(N-1)^{-1}\Sigma(V_i - x)^2]^{1/2}$, $x = N^{-1}\Sigma V_i$, and V_i = estimated or measured albedo.

angle. The constant in the Walthall equation of 2.305 can then be evaluated from the following:

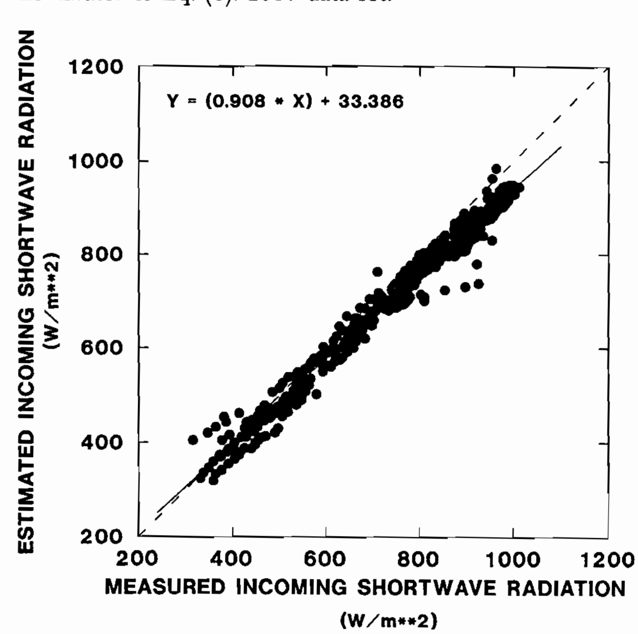
$$\frac{1}{2}\pi\left[\theta_V \sin(2\theta_V) + \frac{1}{2}\cos(2\theta_V) - \theta_V^2 \cos(2\theta_V) - \frac{1}{2}\right] + 2\pi\theta_V^2\left(\frac{1}{2} - \frac{1}{2}\sin^2\theta_V\right), \tag{10}$$

where θ_V is the upper limit of the view (60° in our case). In this case, 60° is used because measurements at 0°, 20°, 35°, and 50° could be expected to provide reliable estimates to at least 60°. The above equation results in a constant of 1.970 instead of 2.305, or 14.5% less. Thus, even if the nadir reflectance were zero, the maximum extrapolation error would be less than 15%. In the integrated Walthall equation, the constant c is the nadir reflectance. For prairie grasses, usually $a < c$. Even if $a = c$, the maximum extrapolation error is 6%. For this analysis, we conclude that the extrapolation errors are less than 5% and probably negligible. Although extrapolation errors may be minor, the appropriateness of the three-term Walthall equation for representation of the BRF distribution based on only principal plane measurements has not been proven for these prairie grasses.

As stated above, the weighting coefficients were determined using knowledge of the spectral distribution of global solar radiation and the MMR waveband limits. When used in the denominator of Eq. (6), the coefficients produce good estimates of incoming shortwave radiation (Figs. 5 and 6, and Table 3). Mean relative errors are less than 5% for the 1987 data set and less than 2% in 1988 when compared to pyranometer data. However, it is possible that these weighting coefficients are not appropriate for use in the numerator of Eq. (6).

It is assumed in the numerator of Eq. (6) that the reflected spectral radiances measured by the MMR are representative of the spectral radiance within the extended bandpass limits (Table 1). This implies that the reflectance of the prairie grasses is constant across both band limit ranges. The MMR, like most remote sensing instruments, is designed to collect data in certain atmospheric "windows"; therefore, by avoiding the major absorption features of the atmosphere, the spectral filters also miss the major absorption features of land surface spectral reflectance patterns. With-

Figure 5. Comparison of measured incoming shortwave radiation with shortwave radiation estimated from the denominator of Eq. (6): 1987 data set.



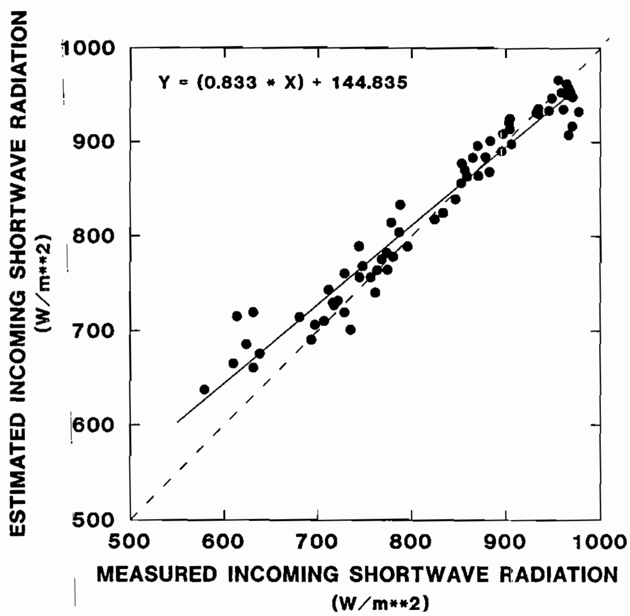


Figure 6. Comparison of measured incoming shortwave radiation with incoming shortwave radiation estimated from the denominator of Eq. (6): 1988 data set.

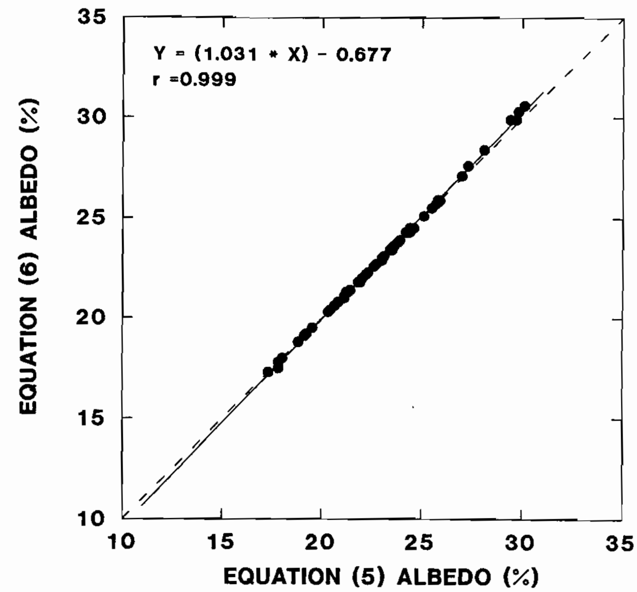


Figure 7. Comparison of estimated albedo computed from Eq. (5) with that computed from Eq. (6). Data acquired on 4 June 1987.

out taking into consideration the response functions of the spectral filters of the MMR and a nominal spectral reflectance curve for the prairie grasses, a bias towards overestimation of the albedo might be expected. Jackson (1984) took these factors into consideration when he developed P/T ratios to be used in the estimation of reflected shortwave radiation from wheat and soil surfaces. His estimates of incoming shortwave radiation were within 5% of pyranometer-measured values.

We tried to obtain a spectral reflectance curve for the grasses of the Konza Prairie. However, this information was not available nor was there instrumentation available to us to construct one. This failure points out the fact that *a priori* data of this type are not always available, which limits the utility of Jackson's approach to those cases where spectral reflectance curves for the surfaces under consideration are readily obtainable. Furthermore, if a technique for albedo estimation is to be extended to use with data obtained from satellite platforms the number of required *a priori* spectral reflectance curves could become impractical to obtain.

Another possible source of systematic error is connected with surface shadowing produced by the A-frame instrumentation. That is, shadows cast on the surface by the instruments and subsequently sensed by the inverted pyranometer would lead to an undermeasured albedo.

To look at this problem experimentally, we

Table 3. Statistical Analysis of Estimates of Incoming Solar Radiation Produced from the Denominator of Eq. (6) Compared to Simultaneously Measured Values

	d	*r*	r^2	*MBE* $(W\,m^{-2})$	*Mre* (%)	*X* $(W\,m^{-2})$	*s* $(W\,m^{-2})$	*RMSE* $(W\,m^{-2})$	E_u $(W\,m^{-2})$	E_s $(W\,m^{-2})$
						1987 Data Set				
Modeled	0.98	0.99	0.98	−33.4	−4.0	734.5	162.5	44.3	24.2	37.1
Measured						767.9	175.9			
						1988 Data Set				
Modeled	0.98	0.97	0.95	8.1	1.4	826.4	95.4	29.1	20.9	20.3
Measured						818.3	112.0			

Table 4. Relative Errors Effected by A-Frame Instrumentation Shadowing near Solar Noon

Time (CDST)	*A-Frame Configuration*	*Actual Reading (V)*	*Control Reading (V)*	*Relative Error (%)*	*Mean Relative Error (%)*
1349	1987	1.2950	1.3448	-3.7032	
1352	1987	1.3055	1.3580	-3.8624	
1353	1987	1.3108	1.3659	-4.0305	
1357	1987	1.2846	1.3423	-4.2950	
					-3.9728
1350	1988	1.2740	1.3553	-5.9987	
1352	1988	1.2793	1.3580	-5.7918	
1354	1988	1.2951	1.3685	-5.3635	
1356	1988	1.2741	1.3528	-5.8141	
					-5.7420

set up three different A-frames: one as a control and one each using the 1987 and 1988 A-frame instrument configuration. The control had one PSP mounted at a height of 40 cm, and the instruments on the other A-frames were mounted at 40 cm. A reading was taken with the control; then each of the other A-frames was brought in to take a reading over the control-viewed area and then removed so that another control reading could be taken. This sequence was followed four times near solar noon—the time of maximal shadowing affect. The results (Table 4) indicate that the shadows from the A-frame instrumentation make up from 4% to 7% relative error in the measured albedo, or alternatively stated, the measured albedo is approximately 1 unit too low. These findings suggest that some of the systematic error is due in part to error in the measurement of albedo, and that this error is higher at the larger solar zenith angles than at the lower ones.

It was noted above that estimates of incoming shortwave radiation compare well to the pyranometer data. Nevertheless, there is a consistent underestimation of approximately 4% for the 1987 data set. This underestimation of the incoming solar component would lead to an estimated albedo that would be about 1 unit too high. The 1988 data set exhibits a small bias (about 1%) towards overestimation of the incoming shortwave radiation; yet the unsystematic and systematic errors in the albedo estimates are approximately the same for both years (Table 2). Clearly, another source of error is responsible for the large bias in the albedo estimates.

In this study, the measurements of canopy bidirectional reflectance were made in the solar principal plane. When the sun and sensor angles are coincident, the sensor view will consist mainly of sunlit leaves except for the shadow of the sensor. For sensor view angles near this coincident angle, sometimes referred to as the canopy "hot spot," canopy bidirectional reflectances can be considerably larger than at other view zenith angles. Based on a model of this "hot spot" phenomena (Kuusk, 1983), a fit of the three-parameter equation (7) to data from only the solar principal plane is likely to overestimate albedo. This occurs because the "hot spot" is a localized peak (or ridge) in the canopy bidirectional reflectance distribution so that fitting this region causes overestimation in bidirectional reflectance at other azimuth view angles. The presence of this ridge in the bidirectional reflectance in the solar principal plane is apparent in the mesured results shown by Deering and Middleton (1990). The "hot spot" effect is pronounced in the visible, but apparent at all wavelengths throughout the solar spectrum; in the near-infrared (MMR Band 4), this "hot spot" effect is smaller, in a relative sense, than in other wavelength bands. Assessing the magnitude of this error is difficult because the instrument shadow may obscure part of the "hot spot." Ignoring the effect of the instrument shadow, based on the model of Kuusk (1983) a relative overestimate of albedo of 20% may not be unrealistic because the maximum view zenith angle was only 50° from nadir. If view zenith angles had extended to 70°, the albedo overestimate would have been smaller because "hot spot" effects would not extend to this view angle with the sun zenith angles that were used.

We do not fully understand why the model estimates of albedo do not agree better with measured values. Since the model produces good estimates of incoming solar radiation, it is unlikely that there is an error due to the MMR calibration, the equations used to calculate the radiation streams, nor that there is a problem with the field reference panels. Although the instruments on the A-frame cast a shadow on the surface seen by the inverted pyranometer, the underestimation of measured albedo caused by that shadow does not appear to explain more than a small amount of the observed differences according to calculations we have made. Inappropriate weighting coefficients in the numerator of Eq. (6) could cause biases in the albedo estimates. However, due to a lack of information we were not able to quantify this potential source of error. It is likely that a considerable portion of the bias is due to measuring bidirectional radiance data only in the solar principal plane.

We will continue to investigate the problem and will seek data sets from other scientists on which we can test our model. At the same time we will share our data with them to test in their models.

This work was performed under NASA Contract NAG 5-894. The authors would like to thank Cindy Hays, Roel Vining, Dave Klazinski, Doug Eschelbrenner, Pedro Zara, Gregg Grosshans, Mark Mesarch, and Vicki Samson for their help in collecting the field data. Also our appreciation is extended to Sharon Kelley, Jan Schinstock, and Lutine Hatley for typing the manuscript. Thanks are also given to Rita Terry for her editorial comments. Jim Irons and Donald Rundquist reviewed the manuscript and provided helpful suggestions. An anonymous reviewer provided helpful suggestions as to other potential sources of error in the albedo estimates.

REFERENCES

Bird, R., and Riordan, C. (1984), Simple solar spectral model for direct and diffuse irradiance on horizontal and tilted planes at the earth's surface for cloudless atmospheres, Solar Energy Research Institute, Golden, Colorado, 29 pp.

Brest, C. L. (1987), Seasonal albedo of an urban / rural landscape from satellite observations, *J. Clim. Appl. Meteorol.* 26:1169–1367.

Brest, C. L., and Goward, S. N. (1987), Deriving surface albedo measurements from narrow band satellite data, *Int. J. Remote Sens.* 8:351–367.

Charney, J., Quirk, W. J., Chow, S., and Kornfield, J. (1977), A comparative study of the effects of albedo change on drought in semi-arid regions, *J. Atmos. Sci.* 34:1366–1385.

Deering, D. W. and Middleton, E. M. (1990), Spectral bidirectional reflectance and effects on vegetation indicies for a prairie grassland, in *Symposium on FIFE,* 7–9 February, Anaheim, CA, American Meteorological Society, Boston, pp. 71–76.

Eaton, F. D., and Dirmhirn, I. (1979), Reflected irradiance indicatrices of natural surfaces and their effect on albedo, *Appl. Opt.* 18:994–1008.

Gillespie, A. R., and Kahle, A. B. (1977), Construction and interpretation of a digital thermal inertia image, *Photogramm. Eng. Remote Sens.* 43:983–1000.

Holm, R. G., Jackson, R. D., Yuan, B., Moran, M. S., Slater, P. N., and Biggar, S. F. (1989), Surface reflectance factor retrieval from Thematic Mapper data, *Remote Sens. Environ.* 27:47–57.

Irons, J. R., Ranson, K. J., and Daughtry, C. S. T. (1988), Estimating big bluestem albedo from directional reflectance measurements, *Remote Sens. Environ.* 25:185–199.

Iqbal, M. (1983), *An Introduction to Solar Radiation,* Academic, Toronto, Canada, 390 pp.

Jackson, R. D. (1984), Total reflected solar radiation calculated from multi-band sensor data, *Agric. For. Meteorol.* 33:163–175.

Jackson, R. D., Moran, M. S., Slater, P. N., and Biggar, S. F. (1987), Field calibration of reference reflectance panel, *Remote Sens. Environ.* 25:145–158.

Kimes, D. S., and Sellers, P. J. (1985), Inferring hemispherical reflectance of the earth's surface for global energy budgets from remotely sensed nadir or directional radiance values, *Remote Sens. Environ.* 18:205–223.

Kimes, D. S., Smith, J. A., and Ranson, K. J. (1980), Vegetation reflectance measurements as a function of solar zenith angle, *Photogramm. Eng. Remote Sens.* 46:1563–1573.

Kimes, D. S., Holben, B. N. Tucker, C. J., and Newcomb, W. W. (1984), Optimal directional view angles for remote sensing missions, *Int. J. Remote Sens.* 5:1–22.

Kimes, D. S., Sellers, P. J., and Diner, D. J. (1987), Extraction of spectral hemispherical reflectance (albedo) of surfaces from nadir and directional reflectance data, *Int. J. Remote Sens.* 8:1727–1746.

Kriebel, K. T. (1976), On the variability of the reflected radiation field due to differing distributions of the irradiation, *Remote Sens. Environ.* 4:257–264.

Kriebel, K. T. (1978), Measured spectral bidirectional reflection properties of four vegetated surfaces, *Appl. Opt.* 17:252–259.

Kriebel, K. T. (1979), Albedo of vegetated surfaces: its variability with differing irradiances, *Remote Sens. Environ.* 8:283–290.

Kuusk, A. (1983), The hot spot effect of a uniform vegetative cover, *Earth Res. Space* 4:90–99 [in Russian: Engl. transl. in *Sov. J. Remote Sens.* 3:645–653 (1985)].

Markham, B. L., Wood, Jr., F. M., and Ahmad, S. P. (1988), Radiometric calibration of the reflective bands of NS001-thematic mapper simulator (TMS) and modular multispectral radiometers (MMR), *SPIE Recent Advances in Sensors, Radiometers and Data Processing for Remote Sensing,* 924:96–108.

Mintz, Y. (1984), in *The Global Climate* (J. T. Houghton, Ed.), Cambridge University Press, Cambridge, London, New York, New Rochelle, Melbourne, Sydney, pp. 79–105.

Nicodemus, F. E., Richmond, J. C., Ginsberg, I.W., and Limperis, T. (1977), *Geometrical Considerations and Nomenclature For Reflectance,* NBS Monograph 160, National Bureau of Standards, U. S. Department of Commerce, Washington, DC.

Norman, J., and Walthall, C. (1985), Analysis of empirical model for hemispherical albedo computation, Final Report, Contract #S-19583-D, NASA, Greenbelt, MD.

Norman, J. M., Welles, J. M., and Walter, E. A. (1985), Contrasts among bidirectional reflectance of leaves, canopies, and soils, *IEEE Trans. Geosci. Remote Sens.* GE-23: 659–667.

Pease, R. W., and Nichols, D. A. (1976), Energy balance maps from remotely sensed imagery, *Photogramm. Eng. Remote Sens.* 42:1367–1373.

Pease, S. R., and Pease, R. W. (1972), Photographic films as remote sensors for measuring albedos of terrestrial surfaces, Technical Report V, USGS Contract 14-08-0001-11914, Washington, DC.

Pease, R. W., Lewis, J. E., and Outcalt, S. (1976), Urban terrain climatology and remote sensing, *Ann. Assoc. Am. Geogr.* 66:557–569.

Robinove, C. J., Chavez, P. S., Gehring, D., and Holmgren, R. (1981), Arid land monitoring using Landsat albedo difference images, *Remote Sens. Environ.* 11:133–156.

Robinson, B. F., Buckley, R. E., and Burgess, J. A. (1982), Performance evaluation and calibration of a modular multiband radiometer for remote sensing field research, Agristars Technical Report SR-P2-04318, Purdue University, Laboratory for Applications of Remote Sensing, West Lafayette, IN.

Salamonson, V. V., and Marlatt, W. E. (1971), Airborne measurements of reflected solar radiation, *Remote Sens. Environ.* 2:1–8.

Schutt, J. B. Holben, B. N., Shai, C. M., and Henninger, J. H. (1981), Reflectivity of TFE—a washable surface—compared with that of B_aSO_4, *Appl. Opt.* 20:2033–2035.

Sellers, P. J., and Hall, F. G. (1987), FIFE experiment plan, NASA, Goddard Space Flight Center, Greenbelt, MD.

Sellers, P. J., Hall, F. G., Asrar, G., Strebel, D. E., and Murphy, R. E. (1988), The first ISLSCP field experiment (FIFE), *Bull. Am. Meteorol. Soc.* 69:22–27.

Slater, P. N. (1980), *Remote Sensing: Optics and Optical Systems,* Addison-Wesley, Reading, MA, p. 231.

Starks, P. J. (1990), Measured and modeled radiation fluxes from prairie vegetation at the FIFE study site, Ph.D. dissertation, University of Nebraska, Lincoln, 179 pp.

Swain, P. H., and Davis, S. M. (1978), *Remote Sensing: The Quantitative Approach,* McGraw-Hill, New York.

Walthall, C. L., Norman, J. M., Welles, J. M., Campbell, G., and Blad, B. L. (1985), Simple equation to approximate the bidirectional reflectance from vegetative canopies and bare soil surfaces, *Appl. Opt.* 24:383–387.

Willmott, C. J. (1981), On the validation of models, *Phys. Geogr.* 2:184–194.

Willmott, C. J. (1982), Some comments on the evaluation of model performance, *Bull. Am. Meteorol. Soc.* 63:1309–1313.

Willmott, C. J., and Wicks, D. E. (1980), An empirical method for the spatial interpolation of monthly precipitation within California, *Phys. Geogr.* 1:59–73.