Variability of emissivity and surface temperature over a sparsely vegetated surface

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Abstract. Radiometric surface temperatures obtained from remote sensing measurements are a function of both the physical surface temperature and the effective emissivity of the surface within the band pass of the radiometric measurement. For sparsely vegetated areas, however, a sensor views significant fractions of both bare soil and various vegetation types. In this case the radiometric response of a sensor is a function of the emissivities and kinetic temperatures of various surface elements, the proportion of those surface elements within the field of view of the sensor, and the interaction of radiation emitted from the various surface components. In order to effectively utilize thermal remote sensing data to quantify energy balance components for a sparsely vegetated area, it is important to examine the typical magnitude and degree of variability of emissivity and surface temperature for such surfaces. Surface emissivity measurements and ground and low-altitude-aircraft-based surface temperature measurements (8–13 μm band pass) made in conjunction with the Monsoon '90 field experiment were used to evaluate the typical variability of those quantities during the summer rainy season in a semiarid watershed. The average value for thermal band emissivity of the exposed bare soil portions of the surface was found to be approximately 0.96; the average value measured for most of the varieties of desert shrubs present was approximately 0.99. Surface composite emissivity was estimated to be approximately 0.98 for both the grass-dominated and shrub-dominated portions of the watershed. The spatial variability of surface temperature was found to be highly dependent on the spatial scale of integration for the instantaneous field of view (IFOV) of the instrument, the spatial scale of the total area under evaluation, and the time of day. For the conditions which existed during most of the Monsoon '90 experiment, the differences in kinetic (physical) temperature between the vegetation and soil background were typically between 10° and 25°C at midday. These differences gave rise to large variations in radiometric composite surface temperatures observed with a ground-based instrument configuration which allowed a ground IFOV of approximately 0.5 m. An evaluation of the frequency distribution for these observations indicated that the variance in surface temperature observed over an intensively sampled target area (approximately 500 m × 120 m) increased significantly in the early to late morning hours of a typical diurnal heating cycle. For aircraft-based composite radiometric temperature measurements at the watershed scale (with ground IFOV of approximately 40 m for each observation), much of the variability in surface temperature due to differences in soil and vegetation temperature was integrated into a single measurement; consequently, the variance between observations over the watershed was not significantly larger than those observed at length scales of 100 m.

Introduction

For relatively homogeneous land surfaces, such as bare soil or mature agricultural crops, physical surface tempera-
quantified as a function of the emissivity and kinetic temperature of a single dominant surface component. For sparsely vegetated areas, however, a sensor views significant fractions of both bare soil and various vegetation types. In this case the radiometric response of a sensor is a function of the emissivities and kinetic temperatures of various surface elements, the proportion of those surface elements within the field of view of the sensor, and the interaction of radiation emitted from the various surface components.

These additional complexities in the radiometric surface temperature over partially vegetated surfaces have given rise to additional complexities in using surface temperature measurements to estimate the sensible heat flux component of the surface energy balance. Though the soil and vegetation components contribute to the composite surface temperature in proportion to the fractional areas of those components exposed at the surface, they contribute to the sensible heat flux in proportion to the degree of aerodynamic contact between the surface component and the near-surface atmosphere [Shuttleworth and Wallace, 1985; Shuttleworth and Gurney, 1991]. Additionally, significant differences in the temperatures of the surface components give rise to complex interactions between the components via the modification of the intercanopy airspace [Ham et al., 1990, 1991]. Several approaches to the problem of using surface temperatures to estimate sensible heat flux over partially vegetated surfaces have been investigated, including: (1) the use of multilayer resistance-based models [Deardorff, 1978; Camillo et al., 1983; Sellers et al., 1986; Taconet et al., 1986; Dickinson et al., 1986; Choudhury and Monteith, 1988; van de Griend and van Boxel, 1989], in which the energy balance of the soil and vegetation layers are considered separately, and (2) use of a single surface temperature in a bulk transfer relationship, but with modification of surface roughness parameters controlling the heat transfer coefficient [Kustas et al., 1989, this issue; Moran et al., this issue].

To evaluate the utility of these various approaches over different time and space scales, it is useful to have a better understanding of the degree of the subpixel variability in emissivity and surface temperature for arid/semiarid regions.

Table 1. Reported Values of Emissivity (8–14 μm Band Pass) for Various Target Types Over Sparsely Vegetated Surfaces

<table>
<thead>
<tr>
<th>Investigation and Field Area</th>
<th>Target Type</th>
<th>Mean</th>
<th>s.d.</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Hipps [1989]/western United States</em></td>
<td>bare soil (sandy)</td>
<td>0.93</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>shrubs (A. tridenta)</td>
<td>0.97</td>
<td>0.005</td>
</tr>
<tr>
<td><em>van de Griend et al. [1991]/Botswana</em></td>
<td>bare soil (loamy sand)</td>
<td>0.914</td>
<td>0.011</td>
</tr>
<tr>
<td></td>
<td>grass (partial cover)</td>
<td>0.956</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td>shrub (partial cover)</td>
<td>0.976</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>shrub (complete cover)</td>
<td>0.986</td>
<td>0.006</td>
</tr>
<tr>
<td><em>Labeled and Stoll [1991]/La Crau, France</em></td>
<td>stony area</td>
<td>0.959</td>
<td>0.075</td>
</tr>
<tr>
<td></td>
<td>vegetated areas:*</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>shortgrass</td>
<td>0.979</td>
<td></td>
</tr>
<tr>
<td></td>
<td>tufts of grass (few centimeters)</td>
<td>0.981</td>
<td></td>
</tr>
<tr>
<td></td>
<td>grassland (=15 cm)</td>
<td>0.983</td>
<td></td>
</tr>
<tr>
<td></td>
<td>bushes (=100 cm)</td>
<td>0.994</td>
<td></td>
</tr>
</tbody>
</table>

Here, s.d. denotes standard deviation.

*Variable portions of soil background and vegetation height and density.

Emissivity values for the soil and vegetation components of sparsely vegetated areas have been reported by several investigators [Hipps, 1989; van de Griend et al., 1991; Labeled and Stoll, 1991]. Labeled and Stoll [1991] included measurements of the spectral dependence of emissivity between 8 and 14 μm, as well as effective values over the integrated 8–14 μm band pass. A summary of the values reported by these investigators is provided in Table 1. The subpixel variability in surface temperatures for surfaces in arid/semiarid regions is not well quantified at any spatial scale. However, under conditions typical of those for the summer rainy season of an arid/semiarid region (in which the root zone of the sparse vegetation layer is well supplied with water and the vegetation layer is actively transpiring, but the substantial fraction of exposed bare soil is dry), variations in component temperatures within pixels would be expected to be extreme.

The overall objective of the present study was to use data from the Monsoon '90 field experiment [Kustas et al., 1991; Kustas and Goodrich, this issue] to evaluate the variability, over several spatial scales, of the factors influencing the composite surface temperature of both grass-dominated and shrub-dominated areas of a semiarid rangeland watershed. The specific objectives were to (1) evaluate typical values of component (i.e., soil, grass, shrub) emissivities and kinetic temperatures derived from spatially limited ground-based radiometric measurements with broadband (8–13 μm) instruments; (2) to define and quantify effective composite surface emissivity and temperature, which must necessarily be used for single layer modeling approaches; (3) evaluate the spatial and temporal variability in surface temperature using intensive ground-based radiometric measurements over a moderate-size ground target area; and (4) evaluate surface temperature variability observed over the watershed with aircraft-based radiometric measurements.

Experiment and Data Acquisition

Experiment

The Monsoon '90 experiment was carried out at the U.S. Department of Agriculture's Agricultural Research Service
Walnut Gulch experimental watershed near Tombstone, Arizona, in the summer of 1990 and included the simultaneous acquisition of ground and remotely sensed data at a variety of spatial scales. An overview of the experiment is provided by Kustas et al. [1991] and Kustas and Goodrich [this issue]. A diagram of the watershed, including the approximate locations of the ground-based meteorological and flux (METFLUX) sites and a description of the soils and vegetation in the study area, is provided by Kustas and Goodrich [this issue]. There is a general trend in dominant vegetation type and density across the watershed in which the west central portions of the watershed are classified as a desert steppe-shrub community (represented by METFLUX sites 1 and 8) and the eastern portions of the watershed are classified as desert grasslands (represented by METFLUX sites 4 and 5). The dominant vegetation type for areas in the east central portion of the watershed (represented by sites 2, 3, 6, 7) are either low shrubs or desert grasses, depending on localized environmental conditions and recent grazing practices. The soils throughout most of the watershed are relatively coarse in texture, ranging from sandy loams to gravelly loamy sands.

Instruments Used for Temperature Measurements

All measurements of apparent temperature described in this paper were made using Everest Interscience infrared radiometers (IRT). (The use of a manufacturer’s name is provided as a matter of information to the reader and is not intended as an endorsement of the product by the U.S. government.) The band pass of these instruments is nominally 8-14 μm, but the response function provided by the manufacturer of the filter used in these instruments indicates a significant decrease in the filter response at wavelength values greater than 12 μm and no response at wavelengths greater than 13 μm.

The infrared radiometers used to acquire the data for the emissivity measurements, most of the ground-based component temperature measurements, and all of the ground- and aircraft-based composite surface temperatures used in this study were calibrated using a standard of known emissivity (0.995) and adjustable body temperature in a constant-temperature room. The instruments were adjusted until the instrument apparent temperature matched the blackbody kinetic temperature as closely as possible over a range of ambient temperatures (10°-40°C) and target temperatures (~10°-60°C).

Emissivity Measurements

Surface temperature measurements were acquired on most days of the experiment for the purpose of computing effective values of emissivity over the 8-13 μm band pass of the IRT for various targets at six of the eight METFLUX sites. The measurements were made in the predawn hours at each site; different sites were visited each morning. For all the measurements an IRT with a 15° field of view was fitted with an aluminum cone such as that described by Fuchs and Tanner [1966]. The diameter of the base of the cone was approximately 40 cm. Approximately 25 targets of either bare soil, clumpy vegetation, or soil/vegetation mixtures were measured at each METFLUX site sampled (sites 1, 3, 4, 5, 6, and 7). In order to compute a value of emissivity for each target, three types of measurements were made for each target within approximately 3 min: (1) the apparent temperature of the surface when the instrument was held approximately 1 m above the surface; (2) the apparent temperature of the surface while it was completely covered with the cone apparatus; and (3) the effective atmospheric temperature, measured by pointing the IRT into the sky at an approximately 30° angle from zenith and making rapid and repeated apparent temperature measurements at approximately 10 different azimuth angles.

Ground-Based Component Temperature Measurements

Ground-based measurements of the apparent surface temperature of soil and vegetation were measured with two different approaches. The first approach was to mount separate instruments on stationary booms over representative areas of bare soil and vegetation at the two METFLUX stations that were intensively studied with other remote sensing observations (site 1, a shrub-dominated site, and site 5, a grass-dominated site). The instruments used for these measurements had a field of view of 3° and were mounted approximately 2 m above the soil surface at site 1 and 1 m above the soil surface at site 5. With this configuration the diameter of the ground area in the field of view of the instruments was about 5 and 2.5 cm, at sites 1 and 5, respectively. Measurements were acquired at 10 s intervals and averaged over 20 min intervals for storage in the data logger.

Yoke-Based Surface Temperature Measurements

All of the yoke-based surface temperature measurements used in this analysis were acquired at site 5 (the grass-dominated site of intensive study). A detailed description of the field site orientation and method of data acquisition is provided by Moran et al. [this issue]. In brief, a large target area (approximately 120 m x 480 m in size) was delineated with an orientation corresponding to the orbital path of the Landsat and SPOT satellites (the long side of the rectangle was oriented 9° east of south). With this orientation the target area straddled a dry wash with half of the area on an east facing slope and half of the area on a west facing slope. Radiometric data were acquired over this large target area by mounting instruments in a yoke apparatus usually carried by four porters simultaneously in four different quadrants of the target area. Each yoke apparatus was equipped with a radiometer with four bands (three in the visible and one near-infrared band) and an IRT, though only data from the IRT were used in the analysis presented here. Both instruments had a field of view of 15° and were carried approximately 2 m above the surface. The target area on the ground “viewed” by the instruments for each measurement or the instantaneous field of view (IFOV) was approximately 50 cm in diameter. Measurements were made nearly continuously as the porters walked along transects within the target area. When all four porters acquired data in each quadrant simultaneously, 768 data points were acquired over the entire area in approximately 10 min. Depending on the daily weather conditions, data were acquired over the transects approximately 5-8 times between the hours of 7 A.M. and 12 noon local time.

Aircraft-Based Surface Temperature Measurements

The acquisition of radiometric data with instruments mounted in a light aircraft is described in detail by Kustas et al. [1991] and Moran et al. [this issue]. In brief, the same
types of instruments used for the acquisition of the ground-based remotely sensed data over the extensive ground target area were also mounted in the light aircraft. For each aircraft overpass run, two repetitions each of two transect lines across the watershed were flown in a pattern such that the average time of acquisition for both measurements at each site was nearly the same. Each of the transect lines was designed to intersect four METFLUX sites, and they were oriented roughly in an east-west direction. The IRT mounted in the aircraft also had a 15° field of view, and the aircraft flew at approximately 100 m above ground level (AGL). The size of the area on the ground "viewed" by the sensor for each measurement was approximately 25 m in diameter. A measurement was recorded approximately every second. At the average aircraft velocity the centers of the viewed areas were approximately 60 m apart. Several overpasses of the watershed were flown on each day of the experiment when weather permitted. The data used in this analysis were acquired on day of years (DOY) 216 and DOY 221.

Computational Methods

Theoretical Background

If an object is a perfect emitter, the relationship between the kinetic temperature of the object and the spectral radiance emitted by the object is described by the Planck function,

\[ B(\lambda, T) = \frac{2hc^2}{\lambda^5(e^{\frac{hc}{\lambda kT}} - 1)} , \quad (1) \]

where \( B(\lambda, T) \) is the spectral radiance given in W \( \text{m}^{-2} \text{sr}^{-1} \mu \text{m}^{-1} \), \( \lambda \) is the wavelength in micrometers, \( T \) is the absolute temperature of the object in degrees Kelvin, \( h \) is the Planck constant, \( 6.63 \times 10^{-34} \text{ joule seconds} \), \( k \) is the Boltzmann constant, \( 1.38 \times 10^{-23} \text{ joules per degree Kelvin} \), and \( c \) is the velocity of light in meters per second. Most natural objects are not perfect emitters, however, and the actual spectral radiance emitted from such a natural object is usually expressed as

\[ L(\lambda, T) = e(\lambda)B(\lambda, T) , \quad (2) \]

where \( L(\lambda, T) \) is the spectral radiance in W \( \text{m}^{-2} \text{sr}^{-1} \mu \text{m}^{-1} \) and \( e(\lambda) \) is the spectral emissivity of the object.

When an instrument with a finite band pass (e.g., \( \lambda_1 - \lambda_2 \)) is used to measure the radiance emitted by an object, the emittance which reaches the sensor can be expressed as

\[ M = \pi \int_{\lambda_1}^{\lambda_2} e(\lambda)f(\lambda)B(\lambda, T_2) \, d\lambda \]

\[ + \int_{\lambda_1}^{\lambda_2} (1 - e(\lambda))f(\lambda)B(\lambda, T_{\text{Atm}}) \, d\lambda , \quad (3) \]

where \( M \) is the emittance in watts per square meter, \( f(\lambda) \) is the normalized response of the instrument in the finite band pass, and \( T_{\text{Atm}} \) is the effective temperature of the atmosphere corresponding to that emitted by the atmosphere in the finite band pass. The first term in (3) describes the emittance by the target, and the second term describes the incoming atmospheric emittance which is reflected by the object and contributes to the total radiant energy received by the sensor.

If the emittance of a surface is assumed to be constant with respect to wavelength for a given interval, then (3) can be rewritten as

\[ M = \pi \int_{\lambda_1}^{\lambda_2} e(\lambda)f(\lambda)B(\lambda, T_2) \, d\lambda \]

\[ + (1 - e) \int_{\lambda_1}^{\lambda_2} f(\lambda)B(\lambda, T_{\text{Atm}}) \, d\lambda , \quad (4) \]

where \( e_2 \) represents the constant value of surface emissivity over the wave band. For land surfaces in the 8–14 \( \mu \text{m} \) band pass, this assumption is not strictly valid; there is experimental evidence of a significant dip in the emissivity in approximately the 8–10 \( \mu \text{m} \) region for surfaces which include substantial fractions of silica-based minerals [Laped and Stoll, 1991]. However, out of necessity to compute effective temperature and emissivity values for the 8–14 \( \mu \text{m} \) band pass over which all the radiometric data used in this study were acquired, the emissivity values were treated as constant over that wave band for the analysis presented here.

Relationship Between the Apparent Temperature and Radiance Received by the Sensor

As described in a previous section, the instruments used in this analysis were calibrated with the goal of matching the apparent temperature displayed on the IRT with the kinetic temperature of a blackbody with emissivity 0.995. The emittance \( M \) (watts per square meter) which would be received by the sensor during the calibration procedure is

\[ M = \pi e_{BB} \int_{8 \mu \text{m}}^{13 \mu \text{m}} f(\lambda)B(\lambda, T_{BB}) \, d\lambda , \quad (5) \]

where \( e_{BB} \) is the emissivity of the "near blackbody" used for calibration, \( T_{BB} \) is the absolute kinetic temperature to which the blackbody has been set, \( \lambda_1 \) and \( \lambda_2 \) are the endpoints of the IRT band pass, and \( f(\lambda) \) is the IRT instrument response. Thus the calibration procedure effectively adjusts the instrument such that the apparent temperature displayed on the instrument panel represents an accurate inversion of (5), i.e., such that the energy received by the instrument is transformed into temperature in manner consistent with (5).

Using the instrument response function provided by the manufacturer and \( e_{BB} = 0.995 \), (5) was numerically integrated over the range of temperature values typical of the target temperatures used in the instrument calibration procedure (283°–333°K). A curve was then fit to the values of temperature and computed emittance. With \( M \) in units of watts per square meter and \( T \) in degrees Kelvin, the form of the equation is

\[ M = \frac{c_1}{e_{BB}T - 1} . \quad (6) \]

For the band pass of these instruments, \( c_1 = 15317.3 \text{ W m}^{-2} \) and \( c_2 = 1472.1 \text{ K} \). The values of \( c_1 \) and \( c_2 \) are also slightly dependent on the target temperature; the results of
the fit indicate that (6) approximates (5) very well over the temperature range used for the fit (10°-50°C).

**Computation of Component Emissivity Values From Radiometric Measurements**

As described in the previous section on the experiment and data acquisition, a series of temperature measurements were made over approximately 25 different targets at most of the METFLUX sites for the purpose of computing emissivity values for the soil and vegetation components of the surface. The procedure for acquiring the data and computing emissivity values is similar to the "cone method" described by Fuchs and Tanner [1966]. In this method the apparent temperature of the target is observed in the normal manner, in which the radiance received by the instrument (described by (6)) is a function of the kinetic temperature of the target, the emissivity of the target, and the reflected incoming longwave radiation. The apparent temperature observed in this manner is referred to here as $T_{rad}$.

When the target surface is covered with the cone apparatus, the cavity becomes an effective blackbody at the kinetic temperature of the target surface, and the apparent temperature measured in this manner is the kinetic temperature of the surface ($T_{kin}$). When the target is covered with the cone apparatus, it does begin to change temperature rather rapidly. For this reason, measurements were made over the covered target for approximately 60 s and interpolated back in time to obtain $T_{kin}$ at the moment that the target was first covered. Measurements of effective sky temperature made at different azimuthal angles were averaged to obtain a single effective sky temperature, $T_{sky}$.

Using (6), the three temperatures $T_{rad}$, $T_{kin}$, and $T_{sky}$ for each target were converted to observed emittances $M_{rad}$, $M_{kin}$, and $M_{sky}$, respectively, all in watts per square meter. Following after (4), but substituting emittance (watts per square meter) in each of the terms, the relationship between the three radiance values can be expressed as

$$M_{rad} = \varepsilon M_{kin} + (1 - \varepsilon)M_{sky}. \quad (7)$$

Solving (7) for $\varepsilon$, gives the expression

$$\varepsilon = \frac{M_{rad} - M_{sky}}{M_{kin} - M_{sky}}. \quad (8)$$

Note that because this calculation is performed with emittance values, the quantity required for the calculation is not the absolute temperature displayed on the IRT but the emittance received by the sensor for the three different types of measurements. The instruments were calibrated to implicitly perform a transformation between radiance and temperature as given by (5). Thus for the very low values of temperature measured for the effective sky temperature (beyond the range of calibration for the instrument), though the absolute temperature displayed by the IRT may not have been accurate, the computed sky emittance observed by sensor should be as accurate as the other emittance values.

**Magnitude of Adjustment to $T_a$ for Emissivity and Reflected Longwave Radiation**

The radiance received by the IRT for a target with apparent temperature $T_{app}$ is equated with the expression describing the radiance emitted by a surface with an actual kinetic temperature $T_a$ to obtain the overall relationship between the actual kinetic temperature of the surface and the apparent temperature measured with the instrument:

$$e_{BB} \int_{13 \mu m}^{15 \mu m} f(\lambda)B(\lambda, T_{app}) \, d\lambda = e_{\lambda} \int_{8 \mu m}^{13 \mu m} f(\lambda)B(\lambda, T_a) \, d\lambda + (1 - e_{\lambda})f(\lambda)L_{sky, 8-13 \mu m}. \quad (9)$$

If one assumes particular values for $L_{sky, 8-13 \mu m}$, $e_{BB}$, and $e_{\lambda}$, it is possible to use (9) to compute the difference between the actual kinetic temperature of a homogeneous target, $T_a$, and the apparent temperature measured with the IRT over a range of observed temperatures. This is the procedure used by Hipps [1989]. The procedure is repeated here using the actual instrument band pass provided by the manufacturer and the value of $e_{BB}$ used in the acquisition of the field data used in this analysis. The differences between the apparent temperature measured by the IRT ($T_a$) and the actual surface temperature ($T_a$) over a range of surface temperatures and typical $e_{\lambda}$ values are shown in Figure 1. The value used for $L_{sky, 8-13 \mu m}$ to construct the differences shown in Figure 1 was 11 W m$^{-2}$ sr$^{-1}$. This value is consistent with effective sky temperatures measured with the IRT in the predawn hours during most days of the Monsoon '90 experiment. It is also consistent with the value of atmospheric emission calculated using the LOWTRAN7 [Kneizys et al., 1988] radiative transfer program with the standard midlatitude summer atmosphere model and the IRT filter function as input.

As stated by Hipps [1989] and shown by the differences plotted in Figure 1, the difference in the apparent surface temperature and the actual surface temperature is larger than 0.5°C for surfaces with emissivities smaller than 0.99. The effects of surface emissivity <1.0 and reflected incoming longwave radiation are of opposite sign but not equal in

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**Figure 1.** The difference between the apparent surface temperature measured with the radiometers used in this study and the true temperature of a surface with emissivity values shown, derived from (11). The incoming longwave radiation was assumed to be 11 W m$^{-2}$ sr$^{-1}$, and the instruments were effectively set for a surface emissivity of 0.995.
magnitude. Because the value of emissivity for natural surfaces is smaller than 1, the apparent temperature measured with a radiometer is lower than the kinetic temperature of the surface. The magnitude of the corrections for emissivity increases with $T_s$. The effect of the additional radiation received by the sensor due to reflected incoming longwave radiation is to make the apparent temperature appear higher than the true temperature. However, the magnitude of this effect remains constant with surface temperature for a given value of surface emissivity. It should be noted that the magnitude of the differences shown in Figure 1 is specific to the band pass of the instrument and the value of $e_{gb}$ used in the analysis. In the analysis presented here, whenever incoming longwave radiation was not measured directly, it was estimated as a function of the near-surface air temperature and the emissivity of the air. The emissivity of the air was estimated with the formula of Idso [1981] for the 8-14 $\mu$m band pass.

## Results and Discussion

### Component Emissivity Measurements

Using (8), emissivity values were calculated for the approximately 20-30 different targets which were measured in the vicinity of six METFLUX sites. Two of the METFLUX sites (sites 2 and 8) were not visited during the experimental period. The size of each of the targets measured, determined by the field of view of the instrument when the cone apparatus was placed on the surface, was approximately 40 cm in diameter. The goal in the selection of the targets at each METFLUX site was to acquire measurements over many different samples of exposed bare soil and rock and the dominant vegetation types at each site. Approximately 8-11 different areas of exposed rock and bare soil were measured at each site. For each of the sites dominated by shrubs, 10-20 measurements of the most prevalent species of shrubs and clumpy vegetation were made. For all of the measurements denoted as shrubs or clumpy vegetation, the vegetation was large enough to completely fill the field of view of the instrument. At sites with smaller shrubs and a significant proportion of grass species, it was possible to measure targets which were a mixture of exposed soil and vegetation.

In each of the three categories the differences in the emissivity values of that target type at the individual sites were generally not significant in comparison to the standard deviation of the measurements at each site. The mean and standard deviation for the emissivity values averaged over all sites for the three categories are given in Table 2. They are in generally good agreement with the results reported by other investigations over arid/semiarid regions.

The mean values obtained for targets which consisted of exposed bare soil and rock ($e = 0.96$) is somewhat high compared to some other reported values for emissivity of bare soils [Taylor, 1979; Hipps, 1989; van de Griend et al., 1991]. However, it should be noted that the presence of coarse rock fragments on the soil surface was a dominant surface feature over most of the watershed. The percentage of the exposed soil surface covered with rock fragments was highly variable over length scales of a few meters, but the estimates of rock cover obtained from intensive surface sampling near the METFLUX sites were about 40-50% for all sites except site 7. Because rougher surfaces are expected to have higher values of emissivity, a mean value of 0.96 for the exposed rock/soil at this field site appears to be within reason. It is also consistent with the results obtained by Labeled and Stoll [1991] over the rocky surface at La Crau.

The mean values obtained for the shrubs and clumpy vegetation types at different sites on different days were very consistent among sites. The overall mean value of 0.994 for these vegetation types is also consistent with previously reported values for very rough, structurally complex vegetation types.

### Composite Emissivity Estimates

As discussed in a previous section, the total response of a sensor viewing a surface with significant fractions of both soil and vegetation is a function of the emissivities and kinetic temperatures of both components. Several researchers have developed physically based models for idealized surfaces which describe the contributions of several surface components to the total thermal emission [e.g., Sutherland and Bartholic, 1977; Becker, 1981; Kimes, 1983; Caselles et al., 1992]. However, these models have been developed primarily for relatively uniform agricultural vegetation. Additionally, they require knowledge of many vegetation parameters which are not likely to be uniform over large areas of natural vegetation and are not known a priori for these types of areas. These physically based models cannot be inverted for component temperature and emissivity of two or more surface components based on a single observation of remotely sensed temperature over a large area.

Thus from the standpoint of semioperational use of remotely sensed data for the estimation of surface energy fluxes, it is desirable to define an effective surface emissivity and temperature in terms of the components of a heterogeneous surface as discussed by Becker et al. [1981], Price [1982], and Becker and Seguin [1985]. They defined an effective regional scale surface emissivity (e.g., pixels of 1 km or larger) as the sum of the components weighted by fractional exposed area. Becker et al. [1981] proposed quantitative criteria for the variability in emissivity and temperature over which these effective definitions would be valid.

For defining composite emissivity at the local scale, a simple linear combination of the emissivity values for soil and vegetation, weighted by the fractional area of surface covered by those components, does not take into account interactions between the components due to scattering. There are no widely accepted methods to quantify this interaction. Models do exist [Sutherland and Bartholic, 1977] which attempt to quantify the effective emissivity of a surface in terms of the component emissivity of the soil and one vegetation layer, and single scattering of radiation between those two components. However, by necessity,
greater than about 1 m. It is also difficult to develop a model practical to measure emissivity values over length scales in the temperatures of the individual components. It is these formulations require the assumption of an idealized surface with one dominant vegetation type and small differences in the temperatures of the individual components. It is difficult to validate such models because it is not logistically practical to measure emissivity values over length scales greater than about 1 m. It is also difficult to develop a model which realistically describes the interaction between radiation emitted by soil and by two vegetation types as structurally different as desert shrubs and desert grasses.

The data given in Table 3 indicate that the vegetation cover at the eight METFLUX sites for the Monsoon '90 experiment consisted of variable mixtures of shrubs, grasses, and forbs. Characteristics such as vegetation structure, density, and distribution are likely to influence the degree and magnitude of soil/vegetation interactions which determine the composite effective emissivity of a surface. For this reason the percent vegetation cover by grass/forbs at each site is distinguished from the vegetation cover at other sites dominated with shrub-type vegetation and less applicable to sites dominated with grass-type vegetation or sites with significant amounts of both grass and shrub-type vegetation.

Two methods were used for estimating the composite emissivity values for each site. The results, along with the vegetation cover characteristics used to compute the composite emissivity values, are shown in Table 3. The two methods for computing the total composite emissivity values are described below.

**Method 1.** Data acquired during the Monsoon '90 experiment on the mean vegetation height and spacing at each site were used with the formulation of Sutherland and Bartholic [1977] to compute a composite effective surface emissivity for each site. That formulation, developed for the idealized surface of relatively uniformly spaced, tall vegetation (orange trees), makes use of the ratio of vegetation height to spacing to compute view factors between idealized "walls" and "cavities." With consideration of a single reflection of radiation between the walls and cavities, they developed an expression for the effective emissivity of the cavities. The reflection of incoming longwave radiation from the sky is also considered in their expression for the total effective emissivity of the surface (their equation (10)). Thus the composite effective emissivity is expressed as a function of the vegetation height to spacing ratio, the emissivity of the soil and vegetation components, and an assumed effective sky emissivity.

The values of the vegetation parameters at each METFLUX site were estimated by Welz et al. [this issue] and are summarized in Table 3. The values of composite emissivity computed with these parameters and the Sutherland and Bartholic [1977] expression are reported in Table 3 in the column labeled "method 1." Because the Sutherland and Bartholic [1977] expression was developed for an idealized surface with regularly spaced clumpy vegetation (i.e., trees), it is likely that their expression would be more applicable to the sites dominated with shrub-type vegetation, and less applicable to sites dominated with grass-type vegetation or sites with significant amounts of both grass and shrub-type vegetation.

**Method 2.** Because many of the field sites in this experiment were not very similar to the idealized surfaces used to develop a physically based expression for the composite emissivity, another method was used which relied instead on measurements at several sites of the rock/soil/vegetation mixtures in between the large shrubs. From the measurements of those intershrub areas, which consist primarily of bare soil at some sites and a mixture of bare soil and grass-type vegetation at others, the dominant factor influencing the effective composite emissivity of the intershrub surface areas appeared to be the amount of grass-type vegetation present in the target area. Thus, to estimate an effective emissivity of the intershrub areas at each site, the sites were divided into four categories according to the percent vegetation cover by grass and forbs at each site. The categories, given in percent cover by grass and forbs, were as follows: <2% (sites 1 and 8); 8–10% (sites 3 and 6); 18–24% (sites 2 and 7); >35% (sites 4 and 5). The effective composite emissivity of the intershrub area of the last category (>35% cover by grass and forbs) was measured at site 4 to be approximately 0.98. The emissivity of bare soil areas such as those constituting the intershrub areas in the first category (<2% cover by grass and forbs) was measured to be approximately 0.96. Interpolating between these two extremes, the intershrub areas for the other two categories

### Table 3. Mean Values for Vegetation Height and Spacing, Percent Vegetation Cover by Type, and Composite Emissivity Values Estimated by Two Different Methods at Each Site

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean Vegetation Height $H_v$, cm</th>
<th>Mean Vegetation Spacing $S_v$, m</th>
<th>Ratio $H_v/S_v$</th>
<th>Percent Cover by Grass and Forbs</th>
<th>Percent Cover by Shrubs</th>
<th>Method 1 $\epsilon_{tot}$</th>
<th>Method 2 $\epsilon_{tot}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.27</td>
<td>0.74</td>
<td>0.37</td>
<td>0.4</td>
<td>25.8</td>
<td>0.979*</td>
<td>0.971</td>
</tr>
<tr>
<td>2</td>
<td>0.23</td>
<td>0.27</td>
<td>0.85</td>
<td>23.4</td>
<td>27.8</td>
<td>0.981*</td>
<td>0.980*</td>
</tr>
<tr>
<td>3</td>
<td>0.19</td>
<td>0.25</td>
<td>0.75</td>
<td>7.9</td>
<td>32.3</td>
<td>0.979*</td>
<td>0.979*</td>
</tr>
<tr>
<td>4</td>
<td>0.18</td>
<td>0.24</td>
<td>0.75</td>
<td>47.6</td>
<td>13.3</td>
<td>0.976*</td>
<td>0.985*</td>
</tr>
<tr>
<td>5</td>
<td>0.10</td>
<td>0.25</td>
<td>0.40</td>
<td>36.3</td>
<td>3.8</td>
<td>0.975*</td>
<td>0.984*</td>
</tr>
<tr>
<td>6</td>
<td>0.21</td>
<td>0.37</td>
<td>0.56</td>
<td>9.5</td>
<td>28.2</td>
<td>0.976*</td>
<td>0.976*</td>
</tr>
<tr>
<td>7</td>
<td>0.07</td>
<td>0.16</td>
<td>0.44</td>
<td>19.7</td>
<td>12.0</td>
<td>0.975*</td>
<td>0.977*</td>
</tr>
<tr>
<td>8</td>
<td>0.50</td>
<td>0.54</td>
<td>0.94</td>
<td>1.7</td>
<td>38.0</td>
<td>0.981*</td>
<td>0.973</td>
</tr>
</tbody>
</table>

*Of methods 1 and 2, the method which is more suitable for estimation of composite emissivity at each site.
The effective composite emissivity was then computed as a linear combination of the emissivity of shrub and intershrub area emissivity values, weighted by the fraction of the surface made up by shrub and intershrub areas.

The implicit assumption in this method is that the interaction between the soil and vegetation (which serves to increase the composite effective emissivity beyond the simple weighted sum of the components) is significant only for the grass/soil mixtures in the intershrub areas, and that interactions between the large shrubs and nearby surfaces are not significant. The validity of this assumption is difficult to quantify. Sutherland and Bartholic [1977] indicated that those interactions were significant when the ratio of vegetation height to spacing was >1. For the field sites in this study, the ratio of vegetation height to spacing (given in Table 3) was much smaller than 1 for all sites except site 8. Thus it is possible that this method would tend to underestimate an effective emissivity value for site 8, and possibly for the other shrub-dominated site (site 1). The most suitable composite emissivity value for each site is noted on Table 3 with the following assumptions: (1) method 1 is more suitable for shrub-dominated sites and (2) method 2 is more suitable for grass-dominated sites and sites with significant fractions of both grass and shrub vegetation. The mean of these values for all the METFLUX sites across the watershed is 0.980 with a standard deviation of 0.003.

Component and Composite Surface Temperatures

The 20-min averages of apparent surface temperature acquired with the instruments mounted on a stationary boom over soil and vegetation targets were adjusted for surface emissivity and longwave radiation as described in a previous section. Using the results of the emissivity measurements reported above, \( e_s \) was assumed to be 0.994 for the vegetation targets and 0.959 for the soil targets. The kinetic temperatures of the soil and vegetation targets at the shrub-dominated site are plotted as a function of local time (MST) for a typical day (day of year (DOY) 221) in Figure 2a. Sky conditions on DOY 221 were fairly clear in the morning and partly cloudy in the afternoon.

The data presented in Figure 2a indicate that the moderate-size shrub (Larrea tridentata; common name creosote) monitored at the shrub-dominated site remains very close to the air temperature measured at 2 m (within 1-3°C), particularly at midday. The shrub species monitored here was the most prevalent vegetation type at this site. At midday the soil background at this site attained a temperature 25°C higher than the temperature of the shrub. The last precipitation event which occurred at this site was 5 days previous to DOY 221. The gravimetric soil moisture content measured at midmorning at this site on DOY 221 was approximately 0.04 g/g [Schmugge et al., this issue].

The temperature of the several other components of the surface (e.g., shrubs other than the type used as a target for the instrument on the stationary boom, sunlit soil, standing dead biomass) were monitored occasionally with a separate IRT with a very small field of view. The temperature of the shaded soil component of the surface generally remained within a few degrees of the vegetation temperatures throughout the morning heating cycle. Small shrubs had a slightly higher surface temperature than the large shrub monitored as described above.

In order to evaluate how well the surface composite temperature could be described with two component temperatures (i.e., the temperatures of the sunlit soil and the predominant shrub type), the component temperature measurements such as those shown in Figure 2a were used to estimate a composite surface temperature during time periods for which yoke-based composite temperatures were measured over a large adjacent area. The component temperatures were converted into emittances by the shrub and soil surface components using the values of component emissivity reported above. These emittances were then weighted by the percent fractional vegetation cover given by Weltz et al. [this issue]. The results are shown in Figure 2b.

Figure 2a. The corrected surface temperature, derived from radiometric temperatures acquired continuously over bare soil and shrub targets at site 1 (shrub-dominated site) on DOY 221. The data are shown as a function of local time and include the air temperature measured at a height of approximately 2 m above the surface.

Figure 2b. Radiometric surface temperature computed from the weighted sum of the soil and vegetation emittances versus the mean radiometric temperature measured over the yoke area at the shrub-dominated site. Data points represent mean temperatures acquired over a 20 min data acquisition interval with the yoke at different times of day on approximately 10 different days.
The root-mean-square error (RMSE) in the estimate of the composite temperature was 1.1°C. These results suggest that for this type of surface the composite surface temperature can be adequately described with the shrub and sunlit soil component of the surface. These observations may have useful implications for the degree of complexity required in multilayer models of heat and moisture transfer in the soil-plant-atmosphere system for this type of ecosystem.

Spatial and Temporal Variability of $T_s$
Over a Large Grassland Target

To evaluate the spatial and temporal variability of surface temperature at a larger spatial scale (of the order of 0.16–60,000 m$^2$), data from periodic ground-based yoke measurements over an extensive ground target area at one of the grassland sites (site 5) were used. As described above, the target area was approximately 120 x 480 m. Under ideal observing conditions, 768 measurements of surface temperature were acquired over the area within approximately 10 min; the instantaneous field of view (IFOV) on the ground surface for each measurement was approximately 40–50 cm in diameter. Given the density, type, and spatial distribution of vegetation at this site, the ground surface constituting the instantaneous field of view for each measurement consisted either solely of bare soil, rocks, grass-type vegetation, or shrubs, or any combination of those components.

A typical frequency distribution for the temperature measurements acquired in this manner at different times of day is shown in Figure 3 for DOY 216. For this particular day, one of four instruments usually used to acquire data over the target area was malfunctioning; the curves shown in Figure 3 represent 576 measurements over approximately 43,000 m$^2$. The distributions shown in Figure 3 indicate that the variance in surface temperature increases significantly with the diurnal cycle of surface heating. In the early morning hours, when the surface temperatures of the vegetation and soil components differ from each other by only a few degrees, the overall variance in temperature measured over the large target area is relatively small.

The relationship between the temporal and spatial variability of surface temperature is shown more clearly in Figure 4a. The mean temperature of the large target area is plotted as a function of time for DOY 216. The standard deviation among the 568 observations acquired for each time period is also plotted in Figure 4a.

The magnitude of the variability observed in surface temperature measurements is dependent on many factors, such as the spatial scale of heterogeneity on the surface, the area of the surface over which the sensor integrates for each measurement (i.e., the IFOV of the sensor, or the “pixel” size of observation), and the total area under examination. For the data presented here, the IFOV of the instrument was larger than the scale of some sources of surface temperature variability (e.g., placement of grass blades), and smaller than other sources of surface variability in surface temperature (e.g., placement of shrubs, variability in the density of the grass cover over spatial scales of approximately 1–10 m). The scale of the data presented here represents the smallest IFOV which could be practically acquired over a large total area.
ground target area with ground-based instruments of this type in a relatively short time period. By definition of the IFOV for a particular sensor, most satellite- or aircraft-based sensors only provide an integrated value of radiometric surface temperature over the IFOV and the "within-IFOV" or "within-pixel" variability is unknown. However, if typical relationships exist between integrated pixel values and within-pixel variability under certain conditions for a particular surface, then perhaps that variability could be estimated and taken into account in future approaches to the interpretation of radiometric data over heterogeneous surfaces. Toward that end, the relationship between the variability of the measurements within the large ground target area and the mean value of surface temperature for the entire target area was evaluated. In Figure 4b the variances among the individual measurements within the large target area are plotted as a function of the difference between the mean surface temperature and air temperature for different time periods on two different days with slightly different surface conditions. On DOY 216, the surface (0-5 cm) gravimetric soil moisture was significantly higher than it was on DOY 221. It must be stressed that this relationship is specific to this particular field site, the conditions which existed during the Monsoon '90 experiment, the spatial scale of the individual measurements, and the total area covered. However, for periods of unstable conditions the relationship shown in Figure 4b is quite consistent for different periods and two different days of the Monsoon '90 experiment. It may be valuable to examine relationships such as these for other field sites and other conditions. Under conditions significantly different than those which existed during the Monsoon '90 experiment, the spatial and temporal variability in surface temperature would be expected to be different than those observed during the experiment. The experiment was intentionally carried out during that portion of the year in which the vegetation was actively growing and transpiring, due to the seasonal availability of water in the root zone.

Ground- and aircraft-based remote sensing observations were also acquired on one day in the dry season prior to the experiment, in June 1990 (DOY 156). On that day the vegetation was senescent, and a subset of the large ground target area at site 5 (192 measurements over 13,000 m²) was sampled in approximately 10 min with yoke-based ground instruments at only two times of day. The frequency distribution for those measurements is shown in Figure 5. These results represent a subsample of the area of coverage shown in Figure 3 and include only two different times of data acquisition. Thus it is not possible to draw firm conclusions from the data shown in Figure 3b. However, these results demonstrate a strong seasonal difference in the spatial and temporal variability (and the interrelationship of spatial and temporal variability) of surface temperatures measured at this scale. The magnitude of the spatial variability is more constant in time under these conditions than it was during the rainy season. This is due to the fact that there was not a significant diurnal variation between the two dominant surface components present on DOY 156, i.e., bare soil and senescent vegetation.

Variability of \( T_z \) and \( H \) at the Watershed Scale

Surface temperatures derived from radiometric data acquired from a light aircraft across the watershed were utilized to evaluate the variability of surface temperature at the watershed scale. At the average altitude and velocity of the airplane, the ground IFOV for these measurements was approximately 25 m in diameter, and the center point of individual measurements was approximately 60 m apart. A typical frequency distribution for surface temperature measurements acquired in this manner at three different times on DOY 216 is shown in Figure 6. These curves each represent approximately 500 observations along two aircraft transect lines across the width of the watershed. The variance in surface temperature for the three data acquisition times shown in Figure 6 is not appreciably larger than the variance observed with ground-based measurements over a much smaller area (Figure 3). This is most likely due to the fact that the most significant source of variability in surface temperature over the study area was the difference in temperature between the vegetation and exposed soil. Both the IFOV for the ground measurements over the grassland target area and the IFOV for the aircraft-based measurements over the watershed were large enough to view both soil and vegetation in the particular areas over

![Figure 5. Frequency distribution for ground-based radiometric temperature data acquired over a 120 m x 480 m target area at site 5 (grass-dominated site) for different time periods on DOY 156. The vegetation at this site was senescent at that time. Times shown are in hours (MST).](image_url)

![Figure 6. Frequency distribution for light aircraft-based radiometric temperature data acquired over transects across the watershed on DOY 216 for three different times of data acquisition. Times shown are in hours (MST).](image_url)
which the sensors operated. Thus the major source of temperature variability was most likely to have been integrated into individual measurements.

These observations of variability at different sensor IFOV sizes and over total target areas of different spatial under- score the need for caution in evaluating the spatial variability of remote sensing measurements. A common tool for describing the spatial variability of a quantity is the semivariogram. However, it is difficult to make effective use of such a tool with a variable such as surface temperature over semiarid surfaces. Because some amount of surface variability is integrated into each measurement over a particular IFOV, the values of semivariance computed with remotely sensed data can only provide an estimate of the “between-pixel” variance for the total area observed in a particular data set. For typical IFOV sizes of satellite sensors the “within-pixel” variability of a semiarid surface can be large.

Summary and Conclusions

The differences in emissivity and kinetic temperature of the soil and vegetation components of a sparsely vegetated surface give rise to significant “within-pixel” variations in emitted energy. All measurements of emissivity and temperature presented in this analysis were acquired with instruments with a band pass of approximately 8–13 μm. The mean value of emissivity for the coarse-textured, rocky soils in this study area was 0.959. The mean value of emissivity for shrubs and other clumpy vegetation types was approximately 0.994. Using two different techniques to compute an effective composite emissivity value at each of the METFLUX sites, the mean value of effective composite emissivity over the watershed was computed to be approximately 0.98. The kinetic temperature of the soil and vegetation components of the surface varied considerably during the course of a typical diurnal heating cycle. At midday, temperature differences of approximately 25°C were observed between the dry soil background and actively transpiring shrubs. The shaded soil areas maintained temperatures between the dry soil background and actively transpiring shrubs. The shaded soil areas maintained temperatures within a few degrees of the vegetation temperatures. When a sparsely vegetated surface is “viewed” by a sensor at within a few degrees of the vegetation temperatures. When a sparsely vegetated surface is “viewed” by a sensor at different look angles, different proportions of soil and vegetation will be present in the field of view of the sensor. The observations of component temperatures presented here suggest that view angle effects on surface temperature observations during active vegetation periods for sparsely vegetated areas would be very significant.

The observed spatial variability of surface temperature is a function of the relative spatial scales of the instantaneous field of view (IFOV) of the instrument used for the measurements, the total area under consideration, and the size of the surface element which generates most of the variability in surface temperature. For the component temperature measurements, in which the IFOV of the instruments was of the order of 1–3 cm, very large variations in temperature were observed over spatial scales of less than 1 m. An analysis of the variability in “composite” surface temperatures, in which a large (120 m × 480 m) ground target area was intensively sampled over a 10-min period with an instrument IFOV of approximately 0.5 m, showed that the variance in surface temperature at that spatial scale increased throughout the morning during a typical diurnal heating cycle. In the early morning hours the observed variance in surface temperature from these measurements was approximately 1°C. By late morning the variance observed in these measurements was typically of the order of 10°C–12°C. The relationship between the spatial and temporal variability of surface temperature at this spatial scale was found to be similar from day to day within the main experimental period, but different for the one day of data acquisition which occurred prior to the rainy season when most of the vegetation was senescent. For aircraft-based composite radiometric temperature measurements at the watershed scale (with ground IFOV of approximately 40 m for each observation), much of the variability in surface temperature due to differences in soil and vegetation temperature was integrated into a single measurement; consequently, the variance between observations over the watershed was not significantly larger than those observed at length scales of 100 m. Additionally, the sensitivity of the surface temperature estimates to adjustment for surface emissivity and reflected incoming long-wave radiation typical for this region was evaluated.

Acknowledgments. A data set such as that acquired during the Monsoon '90 field experiment can only come about with the extraordinary dedication of many individuals and the cooperation of several agencies and universities. The authors are particularly grateful for the technical and logistical support of the personnel at the field operations office of the USDA ARS Walnut Gulch experimental watershed, headed by Howard Larsen, and the establishment and ongoing management of the watershed by personnel at the Southwest Watershed Research Center in Tucson, Arizona. The ground-based remote sensing data was acquired by a team of people led by Thomas Clarke of the USDA ARS U.S. Water Conservation Laboratory (USWCL). We are particularly grateful for the technical and logistical support of the personnel at the USWCL for acquiring the aircraft-based data used in this analysis while he was operating his own instruments, and for the exceptional expertise of pilot David Ammon. Financial support for portions of the data acquisition and analysis described in this paper was provided by NASA Training Grant NGT-50273, a grant from the NASA Interdisciplinary Research Program in the Earth Sciences (reference number IDP-88-086) and a grant from the NASA Earth Observing System Program (reference number NAGW2425). Portions of this work were carried out while K.S.H. was at the Department of Hydrology and Water Resources, University of Arizona, Tucson.

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