#1028

WATER RESOURCES RESEARCH, VOL. 30, NO. 5, PAGES 1351–1361, MAY 1994

Local energy flux estimates for unstable conditions using variance data in semiarid rangelands

W. P. Kustas,[1] J. H. Blanford,[2] D. I. Stannard,[3] C. S. T. Daughtry,[4] W. D. Nichols,[5] and M. A. Weltz[6]

Abstract. A network of meteorological stations was installed during the Monsoon '90 field campaign in the Walnut Gulch experimental watershed. The study area has a fairly complex surface. The vegetation cover is heterogeneous and sparse, and the terrain is mildly hilly, but dissected by ephemeral channels. Besides measurement of some of the standard weather data such as wind speed, air temperature, and solar radiation, these sites also contained instruments for estimating the local surface energy balance. The approach utilized measurements of net radiation (R_n), soil heat flux (G) and Monin-Obukhov similarity theory applied to first- and second-order turbulent statistics of wind speed and temperature for determining the sensible heat flux (H). The latent heat flux (LE) was solved as a residual in the surface energy balance equation, namely, $LE = -(R_n + G + H)$. This procedure (VAR-RESID) for estimating the energy fluxes satisfied monetary constraints and the requirement for low maintenance and continued operation through the harsh environmental conditions experienced in semiarid regions. Comparison of energy fluxes using this approach with more traditional eddy correlation techniques showed differences were within 20% under unstable conditions. Similar variability in flux estimates over the study area was present in the eddy correlation data. Hence, estimates of H and LE using the VAR-RESID approach under unstable conditions were considered satisfactory. Also, with second-order statistics of vertical velocity collected at several sites, the local momentum roughness length was estimated. This is an important parameter used in modeling the turbulent transfer of momentum and sensible heat fluxes across the surface-atmosphere interface.

Introduction

For hydrologists, estimating evapotranspiration (ET) is of great importance since at catchment and regional scales ET is one of the main driving fluxes (precipitation being the other) of the hydrologic cycle. However, one of the main difficulties faced in developing regional scale ET models is evaluating model output with ground truth observations. This has led to the organization of large-scale field experiments having a network of ground truth measurements for validating model output. The studies have taken place in different climatic regimes and ecosystems. For a recent review of experiments, see *Shuttleworth* [1991].

In the Monsoon '90 study, a network of meteorological energy flux (METFLUX) stations was designed to provide ground truth estimates of local and regional scale energy fluxes in a semiarid rangeland watershed for testing and calibrating energy and water balance models [*Kustas et al.*, 1991]. The surface energy balance was determined by the METFLUX network which utilized an indirect approach (called the variance method) for estimating the sensible heat flux, H [e.g., *Wesely*, 1988]. This involved the measurement of the standard deviation in air temperature, σ_T, and an estimate of the friction velocity, u_* (see below).

Compared to instrumentation for eddy correlation and Bowen ratio techniques used in the experiment [*Stannard et al.*, this issue], this system is inexpensive and rugged, requiring little maintenance. This allowed for the continuous operation at eight locations covering a significant portion of the watershed (see Figure 1) and under a wide range of environmental conditions experienced during the field campaign. Such a measurement network would not have been feasible with available funds if commercially available eddy correlation and Bowen ratio systems were used.

Measurements of net radiation, R_n, and soil heat flux, G, were combined with the estimates of H to solve for LE as a residual in the surface energy balance equation, i.e.,

$$LE = -(R_n + G + H) \tag{1}$$

In (1) the units are watts per square meter with fluxes toward the surface assigned a positive value and fluxes away from the surface being negative. At selected sites, measurements of the standard deviation in vertical velocity, σ_w, with the mean wind speed in the surface layer were used to determine

[1]Hydrology Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Beltsville, Maryland.
[2]Institute of Atmospheric Physics, University of Arizona, Tucson.
[3]Water Resources Division, U.S. Geological Survey, Denver, Colorado.
[4]Remote Sensing Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Beltsville, Maryland.
[5]Water Resources Division, U.S. Geological Survey, Carson City, Nevada.
[6]Southwest Watershed Research Center, Agricultural Research Service, U.S. Department of Agriculture, Tucson, Arizona.

Paper number 93WR03084.
0043-1397/94/93WR-03084$05.00

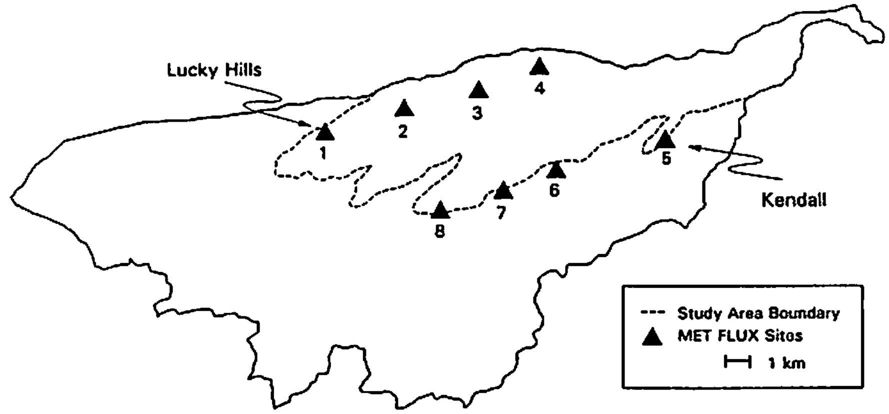

Figure 1. A schematic diagram illustrating approximate locations of the eight METFLUX sites and main study area boundary within the Walnut Gulch watershed. Site 1 is located within the shrub-dominated subwatershed, Lucky Hills, and site 5 is within the grass-dominated subwatershed, Kendall. At these two sites, extensive ground-based remote sensing and other geophysical data were collected [*Kustas and Goodrich*, this issue].

the local roughness, z_{0m} (meters). The roughness z_{0m} is an important parameter for modeling momentum and sensible heat transfer across the surface-atmosphere interface. They were utilized by other investigations in this issue [i.e., *Humes et al.*, this issue; *Kustas et al.*, this issue; *Moran et al.*, this issue].

A review of the approach for computing the surface energy balance is presented. Comparisons between the one-dimensional eddy correlation (EC) measurement of the turbulent fluxes H and LE [*Stannard et al.*, this issue] and the variance-residual (VAR-RESID) method for the unstable conditions are made at two of the METFLUX sites. Since H and LE fluxes under stable conditions are relatively small and have significant uncertainty, this analysis considers only unstable cases. Furthermore, other studies in this issue utilized energy fluxes determined by the METFLUX network primarily under unstable conditions. Therefore comparisons between the VAR-RESID method and EC system for unstable conditions were considered most relevant. Several methods for estimating z_{0m} with σ_w values and with wind profile measurements under near-neutral conditions are compared.

Overview of the METFLUX Network and Data

For a general description of the watershed, study area, and data collected during the Monsoon '90 study, see *Kustas and Goodrich* [this issue] and *Kustas et al.* [1991]. Weather conditions during the main experimental period (July–August) varied from clear skies with low humidity to overcast skies with high humidity. Most days, however, had clear skies in the early morning followed by partly to mostly cloudy skies in the late morning and early afternoon due to strong convection and available moisture in the upper atmosphere. This scenario is typical for the region during the "monsoon" season (July–September). Daytime surface winds normally ranged between 2 and 5 m s^{-1}, and daytime average air temperatures were between 20° and 30°C. The average daytime relative humidity ranged from around 30% to nearly 85%.

The surface energy balance and ancillary meteorological data were determined at eight locations (METFLUX sites) within the study area. Figure 1 is a schematic showing approximate locations of the METFLUX stations with their corresponding reference number. The sites were situated along two parallel transects which made possible the acquisition of remotely sensed data over all locations by a low-flying aircraft. The METFLUX sites were generally located on ridges above the local terrain and, hence, provided measurements which were more representative of the surrounding region. Distances between METFLUX stations along the north and south transects averaged around 2.5 km, except between stations 5 and 6 where it was of order 4 km. The northern and southern transects were separated by about 4 km. Detailed information concerning the type of sensors used and measurement height/depth is given in Table 1. Table 2 lists general soils and vegetation information collected around each METFLUX site.

The vegetation cover was sparse and also highly variable at most of the sites. Shrubs dominated the vegetation type at six of the eight locations. Almost all sites had an average vegetation height, h, of less than 0.5 m and a significant coefficient of variation. The vegetation height measurements were made along five 30-m belt transects around the METFLUX sites with a technique described by *Weltz et al.* [this issue]. Observations by *Stannard et al.* [this issue] at several of the shrub-dominated sites documented a diversity in vegetation species; most species had h values less than 0.5 m, but less prevalent species reached average heights of about 1 m, while others (normally located in emphemeral channels) attained heights of 3–4 m. Most ephemeral channels were hundreds of meters away from the METFLUX sites and not sampled by the belt transects [*Weltz et al.*, this issue]. For the grass sites, Stannard et al. also noted that larger widely spaced vegetation with heights of up to 3 m were present, and in valley bottoms scattered stands of woody vegetation were frequently between 3 and 5 m in height. Finally, from Table 2, it is apparent that most sites had a significant rock fraction in the 0–5 cm layer. For a thorough description of the soils and vegetation for the study area see *Schmugge et al.* [this issue] and *Weltz et al.* [this issue], respectively.

Surface energy balance measurements using the eddy

Table 1. Description of Measurements and Sensors at METFLUX Sites

Measurement Type	Number of Replications	Approximate Height/Depth, m	Model/Manufacturer*
Net radiation	1	3	Q*6/REBS
Solar radiation	1	3.5	LI-200SZ/LiCor
Solar radiation†	1	2	8-48/Eppley
Photosynthetically active radiation (PAR)†	1	3.5	LI-190SA/LiCor
Reflected PAR†	1	3.5	LI-190SA/LiCor
Air temperature	1	4.0	chromel constantan thermocouple/CSI
Air temperature/relative humidity†	1	2.0	207 temperature and relative humidity with radiation shield/CSI
Wind speed and wind direction	1	4.3	03001-5 Wind Sentry/R.M. Young
Surface temperature	1	3	4000LCS/Everest Interscience
Soil heat flux	3	−0.05	HFT-3/REBS
Soil moisture	6	−0.05	fiberglass resistance wafer‡
Soil moisture	6	−0.025	fiberglass resistance wafer‡
Soil temperature	3	−0.025	copper constantan thermocouple‡
Soil temperature	2	−0.05	copper constantan thermocouple‡
Soil temperature	1	−0.15	copper constantan thermocouple‡

Trade names and company names are included for the benefit of the reader and do not imply any endorsement of the product or company by the U.S. government.

*Manufacturers cited: Radiation and Energy Balance Systems, Inc. (REBS), Seattle, Washington; Li-Cor, Inc., Lincoln, Nebraska; the Eppley Laboratory, Inc., Newport, Rhode Island; Campbell Scientific, Inc. (CSI), Logan, Utah; R.M. Young Company, Traverse City, Michigan; and Everest Interscience, Inc., Fullerton, California.

†Measurements made only at Lucky Hills (site 1) and Kendall (site 5).

‡Soil moisture and temperature sensors were manufactured at the U.S. Department of Agriculture's Agricultural Research Service, Southwest Watershed Research Center, Tucson, Arizona.

correlation technique were collocated at some of the METFLUX sites and are discussed by *Stannard et al.* [this issue]. One type of eddy correlation system used a single-axis sonic anemometer with a 12.7-μm-diameter thermocouple and a krypton hygrometer for measuring H and LE. Sensors were positioned around 2 m above the local topography. Another system computed H at 9 m using a 76.2-μm-diameter thermocouple and a styrofoam propeller for measuring vertical wind [*Blanford and Stannard*, 1991].

For the METFLUX sites, net radiation was measured with a REBS Q*6 net radiometer at about 3 m above ground level (AGL), and incoming solar radiation was measured with a LiCor silicon pyranometer model LI-200SZ at close to 3.5 m AGL. Surface soil heat flux was estimated using three soil heat flow plates buried at 0.05 m and a storage term estimated with temperature and soil moisture sensors at 0.05 and 0.025 m below the surface. The sparse vegetative cover and the significant rock content in near-surface soils complicated the interpretation of subsurface measurements of temperature and soil moisture [*Schmugge et al.*, this issue]. As a result, obtaining estimates of soil heat fluxes was difficult. A detailed description of the various methods used in the Monsoon '90 field experiment for computing G is given by *Stannard et al.* [this issue]. Estimates of G for the METFLUX sites follow an approach similar to one outlined by *Kustas and Daughtry* [1990].

At each METFLUX site the mean and variance in air temperature were computed from measurements made with a 76.2-μm-diameter chromel-constantan thermocouple at about 4 m AGL. Wind speed, u, and direction were measured at about 4.3 m AGL with an RM Young Model 03001-5 Wind Sentry having a threshold velocity of about 0.5 m s^{-1}.

Table 2. General Description of Vegetation and Soils at METFLUX Sites

Site	Average Fractional Vegetation (Standard Deviation)	Average Vegetation Height (Standard Deviation), m	Average Ratio of Shrub to Total Vegetation Biomass	Soil Bulk Density (0–5 cm)	Soil Rock Fraction (0–5 cm)
1	0.26 (±0.19)	0.27 (±0.23)	0.92	1.64	0.28
2	0.52 (±0.14)	0.23 (±0.15)	0.66	1.83	0.36
3	0.46 (±0.15)	0.19 (±0.14)	0.85	1.58	0.28
4	0.61 (±0.15)	0.18 (±0.10)	0.22	1.82	0.45
5	0.40 (±0.15)	0.10 (±0.08)	0.29	1.61	0.37
6	0.37 (±0.24)	0.21 (±0.28)	0.63	1.44	0.31
7	0.32 (±0.14)	0.17 (±0.14)	0.69	1.74	0.10
8	0.39 (±0.11)	0.5 (±0.32)	0.995	1.47	0.21

The air temperature sensor used for the variance calculations had a sampling rate $s_r = 4\ s^{-1}$. With the daytime wind speeds typically 2–5 m s^{-1} during the field campaign, the sampling rate for σ_T at $z = 4$ m yields a nondimensional frequency value, $f (= s_r u/z)$, ranging from 3 to 8. Values of $f > 2$ for neutral and unstable conditions contain most of the turbulent scales contributing to the transport [*Deacon*, 1959; *McBean*, 1972; *McMillan*, 1988]. Hence $s_r = 4\ s^{-1}$ was considered adequate for computing H with the variance data. In addition, the time constant, t_c, of the thermocouple was calculated using the equation from *Moore* [1986]. With the above range in observed wind speed (i.e., 2–5 m s^{-1}), the value of t_c varied from 0.09 to 0.06 s. This range in the value of t_c indicated that the differences between sensor measurements of the temperature fluctuations and actual values were usually less than 5% [*Fritschen and Gay*, 1979]. All other meteorological and soil sensors were sampled at 0.1 s^{-1}. The data were averaged over 20-min intervals. Five-minute averages of the radiation data were also stored for use in comparing with "instantaneous" radiation estimates from satellite data [see *Pinker et al.*, this issue].

Near-surface wind profile measurements were made at 2, 3, 4, and 5 m above the soil surface at Lucky Hills and 1, 2, 3, 4, and 5 m above the soil surface at Kendall using R. M. Young photo-chopper cup anemometers. These sensors have a 0.2 m s^{-1} threshold velocity. Inadequate grounding of the anemometer housing at Lucky Hills resulted in malfunctioning of the anemometer at 3 and 5 m during the latter part of the field experiment. Only the reliable data were used in estimating roughness parameters.

In order to minimize variability in net radiation measurements caused by instrument design, several different sensor systems (Q*6, Shenk, and a four-component system) were compared at a few of the METFLUX sites [*Stannard et al.*, this issue]. In addition, intercomparisons among the Q*6 net radiometers were performed after the experiment in June 1991 in Beltsville, Maryland. For several weeks, all net radiometers were placed in a 20 × 40 m bare soil plot about 0.5 m above the surface. It was concluded from these comparisons that while bias among the same sensor designs (i.e., Q*6 net radiometers at the METFLUX sites) could be minimized, it was not clear which sensor package gave the most reliable net radiation values. In general, the Shenk net radiometer measured the lowest R_n, and the four-way system gave the highest values, with the Q*6 net radiometer values falling in between. For further details of the net radiometer analysis, see *Stannard et al.* [this issue].

The solar silicon cell radiation sensors were also evaluated with a recently calibrated Eppley PSP pyranometer (serial number 17675F3) in the Beltsville 1991 study. The instrument is mainly used as a standard to calibrate other pyranometers. It was calibrated at the National Oceanic and Atmospheric Administration (NOAA) Environmental Research Laboratory (ERL) in Boulder, Colorado, in May 1988. There was less than a 0.5% change from the August 1984 calibration. The variation in measured solar radiation, R_{si}, among the sensors was within 5% (on average), and they tended to measure higher than the Eppley by 2–4% around midday. The sensors were recalibrated by using least squares regression equations with the Eppley data as the dependent variable for a clear day, several partly cloudy days, and an overcast day. For two clear days during the field campaign, a comparison of the standard deviation of R_{si} among the eight METFLUX sites using the original factory calibrations versus recalibrations by least squares regression with the Eppley is shown in Figure 2a. This figure shows a significant reduction in the standard deviation of R_{si} values among the eight measurement locations as a result of the recalibration using the Eppley as the standard. A calculation of the mean percent difference (MPD) in R_{si} between the average of all eight sites with the average of Eppley sensors located at Lucky Hills (site 1) and Kendall (site 5) is shown in Figure 2b. These data show that better agreement is attained for a large part of the daytime period using the least squares regression equations from the Beltsville study (i.e., $|\mathrm{MPD}| < 1\%$) than when using the original factor calibrations (i.e., $|\mathrm{MPD}| \sim 4\%$).

The Variance Method for Estimating the Sensible Heat Flux

The sensible heat flux under unstable conditions was estimated using the variance in air temperature data and Monin-Obukhov similarity theory applied to second-order turbulent statistics. A large number of studies have explored flux-variance relationships [e.g., *Mordukhovich and Tsvang*, 1966; *Businger et al.*, 1967; *Wesely et al.*, 1970; *McBean*, 1971; *Phelps and Pond*, 1971; *Wyngaard et al.*, 1971; *Tillman*, 1972; *Smedman-Högström*, 1973; *Högström and Smedman-Högström*, 1974; *Wesely*, 1988; *Weaver*, 1990; *Lloyd et al.*, 1991]. The equation from *Tillman* [1972] was adopted since mathematically it is a continuous function in the transition between near-neutral and unstable conditions,

$$H = -\rho C_p u_* (\sigma_T / C_1)[C_2 - (z - d_{0m})/L]^{1/3}. \quad (2)$$

The symbol ρ is the air density (kilograms per cubic meter), C_p the specific heat at constant pressure (J kg^{-1} K^{-1}), $u_* = (\tau/\rho)^{1/2}$ (meters per second) the friction velocity (τ is the surface shear stress), z the height where σ_T is measured, d_{0m} the displacement height (see below), L the Obukhov length, and the magnitude of C_1 and C_2 are determined experimentally. The Obukhov length [*Monin and Obukhov*, 1954] given by

$$L = u_*^3 / [k(g/T_a)(H_v/\rho C_p)] \quad (3)$$

is a measure of atmospheric stability. The symbol k is von Karman's constant (~0.4), g the acceleration of gravity (m s^{-2}), $H_v = (H + 0.61 T_a C_p E)$ is the virtual sensible heat flux where T_a is the near-surface air temperature (kelvins), and E is the rate of surface evaporation (kg m^{-2} s^{-1}).

Data from other studies suggest the magnitude of C_1 is of order 1, but appears to range from 0.95 [*Wyngaard et al.*, 1971; *Tillman*, 1972; *Hicks*, 1981] to 1.25 [*Wesely*, 1988; *Kader and Yaglom*, 1990]. The value of C_2 has to be evaluated indirectly by analysis of data under near-neutral conditions. This reduces (2) to

$$H = -\rho C_p u_* \sigma_T / C_3, \quad (4)$$

where $C_3 = C_1/C_2^{1/3}$. Values of C_3 are more variable for near-neutral conditions because H and σ_T tend toward zero and hence their ratio becomes quite noisy. In addition, nonstationarity during the periods of near-neutral conditions cannot be accounted for in these formulations [*Tillman*, 1972]. The values of C_3 observed experimentally range from

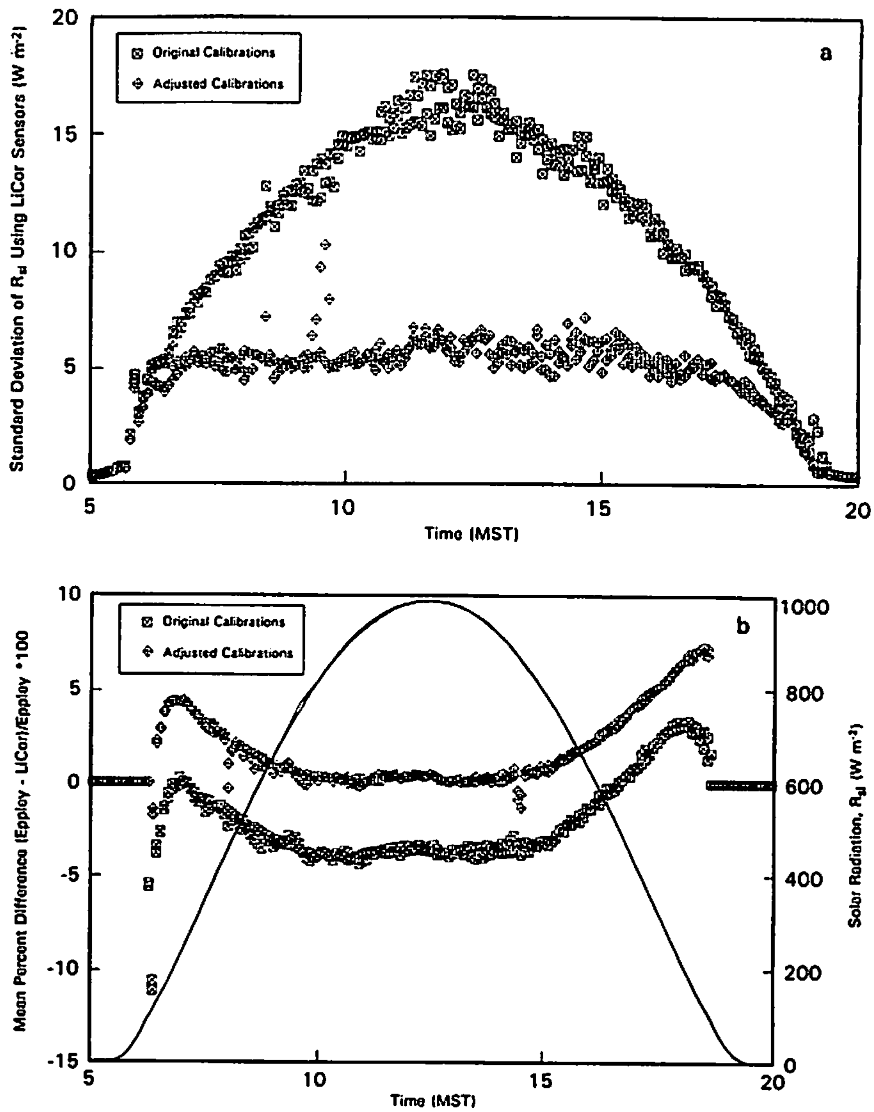

Figure 2. Statistical analysis of solar radiation measurements made at the eight METFLUX sites for two clear days during the field experiment. Illustrated as a function of R_{Si} are (a) the standard deviation of the eight METFLUX sites and (b) the MPD between Eppley-derived values and the average from the METFLUX network, using factory calibrations and recalibrated coefficients from the Beltsville 1991 comparison (see text).

1.85 [*Wesely*, 1988] to 2.9 [*Kader and Yaglom*, 1990]. Other studies found $C_3 \sim 2.5$ [*Tillman*, 1972; *Weaver*, 1990].

In order to calculate H with (2), estimates of u_* are required. Values of u_* came from formulations using measurements of σ_w and mean wind speed u. Application of Monin-Obukhov similarity theory to second-order turbulent statistics yields a functional relationship between u_* and σ_w under unstable conditions which has the form [*Panofsky and Dutton*, 1984]

$$u_* = \sigma_w/\{a[1 - b(z - d_{0m})/L]^{1/3}\} \quad (5)$$

Experimental data [e.g., *Hicks*, 1981; *Wesely*, 1988] suggest the coefficients a and b are of order 1.3 and 2, respectively. Similarly, Monin-Obukhov similarity theory has shown that the relationship between u_* and u is of the form [*Brutsaert*, 1982]

$$u_* = uk/\{\ln [(z - d_{0m})/z_{0m}] - \psi_m\} \quad (6)$$

where ψ_m is the stability correction factor and is a function of $(z - d_{0m})/L$. A recent review of experimentally determined ψ functions by *Högström* [1988] suggests the expression [e.g., *Dyer*, 1974]

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

where $x = [1 - 16(z - d_{0m})/L]^{1/4}$, is suitable for unstable conditions.

Computation of H was obtained by an iterative loop. The procedure was to calculate the Obukhov length with (3) (assuming a value of $L = -1 \times 10^9$ when starting the iteration) which then allowed the computation of u_* using measurements of σ_w with (5) or employing u values in (6) and (7). Then, having estimates of L and u_*, H was evaluated with Tillman's expression, (2). This left LE to be solved as a residual in the energy balance equation, namely by (1). Then L was recalculated with (3) using the estimates of H, LE, and u_* and compared to the former. The iteration converged when the absolute difference between former and latter values of L was less than a prescribed limit (e.g., ~0.001). Typically four to five iterations were required to obtain a solution.

Analysis of Coefficients for the Variance Method

Ideally, the coefficients C_1 and C_2 should be evaluated using measured fluxes from more reliable sensors, such as an eddy correlation system. However, fluxes measured by the eddy correlation technique at several of the METFLUX sites had sensors at significantly different heights above ground level (i.e., ~2 and ~9 m AGL) than the height where variance data were collected (i.e., ~4 m AGL). Therefore the area contributing to the turbulent fluxes is not the same for all measurement systems [e.g., *Schmid and Oke*, 1990]. For complex surfaces with nonuniform sources of sensible and latent heat, these sensor height differences are likely to cause significant variation in the measured scalar flux [*Stannard et al.*, this issue]. As a result, the coefficients could not be evaluated by direct comparisons between H derived from (2), (3), and (5) and the one-dimensional eddy correlation measurements at 2 m for most of the METFLUX sites. One exception was site 7, which was flat and had fairly uniform vegetation cover within several hundred meters of the METFLUX site. Site 1 also had fairly good fetch conditions; however, it had more topographic relief than site 7. Thus only site 7 was used to calibrate (2).

Variation in the value of C_2 had little effect on the computed fluxes. Consequently, its value was computed by the ratio $(C_1/C_3)^3$ with the constant $C_3 = 2.5$, which is essentially the mean value from previous experiments. The values assigned to C_1 were 1, 1.25, and 1.1, the mean of the reported range in C_1, namely, 0.95–1.25.

Differences between H measured by the eddy correlation system at 2 m and the variance technique were quantified by the root mean square error (RMSE) (shown to be a better indicator of model performance than using correlation statistics [*Willmott*, 1982]), the mean absolute difference (MAD), the mean absolute percentage difference (|MPD|) and the mean bias estimate (MBE). The results are listed in Table 3. The results indicate that using $C_1 = 1.1$ yields the closest agreement with the 2-m eddy correlation data. Note that the most significant impact of changing the value of C_1 is in the magnitude of the MBE. Therefore the value adopted for C_1 mainly causes the variance method to calculate systematically higher or lower H values. This suggests that the variance method should always be calibrated with more reliable flux measurement systems. With $C_1 = 1.1$ and $C_3 = 2.5$, the value of $C_2 = 0.085$. These values were adopted for the other sites.

Table 3. Statistical Results Comparing Sensible Heat Flux, H, Estimated by σ_T and σ_w Data in (2) and (5) With C_1 = 1, 1.1, and 1.25 Versus One-Dimensional Eddy Correlation Measurements at Site 7 (n = 126)

C_1	RMSE, W m^{-2}	MAD, W m^{-2}	MBE, W m^{-2}	|MPD|, %
1	31	24	−13	19
1.1	27	22	−1	15
1.25	29	22	11	15

Statistics are defined as follows: root mean square error, RMSE = $[\Sigma_{i=1}^{n} (X_i - Y_i)^2/n]^{1/2}$; mean absolute difference, MAD = $\Sigma_{i=1}^{n} |(X_i - Y_i)|/n$; mean bias estimate MBE = $\Sigma_{i=1}^{n} (X_i - Y_i)/n$; and mean absolute percent difference, |MPD| = $\Sigma_{i=1}^{n} |(X_i - Y_i)/Y_i|/n$, where X_i represents H estimated with σ_T and σ_w data and the value assumed for C_1 and Y_i represents H measured by the one-dimensional eddy correlation system at 2 m.

Estimation of Local Momentum Roughness Parameters

The local momentum roughness parameters, d_{0m} and z_{0m}, required in the above equations were determined for some of the METFLUX sites using several techniques. One method involved using wind profile data under near-neutral conditions. The other approaches were similar in that they used measurements of σ_w and u, and turbulent fluxes under unstable conditions for estimating the roughness parameters.

For the two main study areas, Lucky Hills and Kendall (sites 1 and 5), wind profile measurements at four or five levels were used under near-neutral conditions with an iterative least squares technique to determine z_{0m} and d_{0m} [*Robinson*, 1962; *Kustas et al.*, 1989]. Near-neutral conditions were defined as those cases where $u > 2$ m s^{-1} and $|H| < 10$ W m^{-2}. These criteria resulted in z/L values averaging less than 0.01. For Lucky Hills there were 18 near-neutral cases, while at Kendall there were 62 cases. The significantly lower number of cases at Lucky Hills was primarily due to instrument malfunctions during the latter part of the experiment. Roughly half of the near-neutral cases occurred during transitional periods in the early morning and late afternoon, while the others were under cloudy skies with strong winds (i.e., $u \geq 5$ m s^{-1}).

A second approach utilized measurements of σ_w along with the turbulent fluxes H and LE given by the one-dimensional eddy correlation system at ~2 m and a measurement of near-surface wind speed u at ~4 m [e.g., *Weaver*, 1990]. The procedure consisted of selecting values of z_{0m} and d_{0m} required in (6) for computing u_*, and by iteration to obtain a unique solution using (3) and (6)–(7). This is similar to the method outlined above for computing fluxes with the variance data. The appropriate z_{0m} and d_{0m} were found by plotting σ_w/u_* versus $(z - d_{0m})/L$ to see how closely it fit the curve defined by (5) (D. I. Stannard, personal communication, 1992).

A third method was similar to Stannard's approach except it utilized the 4-m variance data with u_* estimated by (5) and (6) to compute H. When a slope of 1 was obtained between H derived with u_* estimated by (5) versus u_* evaluated with (6), it was concluded that the values of z_{0m} and d_{0m} selected were representative for that site. Five of the METFLUX sites had a Gill propeller anemometer on a 9-m tower for estimating σ_w and, therefore, could be used in estimating z_{0m} and d_{0m} by this technique.

With the latter two approaches there are in theory many possible solutions involving different combinations of z_{0m} and d_{0m}. In fact, it was necessary to vary d_{0m} by 0.5 m

Table 4. Estimates of z_{0m} and d_{0m} for METFLUX Sites Using Methods Discussed in the Text and Values of the Roughness Parameters Employed in (6) for Estimating u_*

METFLUX Site	Near-Neutral Wind Profile*		Method of D. I. Stannard (Equations (3) and (5))		Method of Present Study (Equations (2), (3), (6), and (7))		Values Used in u_* Calculations With (6)	
	z_{0m}, m	d_{0m}, m	z_{0m}, m	d_{0m}, m	z_{0m}, m	d_{0m}, m	z_{0m}, m	d_{0m}, m
1	0.08 (±0.06)†	0.60 (±0.32)	0.04	0.3	0.03	0.5	0.04	0.5
2	...	...	...	...	...	...	0.04	0.5
3	...	...	...	...	...	...	0.04	0.5
4	...	...	...	...	...	...	0.01	0.3
5	0.01 (±0.009)	0.54 (±0.14)	0.004	0.3	0.01	0.5	0.01	0.3
6	...	...	0.04	0.2	0.03	0.5	0.03	0.3
7	...	...	0.05	0.5	0.03	0.5	0.03	0.5
8	...	...	...	...	0.05	0.5	0.05	0.5

*Estimates of z_{0m} and d_{0m} from wind profile data with $(z - d_{0m})/L < 0.01$.
†Standard deviation of wind profile estimates.

increments in order to have any perceptible change in the agreement between the curve defined by (5) and the calculated points (D. I. Stannard, personal communication, 1992). For this study, estimates of d_{0m} were guided by the results given by the wind profile data and Stannard's analysis. For both the shrub- and grass-dominated sites, Table 4 shows d_{0m} values are in most cases larger than the average vegetation height, h, given in Table 2. This seems physically unrealistic. However, the 30-m belt transects used in computing h covered a small fraction of the upwind fetch (of the order of 10^2 m) affecting the wind sensors. In many cases the upwind fetch would include emphemeral channels which support significantly larger and denser vegetation cover [see *Weltz et al.*, this issue]. Thus the h values in Table 2 are weighted much more heavily by the vegetation in relatively close proximity to the METFLUX site.

The resulting estimates of the roughness parameters using the various approaches outlined above are listed in Table 4. Also given are the z_{0m} and d_{0m} values assumed for the energy flux calculations with the variance method (see below). The values of the roughness length in Table 4 suggest that z_{0m} is generally higher for the shrub versus grass-dominated (i.e., sites 4 and 5) areas (see Table 2). Sites where none of the techniques could be employed (i.e., sites 2, 3, and 4) for determining the roughness parameters were estimated by using z_{0m} and d_{0m} values from sites with similar vegetation composition (see Table 2). Therefore site 4 was assumed to have roughness values similar to site 5, while sites 2 and 3 took the same roughness parameters estimated for site 1.

The sensitivity of flux calculations with the VAR-RESID method to the variation in roughness parameters was analyzed. For the displacement height d_{0m}, a comparison of the output with d_{0m} = 0.5 m versus d_{0m} = 0 using either (6) or (7) for computing u_* was made. Differences in H and LE fluxes were less than 3% in all cases. Therefore the d_{0m} values given in Table 4 were used in subsequent calculations. For the roughness length z_{0m}, the output using z_{0m} = 0.01 m versus 0.10 m in (6) was analyzed. Differences in H and LE averaged around 10%, which is similar to differences between (5) and (6) for estimating u_* (see Table 5). More importantly, there was a bias of nearly 20 W m^{-2}, on average, using the larger roughness (z_{0m} = 0.10 m) in the calculations. Thus consistently larger H fluxes computed with the larger roughness lead to smaller evaporative fluxes' being computed by the residual approach. This indicates that values of z_{0m} need to be estimated by a reliable independent method in order to obtain unbiased fluxes.

Comparisons of H Using the Variance Method With u_* Computed by σ_w and u

The relationship between H calculated with σ_T and σ_w, namely, equations (2) and (5), versus the use of σ_T and u, that is, equations (2) and (6), is illustrated in Figure 3a for a shrub-dominated area (site 1) and in Figure 3b for a grass-dominated area (site 5). In general, the agreement is quite good with points falling along the one-to-one line. There does appear to be larger scatter and possibly some bias for $|H|$ > 200 W m^{-2}. More quantitative measures of the difference are listed in Table 5. Given that the magnitudes of |MPD| and RMSE between the two methods were similar to values observed when comparing one-dimensional eddy correlation systems [*Dugas et al.*, 1991] and with the low value of MBE ~ 5 W m^{-2}, it was felt either approach was suitable. But because measurements of u and σ_T were available at all eight sites, this approach was adopted (using the roughness parameters in Table 4) for computing the fluxes with the so-called VAR-RESID technique.

Table 5. Statistical Results for H Estimated by σ_T and σ_w, (Equations (2) and (5)) Versus H Computed With σ_T and u (Equations (2) and (6))

Site	n	RMSE, W m^{-2}	MAD, W m^{-2}	MBE,* W m^{-2}	|MPD|,* %
1	598	16	12	5	11
5	486	16	11	1	10

RMSE, MAD, MBE, and |MPD| are as defined in the footnote to Table 3.

*For the calculations, X_i represents H estimated by σ_T and σ_w, and Y_i represents H estimated by σ_T and u.

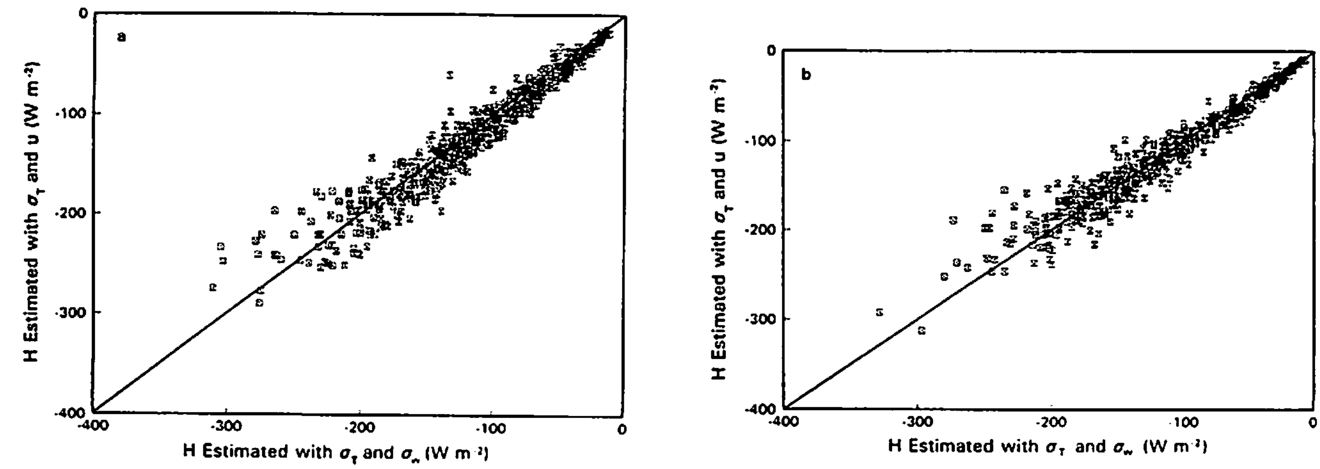

Figure 3. Comparison of H values using σ_T and σ_w versus σ_T and u for (a) site 1 and (b) site 5.

Comparison of Turbulent Fluxes Using Eddy Correlation and Variance-Residual Methods

For the comparison between EC and VAR-RESID methods, sites 1 and 7 were chosen because they contained satisfactory fetch conditions for both techniques [*Stannard et al.*, this issue]. Figures 4a and 4b illustrate the comparison of H values. The agreement in H appears satisfactory since there is fairly small scatter between VAR-RESID and EC estimates and no obvious bias. For latent heat flux, Figures 4c and 4d and the calculations in Table 6 reveal considerably more scatter between the two methods. There is also an increase in MBE.

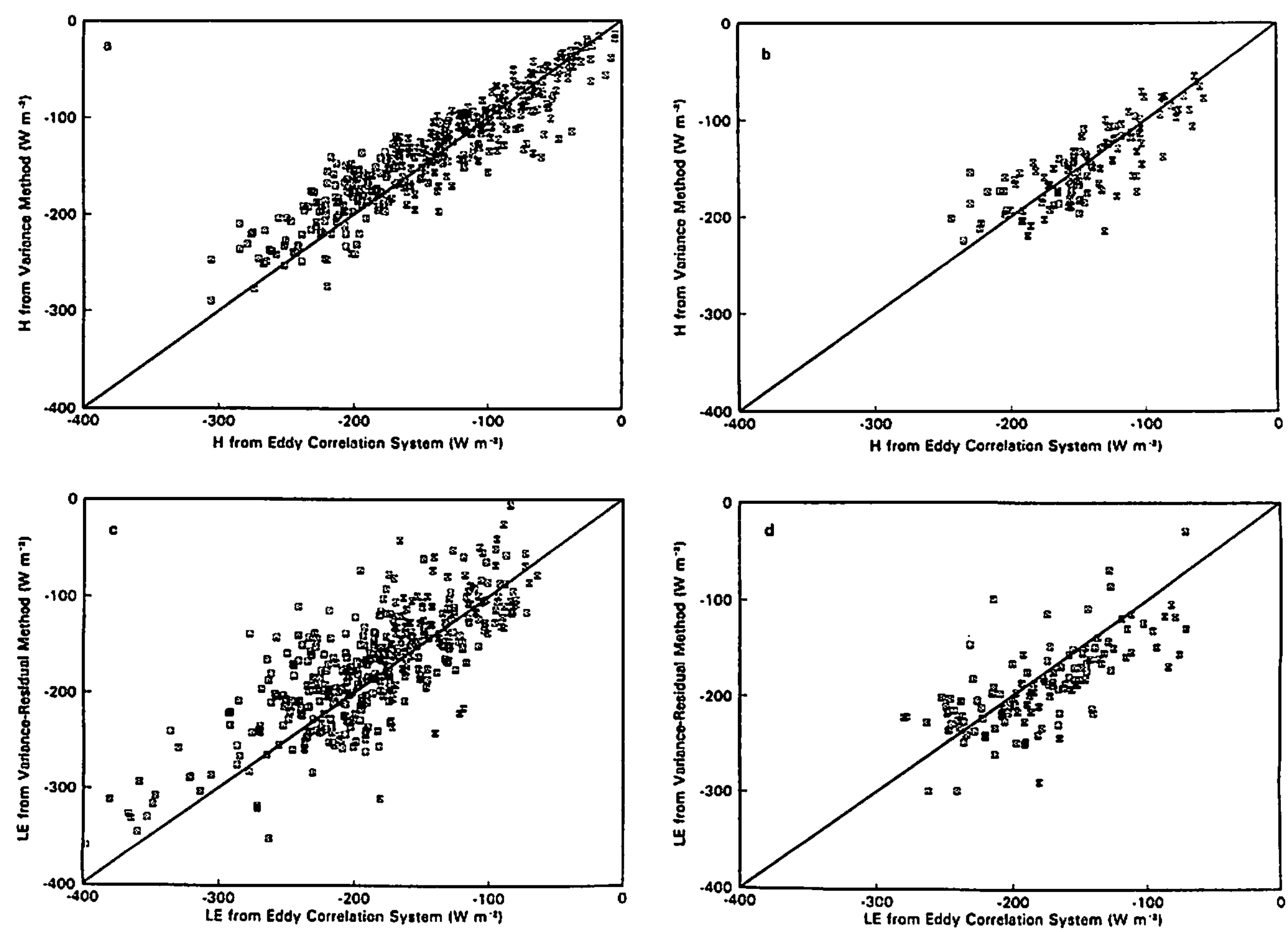

Figure 4. Comparison of the VAR-RESID method versus the EC system for estimating H at (a) site 1 and (b) site 7 and for estimating LE at (c) site 1 and (d) site 7.

Table 6. Statistical Results From Comparing the Sensible (H) and Latent (LE) Heat Fluxes Estimated by VAR-RESID Method and One-Dimensional EC Measurements

		Sensible Heat Flux				Latent Heat Flux				Latent Heat Flux*			
Site	n	RMSE, W m^{-2}	MAD, W m^{-2}	MBE,† W m^{-2}	|MPD|,† %	RMSE, W m^{-2}	MAD, W m^{-2}	MBE, W m^{-2}	|MPD|, %	RMSE, W m^{-2}	MAD, W m^{-2}	MBE, W m^{-2}	|MPD|, %
1	402	27	21	7	17	44	34	15	19	49	39	18	20
7	126	26	20	−3	15	37	29	−10	19	42	33	19	19

RMSE, MAD, MBE, and |MPD| are as defined in the footnote to Table 3.
*These statistical results were obtained by computing LE as a residual in the surface energy balance equation with H values from the one-dimensional EC system and R_n and G measured at the EC site (EC-RESID).
†For the calculations, X_i represents H and LE computed by VAR-RESID or EC-RESID approach, and Y_i represents measurements by the EC system.

One of the main reasons for this increase in scatter is the VAR-RESID estimates of LE use the available energy (R_n + G) measured locally while the EC system directly measures LE using the eddy covariance method [see *Stannard et al.*, this issue]. In general, the residual estimate will not be representative of the area contributing to the turbulent flux LE because (R_n + G) is not measured within the source area [e.g., *Schuepp et al.*, 1990]. This is further complicated when measurements are made in hilly terrain because of topographic influences on the available energy term [*Fritschen and Qian*, 1990]. In addition, the spatial variability in vegetation cover combined with differences in methods to determine G [*Stannard et al.*, this issue] resulted in significant variation in the estimates of available energy.

To illustrate the scatter associated with the use of locally measured R_n and G values, measurements of LE using the EC method are compared with estimates of LE using the residual approach with H, R_n, and G values from the EC site (EC-RESID) at Lucky Hills (Figure 5). In comparing Figures 4c and 4d to Figure 5 and also from the results in Table 6, it can be concluded that the scatter is not significantly reduced using the EC-RESID approach. This suggests that differences between EC-RESID and VAR-RESID for estimating LE are probably of the same order of magnitude whether the EC or VAR method is used for computing H.

Results using EC-RESID and VAR-RESID at site 7 also show that estimates of available energy (i.e., coming from the EC site compared to the METFLUX station) can be significantly different, causing a change in the sign of the MBE. Thus when using the residual approach over nonhomogeneous surfaces, one can expect variations in LE estimates to be at least 20% regardless of the technique used for computing H.

From these results it can be concluded that the |MPD| in H and LE calculated with EC versus the VAR-RESID approach is around 20%. This difference in flux estimates is similar to what was found with the Système Automatique de Mesure de l'Evapotranspiration Réelle (SAMER) stations used in the Hydrologic Atmospheric Pilot Experiment (HAPEX) study [*Andre et al.*, 1990] but is larger than the 5–10% variation expected with most eddy correlation techniques [e.g., *Shuttleworth et al.*, 1988; also E. Swiatek et al., Examination of the internal consistency of eddy correlation measurement of sensible and latent heat flux, submitted to *Agricultural and Forest Meteorology*, 1994].

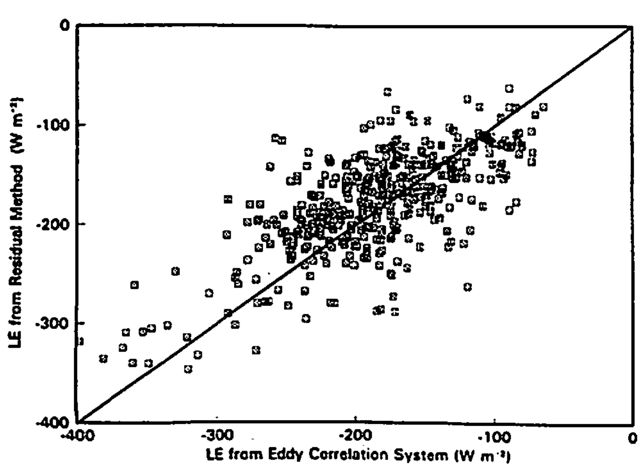

Figure 5. Estimates of LE from the residual approach with H, R_n and G measured at the EC site (EC-RESID) versus the direct measurements of LE at Lucky Hills.

Conclusions

For the Monsoon '90 study, eight METFLUX sites within the study area utilized meteorological observations to compute σ_T and estimate u_* in order to compute the sensible heat flux. The design of these systems satisfied cost constraints and the need for continuous observations over the experimental period. For five of the eight METFLUX sites, estimates of σ_w permitted the determination of the local momentum roughness length z_{0m}. These estimates were used to infer roughness values for the remaining sites. The agreement in H values between variance techniques using σ_w and σ_T versus σ_T and u was good enough that the latter approach was used to calculate the fluxes for all eight METFLUX sites and compare with estimates made by one-dimensional eddy correlation (EC) systems.

Under unstable conditions, the VAR-RESID estimates of H and LE were within 20% of the more traditional EC measurements. However, when comparing LE values, there was an increase in scatter. This result is due in part to the fact that the available energy is a point measurement whereas the EC measurement of LE represents an upwind fetch of order 10^2 m that is contributing to the flux. Furthermore, *Stannard et al.* [this issue] showed that there can be significant variation in estimates of G in this rangeland environment which will contribute to the uncertainty in the available energy term. Yet, it should be kept in mind that differences of 10% in turbulent flux measurements by similar one-dimensional EC systems under good fetch conditions is not uncommon (L. E. Hipps, personal communications, 1992). Furthermore, the results in Table 6 indicate that differences between EC-RESID and VAR-RESID and EC measurement of *LE* are comparable. Hence it can be concluded that the VAR-RESID method provided satisfactory surface energy balance estimates under unstable conditions during the Monsoon '90 experiment.

Estimates of the surface energy balance and local roughness parameters for the eight METFLUX locations are utilized by a number of studies in this issue. In future investigations the variation in the energy fluxes given by the METFLUX network will be analyzed in order to test the utility of remote sensing data for inferring spatial and temporal changes in the surface energy balance.

Acknowledgments. This study would not have been possible without the cooperation and assistance of the USDA ARS Tombstone Laboratory personnel: Howard Larsen, Art Dolphin, John Smith and Jim Smith. Also the assistance of USDA ARS Southwest Watershed Research Center is greatly appreciated. Finally, this project would not have been possible without the financial support of the NASA Interdisciplinary Research Program in the Earth Sciences (NASA reference number IDP-88-086) and from USDA ARS Beltsville Area funds.

References

André, J. C., P. Bougeault, and J. P. Goutorbe, Regional estimates of heat and evaporation fluxes over non-homogeneous terrain: Examples from the HAPEX-MOBILHY Programme, *Boundary Layer Meteorol.*, *50*, 77–108, 1990.

Blanford, J. H., and D. I. Stannard, Spatial variability of energy fluxes at Walnut Gulch, paper presented at Special Session on Hydrometeorology, Am. Meteorol. Soc., Salt Lake City, Utah, Sept. 1991.

Brutsaert, W. H., *Evaporation Into the Atmosphere*, 199 pp., D. Reidel, Norwell, Mass., 1982.

Businger, J. A., M. Miyake, A. J. Dyer, and E. F. Bradley, On the direct determination of turbulent heat flux near the ground, *J. Appl. Meteorol.*, *6*, 1025–1032, 1967.

Deacon, E. L., The measurement of turbulent transfer in the lower atmosphere, *Adv. Geophys.*, *6*, 211–228, 1959.

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.

Dyer, A. J., A review of the flux-profile relationships, *Boundary Layer Meteorol.*, *7*, 363–372, 1974.

Fritschen, L. J., and L. W. Gay, *Environmental Instrumentation*, 216 pp., Springer-Verlag, New York, 1979.

Fritschen, L. J., and P. Qian, Net radiation, sensible and latent heat flux densities on slopes computed by the energy balance method, *Boundary Layer Meteorol.*, *53*, 163–171, 1990.

Hicks, B. B., An examination of turbulent statistics in the surface layer, *Boundary Layer Meteorol.*, *21*, 389–402, 1981.

Högström, U., Non-dimensional wind and temperature profiles in the atmospheric surface layer: A re-evaluation, *Boundary Layer Meteorol.*, *42*, 55–78, 1988.

Högström, U., and A. S. Smedman-Högström, Turbulence mechanisms at an agricultural site, *Boundary Layer Meteorol.*, *7*, 373–389, 1974.

Humes, K. S., W. P. Kustas, and M. S. Moran, Use of remote sensing and reference site measurements to estimate instantaneous surface energy balance components over a semiarid rangeland watershed, *Water Resour. Res.*, this issue.

Kader, B. A., and A. M. Yaglom, Mean fields and fluctuation moments in unstably stratified turbulent boundary layers, *J. Fluid Mech.*, *212*, 637–662, 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., and D. C. Goodrich, Preface, *Water Resour. Res.*, this issue.

Kustas, W. P., B. J. Choudhury, K. E. Kunkel, and L. W. Gay, Estimate of the aerodynamic roughness parameters over an incomplete canopy cover of cotton, *Agric. For. Meteorol.*, *46*, 91–105, 1989.

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*, 1683–1705, 1991.

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 optimal remote sensing from an aircraft platform and atmospheric data collected over semiarid rangelands, *Water Resour. Res.*, this issue.

Lloyd, C. R., A. D. Culf, A. J. Dolman, and J. H. C. Gash, Estimates of sensible heat flux from observations of temperature fluctuations, *Boundary Layer Meteorol.*, *57*, 311–322, 1991.

McBean, G. A., The variation of the statistics of wind, temperature and humidity fluctuations with stability, *Boundary Layer Meteorol.*, *1*, 438–457, 1971.

McBean, G. A., Instrument requirements for eddy correlation measurements, *J. Appl. Meteorol.*, *11*, 1078–1084, 1972.

McMillan, R. T., An eddy correlation technique with extended applicability to non-simple terrain, *Boundary Layer Meteorol.*, *43*, 231–245, 1988.

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 (151), 163–187, 1954.

Moore, C. J., Frequency response corrections for eddy correlation systems, *Boundary Layer Meteorol.*, *37*, 17–35, 1986.

Moran, M. S., W. P. Kustas, A. Vidal, D. I. Stannard, J. H. Blanford, and W. D. Nichols, Use of ground-based remotely sensed data for surface energy balance evaluation of a semiarid rangeland, *Water Resour. Res.*, this issue.

Mordukhovich, M. I., and L. R. Tsvang, Direct measurement of turbulent flows at two heights in the atmospheric ground layer, *Izv. Akad. Sci. Russ. Atmos. Oceanic Phys.*, Engl. Transl., *2*, 786–803, 1966.

Panofsky, H. A., and J. A. Dutton, *Atmospheric Turbulence*, 397 pp., John Wiley, New York, 1984.

Phelps, G. T., and S. Pond, Spectra of temperature and humidity fluctuations and of the fluxes of moisture and sensible heat in the marine boundary layer, *J. Atmos. Sci.*, *28*, 918–928, 1971.

Pinker, R. T., W. P. Kustas, I. Laszlo, M. S. Moran, and A. R. Huete, Basin-scale solar irradiance estimates in semiarid regions using GOES 7, *Water Resour. Res.*, this issue.

Robinson, S. M., Computing wind profile parameters, *J. Atmos. Sci.*, *19*, 189–192, 1962.

Schmid, H. P., and T. R. Oke, A model to estimate source area contributing to turbulent exchange in the surface layer over patchy terrain, *Q. J. R. Meteorol. Soc.*, *116*, 965–988, 1990.

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.

Schuepp, P. H., M. Y. Leclerc, J. I. MacPherson, and R. L. Desjardins, Footprint prediction of scalar fluxes from analytical solutions of the diffusion equation, *Boundary Layer Meteorol.*, *50*, 355–373, 1990.

Shuttleworth, W. J., The Modellion concept, *Rev. Geophys.*, *29*, 585–606, 1991.

Shuttleworth, W. J., J. H. C. Gash, C. R. Lloyd, C. J. Moore, and J. S. Wallace, An integrated micrometeorological system for evaporation measurement, *Agric. For. Meteorol.*, *43*, 295–317, 1988.

Smedman-Högström, A., Temperature and humidity spectra in the atmospheric surface layer, *Boundary Layer Meteorol.*, *3*, 329–347, 1973.

Stannard, D. I., J. H. Blanford, W. P. Kustas, W. D. Nichols, S. A.

Amer, and T. J. Schmugge, Interpretation of surface flux measurements in heterogeneous terrain during the Monsoon '90 experiments, *Water Resour. Res.*, this issue.

Tillman, J. E., The indirect determination of stability, heat and momentum fluxes in the atmospheric boundary layer from simple scalar variables during dry conditions, *J. Appl. Meteorol.*, *11*, 783–792, 1972.

Weaver, H. L., Temperature and humidity flux-variance relations determined by one-dimensional eddy correlation, *Boundary Layer Meteorol.*, *53*, 77–91, 1990.

Weltz, M. A., J. C. Ritchie, and H. D. Fox, Comparison of laser and field measurements of vegetation height and canopy cover, *Water Resour. Res.*, this issue.

Wesely, M. L., Use of variance techniques to measure dry air-surface exchange rates, *Boundary Layer Meteorol.*, *44*, 13–21, 1988.

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.

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

Wyngaard, J. C., O. R. Cote, and Y. Izumi, Local free convection similarity and the budgets of shear stress and heat flux, *J. Atmos. Sci.*, *7*, 1171–1182, 1971.

J. H. Blanford, Institute of Atmospheric Physics, University of Arizona, Tucson, AZ 85721.

C. S. T. Daughtry, Remote Sensing Laboratory, USDA-ARS, Beltsville, MD 20705.

W. P. Kustas, Hydrology Laboratory, USDA-ARS, Beltsville, MD 20705.

W. D. Nichols, Water Resources Division, U.S. Geological Survey, 705 North Plaza Street, Carson City, NV 89701.

D. I. Stannard, Water Resources Division, U.S. Geological Survey, Denver Federal Center, Lakewood, CO 80225.

M. A. Weltz, Southwest Watershed Research Center, USDA-ARS, 2000 East Allen Road, Tucson, AZ 85719.

(Received October 5, 1992; revised April 16, 1993; accepted October 19, 1993.)