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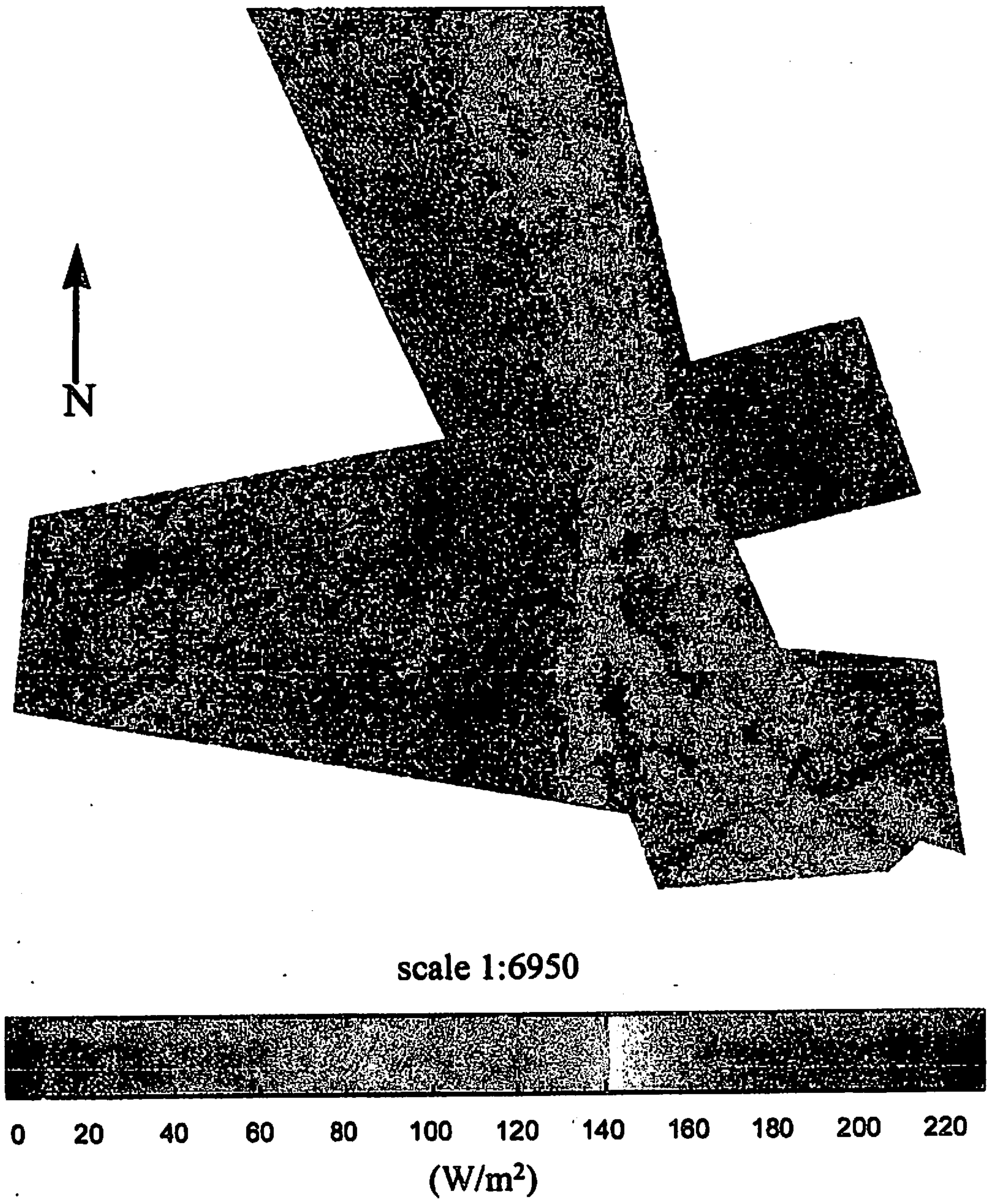

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EVALUATION OF MULTIPLE FLUX MEASUREMENT TECHNIQUES USING WATER BALANCE INFORMATION AT A SEMI-ARID SITE

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1. ABSTRACT

A month-long field experiment was performed at the Lucky Hills Metflux site in the Walnut Gulch Experimental Watershed during the 1996 summer rainy season to evaluate multiple surface water and energy flux measurement techniques using detailed water balance information. Five different surface flux instruments were deployed between July 14 and August 21, 1996. These instruments included a propeller eddy covariance system, a sonic anemometer and infrared gas analyzer based eddy covariance system, a infrared gas analyzer based Bowen ratio system, and two temperature variance systems. The water balance was computed using precipitation measured in 7 nearby rain gauges, flume measured subcatchment runoff, and root zone soil moisture measured using Time-Domain Reflectometry (TDR). Based on the water balance, most of the surface water and energy flux measurement instruments overestimated the evapotranspiration, and there was significant inter-instrument variation. Some of the observed differences may be due to fetch heterogeneity or instrument limitations, however there may also be issues regarding the application of these instruments and their associated measurement theory in this environment.

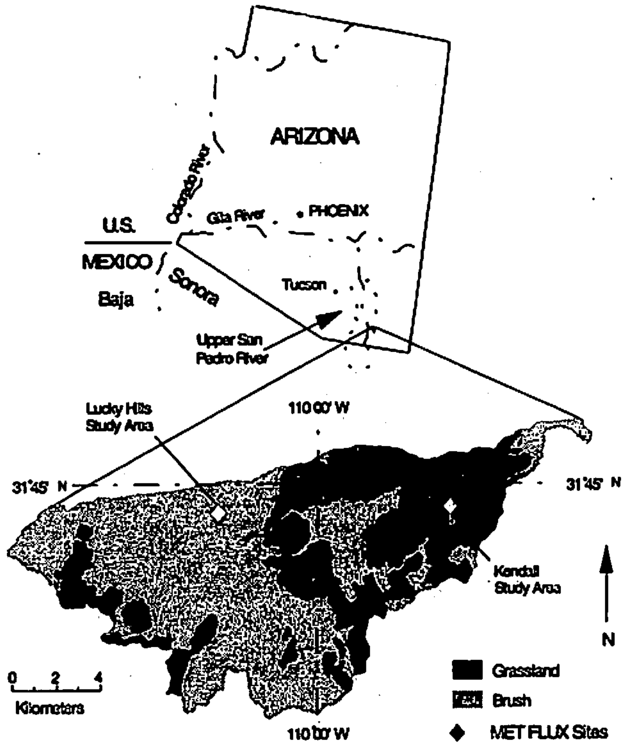

Figure 1: The USDA-ARS Walnut Gulch Experimental Watershed. [Kustas and Goodrich, 1994].

2. SITE DESCRIPTION AND OBSERVATIONS

2.1 LUCKY HILLS, WALNUT GULCH

The Walnut Gulch Experimental Watershed (31° 43' N, 110° 41' W), near Tombstone, Arizona is operated by the Southwest Watershed Research Center (SWRC), Agriculture Research Service (ARS), U. S. Department of Agriculture (USDA). The catchment is an instrumented (85 recording rain gauges, 30 runoff stations, and 2 weather and energy flux stations) area comprising the upper 148 km^2 of the Walnut Gulch drainage basin (Figure 1) [Renard *et al.*, 1993]. The Lucky Hills meteorological-energy flux (Metflux) site is located in the brush-dominated 1.46 ha, LH-102 subwatershed characterized by 26% shrub vegetation cover and a sandy loam soil with 28% rock content (Figure 2) [Stannard *et al.*, 1994].

2.2 STANDARD SURFACE METEOROLOGY OBSERVATIONS

The Lucky Hills Metflux site has been instrumented by the ARS since 1990 to provide continuous measurement of local meteorological conditions and the surface energy-balance. Standard measurements include soil moisture, soil temperature, surface temperature, relative humidity, incoming solar radiation, net radiation, wind speed and direction, and soil heat flux [Stannard *et al.*, 1994].

During the 1996 rainy season, standard surface meteorological measurements were also made by a second weather station. Duplicate measurements were found to agree within a few percent (with the exception of soil heat flux which exhibited large spatial variations), so average values were computed for subsequent use. Diurnal average (the average diurnal pattern produced by averaging values for a particular time of day) values of solar forcing and available energy for

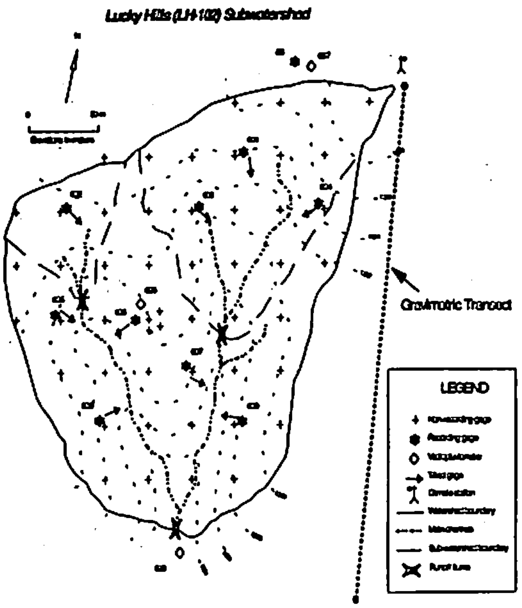

Figure 2: Lucky Hills subwatershed and position of soil moisture transect in relation to Lucky Hills measurements.

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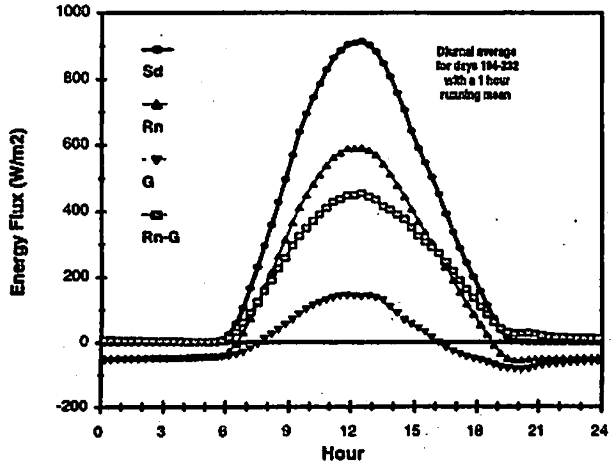

Figure 3: Diurnal average incident solar radiation, S_d, net radiation, R_n, soil heat flux, G, and available energy, R_n-G.

this 38 day study (Day of Year (DOY) 194-232) are shown in Figure 3.

2.3 PRECIPITATION

In semi-arid areas the timing and distribution of precipitation has a large impact on surface-atmosphere interaction. Five weighing raingauges are located nearby the Lucky Hills Metflux site (Figure 2). Two tipping bucket raingauges were deployed during the 1996 rainy season. The 38 day totals for these 7 gauges varied by approximately 5%, so an average was used for water balance calculations. The average tipping bucket rainfall is shown in Figure 4.

2.4 RUNOFF

The volume of runoff in Walnut Gulch (148 km^2) is small in comparison with the rainfall (3-4% of the rainfall) [Osborn and Lane, 1984], but is often between 10 and 20 percent for small upland watersheds like LH-102, and there is no groundwater contribution to surface flows [Renard *et al.*, 1993]. Subsequent evaporation of the water absorbed by transmission loss from the coarse alluvium and by transpiration from riparian vegetation greatly limits groundwater recharge (Renard, 1969). The runoff measured by the fixed cross-section, critical depth, runoff measuring flume at the Lucky Hills subwatershed is shown in Figure 4.

2.5 SOIL MOISTURE

During the 1996 rainy season soil moisture was monitored with surface gravimetric samples, profile TDR observations, and a near-surface Campbell Scientific Inc. Watermark probe (Figure 4).

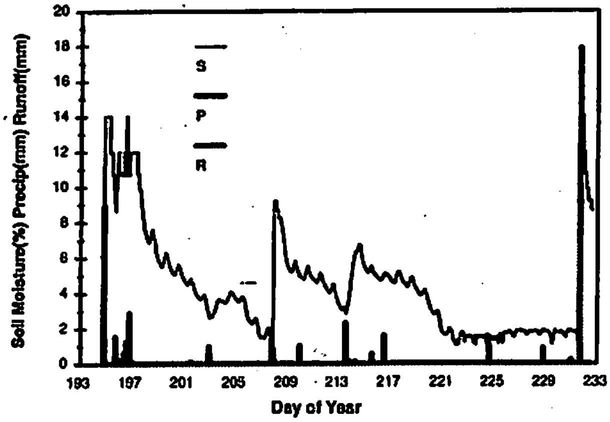

Figure 4: Average tipping bucket precipitation (P), runoff (R), and 5 cm soil moisture (S).

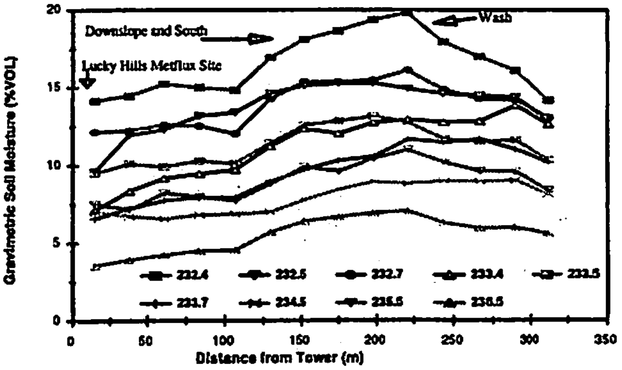

Figure 5: Downslope increase in soil moisture. Transect points measured at the same time are connected by a line. Time is given in DOY (232.5 is noon on DOY 232).

An intensive campaign to monitor a soil moisture dry down event between DOY 232 and 236 resulted in multiple daily gravimetric and TDR soil moisture observations. A 300 m downslope gravimetric transect sampled every 2 m was also measured to assess the soil moisture variability in the micrometeorological instrument fetch (Figure 5). The fetch length was estimated to be 565 to 870 m following Stannard *et al.*, [1994].

2.6 SURFACE WATER AND ENERGY FLUXES

Accurate partitioning of available energy at the surface into sensible and latent heat fluxes is crucial to understanding the interaction between the hydrological cycle and climate processes. However, estimating the sensible and latent heat fluxes requires sometimes difficult micrometeorological measurements and the determination of moisture and plant parameters.

The Lucky Hills ARS Metflux station determines the energy-balance from measurements of net radiation, R_n, soil heat flux, G, and estimates of sensible heat flux, H by either eddy covariance (*ECprop*) or temperature variance (*Tvar*) methods. The *ECprop* measurement of H was calculated from air temperature, T, and vertical wind speed, w, sampled at 4 Hz and at a height of 9 m with a 76.2 µm diameter thermocouple and a Styrofoam propeller respectively. The flux was calculated by:

$$H_m = -\rho C_p \overline{w'T'} \qquad (1)$$

where ρ is air density, C_p is the specific heat of air, bars denote 20 minute means, and primes denote 20 minute deviations [Stannard *et*

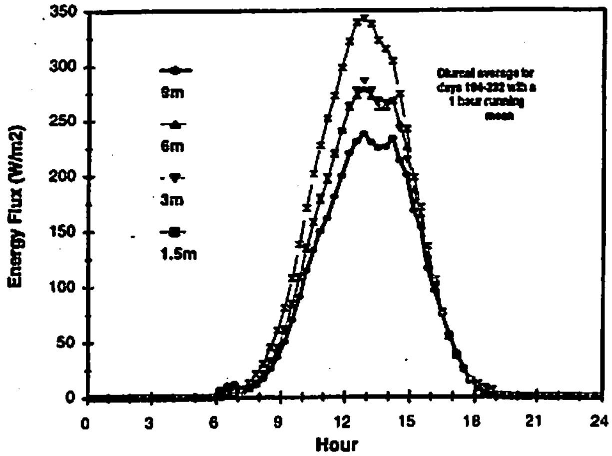

Figure 6: Diurnal average *SigT* sensible heat measurements for DOY 194 to 232 at 9, 6, 3, and 1.5 m.

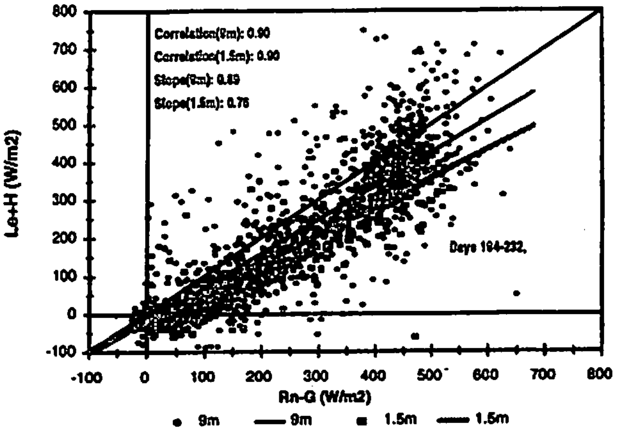

Figure 7: Energy balance for 20 minute *ECsonic H* and L_e fluxes, with linear fits for measurements at 9 and 1.5 m.

al., 1994].

The *Tvar* measurement of *H* was calculated using temperature variance measurements made at 9 and 4 m in an iterative loop method based on Monin Obukhov similarity theory applied to second-order turbulent statistics [Kustas *et al.*, 1994]. Kustas reported that in unstable conditions, estimates of *H* and L_e obtained by the variance method were within 20% of eddy covariance measurements which they considered to be satisfactory.

Sigma-T (*SigT*) observations of *H* were made using 76 μm diameter fine-wire thermocouples at heights of 9, 6, 3, and 1.5 m. The standard deviation relative to a running mean and the arithmetic average of air temperature sampled at 10 Hz were recorded at 20-minute intervals. *H* was computed for unstable, rain-free conditions using a simple procedure [Tillman, 1972]. Diurnal averages of multi-height *SigT* measurements of *H* are shown in Figure 6.

The Bowen ratio-energy balance method (*BRlicor*) measures *H* and L_e based on the infrared gas analyzer measured difference in vapor pressure, *de*, and thermocouple measured difference in potential temperature, *dT*, between two levels above the ground. This allows for estimation of *β*, the Bowen ratio:

$$\beta=\left(\frac{c_p p}{\varepsilon\lambda}\right)\left(\frac{dT}{de}\right) \qquad (2)$$

where *p* is atmospheric pressure, c_p is the specific heat of air, λ is the latent heat of vaporization, and ϵ is the ratio of molecular weight of water to air. Combining the definition of the Bowen ratio with the energy-balance gives:

$$L_e=\frac{(R_n-G)}{(1+\beta)} \qquad (3)$$

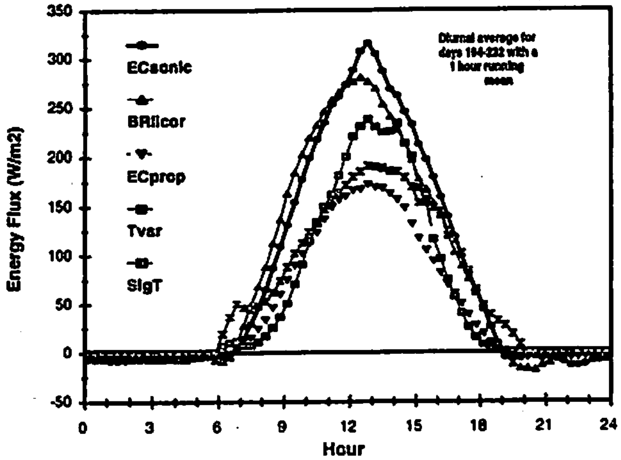

Figure 8: Diurnal average sensible heat flux.

If energy-balance closure is assumed for the *Tvar*, *SigT*, and *ECprop* methods, and R_n-*G* is measured independently, the latent heat flux L_e is solved as a residual, thus:

$$L_e=(R_n-G-H) \qquad (4)$$

Here, fluxes away from the surface are negative, while fluxes towards the surface are positive. For *BRlicor*, L_e is known, and *H* is found using Equation 4.

Eddy covariance (*ECsonic*) observations of *H*, and L_e were made using a 3-axis ultrasonic anemometer and closed-path infrared gas analyzer that measured variations in wind speed and H2O concentration at 20 Hz [Unland *et al.*, 1996]. Fluxes were computed as in Equation 1, with some additional pre-processing to correct for air ducting. Since H and L_e are measured independently, energy balance closure is not assumed, and therefore provides a valuable assessment of system operation (Figure 7). To investigate the effect of measurement height, the *ECsonic* was moved from 9 to 1.5 m on day 225.

The diurnal averages for *H* and L_e from DOY 194 to 232 for the 5 independent surface flux measurements are shown in Figures 8 and 9. Only the highest measurement from each instrument type was used in this comparison.

3.0 WATER BALANCE

Watershed water balance information is critical for understanding hydrologic processes, and is valuable as a independent verification of flux observations. The water balance can be summarized as:

$$P-R-E-D=\Delta S \qquad (5)$$

where *P* is *precipitation*, *R* is runoff, *E* is evapotranspiration, *D* is deep drainage to groundwater, and *ΔS* is change in soil water storage. For small watersheds on an annual basis, *D* and *ΔS* are very small (Renard *et al.*, 1993).

A water balance was computed for Lucky Hills from DOY 194 to 232, 1996 (Table 1). The total precipitation and runoff were derived from the observations described above were 92 and 14 mm, respectively. The change in moisture storage calculated as the depth-interval weighted average of the TDR measurements on DOY 194 and 232 corresponded to a loss of 4 mm when expressed in depth-of-water terms. Neglecting any unobserved changes in soil moisture from greater depths that may have occurred due to deep root

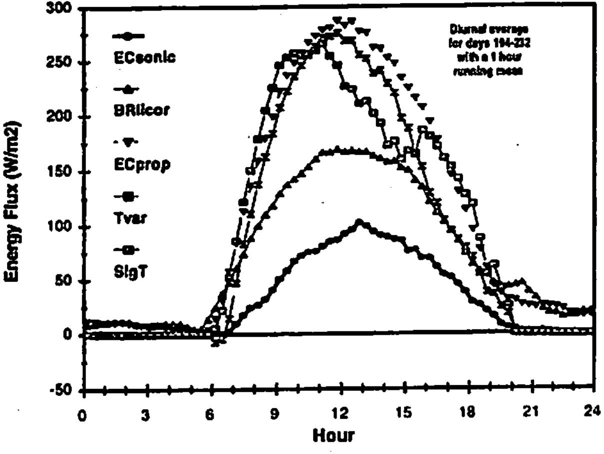

Figure 9: Diurnal average latent heat flux.

Table 1: Lucky Hills evapotranspiration (*E*) for DOY 194 to 232, 1996. The water balance gives a net evapotranspiration of 76 mm.

Measurement System	Daytime *E* (mm)	Nighttime *E* (mm)	Whole-Day *E* (mm)
ECsonic (9m)	41	1	42
BRlicor (2m)	81	15	96
ECprop (9m)	134	14	148
Tvar (9m)	115	—	—
Tvar (4m)	108	—	—
SigT (9m)	119	—	—
SigT (6m)	109	—	—
SigT (3m)	109	—	—
SigT (1.5m)	93	—	—

extraction, these figures suggest that the total loss of water as evaporation over this 38 day period was 76 mm. For the purposes of comparison, the integrated value of the measured evaporation given by the several micrometeorological systems was calculated for each instrument and height. To reduce bias, interpolation were used during several short periods when there was missing data. In the case of the *Tvar* and *SigT*, the measurements are only valid in unstable daytime conditions.

3. DISCUSSIONS

During the 1996 rainy season at Lucky Hills, the available energy, $(R_n\text{-}G)$, reached an average daily maximum of about 500 W/m^2. At night some energy initially leaves the surface as latent and sensible heat, but there is then an approximate balance between net radiation and soil heat flux (Figure 3). The energy balance closure given with the *ECsonic* (Figure 7) is on average reasonably good -- the sum of latent and sensible heat agree with the available energy to within about 10% -- but it is not outstanding, and there is some evidence that the measured energy balance closure changes slightly with observation height.

The agreement between individual instrumental systems is very poor (Figures 8, 9) with differences between the instruments as large as 300%. In terms of sensible heat, the instruments fall into two groups, with the *BRlicor* and *ECsonic* measurements falling in one group and the *Tvar*, *SigT* and *ECprop* measurements falling in the other group. The discrepancies for latent heat flux are greater than for sensible heat flux with the *ECsonic* value less than the *BRlicor* value and the other systems much higher. This amplification of errors may be because latent heat is a small component of the energy balance in semi-arid regions and some of the instrumental systems deduce its value as a residual between large terms in the energy balance. In this case, small percentage errors in the larger energy flux terms combine to give a larger percentage error in the residual latent heat flux.

At this writing, the origin of the discrepancy between measurements made with different instrumental systems is not clear. However, there is some evidence of a height dependency in the *SigT*, *Tvar*, and *ECsonic* observations and it is possible that this provides part of the explanation. The *SigT* observations of sensible heat varied by as much as 30% and, as mentioned above, the energy balance closure given by *ECsonic* also has some height dependence. It is relevant that a comparison of sensible and latent heat fluxes measured at 2 and 9 m during Monsoon '90 [Kustas and Goodrich, 1994] showed that the measured ratio of sensible to latent heat, the Bowen ratio, decreased with height. In that case, a one-dimensional diffusion model was used to demonstrate that measurements made at 2 m (with eddy covariance and a gradient measuring system) were sampling drier, less vegetated ridge tops, whereas the measurements made at 9 m (with an eddy covariance system) was sampling more of the vegetated ephemeral streams. In fact, an increase in soil moisture downslope from the tower was observed in the soil moisture transects made in the present study (Figure 5). It is possible that this systematic decrease in Bowen ratio with height could be very significant in the case of *BRlicor* observations reported here because the areas contributing to the measurements at the two sampling heights differ greatly, especially at night.

In principle, the water balance calculations should help evaluate the relative reliability of the micrometeorological measurements. Table 1 shows the integrated evaporation estimates made with the several systems for daytime, nighttime and all day conditions.

The water balance estimate of evaporation may well be biased low if plant roots access moisture from depth, if precipitation is underestimated due to interference by wind and splash out, and the possible conversion of runoff into soil moisture through downslope reinfiltration or channel loss. The combination of these effects may result in the a systematic underestimate of no more than 1 mm/day. Such an underestimation in the water balance might explain the difference between the water balance estimate (76 mm) and the measurement of evaporation given by the *BRlicor* or the 1.5 m *Tvar*. However, it is hard to believe that the water balance could be in error by 100%, which would be required to explain the results obtained with the other instrumental systems.

Some of the explanation may lie in the height dependency of the measurements described above. Stalling of the propeller at night, which can result in unmeasured sensible heat and an over estimated latent heat may explain why the *ECprop* measurement has the largest overestimate. Similarly, a suspect infrared gas analyzer water vapor calibration is the probable cause of the *ECsonic* underestimate of the energy and water balance. Nonetheless, there are clearly significant issues still to be resolved regarding the accuracy and applicability of some types of micrometerological flux measuring systems when applied in semi-arid environments.

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