Instantaneous and Daily Values of the Surface Energy Balance over Agricultural Fields Using Remote Sensing and a Reference Field in an Arid Environment

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Remotely sensed surface temperature and reflectance in the visible and near infrared wavebands along with ancillary meteorological data provide the capability of computing three of the four surface energy balance components (i.e., net radiation, soil heat flux, and sensible heat flux) at different spatial and temporal scales. As a result, under nonadvective conditions, this enables the estimation of the remaining term (i.e., the latent heat flux). One of the practical applications with this approach is to produce evapotranspiration (ET) maps for agricultural regions which consist of an array of fields containing different crops at varying stages of growth and soil moisture conditions. Such a situation exists in the semiarid southwest at the University of Arizona Maricopa Agricultural Cen-
ter, south of Phoenix. For one day (14 June 1987), surface temperature and reflectance measurements from an aircraft 150 m above ground level (agl) were acquired over fields from zero to nearly full cover at four times between 1000 MST and 1130 MST. The diurnal pattern of the surface energy balance was measured over four fields, which included alfalfa at 60% cover, furrowed cotton at 20% and 30% cover, and partially plowed wheat stubble. Instantaneous and daily values of ET were estimated for a representative area around each flux site with an energy balance model that relies on a reference ET. This reference value was determined with remotely sensed data and several meteorological inputs. The reference ET was adjusted to account for the different surface conditions in the other fields using only remotely sensed variables. A comparison with the flux measurements suggests the model has difficulties with partial canopy conditions, especially related to the estimation of the sensible heat flux. The resulting errors for instantaneous ET were on the order of 100 W m\(^{-2}\) and for daily values of order 2 mm day\(^{-1}\). These findings suggest future research should involve development of methods to account for the variability of meteorological parameters brought about by changes in surface conditions and improvements in the modeling of sensible heat transfer across the surface-atmosphere interface for partial canopy conditions using remote sensing information.

INTRODUCTION

The use of infrared thermometry (Fuchs and Tanner, 1966) to infer the partitioning of radiant energy into the three basic components, i.e., sensible (H), latent (LE), and soil (G) heat flux densities, has been tested using models with varying degrees of complexity. For a review of various approaches, see, for example, Carlson (1986) and Jackson (1985).

Although in recent years some sophisticated models are being used in an operational mode (e.g., Sellers and Dorman, 1987), the amount of information required and the fine tuning of some of the physical parameters may make it difficult to implement in areas where there is limited meteorological, plant physiological, and soils information. On the other hand, the accuracy of simpler empirically based (Jackson et al., 1977) and theoretically based (e.g., Price, 1982) energy balance models, which require appreciably smaller amounts of ground information and are much easier computationally, must be weighted against the accuracy needed.

Clearly, the main objective of these models is to calculate the latent heat flux density, commonly called evapotranspiration (ET) and expressed in mm of water, over an area. The magnitude of ET relative to the other main energy balance components has a broad range of applications in plant physiology and irrigation practices (Jackson, 1982) and to regional and global scale hydrology and meteorology (Brutsaert, 1988; Shuttleworth, 1988; Roundtree and Bolton, 1983).

This paper will focus on an approach which solves for ET as the residual in the energy balance equation (Brown and Rosenberg, 1973; Verma et al., 1976), i.e.,

\[
\text{LE} = \text{R}_n - G - H. \tag{1}
\]

Estimates of \(\text{R}_n\) and \(G\) either come from micro-meteorological measurements or from a combination of commonly available meteorological data and remote sensing information in the visible, near-infrared, and thermal wavelengths (e.g., Jackson et al., 1987). In fact, recent developments in the latter approach may provide estimates of \(\text{R}_n\) and \(G\) with primarily remotely sensed information (Clothier et al., 1986; Jackson et al., 1985). Attempts, however, to provide a simplified parametrization for estimating sensible heat flux have not been as successful because of the relatively strong dependence of the heat transfer coefficient on various surface and meteorological conditions (e.g., Hatfield et al., 1983a; Seguin and Itier, 1983). Consequently, computing reliable values of \(H\) represents the most formidable obstacle in the residual method [i.e., Eq. (1)].

For many applications, accurate values of daily ET are necessary from field scale (of order 10\(^4\) m\(^2\)) to mesoscale (of order 10\(^2\) km\(^2\)). However, remotely sensed data from aircraft and satellite altitudes are essentially instantaneous and may only be available once or twice a day. This has resulted in the development of methods which integrate (1) over the whole day (e.g., Gurney and Camillo, 1984; Jackson et al., 1983; Soer, 1980; Taconet et al., 1986).
One of the forms most easily applicable for computing daily ET comes from simply assuming the difference in daily values of latent heat flux and net radiation is linearly related to the surface–air temperature difference determined around solar noon (Jackson et al., 1977):

$$LE_d - Rn_d = A - B(T_s - T_a)$$  \(2\)

where A and B are constants and $LE_d$ and $Rn_d$ are daily values of LE and Rn, $T_a$ is the air temperature at screen height, and $T_s$ is the remotely sensed surface temperature. Although appearing totally empirical in nature, Seguin and Itier (1983) showed that for clear sky conditions (2) does have a theoretical basis, and is actually a semiempirical equation. Seguin and Itier’s (1983) work has been more recently supported by Rambal et al. (1985), Seguin et al. (1986), and Brunel (1989). Others have used a similar form to (2), but have replaced the surface–air temperature difference and the quantity on the right-hand side of (2) by using a reference crop transpiring at the potential rate (Nieuwenhuis et al., 1985),

$$LE_d = LE_{rd} - B'(T_s - T_{sr})$$  \(3\)

where $LE_{rd}$ is daily evapotranspiration and $T_{sr}$ is the surface temperature from a reference crop.

Equation (3) was developed because, in many agricultural areas, fields are arranged in a checkerboard fashion having different vegetation types, in a range of growing stages and soil moisture conditions. Hence, the capability of computing ET for various fields with the same basic meteorological parameters measured 1–3 m above the surface is not realizable with only ground-based instrumentation.

Although remote sensing may provide information relating to ET at the field scale, (e.g., vegetation indices, surface temperature, albedo) local meteorological conditions (i.e., near surface windspeed, air temperature, and stability) cannot be assessed with remote sensing. The approximations and possible errors involved in extrapolating (2) and (3) to areas with different meteorological and surface conditions has been treated analytically by Gash (1987).

In this paper, an attempt is made to calculate instantaneous and daily values of the latent heat flux over several agricultural fields in Maricopa by solving for $LE$ as a residual in the surface energy balance equation (1), using a reference evapotranspiration and a simplified version of the analytical expression derived by Gash (1987). In addition, the data are used to determine the constants A and B in Eq. (2). The fields which had point measurements of the surface energy balance consisted of actively transpiring alfalfa at roughly 60% cover, furrowed cotton crops at 20% and 30% cover, and a partially plowed wheat stubble field.

**THEORY**

Gash (1987) related the horizontal changes in surface temperature and other surface and meteorological conditions to changes in ET; hence, a reference evaporation is used to extrapolate small perturbations of the terms in (1). Put more simply, deviations from the reference energy balance components can be employed to infer LE over another surface. This is represented by the following equation:

$$LE = LE_r + (Rn - Rn_r) - (G - G_r) - (H - H_r)$$  \(4\)

where the subscript $r$ delineates the reference values. The differences in the components on the right-hand side of (4) are expanded in terms of remote sensing and meteorological variables. For net radiation the equation reads

$$Rn - Rn_r = (\alpha_a - \alpha_s)R_s - \sigma(\varepsilon_sT_s^4 - \varepsilon_{sr}T_{sr}^4 - \varepsilon_aT_a^4 + \varepsilon_{ar}T_{ar}^4)$$  \(5\)

where $R_s$ is incoming solar radiation and is assumed to have little horizontal variation, $\alpha_s$ the surface albedo, $\sigma$ the Stefan–Boltzmann constant ($5.67 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$), $\varepsilon_a$ atmospheric or sky emissivity, and $\varepsilon_s$ the surface emissivity. The subscript $r$ refers to the reference values. As a first approximation, differences in $T_a$ and $\varepsilon_s$ were neglected. Thus (5) reduces to

$$Rn - Rn_r = (\alpha_s - \alpha_a)R_s - \sigma\varepsilon_s(T_s^4 - T_{sr}^4)$$  \(6\)

with $R_s$ obtained from ground-based measurements, $\varepsilon_s$ (= 0.98) estimated by a procedure outlined in Fuchs and Tanner (1966), and $\alpha_s$ and $T_s$ estimated with remotely sensed data. Surface temperatures were measured from a nadir-looking thermal infrared radiometer whereas surface albedos were computed with the visible and near-infrared reflectance data and the expressions from Brest and Goward (1987).
Differences in soil heat flux were computed using the results of Clothier et al. (1986) and Kustas and Daughtry (1990), whereby $G = c R_n$ and $c$ is a function of a vegetation index, either near-infrared/red reflectance ratio or the normalized difference (ND) [(near-infrared − red)/(near-infrared + red)]. Therefore, using (6), the expression for differences in soil heat flux is

$$G - G_r = \left[ (1 - \alpha_s) - c_r (1 - \alpha_{sr}) \right] R_s \tag{7}$$

With the above approximations for computing horizontal changes in $R_n$ and $G$, little ancillary meteorological data are needed, except for air temperature and vapor pressure to calculate atmospheric longwave component of net radiation for the reference field (e.g., Hatfield et al., 1983b).

On the other hand, the change in sensible heat flux requires more serious assumptions because of its dependence upon the type of surface, that is, the size or height of the vegetation (Gash, 1987; Serafini, 1987), and the meteorological conditions (Hatfield et al., 1983a). The one-dimensional bulk resistance equation (also called single-layer formulation) computes $H$ with the surface–air temperature difference, i.e.,

$$H = \frac{\rho C_p (T_a - T_r)}{r_{ah}} \tag{8}$$

where $\rho$ is the air density (kg m$^{-3}$), $C_p$ the specific heat of air at constant pressure, and $r_{ah}$ is the bulk resistance to heat transfer. The magnitude of $r_{ah}$ depends on momentum and scalar roughness parameters, atmospheric stability, and wind speed (Brutsaert, 1982). However, for sparse canopy cover, recent evidence (Kustas et al., 1987; Stewart et al., 1989) has shown that the bulk transfer relationship using infrared surface temperature produces significant errors, suggesting that a single-layer resistance formulation is inappropriate.

The finite difference form of the bulk resistance equation (8) representing the change in sensible heat flux from the reference value in (4) is (Gash, 1987)

$$H - H_r = \frac{\rho C_p}{r_{ahr}} \left[ \frac{1}{r_{ahr}} (T_{ar} - T_{sr})(r_{ah} - r_{ahr}) \right] \frac{1}{r_{ahr}} (T_{sr} - T_{ar}) + (T_{a} - T_{ar}) \right], \tag{9}$$

where the subscript $r$ signifies values of the reference site.

Under nonadvective conditions with most of the net radiation in the reference field converted to ET, then $T_{sr} - T_{sr} \approx 0$. Also, from the assumptions in reducing the expression for $R_n - R_{nr}$ [cf. Eq. (6)], then $T_{a} - T_{ar} \approx T_{a} - T_{sr}$ and Eq. (9) reduces to

$$H - H_r = \rho C_p \frac{1}{r_{ahr}} (T_s - T_{sr}). \tag{10}$$

From all the above approximations, deviations in the reference energy balance components given by (4) in expanded form are obtained by combining the approximations for $R_n - R_{nr}$, $G - G_r$, and $H - H_r$, namely, Eqs. (6), (7), and (10), respectively:

$$LE = LE_r + \left[ (1 - c_r) \alpha_{sr} - (1 - c) \alpha_s + c_r - c \right] R_s \tag{11}$$

$$- \sigma \varepsilon_s \left[ (1 - c) T_s^4 - (1 - c_r) T_{sr}^4 \right]$$

$$- \frac{\rho C_p}{r_{ahr}} (T_s - T_{sr}),$$

where $\alpha$ is determined from the formulas (Brest and Goward, 1987)

$$\alpha = 0.526(\text{VIS}) + 0.326(\text{NIR}) + 0.112(0.5 \text{NIR}) \tag{12a}$$

for a vegetated surface and for sparse or bare soil surface

$$\alpha = 0.526(\text{VIS}) + 0.474(\text{NIR}) \tag{12b}$$

where VIS and NIR represent reflectance data collected in the visible (usually red waveband) and near-infrared wavebands, and the quantity 0.5 NIR approximates the mid-infrared value if one is not available. The value of $c$ is estimated from the findings by Kustas and Daughtry (1990),

$$c = 0.29 - 0.016 (\text{NIR}/\text{red}). \tag{13}$$

Equation (13) relates the midday ratio $G/R_n$ to the amount of vegetation cover, which from many field experiments appears to range from around 0.3 for bare soil to 0.05 for full cover. The value of $r_{ahr}$ or the resistance to heat transfer from the reference field could not be determined with stability corrected log law for wind and temperature due to unusually low windspeed observations (Panofsky and Dutton, 1984). Therefore, an equation by Thom and Oliver (1977) that maintains a solution for low windspeeds and the semi-empirical equations given by Mahrt and Ek (1984) which account for stability effects even for low windspeeds were tried. The Thom and Oliver (1977) equation was adjusted for differences in transfer processes of heat and momentum close to
the surface (Garratt, 1978). This yields

$$r_{ah} = 4.72 \ln \left( \frac{(z - d_0 + z_o)}{z_o} \right) \left\{ \ln \left( \frac{(z - d_0 + z_o)}{z_o} \right) + 2.5 \right\}$$

$$× \left( 1 + 0.54 \frac{u}{z_0} \right)$$

(14)

where $u$ is the windspeed measured at height $z$ and $d_0$ and $z_o$ are the displacement height and roughness length for momentum, respectively. The factor 2.5 accounts for the smaller roughness length for heat observed in past studies (e.g., Heilman and Kanemasu, 1976). Since the reference field was over 60% cover, both $d_0$ and $z_o$ were computed as a fraction of canopy height as summarized in Brutsaert (1982), namely, $d_o = 0.67h$ and $z_o = 0.1h$, where $h$ is the mean canopy height.

The equations given by Mahrt and Ek (1984) were inverted to yield the resistance as defined in (8)

$$r_{ah} = \left\{ \ln \left( \frac{(z - d_0 + z_o)}{z_o} \right) \right\} \left( 1 + 15R_i \right) \left( 1 + 5R_i \right) \frac{1}{u}$$

(15a)

for the stable case (i.e., $T_s - T_a < 0$), and for the unstable case ($T_s - T_a > 0$),

$$r_{ah} = \left\{ \ln \left( \frac{(z - d_0 + z_o)}{z_o} \right) \right\} \left( 1 + C(1 - R_i) \right) \frac{1}{u}$$

(15b)

where $C = 75k' \ln\left( \frac{(z - d_0 + z_o)}{z_0} \right) / \ln\left( \frac{(z - d_0 + z_o)}{z_0} \right)^2$ and $R_i = g(z - d_0)/(T_a^2)$ is a bulk Richardson number. Note that here $r_{ah}$ does not account for differences in resistance to momentum and heat transfer, but will be assumed to be a good approximation since it is not obvious how to make adjustments to Mahrt and Ek’s formulas.

For estimating daily ET, several expressions were derived between daily values of $Rn$, $G$, and $H$ denoted as $R_{n_d}$, $G_d$, and $H_d$, respectively, and the midday “instantaneous” (i.e., 1/2-hourly averages) values from all the test sites. The ratio of $R_{n_d}/R_{n_i}$ agreed with the results of Seguin and Itier (1983), i.e.,

$$R_{n_d}/R_{n_i} \approx 0.3$$

(16)

where the subscript $i$ refers to the “instantaneous” midday values. For the ratio $G_d/R_{n_d}$,

$$G_d/R_{n_d} = -0.1 + G_i/R_{n_i}$$

(17)

with a coefficient of determination $R^2 \approx 0.75$. This result supports the commonly used approximation that for full cover $G_d/R_{n_d} \sim 0$, since $G_i/R_{n_i} \sim 0.1$ (Monteith, 1973). Finally, the quantity

$$H_d/(R_{n_d} - G_d) = -0.1 + 1.1H_i/(R_{n_i} - G_i)$$

(18)

with $R^2 \approx 0.99$. This is comparable with the findings of Brunel (1989), who found $H_d/R_{n_d} \sim H_i/R_{n_i}$.

By substituting (16), (17), and (18) into Eq. (1), which solves for LE as a residual in the energy balance expression, the daily evaporative flux can be related to the midday “instantaneous” fluxes, that is,

$$LE_d = 0.58 R_{n_i} - 0.33 G_i$$

$$-1.1H_i \left( \frac{0.33R_{n_i} - 0.3G_i}{R_{n_i} - G_i} \right)$$

(19)

This was approximated to

$$LE_d \approx \frac{1}{3} (R_{n_i} - G_i - H_i) = \frac{1}{3} \left( LE_i \right)$$

(20)

The formula from Jackson et al. (1983), which relates the temporal trend of solar radiation throughout the daylight period with the latent heat flux, was used to compare with the coefficient in (20):

$$LE_d = \frac{LE_i \left\{ 2N / [\pi \sin(\pi t / N)] \right\} }{N}$$

(21)

where $N$ is the day length and $t$ is the time starting at sunrise. For midday and for this time of year, the values of $N$ and $t$ yield

$$LE_d = 0.38 LE_i$$

(22)

The difference in the coefficient multiplying $LE_i$ in (20) and (22) is around 15%. The fact that the coefficient in (20) is lower is not surprising since (21) implicitly assumes a surface evaporating near the potential rate. Both (20) and (22) will be employed below. In addition, the daily flux values will be used in estimating the constants $A$ and $B$ in the instantaneous midday surface–air temperature difference expression given by (2).

THE DATA

Remote sensing and micrometeorological data were collected at Maricopa Agricultural Center (33.1°N latitude, 112°W longitude) approximately 48 km south of Phoenix, Arizona in June 1987. Energy balance components were measured under clear sky conditions 9–14 June 1987 or days of year (DOYs) 162–165 on agricultural fields ranging from bare soil to nearly full cover alfalfa. Figure 1
illustrates the approximate location of flux stations and a general description of the field conditions.

The Bowen ratio/energy balance and eddy correlation method was used to determine evapotranspiration at the various sites. The instruments for the Bowen ratio systems, which included psychrometers, net radiometers, and soil heat flux disks, were all the same type (AZET system), and details can be found elsewhere (Gay and Greenberg, 1985). The eddy correlation system consisted of a sonic anemometer with a path length of 10 cm, a Krypton or Lyman Alpha hygrometer and a fine wire thermocouple, all manufactured by Campbell Scientific, Inc.* Further details about the instruments can be found in Tanner (1985).

Field 29 contained 20% tilled wheat stubble and 80% standing stubble. The Bowen ratio/energy balance system was situated in the tilled area with upwind fetches of about 200 m to the north, 75 m to the south, 500 m to the east, and 1100 m

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*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 USDA.
to the west. The upper and lower psychrometers were about 1.4 m and 0.5 m above the surface, and two soil heat flow plates were buried about 1 cm below the surface and connected in parallel to yield a single average output. Net radiation was measured with a single dome net radiometer about 1.5 m above the surface.

Field 21, the reference field for model calculations, had around a 60% cover of alfalfa whose mean height was about 0.40 m. The Bowen ratio/energy balance instrument setup was very similar to the one in field 29. The location of the mast resulted in upwind fetches of 300 m to the south, 500 m to the north, 75 m to the west, and 125 m to the east. Wind speed was also measured at a height of about 2 m above the crop.

Field 13, which had east-west oriented furrows and a 1 m row spacing, had cotton plants about 0.4 m in height and 30% cover in the area surrounding the eddy correlation system. The site location resulted in an upwind fetch of about 200 m to the east and west, around 100 m to the north, and 700 m to the south. The flux instruments were positioned roughly 1.5 m above the cotton crop and both net radiation and soil heat flux were measured as well as other meteorological data (i.e., wind speed, air temperature, vapor pressure, and solar radiation). The soil heat flux was estimated by averaging three flux plates connected in series and buried at 1 cm, two in the furrow and one underneath the cotton, whereas net radiation was determined by a single dome net radiometer. It was discovered that measurements of latent flux were consistently lower than the residual method whereby \( R_n \) and \( G \) are measured and combined with measurements of \( H \) to yield values of \( LE \) [cf. Eq. (1)]. Moreover, after the area had been irrigated, the Lyman Alpha hygrometer developed

![Figure 2. Flight path of the low flying aircraft collecting spectral data.](image)
instrument problems which could not be resolved in the field. Consequently, LE estimated as a residual in the surface energy balance equation was used in the analysis presented below.

Field 28 also contained cotton with a 1 m row spacing, but furrows were oriented north–south. There was about a 20% vegetation cover and a mean crop height of about 0.30 m. The field had both a Bowen ratio/energy balance and eddy correlation system situated approximately 100 m from each other (see Fig. 1).

For the Bowen ratio/energy balance site, this resulted in an upwind fetch of about 100 m to the north, 500 m to the east, 175 m to the south, and 1100 m to the west. Two masts containing psychrometers (four in total) were placed together. One pair was approximately 0.5 m and 1 m above the crop while the second pair was at 1 m and 1.5 m. One of two net radiometers (single dome types and both at a 1.5 m height) was situated over the cotton, parallel to the north–south orientation, whereas the other was placed over the furrow, between two rows of cotton. There was good agreement in the Bowen ratio between the two masts, and there was little difference in the value of net radiation given by the two radiometers. The mean soil heat flux was estimated with a pair of soil heat flux plates buried at 1 cm underneath the canopy and the other pair buried in the furrow.

The instruments for the eddy correlation technique were about 100 m southeast of the Bowen ratio masts. This provided upwind fetches of about 150 m to the north, 120 m to the south, 450 m to the east, and 1150 m to the west. The instrument for measuring the latent heat flux was a Krypton hygrometer. The sensors were placed 2.5 m above the surface.

Comparison of LE given by the two methods was analyzed by Kunkel et al. (unpublished manuscript). Satisfactory agreement for the daytime values was obtained in two steps. First, the value of G given by the average of the heat flux plates at the Bowen ratio site was adjusted for the effects of shading on the individual plate values to yield a realistic spatial average G. This resulted in a midday value of $G/R_n$ of order 0.2, which is within the likely range given by Choudhury et al. (1987) for a leaf area index of around 0.5. Second, the value of LE measured by the eddy correlation technique was multiplied by a constant factor so that $G$ solved by (1), assuming values of $R_n$ and $H$ are correct (see Kustas et al., 1989a), would yield a midday value of $G/R_n$ of order 0.2.

For DOY 165, an aircraft flew at an altitude of about 150 m agl with sensors measuring visible, near-infrared reflectance factors with either Landsat Thematic Mapper (TM) or SPOT filters, and thermal infrared irradiance using an Everest infrared thermometer* (8–14 μm) at four times between ~1000 MST and ~1130 MST. The flight path of the aircraft is shown in Figure 2. Total coverage of the fields analyzed in this study...
took about 10 minutes, on average. Instruments were nadir viewing and had a nominal 15° field of view. This resulted in the sensors integrating over approximately a 40 m diameter circle at the surface. Atmospheric attenuation of the irradiance received by the airborne instruments was neglected. For the thermometric observations, ground-based data suggest negligible atmospheric effect at 150 m above ground level (agl) (Kustas et al., 1990). On the other hand, the reflected atmospheric longwave component could add around 1°C to the estimated surface temperature (Fuchs and Tanner, 1966). However, it was felt that errors in using uncorrected $T_s$ values were much smaller than the spatial variability in the remote sensing data (see below) and the approximations made in the Theory section for estimating LE. Plots of the near-infrared/red reflectance ratio and the thermometric observations $T_s$ from the aircraft are given in Figures 3 and 4. Note the spatial variability in these values for several of the fields. For example, in field 29, there is a substantial change in surface temperature several hundred meters from the eastern edge of the field. This is mainly attributable to the eastern portion of the field being plowed, exposing much of the soil, whereas the rest of the field contained standing wheat stubble. For field 13, $T_s$ increased from north to south. This was due to gradual irrigation starting at the northern end of the field on DOY 163.

The temporal changes in the NIR/red ratio vegetation index is relatively large for field 21. The two measurements around 1000 MST were made with the TM filters while the 1100 MST and 1125 MST observations were made with the SPOT filters. Differences in the spectral bandwidths in the red and infrared spectrum will cause some disagreement in the estimated vegetation index (Paul Pinter, personal communication). Moreover, a change in zenith sun angle of 15° between 1000 MST and 1100 MST will contribute to a reduction in NIR/red ratio, especially for partial canopy cover around 50%.

Field 21 appeared to have the least amount of spatial variability in surface temperature and, hence, the surface energy balance; it also had relatively high evaporation rates since surface–air temperature differences were small. Moreover, it contained the meteorological data required in (8). Thus, it was taken as the reference field in application of Eq. (11), the remote sensing model for quantifying perturbations in the surface energy balance components.

Twenty minute and half-hourly averages of the fluxes and other meteorological data were available for all sites. Consequently, a weighted average of the two micrometeorological values around the time of aircraft overpass were used. Measured values of the fluxes and remotely sensed data averaged around each of the flux sites are given in Table 1. For the remotely sensed data, the number

![Figure 4. Similar illustration as Figure 3 except this shows the thermal infrared observations.](Image)
Table 1. Average Values of Components of Surface Energy Balance Measured in Each Field during Aircraft Overpass and Remotely Sensed Data Averaged around Each Flux Site

<table>
<thead>
<tr>
<th>Field</th>
<th>Time (MST, Decimal)</th>
<th>( R_n ) (W m(^{-2}))</th>
<th>( G ) (W m(^{-2}))</th>
<th>( H ) (W m(^{-2}))</th>
<th>( LE ) (W m(^{-2}))</th>
<th>( T_s ) (°C)</th>
<th>Infrared / Red Reflectance</th>
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<tbody>
<tr>
<td>29(a)</td>
<td>9.83</td>
<td>468</td>
<td>136</td>
<td>280</td>
<td>51</td>
<td>495</td>
<td>1.4</td>
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<td>29</td>
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<td>149</td>
<td>267</td>
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<td>529</td>
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<td>28(b)</td>
<td>9.81</td>
<td>491</td>
<td>110</td>
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<td>27(c)</td>
<td>9.98</td>
<td>498</td>
<td>39</td>
<td>-40</td>
<td>499</td>
<td>35.3</td>
<td>10.0</td>
</tr>
<tr>
<td>27</td>
<td>10.09</td>
<td>509</td>
<td>42</td>
<td>-39</td>
<td>506</td>
<td>35.5</td>
<td>9.5</td>
</tr>
<tr>
<td>27</td>
<td>11.17</td>
<td>604</td>
<td>80</td>
<td>-50</td>
<td>574</td>
<td>37.0</td>
<td>7.4</td>
</tr>
<tr>
<td>27</td>
<td>11.29</td>
<td>612</td>
<td>84</td>
<td>-51</td>
<td>579</td>
<td>37.7</td>
<td>6.7</td>
</tr>
<tr>
<td>16(d)</td>
<td>9.97</td>
<td>615</td>
<td>111</td>
<td>-42</td>
<td>546</td>
<td>36.7</td>
<td>2.3</td>
</tr>
<tr>
<td>16</td>
<td>10.11</td>
<td>640</td>
<td>108</td>
<td>-49</td>
<td>582</td>
<td>36.7</td>
<td>2.1</td>
</tr>
<tr>
<td>16</td>
<td>11.16</td>
<td>723</td>
<td>115</td>
<td>-11</td>
<td>620</td>
<td>38.6</td>
<td>2.3</td>
</tr>
<tr>
<td>16</td>
<td>11.30</td>
<td>725</td>
<td>112</td>
<td>-18</td>
<td>631</td>
<td>38.9</td>
<td>2.3</td>
</tr>
</tbody>
</table>

\(a\) Plowed (20%) and standing (80%) wheat stubble; very dry soil surface.  
\(b\) North–south furrowed cotton 20% cover; very dry soil surface.  
\(c\) Alfalfa 60% cover; dry soil surface.  
\(d\) East–west furrowed cotton 30% cover; wet and dry soil surface (in the process of being flood irrigated).

Table 2. Meteorological Data Measured in Each Field and Average Value of Solar Radiation during Aircraft Overpass

<table>
<thead>
<tr>
<th>Field</th>
<th>Time (MST)</th>
<th>( T_a ) (°C)</th>
<th>( e_a ) (mb)</th>
<th>( u ) (m s(^{-1}))</th>
<th>( R_s ) (W m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>29(e)</td>
<td>9.83</td>
<td>37.8</td>
<td>9.1</td>
<td>—</td>
<td>792</td>
</tr>
<tr>
<td>29</td>
<td>10.24</td>
<td>38.2</td>
<td>8.7</td>
<td>—</td>
<td>862</td>
</tr>
<tr>
<td>29</td>
<td>11.04</td>
<td>39.7</td>
<td>9.1</td>
<td>—</td>
<td>947</td>
</tr>
<tr>
<td>29</td>
<td>11.43</td>
<td>40.3</td>
<td>9.3</td>
<td>—</td>
<td>978</td>
</tr>
<tr>
<td>28(d)</td>
<td>9.81</td>
<td>36.3</td>
<td>9.5</td>
<td>—</td>
<td>788</td>
</tr>
<tr>
<td>28</td>
<td>10.26</td>
<td>37.0</td>
<td>9.1</td>
<td>—</td>
<td>865</td>
</tr>
<tr>
<td>28</td>
<td>11.01</td>
<td>38.4</td>
<td>9.2</td>
<td>—</td>
<td>944</td>
</tr>
<tr>
<td>28</td>
<td>11.45</td>
<td>39.1</td>
<td>9.6</td>
<td>—</td>
<td>979</td>
</tr>
<tr>
<td>27(e)</td>
<td>9.98</td>
<td>34.8</td>
<td>16.7</td>
<td>0.35</td>
<td>818</td>
</tr>
<tr>
<td>27</td>
<td>10.09</td>
<td>35.0</td>
<td>16.5</td>
<td>0.40</td>
<td>836</td>
</tr>
<tr>
<td>27</td>
<td>11.17</td>
<td>36.8</td>
<td>15.5</td>
<td>0.50</td>
<td>999</td>
</tr>
<tr>
<td>27</td>
<td>11.29</td>
<td>37.0</td>
<td>15.6</td>
<td>0.50</td>
<td>969</td>
</tr>
<tr>
<td>16(f)</td>
<td>9.97</td>
<td>35.8</td>
<td>13.9</td>
<td>—</td>
<td>814</td>
</tr>
<tr>
<td>16</td>
<td>10.11</td>
<td>35.8</td>
<td>14.8</td>
<td>—</td>
<td>840</td>
</tr>
<tr>
<td>16</td>
<td>11.16</td>
<td>37.4</td>
<td>13.7</td>
<td>—</td>
<td>958</td>
</tr>
<tr>
<td>16</td>
<td>11.30</td>
<td>37.6</td>
<td>16.2</td>
<td>—</td>
<td>968</td>
</tr>
</tbody>
</table>

\(a\) Measurements made between 1.5 m and 2 m above the surface.  
\(b\) Windspeed measured at 2.2 m above the surface or roughly 1.8 m above the canopy.  
\(c\) Plowed (20%) and standing (80%) wheat stubble; very dry soil surface.  
\(d\) North–south furrowed cotton 20% cover; very dry soil surface.  
\(e\) Alfalfa 60% cover; dry soil surface.  
\(f\) East–west furrowed cotton 30% cover; wet and dry soil surface (in the process of being flood irrigated).

of values that were averaged was determined by the location of the flux site with respect to significant changes in the surface conditions as illustrated in Figures 3 and 4. Solar radiation was measured at several sites; the average was employed in the analysis. Table 2 lists the weighted average value of the meteorological data for each field [i.e., air temperature, vapor pressure (\( e_a \)), solar radiation, and windspeed for field 21]. Note that differences in \( T_a \) and \( e_a \) between sites can be on the order of 3°C and 7 mb, respectively. Errors in not accounting for these differences in the model will be examined below.

Wind direction during the period of aircraft overpasses was generally easterly (i.e., the winds came from the east). This meant upwind fetch
conditions for Bowen ratio/energy balance systems of about 500 m for field 29, 100 m for field 21, and about 500 m for field 28. The eddy correlation system in field 13 had about a 200 m upwind fetch whereas the other site in field 28 had over 400 m. Therefore, the flux sites satisfied the common fetch requirement of the ratio of measurement height to fetch of 1:100.

**ANALYSIS**

The remotely sensed data in the visible and near-infrared were used in Eqs. (12) and (13) to obtain estimates of the shortwave albedo \( \alpha \) and the midday ratio of \( G/Rn \), \( c \); these are given in Table 3. The variation in these two parameters was relatively small even for field 21 (see Fig. 3), which exhibited the largest variation (both spatially and temporally) in the NIR/red ratio. The most significant effect of this variation was on the value of \( c \) calculated as a linear function of NIR/red in Eq. (13). The resulting deviation from the mean value listed in Table 3 is about \( \pm 0.03 \). For \( Rn \approx 600 \ W \ m^{-2} \), this produces around a \( \pm 10 \ W \ m^{-2} \) difference from the mean; hence, the error can be neglected for all practical purposes. The value of \( LE_r \) or the estimated latent heat flux from field 21 needed in (11) was determined as a residual in the energy balance equation [i.e., Eq. (1)] which required the remote sensing and meteorological data in Tables 1 and 2 (see Jackson et al., 1987). The equation for computing \( LE_r \) can be deduced from the parametrizations of \( Rn \) [Eq. (5)], \( G \) [Eq (7)], and \( H \) [Eq. (8)] developed in the Theory section, viz.,

\[
LE_r = \left( (1 - \alpha_{sr})R_n + \varepsilon_{sr} \sigma T_{sr}^4 - \varepsilon_{sr} \sigma T_{a}^4 (1 - c_r) - \rho C_p (T_{sr} - T_{a}) \right) / r_{ahr}.
\]

The value of \( \varepsilon_a \) for calculating the atmospheric longwave component [cf. Eq. (5)] was estimated by the equation of Satterlund (1979):

\[
\varepsilon_a = 1.08 \left[ 1 - \exp(-0.016 T_a) \right],
\]

where \( \varepsilon_a \) is the vapor pressure in mb and \( T_a \) in K. Other expressions for estimating \( \varepsilon_a \) are available (for a summary see Brutsaert, 1982), but Satterlund’s expression together with estimates of albedo given by Eq. (12) produced good agreement between measured and computed net radiation in another study (Daughtry et al., 1990).

**Table 3. Mean Values of the Ratio \( G/Rn \) ( \( \equiv c \) ) and the Shortwave Albedo \( \alpha \) for Each Flux Site**

<table>
<thead>
<tr>
<th>Field</th>
<th>( \alpha )</th>
<th>( c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>29, wheat stubble</td>
<td>0.21</td>
<td>0.28</td>
</tr>
<tr>
<td>28, furrowed cotton</td>
<td>0.18</td>
<td>0.26</td>
</tr>
<tr>
<td>21, alfalfa</td>
<td>0.23</td>
<td>0.15</td>
</tr>
<tr>
<td>13, furrowed cotton</td>
<td>0.22</td>
<td>0.25</td>
</tr>
</tbody>
</table>

**Table 4. Root Mean Square Error (RMSE) \(^a\) between Estimated and Measured Energy Balance Components for Fields 29, 28, and 13 with Eq. (11) and for Field 21 Using (23) with Remote Sensing and Meteorological Inputs**

<table>
<thead>
<tr>
<th>Energy Balance Component</th>
<th>RMSE (^b) ((W \ m^{-2}))</th>
<th>RMSE (^c) ((W \ m^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Rn )</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>( G )</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>( H^d )</td>
<td>82</td>
<td>85</td>
</tr>
<tr>
<td>( LE^e )</td>
<td>107</td>
<td>108</td>
</tr>
<tr>
<td>( LE^f )</td>
<td>112</td>
<td>117</td>
</tr>
</tbody>
</table>

\(^a\)RMSE = \( \left[ (1/n) \sum (\text{computed} - \text{measured})^2 \right]^{1/2} \).

\(^b\)Using Eq. (11).

\(^c\)Including in Eq. (11) changes in atmospheric longwave radiation [cf. Eq. (5)] and including \( (T_e - T_{a}) \) term in estimating changes in sensible heat flux [cf. Eq. (9)] with the data in Table 2.

\(^d\)Using the Thom and Oliver expression for \( r_{ah} \), Eq. (14).

\(^e\)Using the Mahrt and Ek equations for \( r_{ah} \) [Eq. (15)].

**Table 5. Values of \( r_{ah} \) Determined by Eq. (8) with \( (T_e - T_{a}) \) from Tables 1 and 2 and \( H \) from Table 1 for Fields 28 (Furrowed Cotton) and 29 (Wheat Stubble)\(^a\)**

<table>
<thead>
<tr>
<th>Approximate Time of Aircraft Overpass (MST)</th>
<th>Field 28 ( r_{ah} ) ((s \ m^{-1}))</th>
<th>Field 29 ( r_{ah} ) ((s \ m^{-1}))</th>
<th>( r_{ahr} ) (Eq. (14)) ((s \ m^{-1}))</th>
<th>( r_{ahr} ) (Eq. (15)) ((s \ m^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>173</td>
<td>46</td>
<td>101</td>
<td>158</td>
</tr>
<tr>
<td>1010</td>
<td>372</td>
<td>61</td>
<td>100</td>
<td>172</td>
</tr>
<tr>
<td>1100</td>
<td>199</td>
<td>63</td>
<td>94</td>
<td>161</td>
</tr>
<tr>
<td>1125</td>
<td>183</td>
<td>61</td>
<td>94</td>
<td>108</td>
</tr>
<tr>
<td>Average</td>
<td>232</td>
<td>58</td>
<td>97</td>
<td>150</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>( \pm 94 )</td>
<td>( \pm 8 )</td>
<td>( \pm 4 )</td>
<td>( \pm 28 )</td>
</tr>
</tbody>
</table>

\(^a\)In addition, values of \( r_{ah} \) for field 21 (i.e., \( r_{ah} \)) computed by Eqs. (14) and (15).
A comparison of LE estimated with (11), which essentially accounts for deviations in the energy balance components from the reference field by changes in remote sensing inputs, for the sites in fields 13, 28, and 29, with measured values is illustrated in Figure 5. Also, LE, calculated with (23) is compared to measured values. For fields 21, 28, and 13, LE is underestimated whereas for field 29 it is overestimated; similar results were obtained with either formulation for \( r_{ah} \). Moreover, even incorporating changes in the atmospheric longwave component from the reference field and the \((T_s - T_a)\) term in Eq. (9) representing perturbations in \( H_r \) into Eq. (11) with the data from Table 2 did not significantly improve the results (see Table 4).

As a means of assessing which component of the energy balance equation contributes most to the deviation from the measured values of latent heat flux, Figure 6 illustrates the comparison between estimated \( R_n \), \( G \), and \( H \) versus the measured values. From this figure and the results in Table 4 one can conclude that the largest error is in the \( H \) values, which suggests that neglecting other terms for calculating changes in \( H_r \) in Eq. (9) may be unacceptable in some cases. Moreover, advection, which is apparent from measured values of \( H \) in fields 21 and 13 (see Table 1) was not detected with the remotely sensed surface temperature–air temperature differences. This disagreement relates, in part, to the partial canopy setting where simply inserting remote sensing observations of \( T_s \) in the bulk resistance expressions for sensible heat flux, i.e., (8)–(10) with semiempirical parameterizations of \( r_{ah} \) like Eqs. (14) and (15) may not be appropriate (see, e.g., Van de Griend and Van Boxel, 1989).

Even when the direction of \( H \) agreed with the sign of \((T_s - T_a)\), significant underestimates (i.e., field 29) and overestimates (i.e., field 28) of the measured sensible heat flux resulted. The major reason for these results can be seen by computing the required values of \( r_{ah} \) needed in (8) with measured \( T_s \) and \( T_a \) in Tables 1 and 2 to obtain the measured \( H \) values in Table 1. In Table 5 are the computed resistances for fields 28 and 29 along with \( r_{ah} \) values used in (10) and (11). The results clearly point to a serious problem in assuming a constant resistance to heat transfer over different surface types. In fact, the large differences in the required \( r_{ah} \) for fields 28 and 29 suggest that the single-layer resistance model [i.e., Eq. (8)] must contain a procedure which accounts for the effects of changing surface conditions on \( r_{ah} \). However, even if such a methodology is developed, the results in fields 21 and 13 would not have changed because in these two cases the problem is the disagreement between the direction of \((T_s - T_a)\) and the sensible heat flux.

With an approximation of LE, for each field around 1130 MST, LE, was computed by multiplying LE, by a coefficient determined with (20)
Figure 6. Comparison of estimated versus measured values of A) net radiation using Eq. (6), B) soil heat flux using Eq. (7), and C) sensible heat flux using Eq. (10) with $r_{ah}$ evaluated with Eq. (14) along with the RMSE. The symbols represented the flux sites in fields 29 (□), wheat stubble; 28 (+), cotton; 21 (△), alfalfa; and 13 (○), cotton. The line represents perfect agreement with measured values.
and (21). The constant obtained with Eq. (21) \[\text{cf. Eq. (22)}\] was 0.39, slightly higher than the coefficient in (22) since the observations were made roughly 1 h before solar noon. Unfortunately, measurements over the 24-h period to compute \(LE_d\) for DOY 165 were available only for field 13; however, daily values for the other fields did not change significantly from the previous 3 days (see Table 6). Consequently, the values of \(LE_d\) measured for the previous 3 days (i.e., DOYs 162–164) in fields 21, 28, and 29 were averaged for each field and these values were used for DOY 165; the actual value for DOY 165 was utilized for field 13. Figure 7 illustrates the relationship between predicted with (20), 0.33 \(LE_i\), and (21), 0.39 \(LE_i\), and measured values. Use of Eq. (21) with the larger coefficient appears to produce better agreement; nonetheless, the error quantified by RMSE is still fairly large = 2.2 mm/day.

Coefficients \(A\) and \(B\) in Eq. (2), which relates the daily difference in net radiation and latent heat flux to the instantaneous midday surface–air temperature difference, were also determined with the data for DOY 165. Since the final thermometric observations were made before solar noon, adjustments to \((T_s - T_a)\) were made using ground-based observations of the rate of change of this quantity to better conform to true midday values. For fields 21 and 13 ground-based measurements of the surface temperature suggested negligible changes whereas observations over 28 and 29 required roughly a 2°C increase in the values. Although there are only four values, the linear regression produces coefficients in Table 7 similar to what has been found by others over agricultural fields (Seguin et al., 1986).

An attempt was made to eliminate the intercept \(A\) in (2) by formally including \(G_d\) in the derivation of an expression similar to (2). This is seen by rewriting the surface energy balance equation using daily fluxes

\[
LE_d - (R_{nd} - G_d) = -H_d.
\]  

In substituting for \(H_d\) in (25) the bulk resistance expression given by (8) and the relationship between \(H_i\) and \(H_d\) in (18) yields

\[
LE_d - (R_{nd} - G_d) = 0.1(R_{nd} - G_d) - 1.1 \left( \frac{R_{nd} - G_d}{R_{ni} - G_i} \right) \rho C_p(T_s - T_a) / r_{ah},
\]  

This simplifies to

\[
LE_d - 1.1(R_{nd} - G_d) = -B(T_s - T_a),
\]  

where

\[
B = 1.1 \left( \frac{R_{nd} - G_d}{R_{ni} - G_i} \right) \rho C_p / r_{ah}.
\]
Table 6. Daily Values of the Energy Balance Components for Each Flux Site

<table>
<thead>
<tr>
<th>Field</th>
<th>DOY</th>
<th>( R_n ) (mm day(^{-1} ))</th>
<th>( G ) (mm day(^{-1} ))</th>
<th>( H ) (mm day(^{-1} ))</th>
<th>( LE ) (mm day(^{-1} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>29(^b)</td>
<td>162</td>
<td>5.98</td>
<td>1.25</td>
<td>4.20</td>
<td>0.53</td>
</tr>
<tr>
<td>29</td>
<td>163</td>
<td>6.44</td>
<td>1.31</td>
<td>4.28</td>
<td>0.85</td>
</tr>
<tr>
<td>29</td>
<td>164</td>
<td>6.29</td>
<td>1.42</td>
<td>4.11</td>
<td>0.79</td>
</tr>
<tr>
<td>29</td>
<td>165</td>
<td>6.23(^*)</td>
<td>1.33(^*)</td>
<td>4.20(^*)</td>
<td>0.72(^*)</td>
</tr>
<tr>
<td>28(^c)</td>
<td>162</td>
<td>6.24</td>
<td>0.84</td>
<td>0.83</td>
<td>4.56</td>
</tr>
<tr>
<td>28</td>
<td>163</td>
<td>6.74</td>
<td>0.80</td>
<td>0.82</td>
<td>5.11</td>
</tr>
<tr>
<td>28</td>
<td>164</td>
<td>6.65</td>
<td>1.02</td>
<td>0.67</td>
<td>4.96</td>
</tr>
<tr>
<td>28</td>
<td>165</td>
<td>6.54(^*)</td>
<td>0.89(^*)</td>
<td>0.77(^*)</td>
<td>4.88(^*)</td>
</tr>
<tr>
<td>21(^d)</td>
<td>162</td>
<td>6.48</td>
<td>0.59</td>
<td>−1.19</td>
<td>7.09</td>
</tr>
<tr>
<td>21</td>
<td>163</td>
<td>6.99</td>
<td>0.67</td>
<td>−1.43</td>
<td>7.75</td>
</tr>
<tr>
<td>21</td>
<td>164</td>
<td>7.02</td>
<td>0.65</td>
<td>−1.26</td>
<td>7.63</td>
</tr>
<tr>
<td>21</td>
<td>165</td>
<td>6.83(^e)</td>
<td>0.64(^e)</td>
<td>−1.30(^e)</td>
<td>7.49(^e)</td>
</tr>
<tr>
<td>13(^f)</td>
<td>162</td>
<td>6.39</td>
<td>0.60</td>
<td>1.37</td>
<td>4.47</td>
</tr>
<tr>
<td>13</td>
<td>163</td>
<td>8.52</td>
<td>−1.03</td>
<td>−1.33</td>
<td>10.97</td>
</tr>
<tr>
<td>13</td>
<td>164</td>
<td>8.43</td>
<td>−0.29</td>
<td>−1.44</td>
<td>10.25</td>
</tr>
<tr>
<td>13</td>
<td>165</td>
<td>8.26</td>
<td>−0.17</td>
<td>−2.16</td>
<td>10.27</td>
</tr>
</tbody>
</table>

\(^a\) Energy balance components obtained from averages of the DOY 162–164 values.
\(^b\) Plowed (20%) and standing (80%) wheat stubble; very dry soil surface.
\(^c\) North–south furrowed cotton 20% cover; very dry soil surface.
\(^d\) Alfalfa 60% cover; dry soil surface.
\(^e\) East–west furrowed cotton 30% cover; wet and dry soil surface.
\(^f\) Flux site was flood irrigated.

Table 7. Evaluation of the Coefficients \( A \) and \( B \) in Eq. (2)

<table>
<thead>
<tr>
<th>( B ) (Standard Error)</th>
<th>( A )</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>1.72</td>
<td>0.75</td>
</tr>
<tr>
<td>(± 0.10)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.20(^a)</td>
<td>1.27(^a)</td>
<td>0.75</td>
</tr>
<tr>
<td>(± 0.06)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Coefficients obtained by including \( G_a \) [see Eq. (27)].

The data for \( (T_s - T_a) \) adjusted to better correspond with solar noon and the daily fluxes for the left-hand side of (27) were used in a least squares regression to determine \( B \). The result, however, is disappointing because the magnitude of the coefficient still remained of order 1 (see Table 7). Clearly, more data are needed to ascertain the generality and accuracy of an equation like (27).

CONCLUSIONS

There appears to be significant limitations in extrapolating evapotranspiration estimates from a reference field with simplified formulations like Eq. (11) that attempt to account for perturbations in the components of the surface energy balance by using only changes in surface conditions determined with remote sensing. From this analysis and previous studies, remote sensing data in the visible, near-infrared, and thermal bands can provide reasonable estimates of net radiation and soil heat flux; but estimates of sensible heat flux, especially for partial canopy covered surfaces, seems to produce significant errors in the resulting estimates of latent heat flux.

Part of the difficulty in computing appropriate estimates of \( H \) stems from using the reference resistance to heat transfer, \( r_{ahr} \), for other fields, which from the results in Table 5 reveal that significantly different turbulent transfer processes may exist. Differences in resistances may be accounted for by specifying different roughness and stability conditions in each field. However, for partial canopy cover, recent evidence (Kustas et al., 1989b) shows that adjustments to the common single-layer approach in estimating \( r_{ahr} \) must be performed in order to obtain satisfactory results. These adjustments, however, do not appear to be applicable under all circumstances (Kustas et al., 1989a). Hence, there may be serious limitations in trying to employ a one-layer model in partial canopy cover situations.

This conclusion is more strongly supported by the results for fields 21 and 13 where the use of the composite surface temperature in Eq. (8), suggested unstable conditions (i.e., \( H > 0 \)) whereas Bowen ratio and eddy correlation data gave a stable or advective situation. Thus, with the range
greatly appreciated, along with the collecting and processing of surface conditions existing in this study, it may be more appropriate to employ two-layer models that partition the energy balance components between the soil/substrate and vegetation while specifying how meteorological conditions vary from the reference field.

For daily estimates of ET, the approach of converting instantaneous values from (11) to daily values with Eq. (21) may be acceptable for cloud-free conditions, although errors of order of 2 mm day\(^{-1}\) may be expected when one has a large range in soil, plant, and meteorological conditions.

Future research should focus on the sensitivity of the approximations used in this study, especially in estimating \(H\), for computing evapotranspiration from a reference crop to other fields. Clearly, this will require the development of techniques to account for spatial variability in some basic meteorological quantities, that is, air temperature, vapor pressure, and windspeed at screen height.

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