

Use of ground-based remotely sensed data for surface energy balance evaluation of a semiarid rangeland

M. S. Moran,¹ W. P. Kustas,² A. Vidal,³ D. I. Stannard,⁴
J. H. Blanford,⁵ and W. D. Nichols⁶

Abstract. An interdisciplinary field experiment was conducted to study the water and energy balance of a semiarid rangeland watershed in southeast Arizona during the summer of 1990. Two subwatersheds, one grass dominated and the other shrub dominated, were selected for intensive study with ground-based remote sensing systems and hydrometeorological instrumentation. Surface energy balance was evaluated at both sites using direct and indirect measurements of the turbulent fluxes (eddy correlation, variance, and Bowen ratio methods) and using an aerodynamic approach based on remote measurements of surface reflectance and temperature and conventional meteorological information. Estimates of net radiant flux density (R_n), derived from measurements of air temperature, incoming solar radiation, and surface temperature and radiance compared well with values measured using a net radiometer (mean absolute difference (MAD) ≈ 50 W/m² over a range from 115 to 670 W/m²). Soil heat flux density (G) was estimated using a relation between G/R_n and a spectral vegetation index computed from the red and near-infrared surface reflectance. These G estimates compared well with conventional measurements of G using buried soil heat flux plates (MAD ≈ 20 W/m² over a range from -13 to 213 W/m²). In order to account for the effects of sparse vegetation, semiempirical adjustments to the single-layer bulk aerodynamic resistance approach were required for evaluation of sensible heat flux density (H). This yielded differences between measurements and remote estimates of H of approximately 33 W/m² over a range from 13 to 303 W/m². The resulting estimates of latent heat flux density, LE , were of the same magnitude and trend as measured values; however, a significant scatter was still observed: MAD ≈ 40 W/m² over a range from 0 to 340 W/m². Because LE was solved as a residual, there was a cumulative effect of errors associated with remote estimates of R_n , G , and H .

Introduction

Increasing concern over escalating costs and shortages of water and energy has spurred research into methods for estimating evapotranspiration (ET) over large areas. Conventional, ground-based methods for estimating regional ET only provide an average value for the region and are difficult, if not impossible, to verify. As an alternative, many approaches use remote sensing techniques as a means for obtaining spatial distributions (maps) of ET over diverse landscapes [Moran and Jackson, 1991]. Such approaches have been moderately successful for application to bare soil

or mature agricultural fields, but have encountered problems when applied to sparsely vegetated areas.

For example, Jackson [1985] proposed an operational method that estimates latent heat flux density (LE : a product of the heat of vaporization L and the rate of evaporation E) by solving the energy balance equation using remotely sensed estimates of surface reflectance and temperature and conventional meteorological information. This technique was successfully applied to mature agricultural fields using ground-, aircraft- and space-based sensors [Reginato *et al.*, 1985; Jackson *et al.*, 1987a; Moran *et al.*, 1990]. However, serious difficulties were encountered when the method was applied to surfaces only partially covered by vegetation, such as immature crops and rangelands [Kustas *et al.*, 1989]. These difficulties centered around the estimation of the sensible heat flux density term, H , in the energy balance equation (see equation (1)).

According to the single-layer or bulk resistance approach, sensible heat flux density is a function of the surface-air temperature difference ($T_s - T_a$) and the resistance to heat transfer (see equation (5)). In the case of full cover vegetation, T_s measured by an infrared (IR) sensor corresponds fairly well with T_s in (5) [Choudhury *et al.*, 1986], and the resistance term is a function of wind speed, stability, and surface roughness (see equation (6)). When the surface is only partially covered by vegetation, T_s measured radiometrically is a composite of the soil and vegetation temperatures

¹U.S. Water Conservation Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Phoenix, Arizona.

²Hydrology Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Beltsville, Maryland.

³CEMAGREF-ENGREF Remote Sensing Laboratory, Montpellier, France.

⁴Water Resources Division, U.S. Geological Survey, Denver, Colorado.

⁵School of Renewable Natural Resources, University of Arizona, Tucson.

⁶Water Resources Division, U.S. Geological Survey, Carson City, Nevada.

[Kustas *et al.*, 1990], and the resistance term is a function of both the soil and vegetation resistances [Kustas, 1990]. For a sparse canopy, Kustas *et al.* [1989] observed that H changed relatively little compared to the changes in $T_s - T_a$, and concluded that the composite resistance was, in part, related to radiometric measurements of surface temperature. Consequently, for incomplete canopies, they found that it was necessary to incorporate an additional resistance to sensible heat transfer linked to $T_s - T_a$.

This study addresses application of the energy balance approach using remotely sensed data to a sparsely vegetated rangeland site, Walnut Gulch experimental watershed, in southeast Arizona. Energy balance components were computed for two sites, one grass dominated and the other shrub dominated, using radiometric measurements of surface reflectance and temperature and on-site measurements of wind speed, air temperature, and incoming solar radiation. To account for the additional resistance to heat transfer associated with the sparsely vegetated sites, similar data from another rangeland in Owens Valley, California, were analyzed, and empirical relations were derived to correlate resistance with $(T_s - T_a)$. These relations were applied to data from the Walnut Gulch sites to compute suitable values of H and LE . The overall accuracy of the method was assessed by comparing estimates of energy balance components with ground-based measurements at the two Walnut Gulch sites.

Theory

The procedure for estimating energy balance components from remote sensors and ground-based meteorological instruments is based on the one-dimensional form of the energy balance equation [Jackson, 1985], i.e.,

$$LE = R_n - G - H, \quad (1)$$

where R_n is the net radiant flux density, G is soil heat flux density, and values of LE , G , and H are positive when directed away from the surface.

Net radiant flux density (R_n) is the algebraic sum of incoming and outgoing radiant flux densities, i.e.,

$$R_n = R_{S\downarrow} - R_{S\uparrow} + R_{L\downarrow} - R_{L\uparrow}, \quad (2)$$

where the subscripts S and L signify solar (shortwave) radiation (0.15–4 μm) and longwave radiation (>4 μm) respectively, and the arrows indicate the flux direction (downward denotes incoming, upward denotes outgoing). Jackson *et al.* [1985] proposed that incoming solar radiant flux density $R_{S\downarrow}$ can be measured with a calibrated pyranometer sensitive to radiation over most of the solar spectrum, and incoming longwave radiant flux density $R_{L\downarrow}$ can be estimated from ground-based measurements of air temperature and vapor pressure using the relation

$$R_{L\downarrow} = \epsilon_a \sigma T_a^4, \quad (3)$$

where $\epsilon_a = 1.24(e_0/T_a)^{1/7}$ [Brutsaert, 1975], σ is the Stefan-Boltzmann constant ($\text{W m}^{-2} \text{K}^{-4}$), T_a is air temperature (kelvins), and e_0 is vapor pressure (millibars) at T_a . The outgoing terms ($R_{S\uparrow}$ and $R_{L\uparrow}$) can be obtained from data collected with downlooking multispectral sensors. Jackson [1984] described a method by which the total reflected solar radiant flux density $R_{S\uparrow}$ (0.15–4 μm) was

estimated from the radiance measured using a multispectral radiometer. The outgoing longwave radiant flux density $R_{L\uparrow}$ can be obtained from the remotely measured surface temperature, $R_{L\uparrow} = \epsilon_s \sigma T_s^4$, where ϵ_s is surface emissivity and T_s is surface temperature (kelvins) measured by a thermal radiometer.

The G term, though traditionally measured with temperature and heat flow sensors buried just beneath the soil surface, can be determined by a relation between G/R_n and spectral reflectance factors in the red and near-infrared (NIR) spectral bands. This permits values of G to be estimated over large, diverse areas. An exponential relation suggested by Jackson *et al.* [1987a] is

$$G/R_n = 0.583e^{-2.13\text{ND}}, \quad (4)$$

where ND is the normalized difference [(NIR – red)/(NIR + red)], a spectral index that is sensitive to the amount of green vegetation present. This expression and others like it were derived for clear sky conditions during midday [Clothier *et al.*, 1986; Kustas and Daughtry, 1990].

The sensible heat flux density can be expressed as

$$H = \rho c_p (T_s - T_a) / r_{ah}, \quad (5)$$

where ρc_p is the volumetric heat capacity ($\approx 1150 \text{ J m}^{-3} \text{ C}^{-1}$) and r_{ah} is a resistance to heat transfer (seconds per meter). This resistance term can be defined as

$$r_{ah} = \{[\ln((z-d)/z_{0m}) + \ln(z_{0m}/z_{0h}) - \psi_h] \cdot [\ln((z-d)/z_{0m}) - \psi_m]\} / k^2 U, \quad (6)$$

where z is the height (meters) above the surface at which the wind speed and air temperature are measured, d is the displacement height (meters), z_{0m} and z_{0h} are the roughness length for momentum and scalar roughness for heat (meters), respectively, k is von Karman's constant (≈ 0.4), U is wind speed (meters per second), and ψ_h and ψ_m are the stability corrections for heat and momentum, respectively. The distinction between the roughness lengths for heat and momentum is necessary due to the dissimilarity between heat and momentum transfer mechanisms. Heat transfer near a surface is controlled primarily by molecular diffusion, whereas momentum transfer takes place as a result of both viscous shear and local pressure gradients [Brutsaert, 1982]. This difference results in an additional resistance to heat transfer (where $z_{0m} > z_{0h}$), which has been expressed as $kB^{-1} = \ln(z_{0m}/z_{0h})$ [Chamberlain, 1968]. For a uniform vegetative surface, kB^{-1} is observed to be fairly constant, having a value ≈ 2 [Garratt and Hicks, 1973].

The integral stability functions summarized by Beljaars and Holtslag [1991] for the unstable condition ($T_s > T_a$) are

$$\psi_m(\zeta) = 2 \ln[(1+x)/2] + \ln[(1+x^2)/2] - 2 \arctan(x) + \pi/2, \quad (7)$$

$$\psi_h(\zeta) = 2 \ln[(1+x^2)/2], \quad (8)$$

and, for the stable condition ($T_s < T_a$),

$$\psi_m(\zeta) = \psi_h(\zeta) = -5\zeta \quad 0 < \zeta < 0.5 \quad (9)$$

$$\psi_m(\zeta) = \psi_h(\zeta) = a\zeta + b(\zeta - c/d)e^{-d\zeta} + bc/d \quad \zeta \geq 0.5 \quad (10)$$

where $a = 0.7$, $b = 0.75$, $c = 5$, and $d = 0.35$, $x = (1 - 16\zeta)^{1/4}$, and ζ is a dimensionless variable $\{\zeta = (z - d)/L\}$

proposed by *Monin and Obukhov* [1954]. The *Obukhov* [1946] stability length, L , is defined as

$$L = (-u_*^3 \rho c_p T_a) / (kgH), \quad (11)$$

where u_* is the friction velocity $\{u_* = kU / [\ln((z-d)/z_{0m}) - \psi_m]\}$ and g is the acceleration due to gravity ($\approx 9.8 \text{ m/s}^2$). The L value can be determined by an iteration of (5)–(11), based on estimates of d , z_{0m} , and kB^{-1} and measurements of T_s , T_a , and U .

Two methods are proposed to account for the additional heat transfer resistance associated with sparse vegetation; they are distinguished by their conceptual approach. One associates the additional resistance with the differences in transfer processes of heat and momentum by assuming that the kB^{-1} value is not a constant, but rather, a function of the composite surface temperature (termed the kB^{-1} method). The other attempts to divide the total resistance into its component parts: one related to plant height, one to canopy structure, and an additional resistance to account for the effect of partial canopy surface temperature (termed the r_{ss} method).

Additional Resistance, kB^{-1} Method

Kustas et al. [1989] found that when T_s was measured radiometrically, appropriate values of r_{ah} for sparsely vegetated surfaces could not be obtained using (6) with values of kB^{-1} from previous experimental and theoretical work [Brutsaert, 1982]. To obtain proper values of the resistance, it was necessary to link kB^{-1} to the value of $(T_s - T_a)$. The calibration of the kB^{-1} expression was performed with data from an experiment conducted in Owens Valley, California, at a site characterized by shrubby vegetation covering about 20–30% of the soil surface. Surface temperatures were measured at times 1000, 1200 and 1400 hours on three days in June 1986 with an infrared thermometer mounted on a low-flying aircraft, and values of H were measured at several sites using Bowen ratio and eddy correlation systems. Site-specific values of kB^{-1} were computed from measurements of H . A least squares regression, forcing the intercept through zero, gave the following relationship (Figure 1a):

$$kB^{-1} = |s_{kb}U(T_s - T_a)|, \quad (12)$$

where $s_{kb} = 0.17$ for the Owens Valley rangeland data. Substituting the empirical (12) into (6), equation (5) is expanded to

$$H = \rho c_p (T_s - T_a) / \{ [\ln((z-d)/z_{0m}) + |s_{kb}U(T_s - T_a)| - \psi_h] \cdot [\ln((z-d)/z_{0m}) - \psi_m] / [k^2U] \}. \quad (13)$$

Kustas et al. [this issue (b)] recently revised (12) based on improvements to the estimation of the momentum roughness parameter, thus reducing the empirical estimate of s_{kb} from 0.17 to 0.13.

Additional Resistance, r_{ss} Method

The “ r_{ss} ” method approaches the problem by defining a resistance term that is independent of aerodynamic resistance and related only to the soil surface temperature. In this method, convective exchanges between leaves and the atmosphere are controlled by a sum of resistances [Vidal and Perrier, 1989],

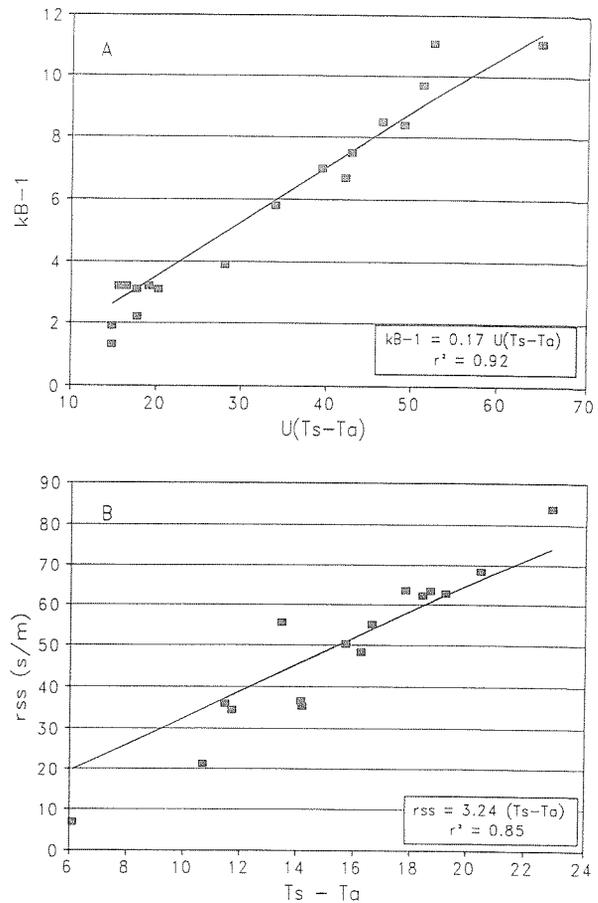


Figure 1. Linear regression equations for (a) kB^{-1} and (b) r_{ss} based on measurements of surface and air temperatures (T_s and T_a) and wind speed (U) acquired at a shrubby site in Owens Valley, California, 1986. The solid line represents the best fit relationship between the variables, forcing the intercept through zero.

$$r_{ah} = r_0 + r_{ss} + r_a, \quad (14)$$

where r_0 is the structural resistance due to stratification of the leaves in the crop (a function of leaf area index, LAI) and r_{ss} is the “soil surface effect” resistance representing the effect of soil surface temperature in the radiometric measurement of T_s . In (14), r_a is the stability-corrected aerodynamic resistance related to average plant height (h), where

$$r_a = \{ \ln [(z-h)/z_0] / k \}^2 (1 + 15Ri)(1 + 5Ri)^{1/2} / U, \quad (15)$$

(adapted from *Mahrt and Ek* [1984]) for the stable case, and

$$r_a = \{ \ln [(z-h)/z_0] / k \}^2 \{ 1 - 15Ri / [1 + C(-Ri)^{1/2}] \}^{-1} / U, \quad (16)$$

for the unstable case. In (15) and (16), Ri is a variation of the bulk *Richardson* [1920] number related to h rather than $(d + z_0)$ (where $Ri = g(T_a - T_s)(z-h)/T_a u_*^2$), $C = 75k^2 \{ [(z-h)/z_0]^{1/2} / \{ \ln [(z-h)/z_0] \}^2 \}$, and $z_0 = h(1 - e^{-(LAI/2)}) e^{-(LAI/2)}$ [Perrier, 1982].

For sparse canopies, where the proportion of soil to vegetation is large, the turbulent exchange between the surface and the atmosphere depends largely on the air-soil

temperature difference. Consequently, the resistance to turbulent exchange can be expressed as a function of $T_s - T_a$. Using Owens Valley data compiled by *Kustas et al.* [1989] for a site with LAI = 0.47 and assuming $r_0 = 10$ [Perrier, 1975], an empirical relation was defined between r_{ss} and $(T_s - T_a)$ (Figure 1b), where

$$r_{ss} = |3.24(T_s - T_a)|. \quad (17)$$

Thus (5) can be rewritten to account for radiometric measurements of T_s , where

$$H = \rho c_p (T_s - T_a) / \{r_0 + |3.24(T_s - T_a)| + r_a\}. \quad (18)$$

Experiment

An experiment was conducted at the Walnut Gulch experimental watershed near Tombstone, Arizona, to acquire the hydrometeorological and remote sensing data necessary to test the remote energy balance method for rangeland vegetation. These data were acquired as part of a larger study focusing on the general utility of remote sensing to provide a practical means for monitoring some of the important factors controlling land surface processes [Kustas et al., 1991a]. The experimental sites were located in an area comprising the upper 150 km² of the Walnut Gulch drainage basin, from about 1300 m above mean sea level (MSL) to about 1800 m MSL 20 km east. In this region, precipitation ranges from 250 to 500 mm/yr, with two thirds of the rainfall occurring during the summer "monsoon season" in July and August. For this study, data were obtained during the dry season in June while most vegetation was still dormant and during the monsoon season in late July and early August (Table 1), when the vegetation was at peak greenness and soil moisture was highly variable in time and space due to recent precipitation events [Schmugge et al., this issue]. The majority of the measurements used in this analysis were made in the first half of the day.

This analysis was limited to two sites, namely Lucky Hills and Kendall, characterized by sparse shrubs and grass, respectively. At both sites, a large ground target was delimited over which surface temperature and reflectance were measured from a height of 2 m above the ground surface, using yoke-based radiometers and a calibrated reference reflectance panel [Jackson et al., 1987b]. Data were acquired at 1 m increments along transects through the target, covering the entire target in less than 15 min (this technique was similar to that described by Slater et al. [1987]). The Lucky Hills target was approximately 120 by 120 m in size, typified by relatively flat topography and primarily shrub vegetation of ≈ 0.6 m height covering 20% of the soil surface. The Kendall target was much larger, 480 by 120 m, located in a hilly, grass-dominated site, stretching from the top of one hill eastward to the top of another.

An eddy correlation system [Tanner, 1988] was located near the Lucky Hills target and a Bowen ratio system [Spittlehouse and Black, 1980] near the Kendall target to measure H and LE on site. R_n and G were measured using a single-dome shielded net radiometer and a grid of strategically placed soil heat flux plates [Stannard et al., this issue]. At Lucky Hills, flux densities of latent and sensible heat were measured by the eddy correlation system using a single-axis sonic anemometer with fine wire thermocouple and krypton hygrometer and at both sites by the Bowen ratio

Table 1. Summary of Dates and Times for Simultaneous Acquisition of Spectral, Meteorological, and Flux Measurements

DOY	Date	Time of Day, decimal hours
<i>Kendall</i>		
156	June 5	9.0*, 11.0*
212	July 31	11.4, 11.8, 12.2
213	Aug. 1	10.4, 10.7*
214	Aug. 2	9.0, 9.4
216	Aug. 4	7.7, 8.2
217	Aug. 5	9.2, 9.5
220	Aug. 8	7.1, 7.4, 8.8, 9.1, 9.7*, 10.0, 10.4, 12.0, 12.5
221	Aug. 9	7.2*, 7.4*, 9.1*, 9.4*, 10.7*, 11.1*, 11.3*
222	Aug. 10	9.0, 9.2, 9.4, 9.6, 10.9, 11.1, 11.3, 11.5
<i>Lucky Hills</i>		
156	June 5	8.6*, 10.1*, 11.1*
211	July 30	11.1, 13.1
212	July 31	11.4*
213	Aug. 1	10.4*, 10.7
214	Aug. 2	9.0, 9.4
216	Aug. 4	7.7, 8.1, 9.3, 9.7, 10.2, 11.1, 11.6
217	Aug. 5	9.3, 9.7, 12.0, 12.3
220	Aug. 8	9.5*, 10.0*, 10.4, 12.2, 12.5
221	Aug. 9	7.2*, 7.4*, 9.1*, 9.4*, 10.1*, 10.6*, 11.1, 11.4, 14.3, 14.6

DOY denotes day of year.

*Days when the solar path was not occluded by clouds during the measurement period (termed "clear sky" conditions in the text).

system using un aspirated, unshielded thermocouples and a single cooled mirror dew point hygrometer [Tanner, 1988]. The area around Kendall has significantly rougher topography than the Lucky Hills site, resulting in less than adequate fetch conditions.

A meteorological and flux (METFLUX) station was erected at both sites to measure meteorological conditions and estimate the surface energy balance [Kustas et al., this issue (a)]. R_n and G were measured as described above, and H was measured with the variance method [Tillman, 1972] and the eddy correlation technique using a tower with a propeller anemometer and fine wire thermocouple [Amiro and Wuschke, 1987]. Although these two techniques are not as accurate as eddy correlation using a sonic anemometer [e.g., Wesely et al., 1970], the location of the METFLUX sites (along ridgetops) and the height of the METFLUX instruments (T_a at 4 and 9 m, U at 4.5 m and vertical wind speed (W) at 9 m) ensured spatially averaged turbulent energy flux values indicative of the surrounding terrain. LE was solved as a residual using the energy balance equation (equation (1)) and METFLUX values of R_n , G , and H .

The eddy correlation, Bowen ratio, and METFLUX data were acquired at 20-min intervals and averaged to hourly values to bracket the time of spectral data collection. This was necessary because a 20-min period was not adequate to take a representative sample of the energy-carrying eddies at the 9-m tower height. Tower estimates of H were multiplied by 1.1 to correct for the slow response time of the propeller anemometers as suggested by Moore [1987]. Blanford and Stannard [1991] found that hourly averages of H estimated

Table 2. Mean Absolute Difference (MAD) and Range of Data Presented in Figures 2–8

Figure	X	Y	n	MAD W/m ²	X Minimum	X Maximum
2a	R_n , ECBR	R_n , METFLUX	73	12.1	113	717
2b	G , ECBR	G , METFLUX	73	14.2	-25	228
2c	H , EC	H , METFLUX	31	32.5	12	375
2d	LE , EC	LE , METFLUX	31	20.6	20	390
3a, all	R_n , METFLUX	R_n , remote	73	56.9	115	670
3b, clear	R_n , METFLUX	R_n , remote	19	40.8	115	612
4a, all	G , METFLUX	G , remote	73	19.0	-13	213
4b, clear	G , METFLUX	G , remote	19	24.8	-13	213
5a, all	H , METFLUX	H , kB^{-1}	73	33.4	13	303
5a, all	H , METFLUX	H , r_{ss}	73	34.8	13	303
5b, clear	H , METFLUX	H , kB^{-1}	19	40.6	26	303
5b, clear	H , METFLUX	H , r_{ss}	19	36.9	26	303
6a, all	H , METFLUX	H , no adjustment	73	279.0	13	303
6b, clear	H , METFLUX	H , no adjustment	19	297.2	26	303
7a*, all	LE , METFLUX	LE , kB^{-1}	73	40.0	0	340
7a, all	LE , METFLUX	LE , r_{ss}	73	75.8	0	340
7b, clear	LE , METFLUX	LE , kB^{-1}	19	22.9	0	296
7b, clear	LE , METFLUX	LE , r_{ss}	19	52.5	0	296
8a*, all	LE , METFLUX	LE , kB^{-1}	73	33.4	0	340
8a, all	LE , METFLUX	LE , r_{ss}	73	34.8	0	340
8b, clear	LE , METFLUX	LE , kB^{-1}	19	40.6	0	296
8b, clear	LE , METFLUX	LE , r_{ss}	19	36.9	0	296

*In Figure 7, remote LE (Y axis) was computed using remote estimates of R_n , G , and H . In Figure 8, remote LE (Y axis) was computed using remote estimates of H and METFLUX measurements of R_n and G .

by the tower instruments agreed well with results from the eddy correlation system for a site with adequate fetch.

Comparison of METFLUX Data With Eddy Correlation and Bowen Ratio Outputs

The first step in the analysis was to determine the agreement between the eddy correlation (EC) and Bowen ratio (BR) data (referred to collectively as ECBR), and data acquired using the instruments of the METFLUX station. The mean absolute difference (MAD: the average of the absolute differences of corresponding data values) and the range was computed for R_n , G , H , and LE (Table 2).

For data collected at several times per day during the dry and monsoon seasons at the Lucky Hills and Kendall sites (Table 1), there was good agreement between the estimates of R_n at the ECBR stations and the METFLUX station, MAD = 12.1 W/m² (Figure 2a). There were significant differences at times between the ECBR and METFLUX values of R_n , probably due to differences in location of the instruments. Considering that these data were averaged over a 1-hour period during which the sky and surface conditions were highly variable, it was expected that R_n measurements at different locations would reflect this variability.

Measurements of G showed some scatter along the 1:1 line (Figure 2b); however, the MAD of ECBR and METFLUX data was only 14.2 W/m². Considering the likely spatial variation in G values and that ECBR and METFLUX values generally differed by less than 50 W/m² over a range from -25 to 228 W/m², the correlation was considered satisfactory.

Due to the rough terrain and limited fetch conditions at the

Kendall site and intermittent problems with the Bowen ratio equipment, it was deemed preferable to use the Lucky Hills data for evaluation of METFLUX H and LE values. The mean of the METFLUX "variance" and "tower" estimates of H tended to be slightly lower than the eddy correlation estimates at Lucky Hills (Figure 2c). However, as with the G values, the difference was generally less than 50 W/m², and the MAD was relatively small, 32.5 W/m². Since the variance and tower values were similar, means of the two values were computed and used for evaluation of residual LE . Comparison of eddy correlation LE and METFLUX LE showed similar agreement (Figure 2d), MAD = 20.6 W/m².

The differences in the METFLUX estimates and EC measurements of H and LE are due to several factors, including the fact that the instrumentation for determining H at the METFLUX sites is not as accurate as the EC instrumentation. Another factor is the height of the tower (≈ 9 m) and variance (≈ 4 m) measurements, compared to eddy correlation (≈ 2 m), resulting in the METFLUX site integrating over 4–20 times the area sampled by the eddy correlation system. In fact, H evaluated at the METFLUX site is influenced by conditions 500–1000 m upwind, whereas ECBR systems represent a 200–300 m upwind footprint. Based on this analysis, the METFLUX data were considered reliable, indicative of about 1 km upwind from the site, and suitable for use in evaluation of the remote energy balance method.

It should be emphasized that the comparison of latent and sensible heat flux densities measured by systems of different designs is inherently difficult due in part to differences in spatial and temporal measurement scales, instrument cali-

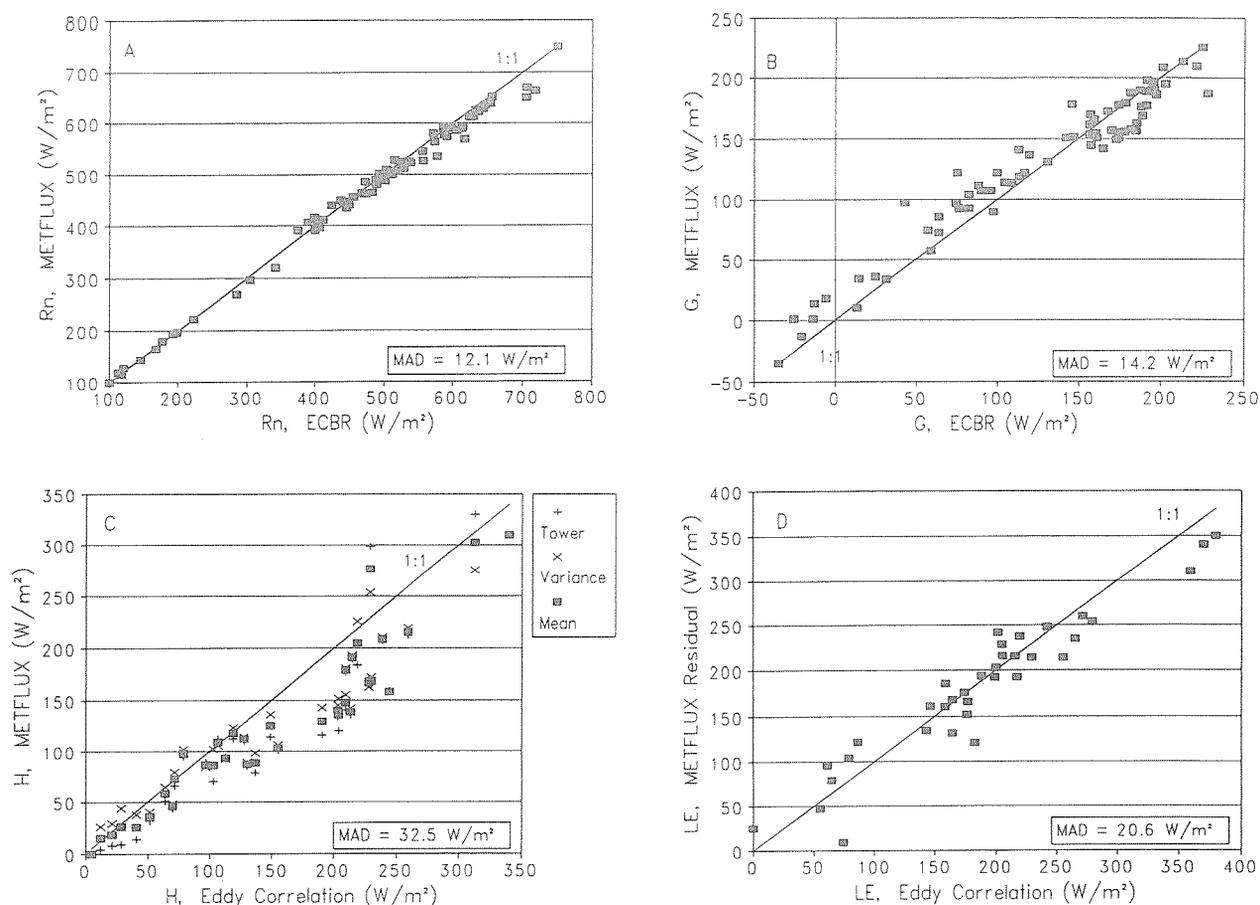


Figure 2. (a) Net radiant flux density (R_n), (b) soil heat flux density (G), (c) sensible heat flux density (H), and (d) latent heat flux density (LE), measured with the METFLUX instruments and compared with that measured using the eddy correlation and Bowen ratio (ECBR) instruments. The solid line represents the 1:1 relationship. Note that R_n and G were compared at both the Lucky Hills and Kendall sites, and H and LE were compared only at the Lucky Hills site using eddy correlation (EC) data. Results of statistical analysis for data in this and subsequent figures are presented in Table 2.

brations, sensor response times, and calculation algorithms. For example, *Dugas et al.* [1991] reported results from an experiment in which four Bowen ratio systems and three eddy correlation instruments were installed in a single wheat field over a 2-day period. They found that the average eddy correlation measurements of H and LE differed from the average values derived from Bowen ratio measurements by up to 31% and 33%, respectively. Thus, though differences in flux measurements appear large at times, they must be considered within the context of measurement scales and complexity.

Results and Discussion

The accuracy of the energy balance method proposed by *Jackson* [1985] for evaluation of R_n , G , H , and LE was assessed based on simultaneous measurements of spectral and meteorological data acquired at the Lucky Hills and Kendall sites in June, and late July and early August (Table 1). Data were acquired for a variety of atmospheric conditions, including occasions when the Sun was occluded from view. The following analysis presents results for the entire data set (termed "all days") and for a subset of the data that included only days and times when the solar path was

cloud-free (termed "clear sky"). This distinction was made because cloudy conditions can cause bias in measurements of surface temperature and, to a greater degree, surface reflectance factors.

Remote Estimation of R_n and G

Based on (2), values of R_n were computed using radiometric measurements of $R_{S\uparrow}$ and T_s , and hourly averages of $R_{S\downarrow}$, T_a , and e_0 . These "remote" estimates of R_n were compared with METFLUX measurements for all days at the Lucky Hills and Kendall sites (Figure 3a). Remote R_n values compared well with METFLUX R_n values for all days (MAD = 56.9 W/m² over the range from 115 to 670 W/m²) but tended to underestimate R_n for values greater than 550 W/m². There was an improvement when data were limited to only clear sky days, MAD = 40.8 W/m² (Figure 3b). This improvement could be due to the increased accuracy of $R_{S\uparrow}$ estimates during cloud-free conditions. It could also be due to the fact that the estimation of R_L using (3) is based on the assumption of clear skies [*Brutsaert*, 1975] and is not reliable for application during cloudy conditions.

The relation between G/R_n and ND (equation (4)) was originally derived from data collected during late morning and midday from an irrigated alfalfa field in central Arizona.

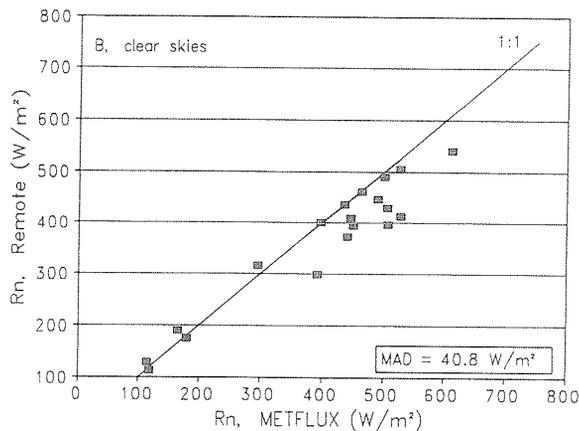
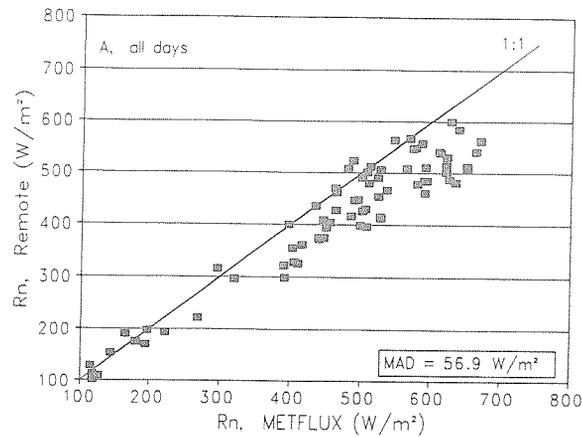


Figure 3. Net radiant flux density (R_n) estimated with the remote method and compared with results from the METFLUX measurements for (a) all days and for (b) clear sky conditions. The solid line represents the 1:1 relationship.

However, because G/R_n varies with time of day (the morning rise in G precedes that of R_n , and G declines more rapidly than R_n in the late afternoon), (4) tended to overestimate G in the early morning (Figure 4). However, for a wide range of meteorological conditions during midday, the remote G values correlated well with METFLUX values, though differences at times were large ($>50 \text{ W/m}^2$).

The limitation of (4) was particularly evident for instances in the early morning when METFLUX measurements of G were negative. There was no improvement in the correlation when the data set was limited to clear sky conditions (Figure 4b). This analysis indicated that (4) should be reevaluated as a function of both ND and time of day to account for the time lag between G and R_n and to allow for negative G values.

Remote Estimation of H

Values of H were computed with the kB^{-1} and r_{ss} methods (equations (13) and (18), respectively), using remotely sensed spectral data and hourly averages of T_a , e_0 , and U measured at the Lucky Hills and Kendall sites. For this analysis, s_{kb} was assumed to be 0.17 [from Kustas *et al.*, 1989] and the agronomic and meteorological parameters associated with each site are summarized in Table 3. The "remote" values of H were compared with the mean of the METFLUX variance and tower values for all days (Figure 5a) and for clear sky conditions (Figure 5b). Though there

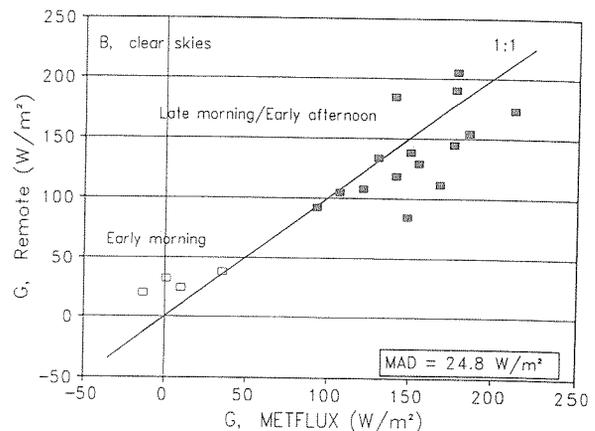
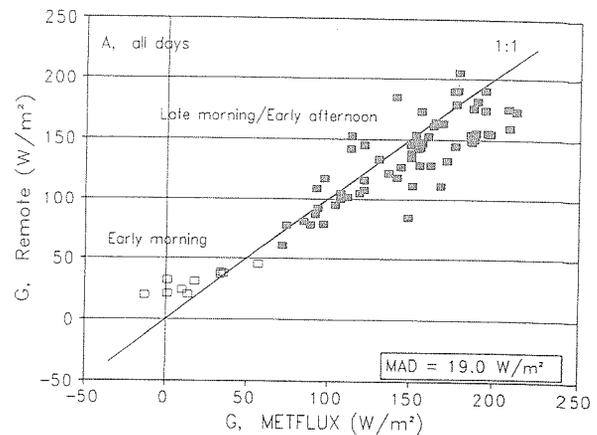


Figure 4. Soil heat flux density (G) estimated with the remote method and compared with results from the METFLUX measurements for (a) all days and for (b) clear sky conditions. The solid line represents the 1:1 relationship.

was considerable scatter about the 1:1 line, the MAD was relatively low in all cases ($<35 \text{ W/m}^2$).

Results using the kB^{-1} method tended to underestimate H over the entire range, possibly due to uncertainty in estimation of z_0 and d and the high sensitivity of (6) to those inputs. Though the values of z_0 and d listed in Table 3 were determined using standard methods [Kustas *et al.*, this issue (a)], the values differed slightly from those determined for the same sites using another approach described by Stannard *et al.* [this issue]. The value of s_{kb} in (13) was another source of uncertainty in this analysis. Assuming in (13) that $s_{kb} = 0.13$ [from Kustas *et al.*, this issue (b)] rather than $s_{kb} = 0.17$, H values were slightly increased, resulting in an overall decrease in the MAD from 33.4 to 30.9 W/m^2 .

The r_{ss} method resulted in overestimations of H in many cases, but generally followed the same trend and was of the same magnitude of the METFLUX data. In contrast, when the added resistance to heat transfer was not accounted for (assuming $kB^{-1} = 1.0$ in (6)), the difference between remote H and METFLUX H was striking; the MAD increased to more than 250 W/m^2 (Figures 6a and 6b). It is readily apparent that when using a single-layer model with radiometric estimates of T_s for sparse canopies, there must be some adjustment for excess resistance, especially at high $T_s - T_a$ values.

Table 3. Site Measurements and Assumptions Regarding Lucky Hills and Kendall Targets for Solution of (1)–(18)

	Kendall	Lucky Hills
<i>For Both Methods</i>		
Instrument height (z)	4.5 m	4.5 m
Emissivity (ϵ_s)*	0.96	0.96 (dry season)
Emissivity (ϵ_s)*	0.98	0.98 (monsoon season)
<i>For kB^{-1} Method</i>		
Roughness (z_0)†	0.01 m	0.04 m
Displacement (d)†	0.50 m	0.50 m
<i>For r_{ss} Method</i>		
LAI	0.5	0.5
r_0	10 s/m	10 s/m

*Surface emissivity was measured at each site using a method described by Humes *et al.* [this issue]. Emissivities for the dry and monsoon seasons were computed as an average of the emissivities of the soil and shrubs weighted by their percent cover at each site [Moran *et al.*, this issue].

†Roughness length and displacement height were estimated using standard methods described by Kustas *et al.* [this issue (a)].

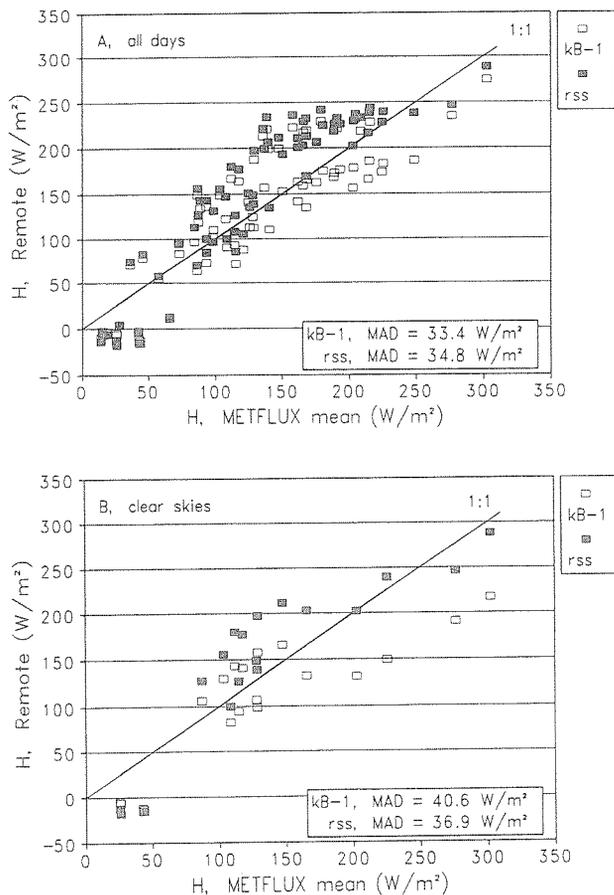


Figure 5. Sensible heat flux density (H) estimated with the remote method using the kB^{-1} and r_{ss} assumptions, and compared with results from the METFLUX station for (a) all days and (b) clear sky conditions. The solid line represents the 1:1 relationship.

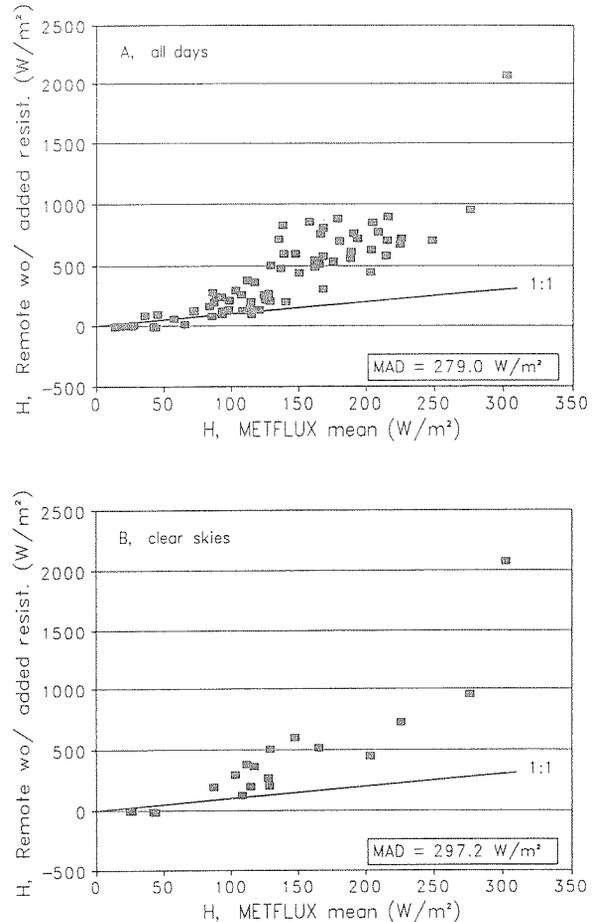


Figure 6. Sensible heat flux density (H) estimated with the remote method without accounting for additional resistance due to partial canopy conditions, and compared with results from the METFLUX station for (a) all days and for (b) clear sky conditions. Note the change in scale of the Y axis relative to that of Figure 5.

Remote Estimation of LE

Values of “remote” LE were computed based on solution of (1) and remote estimates of R_n and G using (2)–(4) and H using the kB^{-1} method (equation (13)) and the r_{ss} method (equation (18)). These values were compared with hourly averages of LE computed using METFLUX measurements of R_n , G , and H for all days and for clear sky conditions (Figure 7). The remote estimates of LE were of the same magnitude and trend as the METFLUX measurements of LE for all days, though the overall scatter was considerable (Figure 7a). The correlation was improved when data analysis was limited to clear sky conditions (MAD = 22.9 and 52.5 W/m^2 for the kB^{-1} and r_{ss} methods, respectively). With the exception of several outliers, the remote LE estimates for clear sky conditions tended to follow the 1:1 line.

Because LE is solved as a residual (equation (1)), there can be a cumulative effect of errors associated with remote estimates of R_n , G , and H . For example, consider the hypothetical case in which the remote measurement of surface temperature is erroneously high. For midday measurements at Walnut Gulch, a 2° overestimation of T_s would result in $\approx 20 W/m^2$ underestimation of R_n , $\approx 3 W/m^2$

underestimation of G , and $\approx 20 \text{ W/m}^2$ overestimation of H . Using (1), the resultant error in LE would be equal to 37 W/m^2 ; that is, the error in LE would be equal to the sum of the errors in R_n and H , offset by the error in G .

For a direct evaluation of the effect of application of the kB^{-1} and r_{ss} methods on estimation of LE , it is reasonable to evaluate LE using the 1-hour averages of R_n and G from the METFLUX stations and the remote estimates of H . When this value is compared with the METFLUX estimates of LE , any differences between the remote and METFLUX LE estimates are directly attributable to differences in the estimation of H . These data showed that acceptable values of LE for rangeland vegetation can be obtained ($\text{MAD} \approx 34 \text{ W/m}^2$) based on remote estimates of H , providing that an adjustment is made for the additional resistance associated with partial cover vegetation (Figure 8). The differences between remote and METFLUX data could be attributed to several sources, including the inaccuracy of the variance and tower data [Weaver, 1990; Blanford and Stannard, 1991], the unavoidable variation caused by 15-min versus 1-hour time integrations, and differences in the location and spatial integration of the instruments.

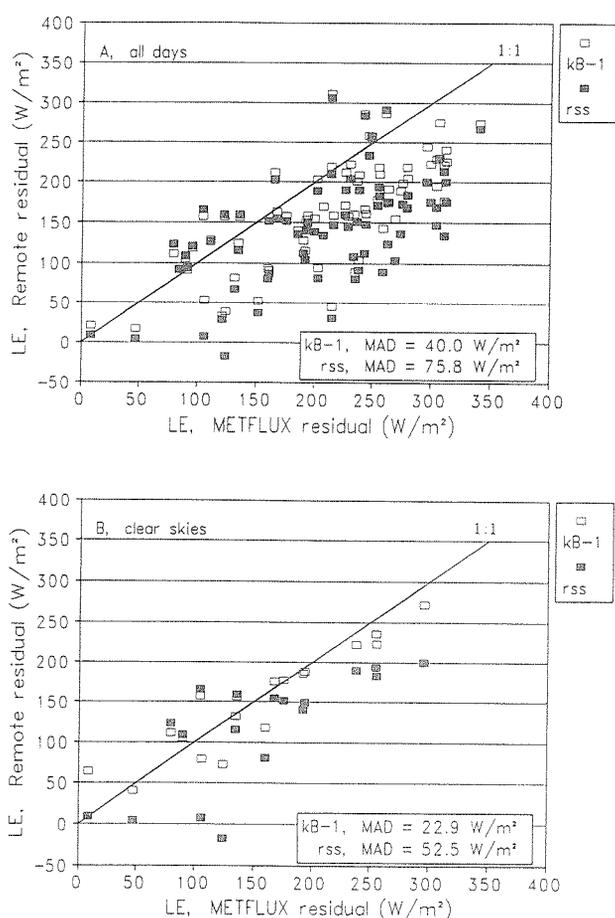


Figure 7. Residual latent heat flux density (LE) computed from remote estimates of R_n , G , and H using the kB^{-1} and r_{ss} assumptions for estimation of H , and compared with results from the METFLUX station for (a) all days and (b) clear sky conditions. The solid line represents the 1:1 relationship.

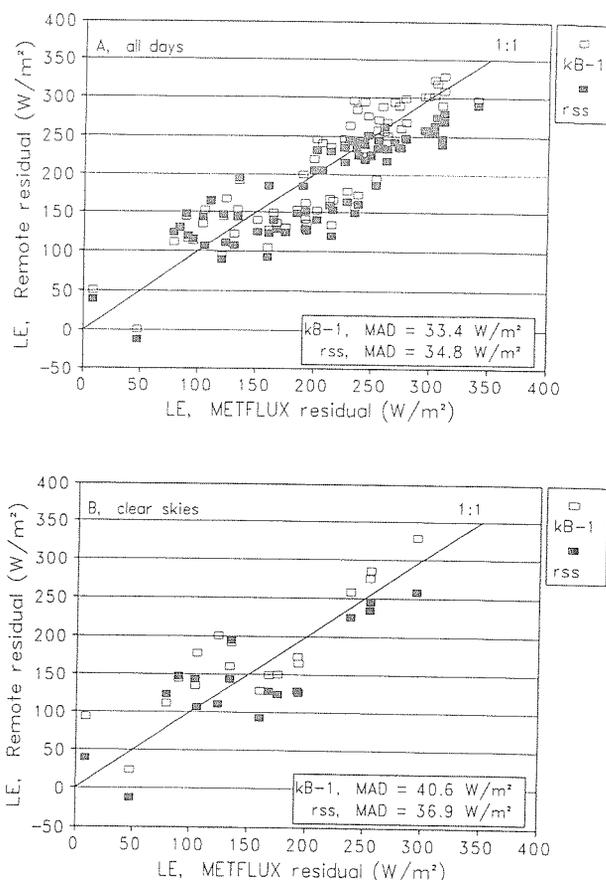


Figure 8. Residual latent heat flux density (LE) computed from remote estimates of H using the (a) kB^{-1} and (b) r_{ss} assumptions, and compared with LE from the METFLUX station. The Y axis differs from that of Figure 7 because METFLUX measurements of R_n and G were substituted for remote estimates of R_n and G in the computation of remote LE .

Concluding Remarks

A single-layer, one-dimensional energy balance method that relies on remote sensing and ancillary meteorological data for evaluation of latent heat flux density (LE) was applied to rangeland vegetation in southeast Arizona. The mean absolute difference (MAD) of remote estimates of R_n was 57 W/m^2 over a range from 115 to 670 W/m^2 . The empirical relation for estimation of G worked well for the observations taken in midday, but needs to be reevaluated for use in the early morning or late afternoon. The adjustments to the aerodynamic resistance using the kB^{-1} or r_{ss} method significantly improved estimates of H at Lucky Hills and Kendall, decreasing the MAD from nearly 300 to less than 35 W/m^2 . Remote estimates of LE were of the same magnitude and trend as ground-based measurements; however, differences with measured values of the order of 50 W/m^2 can be expected. This was in part due to the inaccuracies in the METFLUX data, the cumulative effect of errors associated with remote estimates of R_n , G , and H , and the spatial integration of R_n and G versus point measurements at the METFLUX stations. However, results confirmed that reasonable values of LE could be obtained for rangeland vegetation, based on remote estimates of H properly adjusted for the additional resistance associated with sparse

vegetation. Furthermore, the method was found to be reliable for use during both cloudy and clear sky conditions. It should be emphasized, however, that these results were obtained using data acquired mainly during the first half of the day; bias associated with the time of data acquisition may have influenced the conclusions of this analysis.

Future work will attempt to improve methods in estimating the three energy balance components, namely R_n , G , and H . This will involve improvements in evaluating the radiation balance, a reevaluation of the G/R_n relation for semiarid rangelands, and possible incorporation of soil and vegetation components for evaluating sensible heat flux [Kustas, 1990]. Once these changes have been tested and incorporated into the method, it will be used with aircraft- or satellite-based remote sensing data to provide spatially continuous maps of surface flux over the watershed. However, this next step will involve other issues such as how measurements of T_s vary with sensor spatial resolution, what area scales the estimated fluxes are representing, and the areal limitation of the remote method as determined by the height and spatial density of the meteorological data, particularly T_a and U [Kustas et al., 1991b]. Future work will also address the extrapolation of instantaneous LE to values of daily ET (millimeters per day) [Jackson et al., 1983], for practical application to rangeland, watershed and farm management.

Acknowledgments. The data reported here were taken from a larger data set acquired with support from the NASA Interdisciplinary Research Program in Earth Sciences (NASA reference number 1DP-88-086). Thanks are due to our outstanding field crew, led by Tom Clarke and including Bob Anderson, Ghani Chehbouni, Karen Humes, Jim Washburn, Skip Mueller, and Gao Xiasong. We also appreciate the cooperation and assistance of personnel at the USDA ARS Southwest Watershed Research Center, Tucson, and the USDA ARS Tombstone facility.

References

- Amiro, B. D., and E. E. Wuschke, Evapotranspiration from a boreal forest drainage basin using an energy balance/eddy correlation technique, *Boundary Layer Meteorol.*, **38**, 125–139, 1987.
- Beljaars, A. C. M., and A. A. M. Holtslag, Flux parameterization over land surfaces for atmospheric models, *J. Appl. Meteorol.*, **30**, 327–341, 1991.
- Blanford, J. H., and D. I. Stannard, Spatial variability of energy fluxes at Walnut Gulch, paper presented at special session on hydrometeorology, 10th Conference on Biometeorology and Aerobiology, Am. Meteorol. Soc., Salt Lake City, Utah, Sep. 10–13, 1991.
- Brutsaert, W. H., On a derivable formula for long-wave radiation from clear skies, *Water Resour. Res.*, **11**, 742–744, 1975.
- Brutsaert, W. H., *Evaporation Into the Atmosphere*, p. 299, D. Reidel, Norwell, Mass., 1982.
- Chamberlain, A. C., Transport of gases to and from surfaces with bluff and wave-like roughness elements, *Q. J. R. Meteorol. Soc.*, **94**, 318–332, 1968.
- Choudhury, B. J., R. J. Reginato, and S. B. Idso, An analysis of infrared temperature observations over wheat and calculation of the latent heat flux, *Agric. For. Meteorol.*, **37**, 75–88, 1986.
- Clothier, B. E., K. L. Clawson, P. J. Pinter, Jr., M. S. Moran, R. J. Reginato, and R. D. Jackson, Estimation of soil heat flux from net radiation during growth of alfalfa, *Agric. For. Meteorol.*, **37**, 319–329, 1986.
- Dugas, W. A., L. J. Fritschen, L. W. Gay, A. A. Held, A. D. Matthias, D. C. Reicosky, P. Steduto, and J. L. Steiner, Bowen ratio, eddy correlation and portable chamber measurements of sensible and latent heat flux over irrigated spring wheat, *Agric. For. Meteorol.*, **56**, 1–20, 1991.
- Garratt, J. R., and B. B. Hicks, Momentum, heat and water vapour transfer to and from natural and artificial surfaces, *Q. J. R. Meteorol. Soc.*, **99**, 680–687, 1973.
- Humes, K. S., W. P. Kustas, M. S. Moran, W. D. Nichols, and M. A. Wetz, Variability of emissivity and surface temperature over a sparsely vegetated surface, *Water Resour. Res.*, this issue.
- Jackson, R. D., Total reflected solar radiation calculated from multi-band sensor data, *Agric. For. Meteorol.*, **33**, 163–175, 1984.
- Jackson, R. D., Evaluating evapotranspiration at local and regional scales, *Proc. IEEE*, **73**, 1086–1096, 1985.
- Jackson, R. D., J. L. Hatfield, R. J. Reginato, S. B. Idso, and P. J. Pinter, Jr., Estimation of daily evapotranspiration from one time-of-day measurements, *Agric. Water Manage.*, **7**, 351–362, 1983.
- Jackson, R. D., P. J. Pinter, Jr., and R. J. Reginato, Net radiation calculated from remote multispectral and ground station meteorological data, *Agric. For. Meteorol.*, **35**, 153–164, 1985.
- Jackson, R. D., M. S. Moran, L. W. Gay, and L. H. Raymond, Evaluating evaporation from field crops using airborne radiometry and ground-based meteorological data, *Irrig. Sci.*, **8**, 81–90, 1987a.
- Jackson, R. D., M. S. Moran, P. N. Slater, and S. F. Biggar, Field calibration of reference reflectance panels, *Remote Sens. Environ.*, **22**, 145–158, 1987b.
- Kustas, W. P., Estimates of evapotranspiration with a one- and two-layer model of heat transfer over partial canopy cover, *J. Appl. Meteorol.*, **29**, 704–715, 1990.
- Kustas, W. P., and C. S. T. Daughtry, Estimation of the soil heat flux/net radiation ratio from spectral data, *Agric. For. Meteorol.*, **49**, 205–223, 1990.
- Kustas, W. P., B. J. Choudhury, M. S. Moran, R. J. Reginato, R. D. Jackson, L. W. Gay, and H. L. Weaver, Determination of sensible heat flux over sparse canopy using thermal infrared data, *Agric. For. Meteorol.*, **44**, 197–216, 1989.
- Kustas, W. P., B. J. Choudhury, Y. Inoue, P. J. Pinter, Jr., M. S. Moran, R. D. Jackson, and R. J. Reginato, Ground and aircraft infrared observations over a partially-vegetated area, *Int. J. Remote Sens.*, **11**, 409–427, 1990.
- Kustas, W. P., et al., An interdisciplinary field study of the energy and water fluxes in the atmosphere-biosphere system over semiarid rangelands: Description and some preliminary results, *Bull. Am. Meteorol. Soc.*, **72**, 1683–1706, 1991a.
- Kustas, W. P., M. S. Moran, P. J. Pinter, Jr., L. E. Hipps, E. Swiatek, D. I. Stannard, and J. H. Blanford, Issues in mapping evapotranspiration over large areas with remote sensing data from Monsoon 90, paper presented at special session on hydrometeorology, 10th Conference on Biometeorology and Aerobiology, Salt Lake City, Utah, Sept. 10–13, 1991b.
- Kustas, W. P., J. H. Blanford, D. I. Stannard, C. S. T. Daughtry, W. D. Nichols, and M. A. Wetz, Local energy flux estimates for unstable conditions using variance data in semiarid rangelands, *Water Resour. Res.*, this issue (a).
- Kustas, W. P., M. S. Moran, K. S. Humes, D. I. Stannard, P. J. Pinter, Jr., L. E. Hipps, E. Swiatek, and D. C. Goodrich, Surface energy balance estimates at local and regional scales using optical remote sensing from an aircraft platform and atmospheric data collected over semiarid rangelands, *Water Resour. Res.*, this issue (b).
- Mahrt, L., and M. Ek, The influence of atmospheric stability on potential evaporation, *J. Clim. Appl. Meteorol.*, **23**, 222–234, 1984.
- Monin, A. S., and A. M. Obukhov, Basic laws of turbulent mixing in the ground layer of the atmosphere, *Tr. Geofiz. Inst. Akad. Nauk SSSR*, no. 24, 163–187, 1954.
- Moore, C. J., Frequency response corrections for eddy correlation systems, *Boundary Layer Meteorol.*, **37**, 17–35, 1987.
- Moran, M. S., and R. D. Jackson, Assessing the spatial distribution of evapotranspiration using remotely sensed inputs, *J. Environ. Qual.*, **20**, 725–737, 1991.
- Moran, M. S., R. D. Jackson, L. H. Raymond, L. W. Gay, and P. N. Slater, Mapping surface energy balance components by combining Landsat thematic mapper and ground-based meteorological data, *Remote Sens. Environ.*, **30**, 77–87, 1990.
- Moran, M. S., T. R. Clarke, W. P. Kustas, M. A. Wetz, and S. A. Amer, Evaluation of hydrologic parameters in a semiarid range-

- land using remotely sensed spectral data, *Water Resour. Res.*, this issue.
- Obukhov, A. M., Turbulence in an atmosphere with non-uniform temperature, *Tr. Inst. Teor. Geofiz. Akad. Nauk SSSR*, no. 1, 1946. (English transl., *Boundary Layer Meteorol.*, 2, 7-29, 1971.)
- Perrier, A., Etude physique de l'évapotranspiration dans les conditions naturelles, I, Evaporation et bilan d'énergie des surfaces naturelles, *Ann. Agron.*, 26, 1-18, 1975.
- Perrier, A., Land surface processes: Vegetation, in *Land Surface Processes in Atmosphere General Circulation Models*, edited by P. S. Eagleson, pp. 395-448, Cambridge University Press, New York, 1982.
- Reginato, R. J., R. D. Jackson, and P. J. Pinter, Jr., Evapotranspiration calculated from remote multispectral and ground station meteorological data, *Remote Sens. Environ.*, 18, 75-89, 1985.
- Richardson, L. F., The supply of energy from and to atmospheric eddies, *Proc. R. Soc. London, Ser. A*, 97, 354-373, 1920.
- Schmugge, T. J., T. J. Jackson, W. P. Kustas, R. Roberts, R. Parry, D. C. Goodrich, S. A. Amer, and M. A. Weltz, Push broom microwave radiometer observations of surface soil moisture in Monsoon '90, *Water Resour. Res.*, this issue.
- Slater, P. N., S. F. Biggar, R. G. Holm, R. D. Jackson, Y. Mao, M. S. Moran, J. M. Palmer, and B. Yuan, Reflectance- and radiance-based methods for the in-flight absolute calibration of multispectral sensors, *Remote Sens. Environ.*, 22, 11-37, 1987.
- Spittlehouse, D. L., and T. A. Black, Evaluation of the Bowen ratio/energy balance method for determining forest evapotranspiration, *Atmos. Oceans*, 18, 98-116, 1980.
- Stannard, D. I., J. H. Blanford, W. P. Kustas, W. D. Nichols, S. A. Amer, T. J. Schmugge, and M. A. Weltz, Characteristic spatial and temporal surface-flux scales in semiarid rangeland, *Water Resour. Res.*, this issue.
- Tanner, B. D., Use requirements for Bowen ratio and eddy correlation determination of evapotranspiration, in *Planning Now for Irrigation and Drainage in the 21st Century*, edited by R. H. DeLynn, pp. 605-616, Irrigation and Drainage Division, American Society of Civil Engineers, New York, 1988.
- Tillman, J. E., The indirect determination of stability, heat and momentum fluxes in the atmospheric boundary layer from simple scalar variables during dry unstable conditions, *J. Appl. Meteorol.*, 11, 783-792, 1972.
- Vidal, A., and A. Perrier, Analysis of a simplified relation used to estimate daily evapotranspiration from satellite thermal data, *Int. J. Remote Sens.*, 10, 1327-1337, 1989.
- Weaver, H. L., Temperature and humidity-variance relations determined by one-dimensional eddy correlation, *Boundary Layer Meteorol.*, 44, 13-31, 1990.
- Wesely, M. L., G. W. Thurtell, and C. B. Tanner, Eddy correlation measurements of sensible heat flux near the Earth's surface, *J. Appl. Meteorol.*, 9, 45-50, 1970.
- J. H. Blanford, School of Renewable Natural Resources, University of Arizona, 325 Bio Science East, Tucson, AZ 85721.
- W. P. Kustas, USDA Agricultural Research Service, Hydrology Laboratory, BARC-East, Beltsville, MD 20705.
- M. S. Moran, USDA Agricultural Research Service, U.S. Water Conservation Laboratory, 4331 E. Broadway, Phoenix, AZ 85040.
- W. D. Nichols, U.S. Geological Survey, Water Resources Division, Room 229, Federal Building, 705 Plaza Street, Carson City, NV 85701.
- D. I. Stannard, U.S. Geological Survey, Water Resources Division, Box 25046, Mail Stop 413, Denver, CO 80225.
- A. Vidal, CEMAGREF-ENGREF Remote Sensing Laboratory, 361 Rue J. F. Breton, Boite Postale 5095, F-34033 Montpellier, France.

(Received August 13, 1992; revised April 18, 1993; accepted October 19, 1993.)

