#1025
1992

TENTH CONFERENCE ON BIOMETEOROLOGY AND AEROBIOLOGY

SPECIAL SESSION ON HYDROMETEOROLOGY

September 10–13, 1991
Salt Lake City, Utah

Sponsored By

AMERICAN METEOROLOGICAL SOCIETY

Front Cover: After Griffiths and Driscoll, *Survey of Climatology*, Merrill, 1982, New York.

The manuscripts reproduced herein are unrefereed papers presented at the *Tenth Conference on Biometeorology and Aerobiology* and the *Special Session on Hydrometeorology*. Their appearance in this collection does not constitute formal publication.

AMERICAN METEOROLOGICAL SOCIETY

45 Beacon Street, Boston, Massachusetts USA 02108-3963

8.3

USE OF REMOTELY SENSED SPECTRAL DATA FOR EVALUATION OF HYDROLOGIC PARAMETERS IN SEMIARID RANGELAND

M.S. Moran[1], W.P. Kustas[2], L.B. Bach[3], M.A. Weltz[3], A.R. Huete[4], S.A. Amer[3]

[1]USDA-ARS, U.S. Water Conservation Laboratory, Phoenix, Az.
[2]USDA-ARS Hydrology Laboratory, BARC-East, Beltsville, Md.
[3]USDA-ARS Aridland Watershed Management Research Unit, Tucson, Az.
[4]Department of Soil and Water Science, University of Arizona, Tucson, Az.

1. INTRODUCTION

A major objective of hydrology is to better understand and quantify the processes that cause the changes in hydrologic storages and fluxes at local, regional and global scales. Toward this goal, numerical hydrological models have been developed to evaluate surface conditions and the energy/water budget and to monitor their long term evolution (see, for example, the model described by Sellers et al., 1986). Most of these approaches suffer from a lack of information about states (e.g., initial soil moisture) and knowledge of the spatial and temporal distribution of several surface characteristics (e.g., vegetation cover). It is physically and economically impossible to acquire such information using conventional point measurement techniques over a heterogeneous landscape.

Remotely sensed spectral measurements can provide an indirect means of deriving the spatial distribution of geophysical quantities required as inputs to hydrological models. Satellite- and ground-based measurements of surface reflectance and temperature have been related to critical model requirements, such as soil moisture (Idso et al., 1975), land cover (Huete, 1988), precipitation (Rosema, 1990) and vegetation status (Jackson, 1982). Furthermore, surface temperature and reflectance have been combined with ground-based meteorological data to directly evaluate surface energy fluxes, such as net radiation and evaporation (Jackson, 1985). Most of these relations were derived for agricultural sites where the vegetation is generally uniform and lush. Thus, they cannot be easily applied to heterogeneous rangeland sites.

A recent experiment conducted at the Walnut Gulch Watershed in southeast Arizona (Kustas et al., 1991) provided the opportunity to derive relationships between remotely-sensed data and basic hydrologic factors for a semiarid rangeland. The results reported here demonstrate that remotely sensed measurements of surface reflectance and temperature can be used to estimate the spatial distribution of vegetation cover, soil moisture and surface evaporation over a rangeland landscape.

2. EXPERIMENT

An experiment (dubbed Monsoon'90) was conducted at the Walnut Gulch Watershed near Tombstone, Arizona, in an area comprising the upper 150 km^2 of a drainage basin, from about 1300 to 1800 m above mean sea level. In this region, precipitation ranges from 250 to 500 mm/yr, with 2/3 of the rainfall occurring during the summer "monsoon season" in July and August. The experiment was designed to acquire remotely sensed data in the visible, near-infrared (NIR), thermal and microwave wavelengths from ground, aircraft and satellite platforms, with concurrent measurements of soil moisture and temperature, and energy and water fluxes, in a hydrologically well-instrumented semiarid rangeland watershed (Kustas et al., 1991). Data were acquired during the dry season in early June, when the vegetation was senescent, and during the wet or monsoon season in late July and early August, when the vegetation was near peak green leaf area, soil moisture was highly variable, and there were several significant precipitation events.

The data presented here are only a fraction of the total Monsoon'90 data set. Analysis was limited to eight sites, termed METFLUX stations (herein referred to as MF1 to MF8), containing instrumentation for measuring both general meteorological conditions and estimating the surface energy balance. The METFLUX sites were located along two parallel transects covering the two dominant vegetation types (brush and grasses) and the transition from one to the other. Two of the eight METFLUX sites contained considerably more micrometeorological instrumentation than the others: MF1 (named Lucky Hills) was located in a relatively flat, brush-dominated ecosystem and MF5 (named Kendall) was in a hilly, grass-dominated subwatershed.

2.1 Hydrologic Factors

Latent heat flux density (LE: a product of the heat of vaporization L and the rate of evaporation E) was determined for half-hourly intervals at each METFLUX site using the one-dimensional energy balance equation (Brutsaert, 1982),

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

where R_n is net radiation, G and H are the soil and sensible heat flux densities, respectively, and fluxes away from the surface are negative. R_n was measured with a net radiometer and G with a series of soil heat flux plates. Sensible heat flux density was measured with the variance method (Tillman, 1972) using a tower with a propeller anemometer and fine wire thermocouple. Values of daily evaporation (E_d) were computed by summing the half-hourly estimates of LE over a 24-hour period and converting that sum from energy units to units of mm/day. METFLUX measurements of R_n, G, H and LE were verified by comparison with concurrent measurements using a conventional eddy correlation apparatus on site (Moran et al., 1991).

Gravimetric water content over the 0-5 cm depth was measured at each METFLUX site on a daily basis using three representative samples per site. The values were converted to volumetric water content using in-situ bulk density measurements obtained at each site. During the July-August field campaign, percent plant, soil and rock cover were estimated at each METFLUX site. These estimates were based on measurements along five line transects of 30 m traversing each METFLUX site.

2.2 Remotely Sensed Data

Ground- and aircraft-based spectral radiometers [with spectral filters covering 0.45-0.52 μm (blue), 0.53-0.61 μm (green), 0.62-0.69 μm (red) and 0.78-0.90 μm (NIR)] and infrared thermometers (IRT, 8-14 μm) were deployed on June 5, during the July-August field campaign, and again on 9 Sept 1990. Ground-based measurements of surface reflectance and temperature were made from a height of 2 m above ground level (AGL) using yoke-based radiometers at the MF1 and MF5 sites (Moran et al., 1991). The MF1 target was approximately 120 by 120 m in size and the MF5 target was 480 by 120 m, stretching from the top of one ridge eastward to the top of another. By deploying four sets of radiometers at MF5 and one at MF1, it was possible to cover both targets simultaneously in less than 15 minutes.

Radiometers similar to those deployed at ground-level were mounted in an aircraft along with a color video camera designed to document the ground locations of spectral measurements. The flying altitude for the aircraft was a nominal 150 m AGL, resulting in a spatial resolution (a pixel) of approximately 40 m on the surface. The aircraft was flown several times per day along the two parallel transects containing the 8 METFLUX stations starting around 0900 MST each day.

Surface emissivities (ϵ) of 0.975 and 0.985 were computed for the MF1 and MF5 sites, respectively, using a technique described by Taylor (1979). Measurements of ϵ are necessary to convert radiometric surface temperature (T_r) measured with an IRT to absolute (kinetic) surface temperature (T_s), where $T_s = T_r/\epsilon^{1/4}$. Values of ϵ were not available for all eight METFLUX sites; however, based on the similarity between ϵ measured at the MF1 and MF5, it appeared that ϵ was relatively consistent across the grass/shrub continuum. Consequently, an average ϵ of 0.98 was assumed for all sites, resulting in less than a 1°C correction in most cases.

Five dates were selected for this study to cover a variety of soil moisture and vegetation density conditions, while maintaining relatively cloud-free conditions during the overflight: 5 June (Day Of Year 156), 28 July (DOY 209), 4 August (DOY 216), 9 August (DOY 221) and 9 September (DOY 252). For each date, a set of ground- and aircraft-based measurements of surface reflectance and temperature were compiled corresponding to a measurement time of approximately 10:00 MST. The ground-based data for the MF1 and MF5 targets were averaged to produce a single estimate of surface reflectance and temperature for each ground target. The geographic locations of aircraft-based measurements were determined by viewing the video tapes. The reflectance and temperature data acquired over three pixels covering the general location of each METFLUX site were averaged to obtain a mean value for each site on each date.

The spectral reflectance data were converted to a spectral "vegetation index", which is more sensitive than individual reflectance factors to vegetation characteristics such as biomass and percent vegetation cover. The soil-adjusted vegetation index (SAVI) was designed to be sensitive to vegetation yet insensitive to soil background differences (Huete, 1988);

$$\mathrm{SAVI} = (\mathrm{NIR}-\mathrm{red})/(\mathrm{NIR}+\mathrm{red}+L)(1+L), \qquad (2)$$

where L is the soil correction term, assumed in this case to be 0.5.

3. RESULTS AND DISCUSSION

Though five dates were selected for analysis, some data sets were not complete due to instrument failures or on-going data processing. The subsequent analyses were conducted based on all data available at this time.

3.1 Ground- and Aircraft-based Spectral Data

Surface temperature and SAVI data acquired with ground-based sensors were compared with aircraft-based data for the five measurement dates at the MF5 site (Figure 1). As expected, SAVI increased and T_s decreased during the monsoon season. Even though the aircraft- and ground-based measurements were made at slightly different locations and at largely different scales, the two measurements corresponded well over time. With this verification, aircraft data were considered appropriate for analysis of the other METFLUX sites where ground-based data were not available.

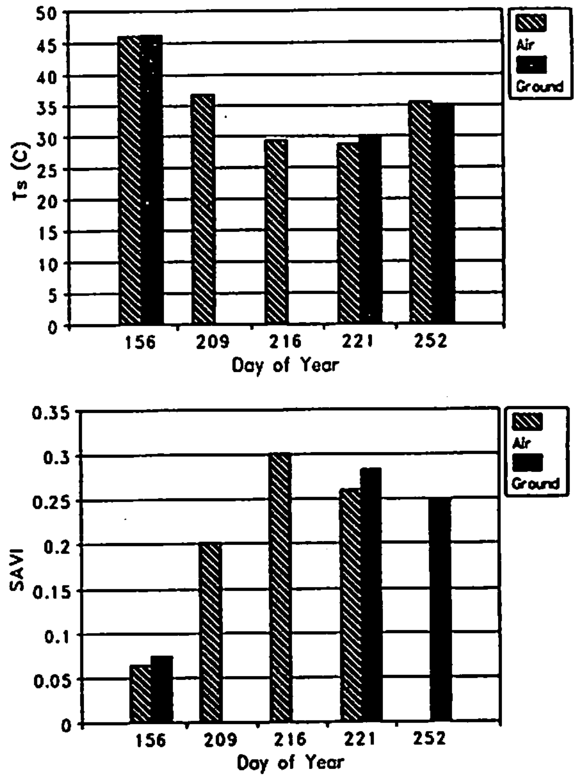

Figure 1. Surface temperature (T_s) and soil-adjusted vegetation index (SAVI) measured with ground- and aircraft-based sensors at the Kendall METFLUX site (MF5).

Aircraft-based surface temperature and SAVI data for 8 METFLUX sites were compared for the five measurement dates (Figure 2). It was apparent that though surface temperatures changed significantly over time (a range of nearly 25°C), they varied by only 1-4 °C for these five sites on a single day. The variance between values on a given day was greatest when soil moisture was lowest (e.g., DOYs 156 and 209), and was least on DOY 216, immediately after a rainfall event. This was due to the damping effect of soil moisture on surface temperature variation. On the other hand, SAVI varied significantly with time and space during the monsoon season. On DOYs 216 and 221, the vegetation density had not noticeably changed from the previous measurement date (DOY 209), however the range of SAVI values was noticeably larger. This variation in SAVI was possibly due to surface differences caused by localized rainfall events on DOY 215 and several days of drying from DOY 216 to 221.

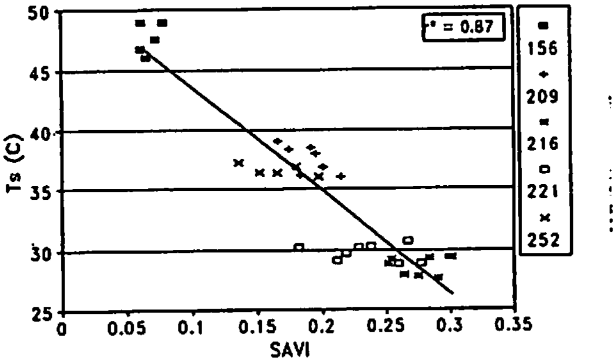

Figure 2. Comparison between surface temperature measurements (T_s) and the soil-adjusted vegetation index (SAVI) for eight METFLUX sites over five measurement dates: days 156, 209, 216, 221 and 252.

For all METFLUX sites and all possible measurement days (DOYs 156, 209, 216, 221 and 252), there was a strong correlation between surface temperature and SAVI ($r^2 = 0.87$), indicating the sensitivity of both values to similar surface characteristics (Figure 2). Since the relationship was inversely proportional (SAVI increased with decreasing T_s), it is conceivable that a combination of the two values, such as a ratio, could enhance the individual discriminatory powers of each value. This hypothesis will be explored in later sections.

3.2 Vegetation Cover

The relation between SAVI and percent vegetation cover was positive but weak for the limited period during which data were available (Figure 3). The weak relationship could be due to the difficulty of making quantitative estimates of vegetation cover at shrub- and grass-dominated sites. Vegetation is generally not uniformly distributed and conventional methods for computing vegetation cover along multiple transects can lead to bias. These cover estimates are currently being recomputed to account for the non-uniform distribution of vegetation at these sites. This situation illustrates the inherent advantage of remotely sensed data for estimation of local and regional surface characteristics. Spectral data acquired at aircraft and satellite altitudes can provide integrated measurements of surface conditions.

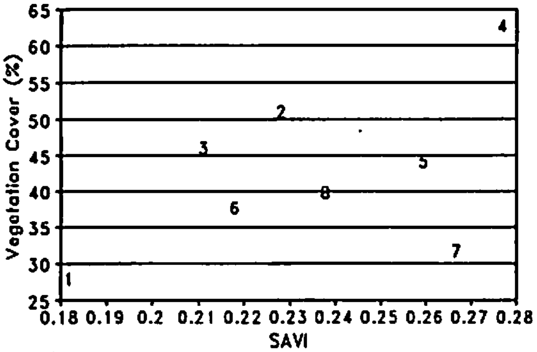

Figure 3. The soil-adjusted vegetation index (SAVI) and percent vegetation cover at all eight METFLUX sites (labeled 1-8) on day of year 221.

3.3 Soil Moisture

Volumetric moisture content of the soil at 0-5 cm depth was measured daily at each METFLUX site during the July-August field campaign at the peak of the monsoon season. This 2-week period provided an opportunity to examine the influence of soil moisture on spectral data during a period when vegetation growth was stable and soil moisture content was temporally and spatially variable. For DOYs 209, 216 and 221, radiometric surface temperature measurements followed a curvilinear trend with soil moisture content (Figure 4A). Though the relation was significant, there was a considerable amount of scatter along the curve. Some of this scatter was minimized and a better least-squares fit was obtained when T_s was normalized for differences in air temperature (T_a) (Figure 4B).

The SAVI was also found to be significantly correlated with soil moisture content ($r^2 = 0.80$), following a more linear trend (Figure 4C). It appeared that either the SAVI was sensitive to soil background reflectance despite the soil-adjustment, or the SAVI was detecting changes in leaf turgor due to increases in available soil water. In any case, considering that both T_s and SAVI were correlated with soil moisture, an attempt was made to correlate soil moisture with the ratio of T_s-T_a and SAVI (Figure 4D). Though the ratio did not provide a *statistically* significant improvement over the relation with T_s-T_a alone ($r^2 = 0.86$ for both regressions), there was a detectable decrease in the scatter of data for DOYs 209 and 216 from Figure 4B to Figure 4D.

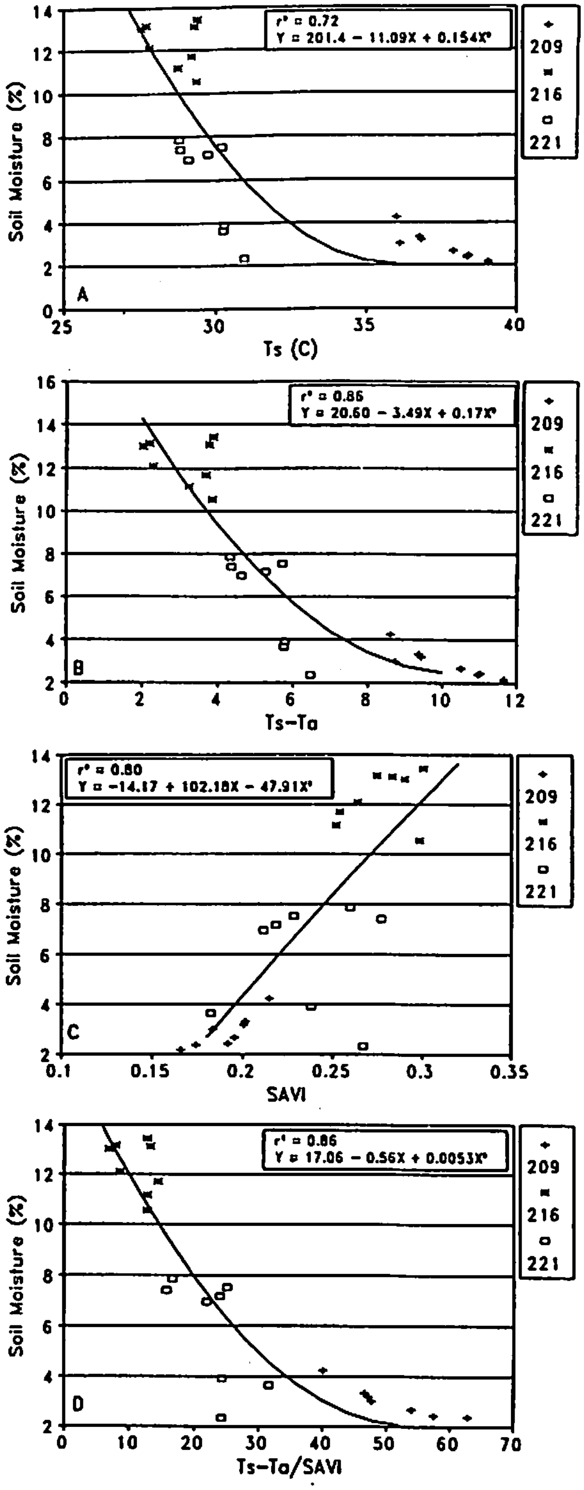

Figure 4. Relations between volumetric soil moisture content and four spectral measurements: A) surface temperature (T_s), B) surface - air temperature (T_s-T_a), C) soil-adjusted vegetation index (SAVI) and D) T_s-T_a/SAVI.

Though an attempt was made to fit a least-squares relation to these data (Figures 4A-4D), the shape of the curve is still uncertain. This data set provides only a small sample of the range of soil moisture contents and surface temperatures that are possible at this location. For example, in a similar experiment conducted on bare soil in central Arizona, Idso et al. (1975) found that there was a *linear* relation between T_s-T_a and volumetric soil water content (0-4 cm depth) over the range from 0 to 32%.

3.4 Daily Evaporation

An expression relating daily surface evaporation (E_d) to T_s-T_a was developed by Jackson et al. (1977) based on a simplification of Eq. (1),

$$E_d = R_{nd} - B(T_s - T_a), \tag{3}$$

where B is an empirical constant. They suggested that it was better to use the relation for E_d and T_s-T_a alone rather than to use a seasonal average value of R_n in Eq. (3), thus simplifying the equation to a linear fit between E_d and T_s-T_a.

A linear relation ($r^2 = 0.82$) was derived for the values E_d and T_s-T_a measured at eight METFLUX stations during the dry and monsoon seasons (Figure 5A). The systematic scatter of data in Figure 5A was apparently related to differences between dates rather than between the METFLUX sites on a given day, perhaps due to differences in the time of day the T_s-T_a measurements were made. Data were acquired on each date at ≈1000h ± 30 minutes due to weather and instrument constraints.

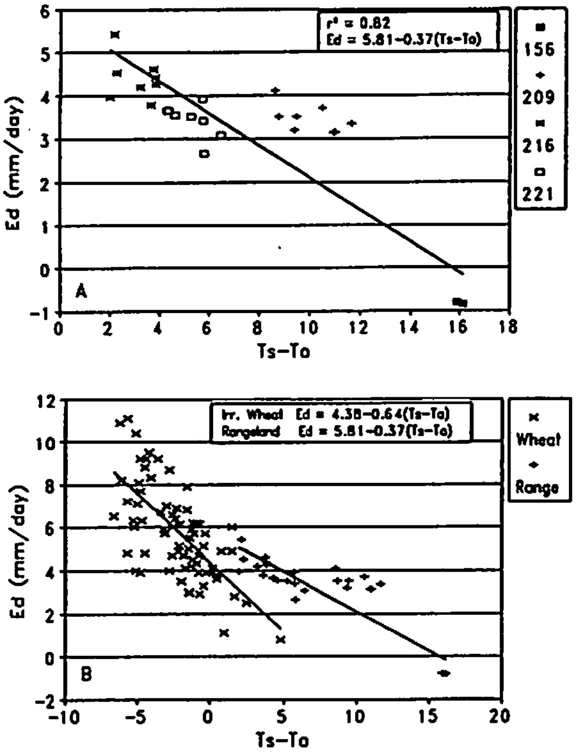

Figure 5. A) Relation between daily surface evaporation rate (mm/day) and surface-air temperatures (T_s-T_a) for the eight METFLUX sites on days 156, 209, 216 and 221. B) Comparison of the rangeland data illustrated in Figure 5A with similar measurements in irrigated wheat published by Jackson et al. (1977).

A comparison of this relation with the relation derived by Jackson et al. (1977) for irrigated wheat (Figure 5B) emphasizes the importance of reevaluating the empirical equation for rangelands conditions. If the relation for irrigated wheat (derived for T_s-T_a < 5.0) had been extrapolated for use at the Walnut Gulch site (where T_s-T_a ranged from 2.0 to 17.0), the error in estimates of E_d could have been as large as 5.5 mm/day. In fact, this data set supports the opinion that the relation for stable conditions (when T_s-T_a<0) is different than for unstable conditions (when T_s-T_a>0) (Seguin and Itier, 1983). Nevertheless, it appears possible to develop a simple relation such as (3) that would be useful for estimating evaporation from rangelands.

4. CONCLUDING REMARKS

Significant relationships were found between aircraft-based spectral data and the hydrologic factors of soil moisture and daily evaporation for a semiarid rangeland site. The relations differed in shape and magnitude from those determined previously for irrigated agricultural targets. These results emphasized the need for reevaluation of common empirical equations for application to rangeland areas. Considering that rangeland covers over 30% of the earth's land surface, this reevaluation is essential in order to provide the spatially-distributed information required by hydrologic models for application on a global scale.

5. ACKNOWLEDGEMENTS

The data reported here were acquired with support from the NASA Interdisciplinary Research Program in Earth Sciences (NASA Ref. Num. IDP-88-086). Thanks are due to our outstanding ground crew, led by Tom Clarke, to our pilot, David Ammon, and to Paul Pinter for operating this airborne system along with his own instrumentation.

6. REFERENCES

Brutsaert, W., 1982: *Evaporation into the Atmosphere.* D. Reidel Dordrecht, Holland. 299 p.

Huete, A.R., 1988: A soil-adjusted vegetation index (SAVI). *Remote Sens. Environ.* 27,47-57.

Idso, S.B., T.J. Schmugge, R.D. Jackson and R.J. Reginato, 1975: The utility of surface temperature measurements for the remote sensing of surface soil water status. *J. of Geophys. Resear.* 80,3044-3049.

Jackson, R.D., 1982: Canopy temperature and crop water stress, IN *Advances in Irrigation*, D.I. Hillel (ed.), Academic Press, p. 43-85.

Jackson, R.D., 1985: Evaluating evapotranspiration at local and regional scales. *Proc. IEEE* 73,1086-1096.

Jackson, R.D., R.J. Reginato and S.B. Idso, 1977: Wheat canopy temperature: a practical tool for evaluating water requirements. *Water Resour. Res.* 13,651-656.

Kustas, W.P., D.C. Goodrich, M.S. Moran, S.A. Amer, J.H. Blanford, L.E. Hipps, T.J. Jackson, R. Parry, T.J. Schmugge, A.M. Shutko and D.I. Stannard, 1991: An interdisciplinary field study of the energy and water fluxes in the atmosphere-biosphere system over semiarid rangelands: description and some preliminary results. *to be published in Bull. Amer. Meteorol. Soc.*

Moran, M.S., W.P. Kustas, A. Vidal, D.I. Stannard and J. Blanford, 1991: Use of ground-based remotely sensed data for surface energy balance calculations during Monsoon'90. *to be published in Proc. IEEE Geosci. and Rem. Sens. Symp.* Helsinki, Finland, 3-6 June 1991.

Rosema, A., 1990: Comparison of Meteosat-based rainfall and evapotranspiration mapping in the Sahel region. *Int. J. Rem. Sens.* 11,2299-2309.

Seguin, B. and B. Itier, 1983: Using midday surface temperature to estimate daily evaporation from satellite thermal IR data. *Int. J. Rem. Sens.* 4,371-383.

Sellers, P.J., Y. Mintz, C. Sud and A. Dalcher, 1986: A simple biosphere model (SiB) for use within general circulation models. *J. Atmos. Sci.* 43,505-531.

Taylor, S.E., 1979: Measured emissivity of soils in the Southeast United States. *Rem. Sens. Environ.* 8,359-364.

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