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Evaluating Energy Balance of Semiarid Rangeland from Combined Optical-Microwave Remote Sensing

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Introduction

Estimation of the energy fluxes of vegetated surfaces is of great interest for hydrology and climatology. Surface energy transfer models provide a means of estimating surface energy flux based on vegetation and soil information, such as plant density, structure and soil moisture. However, the detailed site information required as input to these models is generally not known and it is impractical to measure these inputs at regional scales using conventional techniques. On the other hand, it may be possible to use optical (visible to thermal infrared spectrum) and active microwave (SAR: Synthetic Aperture Radar) remote sensing data obtained from satellite-based sensors to provide simultaneous vegetation and soil information for input to such models. Specifically, SAR data can be used to estimate the soil moisture at the 0-5 cm level, which can be related to the soil minus air temperature (T_s-T_a). If T_a and (T_s-T_a) are known, and if the composite soil-vegetation temperature is obtained from thermal infrared measurements, the vegetation surface temperature can be deduced from soil and vegetation proportions and thus energy fluxes can be estimated. An experiment, referred to as WG'92, was conducted to investigate the use of satellite-based optical and microwave data in combination with physical models for characterization of seasonal land surface and hydrologic variations of the USDA-ARS Walnut Gulch (WG) experimental watershed in southeastern Arizona during the 1992 dry and monsoon (wet) seasons. The limited results presented here cover the use of combined microwave and thermal-infrared airborne and satellite data to estimate the sensible heat flux density, H, over the sparsely-vegetated rangeland watershed.

Experimental Design

The WG'92 experiment was conducted during the dry, early-monsoon, mid-monsoon, post-monsoon and "drying" seasons (from April through November 1992). The experiment was designed to acquire remotely sensed data in the visible, near-infrared (NIR), thermal and microwave wavelengths from a variety of ground, aircraft and satellite platforms, with concurrent measurements of soil moisture, vegetation growth, and energy and water fluxes (summarized in Table 1). The WG site was chosen due to a history of hydrologic remote sensing experiments (Kustas et al., 1991) and extensive hydrologic instrumentation (Renard, 1970).

Though aircraft and satellite coverage extended over the entire watershed, most ground-based measurements were limited to eight sites within the watershed, originally termed Metflux (MF) sites by Kustas et al. (1991). During 1992, only two of the eight Metflux sites actually contained instrumentation for measuring both general meteorological conditions and estimating the surface energy balance: MF1 (Lucky Hills subwatershed) was located in a brush-dominated ecosystem and MF5 (Kendall subwatershed) was in a hilly, grass-dominated subwatershed.

Table 1. Summary of data acquisition and on-site field measurements, where DOY=day of year, TM=Landsat Thematic Mapper, ERS-1=ERS-1 Synthetic Aperture Radar, OD=atmospheric optical depth, RP=radiosonde atmospheric profile, VS=vegetation measurements at 2-6 sites, SM=gravimetric soil moisture at 4 sites, STR=ground- (G) and aircraft-based (A) measurements of surface temperature and reflectance.

DOY	Weather	TM	ERS-1	VS	OD	RP	SM	STR
114	Marginal	yes	25 Apr	21-23 Apr	yes	yes	yes	G
130	Clear		14 May		yes	yes	yes	G
146	Cloudy			27-28 May		yes	yes	G
162	Clear	yes	18 Jun		yes	yes	yes	G
178	Clear	yes		22-23 Jun		yes	yes	G
194	Good	yes		14-15,17 Jul	yes			G
210	Cloudy			28 July		yes	yes	G&A
224	Clear			11-12 Aug	yes			G
226	Marginal	yes		13 Aug	yes	yes	yes	G
242	Cloudy		27 Aug			yes		
250	Clear				yes			G&A
251	Clear				yes			G&A
258	Cloudy			15-16 Sep			yes	A
274	Clear	yes	1 Oct	30 Sep	yes	yes	yes	G&A
290	Clear			16-17 Oct	yes	yes	yes	G&A
306	Clear	yes			yes	yes	yes	G&A
322	Clear	yes		18-20 Nov	yes	yes	yes	G&A

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Meteorological-Energy Flux (Metflux) The Metflux stations at Lucky Hills and Kendall provided measurements of net radiation, air temperature, surface temperature, wind speed and direction, relative humidity, solar radiation, photosynthetically active radiation (PAR), soil heat flux, soil moisture and soil temperature. The energy balance was determined by taking measurements of net radiation (R_n), soil heat flux density (G), and the temporal variance of air temperature, which was used in computing sensible heat flux density (H) and solving for latent heat flux density (LE) as a residual, i.e., $LE = -(R_n-G-H)$, where fluxes away from the surface are negative. The instrumentation and theoretical foundation for these stations were described in detail by Kustas et al. (1991).

Vegetation and Soils At the Kendall site, monthly measurements of vegetation cover, vegetation height and volume by species, total leaf area index (LAI) and biomass, litter, and plant water content were made throughout the experimental period in grazed and ungrazed sites with both south- and north-facing slopes. During the period of peak vegetation cover (mid-September), vegetation measurements were also made at five of the eight Metflux sites in addition to the Kendall site.

Gravimetric soil moisture samples of the upper 5 cm (three replications) were collected at four representative Metflux sites during each satellite overpass. At the Kendall and Lucky Hills sites, soil-moisture resistance sensors were used to automatically measure near-surface soil moisture at hourly intervals. Data on the vertical distribution of soil moisture and temperature were collected every two-weeks at Kendall and Lucky Hills using time domain reflectometry (TDR) and copper-constantan thermocouples, respectively.

Remotely Sensed Spectral Data Ground-based observations of surface reflectance and temperature were made over designated areas at the Kendall site using Exotech[1] 4-band radiometers, a Barnes Modular Multispectral Radiometer (MMR) and Everest infrared thermometers (IRT) during the satellite overpasses. The ground target covered a large area (480mx120m) over both north- and south-facing slopes representing multiple resolution cells (pixels) of the satellite-based sensors. Radiometers were mounted in portable yokes at a height of 2 m (resulting in a spatial resolution of about 0.5 m) and deployed over a fine sampling grid resulting in nearly 400 samples over the Kendall target.

A Cessna aircraft was flown along the parallel Metflux transects with instruments including a 4-band radiometer with Landsat Thematic Mapper (TM) filters (TM1-TM4), an IRT, color video camera and occasionally a thermal-IR scanner. The aircraft flew at a nominal altitude of 100 m above ground level (resulting in a spatial resolution (a pixel) of approximately 25 m diameter on the surface) and flights were scheduled to coincide with the satellite overpass times.

Eight Landsat TM scenes and five ERS-1 SAR images were acquired to monitor the seasonal surface changes associated with the dry, monsoon and post-monsoon seasons (Table 1). The nadir-looking Landsat TM sensor has six reflective bands ranging from 0.45 to 2.35 μm with 30 m spatial resolution and one thermal band (10.42-11.66 μm) with a spatial resolution of 120 m. The ERS-1 microwave sensor has a spectral frequency of 5.3 GHz and a radiometric resolution of 2.5 Db at -18 Db (C band); sensor polarization is VV and the spatial resolution is 21.5x12.5m resampled to 30x30m.

Theory

The classical expression of the energy balance equation is based on a one-dimensional formulation that can be applied to continuous canopy. In the case of a sparse canopy, it is necessary to take into account the exchanges between the different levels of the soil-vegetation-atmosphere continuum. This can be done by using multi-layer models in which each layer is a surface for which exchanges can be expressed as a single layer. Our approach is based on a two-layer model (soil and vegetation) similar to the one proposed by Shuttleworth and Wallace (1985).

This model is based on a system of temperatures and resistances between soil, vegetation canopy and air mass (s, c and a, corresponding respectively to soil, canopy and air) controlling sensible heat flux densities between the different layers. The sensible heat flux density can be expressed as

$$H = \rho Cp[(T_c-T_a)/r_c+(T_s-T_a)/r_s]/[1+r_a/r_c+r_a/r_s] \quad (1)$$

in units (W/m^2), where ρCp is the volumetric heat capacity of air, and T and r are temperature and resistance, respectively. The different resistances can be estimated using expressions from Mahrt and Ek (1984) and Shuttleworth and Wallace (1985).

Results and Discussion

Based on preliminary examination of the seasonal trends in the optical data (Figure 1), it appears that the 8-month experiment succeeded in covering a wide range of vegetation cover and soil moisture conditions. The peaks and dips in the simple ratio (SR) of NIR and red reflectance at the Kendall site correspond to variations in vegetation associated with the warm, rainy seasons in the spring and late summer, the dry, hot summer and the dry, cool conditions in late fall (Figure 1a). Variations in surface-air temperature (T_s-T_a) correspond to variations in both plant cover and surface soil moisture conditions (Figure 1b).

Backscattering coefficients σ_o were derived from georeferenced ERS-1 SAR data acquired on the WG watershed on days 116, 135, 170, 240 and 275, using the following equation,

$$\sigma_o = 10\log_{10}(DN^2) + K + 10\log_{10}(\sin\theta_s/\sin\theta_{ref}) \quad (2)$$

in units (dB), where DN^2 is the average value of squared digital numbers DN obtained on each 120x120m Metflux site, K is a calibration constant, θ is the satellite incidence angle for the central pixel of the plot and θ_{ref} is the satellite incidence angle for the center of the ERS-1 image (23°).

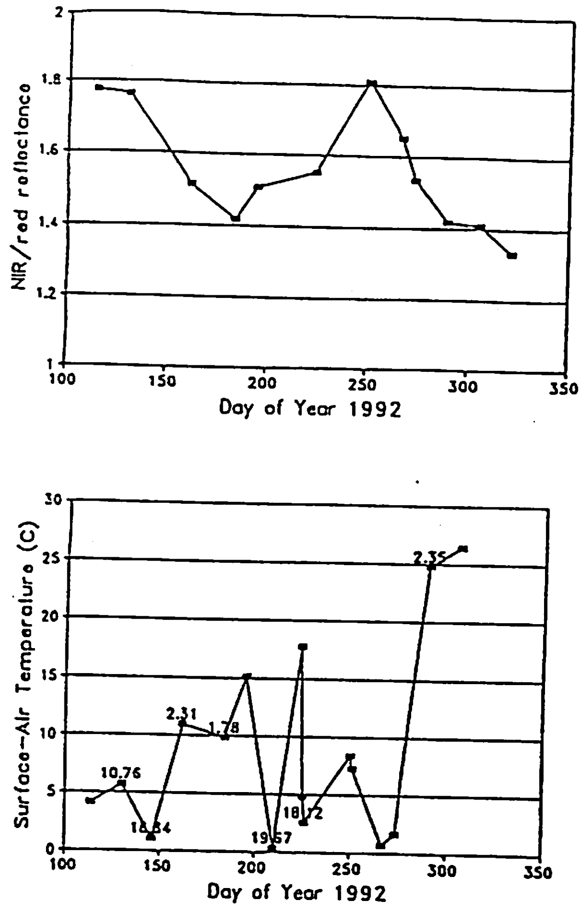

Figure 1. Seasonal trends of a) the simple ratio (SR) of NIR and red reflectance and b) the surface-air (T_s-T_a) temperatures (C) at the grass-dominated Kendall site at Walnut Gulch Experimental Watershed. For 1b, volumetric soil moisture data (%) were listed with several data points.

Constant K was estimated from data obtained by the NASA/JPL airborne SAR instrument (AIRSAR) on WG during the Monsoon'90 experiment (Dubois et al., 1990). AIRSAR backscatter coefficients obtained on each Metflux site on 1 August 1990 were averaged and used as a reference for ERS-1 backscatter coefficients obtained on day 135, with similar soil moisture conditions (0-5 cm volumetric soil water content near 5%). The value obtained was K = -71.34 dB. Figure 2 shows the evolution of σ_0 on several Metflux sites during WG'92. There were similar trends for all the sites except MF3, possibly due to the dense succulent shrub vegetation that may have exhibited a different water-holding capacity.

The value σ_0 may be correlated to surface soil moisture (0-5 cm), but since few soil samples were processed at this time, we preferred to find a direct correlation between σ_0 and (T_s-T_a), which was actually the variable we would use in estimations of H. The T_s was derived for each day from the 0.5m-resolution, yoke-based spectral measurements at

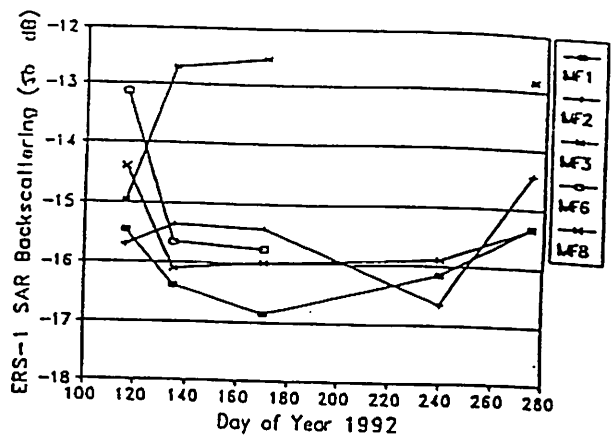

Figure 2. Evolution of ERS-1 SAR backscattering coefficients σ_0 on Metflux sites 1,2,3,6 and 8 during WG'92. All sites have similar behaviors except site MF3, possibly due to a higher shrub density.

the Kendall site by assuming that the yoke-based sample with 1) lowest spectral vegetation index and 2) highest surface temperature was likely bare, dry soil. Since the Kendall site was not covered by all the ERS-1 scenes, maximal (T_s-T_a) differences were derived from the Kendall yoke-based measurements and correlated to the minimal backscattering coefficients of a 30x30 pixel with characteristics similar to Kendall, but covered by all the scenes. The results are shown in Figure 3, and yield the following empirical relation (r^2=0.87)

$$T_s - T_a = -3.78\sigma_0 - 47.7 \qquad (3)$$

in units (°C), where T_s is the soil surface temperature and T_a is the air temperature at 2m.

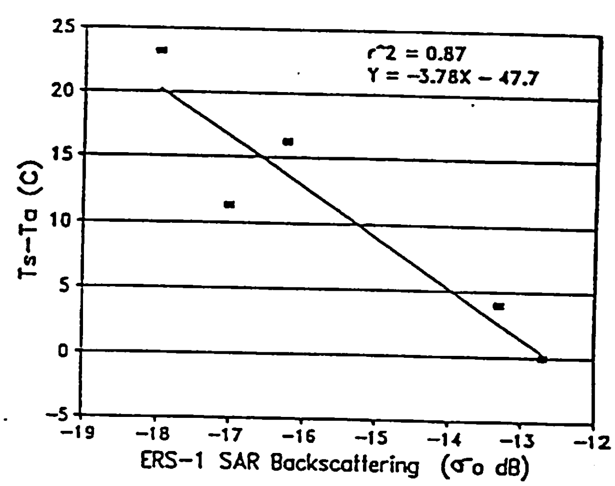

Figure 3. Relation between calibrated ERS-1 SAR backscattering coefficients σ_0 and the soil surface minus air temperature difference on Lucky Hills during WG'92. The line corresponds to the regression equation.

Measurements of H were obtained at the Lucky Hills and Kendall sites using the Metflux station instrumentation. On days when one or two of these sites were covered by the ERS-1 scenes, SAR-derived T_s-T_a values were used to estimate H by combining Landsat TM-derived composite temperature in a two-layer model using Eq. (1). Data of the Monsoon'90 experiment (Kustas et al., 1991), especially the NASA/JPL AIRSAR data, were also integrated in this data set, yielding estimated H values for 7 Metflux sites on day 213 of 1990.

Results of the comparison between values of measured fluxes with remotely-sensed estimates (Figure 4) were satisfactory, yielding an overall root mean squared error (RMSE) of 39 W/m^2 over a range of H values from 100 to 210 W/m^2. Though the estimated H values were similar to the measured H values, the scatter about the 1:1 line was significant and differences at times were nearly 80 W/m^2. Furthermore, there was a tendency to underestimate the fluxes for the available 1992 data. These preliminary results will likely be improved with the ultimate inclusion of the entire WG'92 data set and the consequent increase in the range of measured T_s and H values.

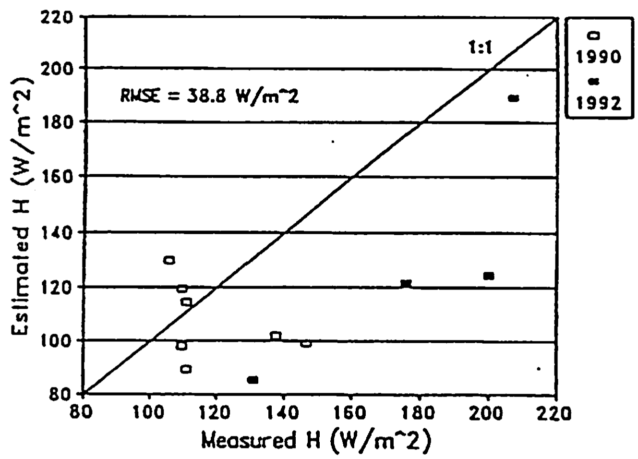

Figure 4. Comparison of remotely-sensed sensible heat flux H vs. measured H, during WG'92 (Metflux sites 1 and 5 on day 116 and Metflux site 1 on days 170 and 275) and Monsoon'90 (7 Metflux sites on day 213).

Concluding Remarks

- Active microwave data from ERS-1 SAR can be used to estimate the soil minus air temperature (T_s-T_a) of a semiarid rangeland.
- By combining estimates of (T_s-T_a) with measurements of T_a, TM-derived composite surface temperature, and spectral vegetation indices, it is possible to estimate vegetation temperature. Vegetation, soil and air temperatures can be introduced in a two-layer model based on the formalism of Shuttleworth and Wallace, to estimate the sensible heat flux density with reasonable accuracy.

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[1] The use of company names and brand names are necessary to report factually on available data; however, the authors' affiliations neither guarantee nor warrant the standard of the product, and the use of the name implies no approval of the product to the exclusion of others that may also be suitable.