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Relationships between Evaporative Fraction and Remotely Sensed Vegetation Index and Microwave Brightness Temperature for Semiarid Rangelands

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ABSTRACT

Measurements of the microwave brightness temperature (TB) with the Pushbroom Microwave Radiometer (PBMR) over the Walnut Gulch Experimental Watershed were made on selected days during the MONSOON 90 field campaign. The PBMR is an L-band instrument (21-cm wavelength) that can provide estimates of near-surface soil moisture over a variety of surfaces. Aircraft observations in the visible and near-infrared wavelengths collected on selected days also were used to compute a vegetation index. Continuous micrometeorological measurements and daily soil moisture samples were obtained at eight locations during the experimental period. Two sites were instrumented with time domain reflectometry probes to monitor the soil moisture profile. The fraction of available energy used for evapotranspiration was computed by taking the ratio of latent heat flux (LE) to the sum of net radiation (Rn) and soil heat flux (G). This ratio is commonly called the evaporative fraction (EF) and normally varies between 0 and 1 under daytime convective conditions with minimal advection. A wide range of environmental conditions existed during the field campaign, resulting in average EF values for the study area varying from 0.4 to 0.8 and values of TB ranging from 220 to 280 K. Comparison between measured TB and EF for the eight locations showed an inverse relationship with a significant correlation ($r^2 = 0.69$). Other days were included in the analysis by estimating TB with the soil moisture data. Because transpiration from the vegetation is more strongly coupled to root zone soil moisture, significant scatter in this relationship existed at high values of TB or dry near-surface soil moisture conditions. It caused a substantial reduction in the correlation with $r^2 = 0.40$ or only 40% of the variation in EF being explained by TB. The variation in EF under dry near-surface soil moisture conditions was correlated to the amount of vegetation cover estimated with a remotely sensed vegetation index. These findings indicate that information obtained from optical and microwave data can be used for quantifying the energy balance of semiarid areas. The microwave data can indicate when soil evaporation is significantly contributing to EF, while the optical data is helpful for quantifying the spatial variation in EF due to the distribution of vegetation cover.

1. Introduction

The ability to monitor the hydrologic cycle in arid and semiarid regions is important for climate change research because of the close linkages between the hydrologic processes and ecosystem dynamics (Schlesinger et al. 1990). Quantifying the variation in the surface energy balance and, consequently, evapotranspiration (ET) at regional scales for these areas provides important information on the state of the surface and lower atmosphere, both of which are critical feedbacks to climate (Pielke and Avissar 1990).

Many approaches for evaluating regional ET have utilized satellite remote sensing technology because the observations provide synoptic information. Data collected in the visible, near-infrared, and thermal-infrared wave bands give spatial and temporal information on vegetation cover and surface temperature, which are important for energy balance modeling (e.g., Jackson 1985; Carlson 1986; Taconet et al. 1986; Schmugge and Becker 1990). Observations with optical sensors require cloud-free conditions and atmospheric corrections. The sparse and heterogeneous nature of the vegetation cover for arid and semiarid areas further complicates the interpretation of these measurements, thus making it difficult to utilize optical data in energy balance models (Kustas et al. 1989; Smith and Choudhury 1991). The low vegetation cover in these regions results

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in the soil surface having a major influence on the partitioning of energy fluxes between the soil and vegetation. This may require modeling approaches that evaluate the energy balance of individual soil and vegetation components (Kustas 1990; Shuttleworth and Gurney 1990; Camillo 1991; Massman 1992; Nichols 1992). However, there are serious limitations in employing satellite remote sensing data in this type of ET model (Smith and Choudhury 1991). For instance, many of these approaches require the separation of a composite surface temperature into soil and vegetation temperatures. This is difficult to do, especially over sparse vegetation cover containing natural vegetation. Second, the fractional vegetation cover and leaf-area index are important parameters in these models, but they are difficult to estimate for this environment using remotely sensed vegetation indices (Myneni et al. 1992).

Observations and theory have shown that passive microwave at L band (21 cm) is highly correlated to near-surface (0–5 cm) soil moisture (Schmugge et al. 1986). The attenuation of the microwave signal under most vegetation cover conditions (except for forests) can be evaluated using a simple algorithm that uses readily available data (Jackson et al. 1982; Jackson and Schmugge 1991). The effects of soil roughness can be quantified with an empirical model (Choudhury et al. 1979). The major drawback of microwave observations from satellite altitudes is the resolution problem (Jackson and Schmugge 1989), which results in pixel sizes of the order of tens of kilometers for feasible antennas. These instrumental limitations are being addressed (e.g., LeVine et al. 1989) while attempts at using existing satellite-based microwave sensors operating at shorter wavelengths for estimating soil moisture have met with some success (Wang 1985; Heymsfield and Fulton 1992).

Models estimating bare-soil evaporation have been developed that make use of microwave remote sensing observations to initialize or update near-surface soil moisture conditions (e.g., Bernard et al. 1981; Prevot et al. 1984; Bernard et al. 1986; Bruckler and Witono 1989). Yet these models require atmospheric forcing inputs (e.g., wind speed, air temperature, and humidity at screen height) and information on soil properties that are difficult to obtain for regional energy balance estimates. The utility of using remotely sensed data exclusively to infer the fraction of available energy used for ET was investigated in this study. This approach for estimating regional ET may be useful in areas where limited climatic and ground information is available (Owe and van de Griend 1990).

The analysis focuses on the use of passive microwave and optical remote sensing for evaluating the fraction of available energy used for evapotranspiration (ET) over semiarid rangeland environments. The microwave brightness temperatures (TB) collected by the Pushbroom Microwave Radiometer (PBMR) from an aircraft platform are utilized since TB values are highly correlated with 0–5-cm soil moisture (Schmugge et al. 1992; Schmugge et al. 1993). The optical data is used to estimate the distribution of vegetation cover using a vegetation index (VI) (Ormsby et al. 1987). These observations are compared to the daytime evaporative fraction (EF) given by

$$\mathrm{EF} = -\frac{\mathrm{LE}}{\mathrm{Rn} + G}, \tag{1}$$

where LE is the latent heat flux, Rn is the net radiation, and G is the soil heat flux. The minus sign is to account for the sign convention adopted in the surface energy balance equation [see Eq. (2)]. Equation (1) represents the fraction of available energy (Rn + G) used for evaporating water and should vary between 0 and 1 under conditions of minimal advection (MacQuarrie and Nkemdirim 1991).

Shuttleworth et al. (1989) found on selected days from the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) (Hall et al. 1991) that daytime values of EF were fairly constant. They suggested that remotely sensed data may be useful in estimating EF, which in turn would allow simple modeling of daily ET without a great deal of ancillary data. More recently, Sugita and Brutsaert (1991) demonstrated with the FIFE data that EF was fairly constant under a wider range of environmental conditions and could be quantified with atmospheric data. In this study microwave and optical data will be used to investigate whether remote sensing can infer the magnitude of EF over semiarid rangelands.

From the onset, the authors were aware that microwave measurements are sensitive only to near-surface soil moisture available for direct evaporation from the soil surface and that the optical data can give only some indication of the amount of vegetation cover but would be site specific. Therefore, these measurements may be most useful when incorporated in physically based models estimating the soil moisture profile (Jackson 1986) and the surface energy balance (Carlson et al. 1990). The objective of this preliminary investigation, however, is to determine what relationship, if any, exists between EF and TB and EF and VI, and the limitations of these observations to directly quantify the amount of available energy used for ET in semiarid rangelands.

2. The experiment

a. Study site

Data used in this analysis were collected during the MONSOON 90 field campaigns in the Walnut Gulch Experimental Watershed (34°43′N, 110°W) operated by the Southwest Watershed Research Center of USDA Agricultural Research Service near Tucson, Arizona. A detailed description of the watershed and measurements made during the field campaigns are given in

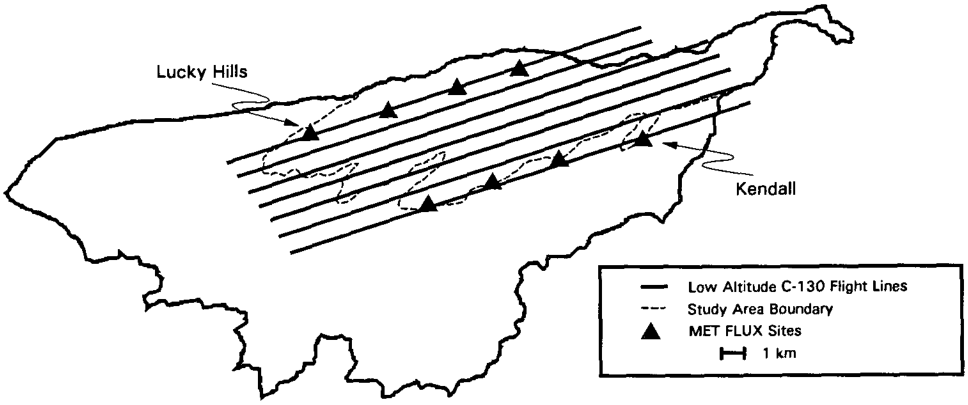

FIG. 1. Illustration of the PBMR flight lines, study area, and METFLUX sites. The separation between the lines is approximately 500 m.

Kustas et al. (1991). A short field campaign to obtain baseline measurements was held during the dry season (June 1990). The main study period (July–August 1990) coincided with the summer "monsoon" season for the southwestern United States. During the "monsoon" season roughly two-thirds of the 250–500 mm of annual precipitation occurs.

The mean elevation of the watershed is about 1500 m, and the topography is composed of rolling hills 10–30 m in height. Distances between hilltops are nominally 500 m with the main ephemeral channels running west-southwest. Many smaller drainage channels run north–south, significantly dissecting the area. The vegetation cover is sparse and highly variable. Shrub-type vegetation dominates the western half of the basin while the eastern half is primarily grasses. The soil surface contains a significant rock fraction, which does affect the sensitivity of the microwave brightness temperature to soil moisture (Jackson et al. 1992).

b. Measurements

The PBMR instrument was flown on the NASA C-130 aircraft at an altitude of 600 m above ground level (AGL) over the study site. This produced an instantaneous field of view of 180 m. Figure 1 illustrates the seven flight lines used to cover the study area. Flight times were generally between 0900 and 1100 MST with the northernmost line flown first. Measurements of TB were obtained on 6 days. A summary of the coverage and general information concerning the surface and meteorological conditions is given in Table 1. The missions appeared to cover the full dynamic range in brightness temperatures expected for this surface during the "monsoon" season.

Optical data were collected on the outermost flight lines in Fig. 1 by a Cessna aircraft flying at an altitude of approximately 100 m AGL. On board the aircraft was a nadir-looking Exotech[1] radiometer with a 15° field of view. At 100 m AGL, this resulted in a pixel size of 25 m in diameter. The instrument had four bandpasses covering the 0.50–0.90-μm range. Flights were made throughout the experimental period. On a typical day, two to three missions were flown covering the morning and early afternoon period. Optical data collected on DOY (day of the year) 209 (28 July 1990) were utilized in this study because the soil surface was uniformly dry and there were clear sky conditions. Therefore, any effects of clouds or variation in surface soil moisture on the reflectance data could be neglected.

TABLE 1. A summary of PBMR observations for the six days of coverage, including environmental conditions over the study area.

DOY	Date	Time (MST)	Soil moisture (0–5 cm)	TB (K)	EF*	Cloud cover
212	31 July 1990	0930–1110	1%–2%	280–285	0.4–0.5	mostly sunny
214	2 August 1990	0915–1040	11%–20%	225–245	0.6–0.75	partly cloudy
216	4 August 1990	0830–0940	11%–13%	225–250	0.6–0.8	partly cloudy
217	5 August 1990	1000–1100	5%–11%	260–270	0.5–0.6	partly cloudy
220**	8 August 1990	0900–0915	3%–13%	255–265	0.5–0.6	mostly sunny
221	9 August 1990	1010–1115	2%–8%	270–280	0.5–0.65	mostly sunny

* Range in midday evaporative fraction from the eight METFLUX sites.
** Northernmost and southernmost flight lines only.

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[1] Company names are given for the benefit of the reader and do not imply any endorsement of the product by the USDA.

For more details concerning the acquisition and analysis of the optical data, see Moran et al. (1991), Moran et al. (1993), and Kustas et al. (1993b).

Components of the surface energy balance and meteorological data were measured at the eight meteorological energy flux (METFLUX) stations. Net radiation was measured at each site. The soil heat flux was estimated using several heat flow plates buried at 5 cm and the storage term for the soil above the plates evaluated with soil temperature and moisture sensors at 2.5 cm below the surface.

The sensible heat flux H was estimated using a variance approach (Tillman 1972) and LE was solved as a residual; that is,

$$\mathrm{LE} = -(\mathrm{Rn} + G + H), \tag{2}$$

where fluxes away from the surface are negative. Comparison of turbulent fluxes H and LE estimated at several of the METFLUX sites with an eddy correlation system stationed nearby showed satisfactory agreement (Kustas et al. 1991; Kustas et al. 1993a). At several of the sites, other analyses of the variability in the energy balance components estimated by different micrometeorological systems were performed by Blanford and Stannard (1991) and Stannard et al. (1993).

Data on the vertical distribution of soil moisture were collected at Lucky Hills (shrub-dominated site) and Kendall (grass-dominated site) using the time domain reflectometry (TDR) technique of Topp and Davis (1985). The TDR probes were positioned at multiple depths from approximately 5 to 50 cm. The data were usually collected once a day. At Lucky Hills, the measurements were made in open areas and underneath the brush (three replications). At Kendall, measurements were made on north- and south-facing slopes midway between the stream channel and ridge, both in grazed and ungrazed areas. For more details see Kustas et al. (1991) and Amer et al. (1993, personal communication).

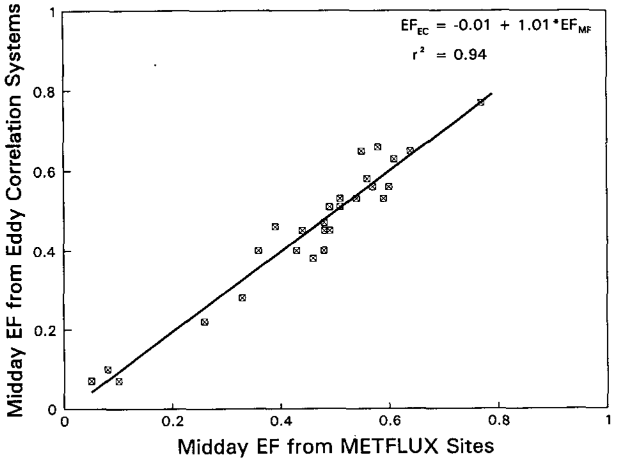

FIG. 2. Comparison between midday (1030–1430 MST) EF from the METFLUX sites and nearby eddy correlation systems during the June and July–August field campaigns.

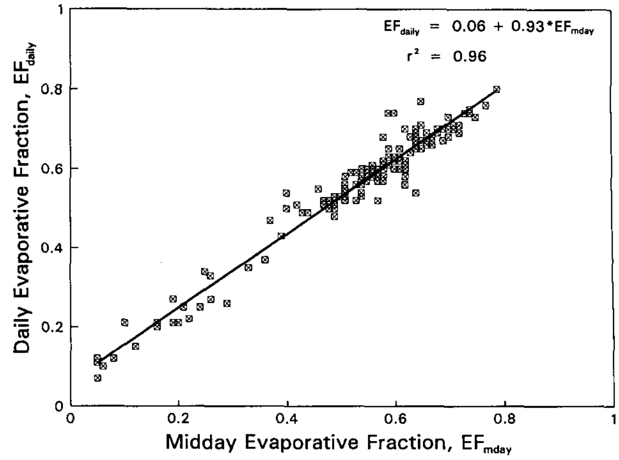

FIG. 3. Midday EF versus daytime (0700–1800 MST) EF from the METFLUX sites during the June and July–August field campaigns.

3. Data analysis

Twenty-minute averages of the energy balance components were computed. However, there was significant noise in the 20-min data, mainly caused by the variance technique for estimating H. Therefore, the midday evaporative fraction was evaluated for the period 1030–1430 MST. This is essentially ±2 h of solar noon (about 1230 MST). A comparison between METFLUX estimates of midday EF and those derived from an eddy correlation system during the June and July–August field campaigns is shown in Fig. 2. The good agreement (r^2 = 0.94 and slope of approximately 1) between METFLUX and eddy correlation estimates gives some confidence in the station values. The midday EF values from all eight METFLUX sites are also compared to the daytime values in Fig. 3. The daytime EF was computed by summing all fluxes in (1) between 0700 and 1800 MST, which was usually the period where Rn > 100 W m^2. The relationship between midday and

TABLE 2. Estimates of SAVI from the aircraft spectral data and ground-based estimates of canopy cover for the eight METFLUX sites.

METFLUX site	SAVI	Vegetation cover (%)
1	0.182	26
2	0.215	52
3	0.183	40
4	0.205	61
5	0.206	40
6	0.175	37
7	0.201	32
8	0.192	39

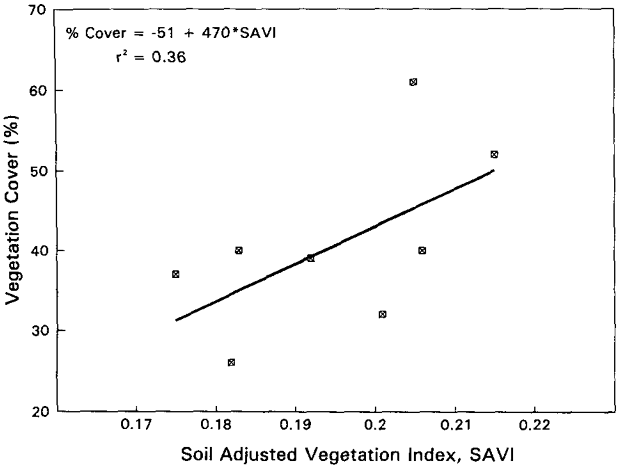

FIG. 4. Comparison of SAVI estimated with the spectral data from the Cessna aircraft and ground-based percent vegetation cover estimates for the eight METFLUX sites.

daytime EF is significant ($r^2 = 0.96$), although the equation in Fig. 3 indicates a tendency (average percent difference of 8%) for midday EF to underestimate daytime values. The relatively small scatter in Fig. 3 suggests that cloudiness or other atmospheric conditions present during the field experiments did not significantly affect this relationship.

The spectral data were used to compute the soil-adjusted vegetation index (SAVI) developed by Huete (1988) to minimize the influence of the soil background:

$$\mathrm{SAVI} = \left(\frac{\mathrm{NIR} - \mathrm{red}}{\mathrm{NIR} + \mathrm{red} + L}\right)(1 + L), \tag{3}$$

where NIR and red are the reflectances given by the red filter (0.62–0.69 μm) and near-infrared filter (0.78–0.90 μm) from the radiometer, and L is the soil correction term, estimated to be 0.5 for this surface (Moran et al. 1991). Table 2 lists the values of SAVI estimated around each METFLUX site from aircraft data collected on DOY 209 along with vegetation-cover estimates from Weltz et al. (1993). A comparison of SAVI versus vegetation cover in Fig. 4 suggests that the relationship probably changes significantly as a function of vegetation type as well as amount (i.e., grasses versus shrubs). A linear regression between SAVI and vegetation cover gave a small r^2 ($\approx$0.36).

Daily volumetric soil moisture (VSM) for the levels in the soil profile that influence soil evaporation and plant transpiration were investigated for Lucky Hills and Kendall. The VSM values for Lucky Hills represented an average of the measurements taken under the vegetation and in the open areas. For Kendall, the values were an average of the plots in the grazed north- and south-facing slopes.

In Fig. 5a the 0–5-cm gravimetric samples are compared to the 15- and 30-cm TDR data for Lucky Hills. The 15–30-cm layer is where most of the active roots for water uptake are located for the shrub species. Over the study period, VSM at 15 and 30 cm changed little relative to the 0–5-cm values. In Fig. 5b, the TDR measurements made at 5- and 10-cm depths are plotted along with the 0–5-cm gravimetric data. The 0–10-cm depth in the soil profile probably contributes most of the moisture for soil evaporation (e.g., Chanzy and Bruckler 1993). Changes in VSM at 5 and 10 cm caused by drying and rewetting from precipitation on days 213 and 215 are more dramatic than at 15 and 30 cm, but the variation is considerably damped compared to the near-surface data. The soil moisture profiles illustrated in Figs. 5a and 5b indicate that adequate moisture was available for plant transpiration during the experimental period and that the main change in ET over time was caused by changes in the relative contribution of soil evaporation to the total flux.

A similar conclusion was obtained with the VSM profile data from Kendall. In Fig. 6a, the TDR mea-

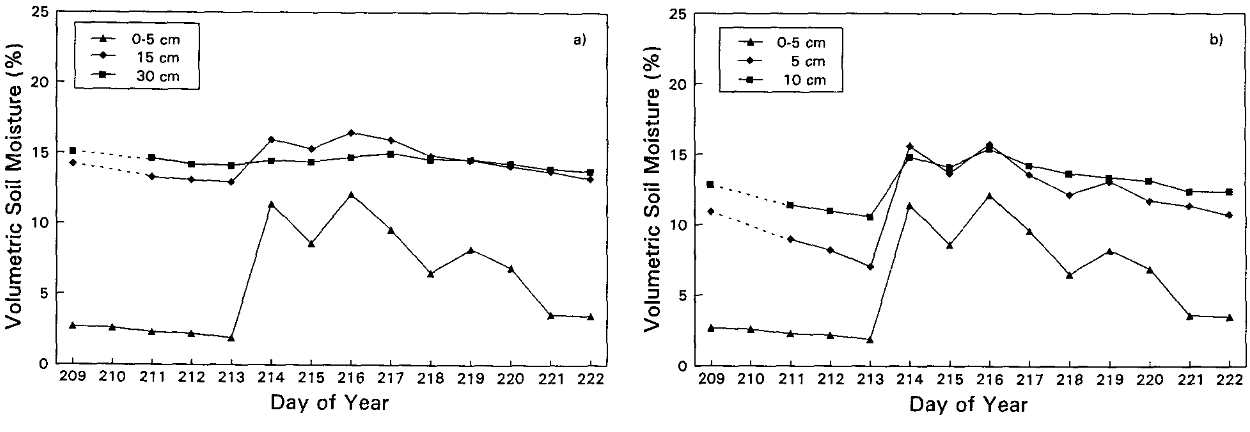

FIG. 5. Daily values of volumetric soil moisture for Lucky Hills from TDR measurements and gravimetric samples at (a) 30, 15, and 0–5 cm, and (b) 10, 5, and 0–5 cm.

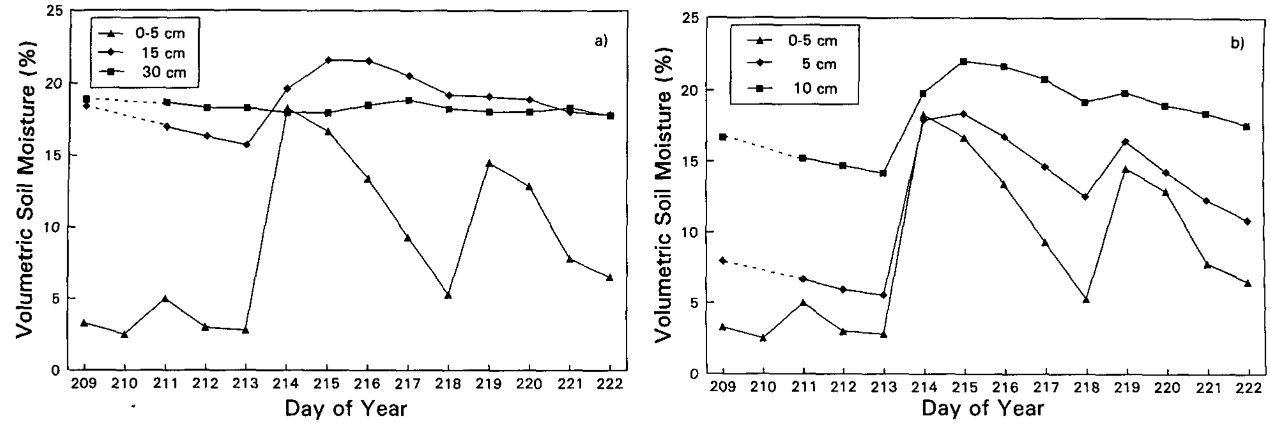

FIG. 6. Daily values of volumetric soil moisture for Kendall from TDR measurements and gravimetric samples at (a) 30, 15, and 0–5 cm, and (b) 10, 5, and 0–5 cm.

surements at 15 and 30 cm behave similarly to the data collected at Lucky Hills (Fig. 5a). The plot of soil moisture data for the 0–10-cm layer in Fig. 6b resembles the variation seen in the Lucky Hills data (Fig. 5b) except the daily VSM values at 5 cm track the 0–5-cm data more closely. It is hypothesized that this is a function of the root distribution with the grass-dominated site having more effective roots close to the surface, which can take advantage of available moisture in the near-surface layer.

For the six flight missions with the PBMR, values of the microwave brightness temperature TB ranged from about 230 to 285 K, while the midday EF ranged from about 0.4 to 0.8 (see Table 1). A plot of midday EF versus TB is shown in Fig. 7. The linear regression result ($r^2 \approx 0.7$) is significant at the 0.01 level using the assumption that the data are a random sample from a bivariate normal population (Freund and Walpole 1980). Thus about 70% of the variation in midday EF, and consequently the daytime value (see Fig. 3), can be accounted for using observations of TB under the conditions observed in this experiment. An EF map of the region can be produced given a brightness temperature image. This is illustrated in Fig. 8 for the PBMR mission before (DOY 212) and after several rainfall events (DOY 216) in the study area. The TB values were fairly constant over the study area on DOY 212; hence, the map of EF for DOY 212 shows little spatial structure. Several localized rainfall events on DOY 213 and 215 had significant spatial structure (Kustas et al. 1991). This produced a more heterogeneous TB image for DOY 216 that results in a more spatially variable EF map.

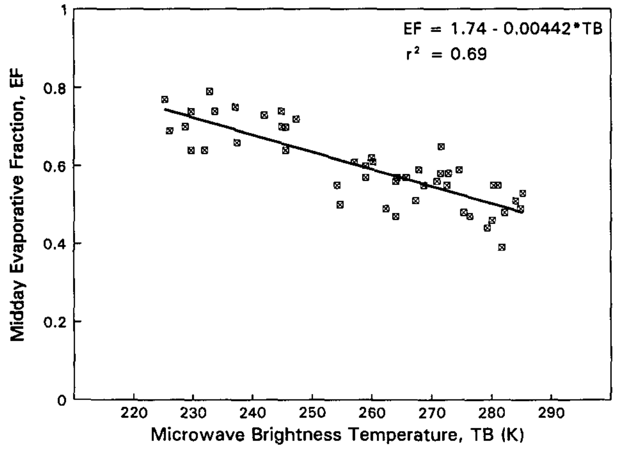

FIG. 7. Comparison of midday EF versus TB for the six days of observation. The line represents the least-squares fit through the data.

The spatial distribution of vegetation cover can significantly influence the spatial and temporal variation in EF over a landscape since it accesses water in deeper soil layers. The influence of vegetation cover on the magnitude of EF would be greatest when soil evaporation is minimal. The microwave observations can provide near-surface soil moisture information for determining when this condition is occurring; however, this is complicated by the fact that available moisture below the near-surface layer can contribute to soil evaporation and thus affect the magnitude of EF. Unfortunately, vegetation cover and soil moisture below the near-surface layer cannot be detected using a single-frequency sensor like the PBMR (Jackson and Schmugge 1989).

During the field campaign, the near-surface soil moisture varied from 2% to 20%. In addition, there were days when near-surface soil moisture was nonuniform over the study area due to the localized nature of the precipitation events (Kustas et al. 1991). This nonuniformity provided an opportunity to assess the impact of the spatial variation in vegetation cover and temporal variation in near-surface soil moisture on the TB–EF relationship. The data were included in the analysis by having TB estimated from the daily

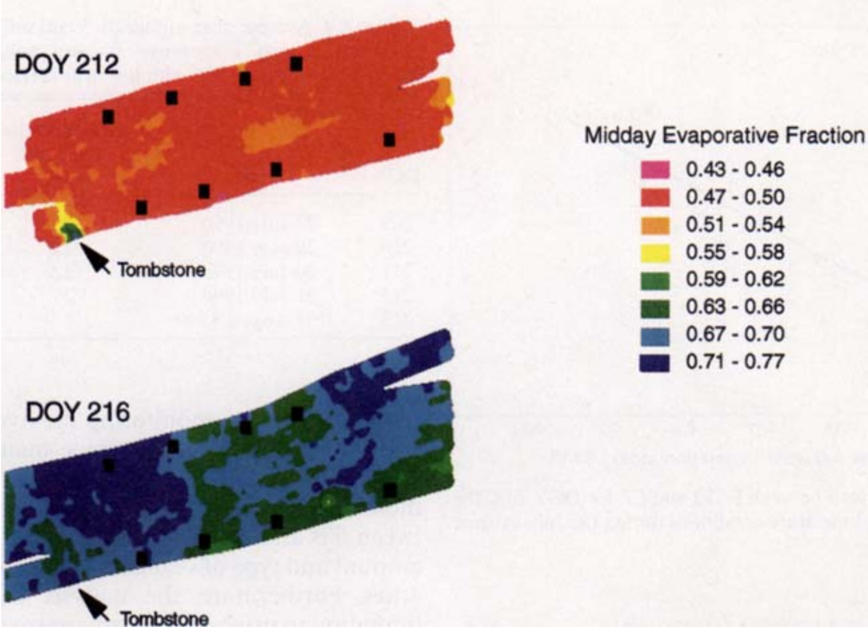

FIG. 8. Mapping the midday EF from TB observations on DOY 212 before any rainfall in the study area and on DOY 216 after several rainfall events. The approximate locations of the METFLUX sites and the town of Tombstone are indicated by the squares and arrow, respectively.

gravimetric samples of the near-surface soil moisture (0–5 cm) collected at the eight METFLUX sites. A least-squares regression equation was determined for each METFLUX site with soil moisture as the independent variable and TB as the dependent variable. The value of r^2 ranged from 0.84 to 0.95 (Schmugge et al. 1993).

The comparison between TB and EF for the six days with observations and the other days with TB estimated using the regression equations with soil moisture is illustrated in Fig. 9. There was a substantial decrease in r^2 to 0.4. Yet the correlation is still significant at the 0.01 level. The increase in scatter is mainly at the higher values of TB, which correspond to low surface soil moisture conditions. Although the scatter is due in part to the use of the near-surface soil moisture data to estimate the brightness temperatures and the fact that the measurement depth of a microwave sensor changes as a function of the amount of water in the soil layer (Engman 1991), other factors were believed to be the primary cause.

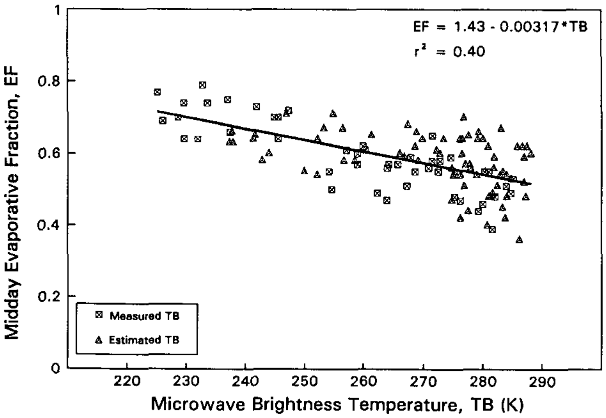

FIG. 9. Correlation between midday EF and both measured and estimated values of TB for the July–August field campaign.

It was suspected that the main factors causing a deterioration in the TB–EF relationship were the variation in the amount of vegetation cover and a gradual change in available moisture from the 0–10-cm layer contributing to soil evaporation. Support for the influence of the vegetation is given in Fig. 10. In the figure is a comparison between SAVI and EF for DOY 213, the day with the driest soil moisture conditions during the July–August campaign. The regression ($r^2 = 0.62$) is significant at the 0.05 level and indicates that SAVI may be useful under dry near-surface soil moisture conditions in accounting for variability in EF caused by the spatial variation in vegetation cover.

Regression results between SAVI and EF for the driest period, namely, DOYs 209–213 (see Figures 5b and 6b), during the July–August campaign are listed in Table 3. The statistical results indicate that the SAVI–EF relationship is significant for each day but that the values of the regression coefficients change. This change is probably caused by a gradual decrease in the relative contribution of soil evaporation to the total evaporative flux from DOY 209 to 213. This conclusion is supported by the monotonic decrease in VSM at 5 and 10 cm illustrated in Figs. 5a and 6a. Further

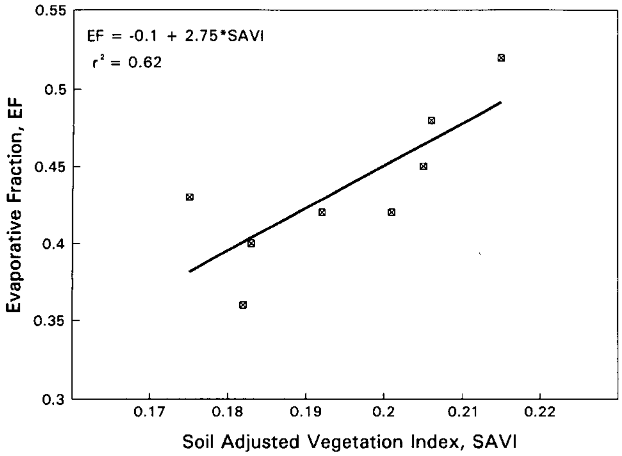

FIG. 10. A comparison between SAVI and EF for DOY 213, the day with the driest soil moisture conditions during the July–August field campaign.

proof is given in Table 4, which lists the average 0–5-cm soil moisture, TB and EF for this period. The table shows that while EF decreases, the 0–5-cm soil moisture changes are negligible. Thus having low near-surface soil moisture but available moisture below resulted in both the spatial variation in vegetation cover and temporal variation in soil evaporation to degrade the TB–EF relationship observed in Fig. 8.

When TB is near the maximum (≈280 K), the average calculated EF is approximately 0.5 (see Figs. 7 and 9). This combination of TB and EF for the study area indicates a condition when soil evaporation is a minor component of ET and hence transpiration is the primary contributor to the total evaporative flux. Under this situation, remotely sensed SAVI appears to be correlated with EF and provides additional information as to the spatial variability in this quantity.

4. Conclusions

For semiarid rangelands and under certain environmental conditions, passive microwave remote sensing has potential for mapping midday and daytime evaporative fraction at basin scales. This capability would be very useful for monitoring the hydrologic cycle in arid and semiarid regions since many of these areas contain inadequate climatic and soils information for more detailed modeling. However, the relationship between TB and EF is site specific and depends on the amount and type of vegetation cover and on soil properties. Furthermore, the analysis illustrates a major limitation in using only the microwave brightness temperature for estimating EF because the influence of vegetation and moisture below 5 cm in regulating EF cannot be assessed.

TABLE 3. Regression results with SAVI as the independent variable and EF as the dependent variable for DOYs 209–213, the driest period during the July–August field campaign.

DOY	Slope	Intercept	r^2	Hypothesis test*
209	2.49	0.12	0.57	0.05
210	2.54	0.04	0.63	0.05
211	2.54	0.06	0.57	0.05
212	3.16	−0.14	0.75	0.01
213	2.75	−0.10	0.62	0.05

* Listed is the level of significance that one could reject the null hypothesis of no correlation between SAVI and EF.

TABLE 4. Average near-surface (0–5 cm) soil moisture, brightness temperature, and evaporative fraction values from the eight METFLUX sites for days with low near-surface soil moisture.

DOY	Date	Soil moisture (0–5 cm) (%)	TB (K)	EF
209	28 July 1990	3	280	0.61
210	29 July 1990	2.5	280	0.54
211	30 July 1990	2.5	282	0.56
212	31 July 1990	2	282	0.48
213	1 August 1990	2	284	0.44

The microwave brightness temperature data were most strongly correlated with EF in the transition from high to low soil evaporation. The loss of sensitivity of EF to TB corresponded to the point at which there was a dry near-surface soil moisture condition, and hence, transpiration was the dominant mechanism regulating EF. Under these conditions, remote sensing measurements in the visible and near-infrared used in computing SAVI for the eight METFLUX sites were correlated with EF. Therefore, information from microwave observations when combined with the optical data is potentially very useful for physically based energy balance models that treat separately the contributions of soil evaporation and plant transpiration.

Investigations concerned with utilizing multiple wavelength observations for energy balance modeling are starting to gain more attention (e.g., Perry and Carlson 1988; Soares et al. 1988; van de Griend and Gurney 1988; Choudhury 1990, 1992; Humes et al. 1993). This study suggests that combining information obtained from microwave and optical remote sensing is a valuable tool for evaluating the surface energy balance in semiarid climates and warrants further research and field studies. In addition, the development of a satellite-based L-band sensor capable of adequate spatial resolution (say on the order of 5–10 km) for hydrologic applications should be given high priority.

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