Sensible Heat Flux–Radiometric Surface Temperature Relationship for Eight Semiarid Areas

J. B. STEWART

Institute of Hydrology, Wallingford, Oxfordshire, United Kingdom

W. P. KUSTAS AND K. S. HUMES

USDA-ARS, Hydrology Laboratory, Beltsville, Maryland

W. D. NICHOLS

USGS Water Resources Division, Carson City, Nevada

M. S. MORAN

USDA-ARS, U.S. Water Conservation Laboratory, Phoenix, Arizona

H. A. R. DE BRUIN

Agricultural University, Wageningen, the Netherlands

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ABSTRACT

Measurements of sensible heat flux, radiometric surface temperature, air temperature, and wind speed made at eight semiarid rangeland sites were used to investigate the sensible heat flux–aerodynamic resistance relationship. The individual sites covered a wide range of vegetation (0.1–4 m tall) and cover (3%–95% bare soil) conditions. Mean values of kB^{-1}, a quantity related to the resistance of heat versus momentum transfer at the surface, for the individual sites varied between 3.5 and 12.5. A preliminary test of the utility of an excess resistance based on the mean value of kB^{-1} showed that the difference between the mean estimated and measured sensible heat fluxes varied ±60 W m^{-2} for the eight semiarid sites. For the eight sites the values of kB^{-1} were plotted against the roughness Reynolds number. The plot showed considerable scatter with values ranging between and beyond the theoretical curves for bluff rough and permeable rough surfaces.

1. Introduction

Several recent field experiments have been conducted in semiarid regions because little is known about the spatial and temporal variation in energy and water fluxes and how they are affected by soil and vegetation properties (Van de Griend et al. 1989; Kustas et al. 1991; Wallace et al. 1991). The precipitation over semiarid regions is extremely variable in time and space, resulting in large spatial variability in soils and vegetation cover as well as in the fluxes of heat and water vapor from the surface. An integral part of these field campaigns has been the collection of remotely sensed data since only this technology has the potential to assess the spatial variability.

Remotely sensed surface temperature or radiometric surface temperature T_S^R from ground, aircraft, and satellite platforms has been used in models quantifying the surface energy balance from field to regional scales (Jackson 1985; Carlson 1986). The ultimate objective is to compute reliable latent heat fluxes or evapotranspiration for initializing, updating, and testing surface flux parameterizations used in regional- and global-scale hydrologic and atmospheric models.

One of the common uses of T_S^R is in the estimation of sensible heat flux, one of the turbulent flux terms in the surface energy balance equation. The surface–air temperature difference is made proportional to the sensible heat flux by means of an aerodynamic (single layer) resistance. However, use of the classical formula to calculate this resistance can produce errors of greater than 50% caused by failure to use an appropriate value for the roughness length for heat, z_{0h}, especially over sparse canopies (Choudhury et al. 1986; Kustas et al. 1987; Stewart et al. 1989). As a result, some have con-

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Corresponding author address: Dr. John B. Stewart, Institute of Hydrology, MacLean Building, Crownmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB, United Kingdom.

TABLE 1. Location, dominant vegetation type, and mean annual precipitation for the eight sites.

Project	Location	Latitude	Longitude	Altitude (m)	Vegetation	Precipitation (mm)
SEBEX	Niger	13°15′N	2°18′E	240	Savanna	564
SEBEX	Niger	13°12′N	2°15′E	260	Open forest	564
MONSOON 90	Arizona	33°44′N	110°3′W	1526	Grass	241
MONSOON 90	Arizona	33°45′N	109°56′W	1371	Shrubs	241
Owens Valley	California	37°15′N	118°15′W	1220	Shrubs	125
Smith Creek Valley	Nevada	39°19′N	117°30′W	1850	Shrubs	250
Smoke Creek Desert	Nevada	40°32′N	119°49′W	1192	Shrubs	155
La Crau	France	43°34′N	4°51′E	13	Stones/grass	350

cluded that T_S^R is not very useful for computing the sensible heat flux (e.g., Hall et al. 1992).

Sensitivity studies with atmospheric numerical prediction models have shown that the value adopted for z_{0h} can greatly influence model output (Beljaars and Holtslag 1991; Betts et al. 1993). In models using the single-layer resistance approach, the height $z_{0h} + d_0$ (where d_0 is the displacement height) is the source–sink height for heat because mathematically it is the level where the extrapolated Monin–Obukhov temperature profile attains its surface value. With the use of the radiometric surface temperature, problems associated with extrapolating the highly nonlinear temperature profile to the surface can be avoided. However, the radiometric surface temperature for a particular surface is a function of the amount of vegetation cover, the canopy architecture, the sensor view angle, the solar zenith angle, the terrain, and other surface features (Brunet et al. 1991). In addition, there is a significant atmospheric effect when measurements are made from aircraft- and satellite-based sensors. Accounting for all these factors makes it extremely difficult to develop a simple procedure for relating z_{0h} to surface properties influencing the turbulent transport of heat and the radiometric temperature measurements.

Observations in semiarid areas suggest that afternoon surface–air temperature differences are typically greater than 5 K (e.g., Kustas et al. 1989). Errors in satellite-based measurements of surface temperature due to emissivity and atmospheric variations are expected to be 1–2 K, resulting in typical errors in the surface–air temperature difference of about 25%. This would still allow its use to estimate sensible heat fluxes if the large errors previously reported could be overcome. Unfortunately, most other factors require details of the surface that cannot be measured with the resolution of satellite-based sensors. Consequently, complex approaches, such as the use of a two-component model for computing the energy balance of the vegetation and soil, cannot be used with existing operational satellites (Smith and Choudhury 1991).

In this paper, the analysis of the aerodynamic resistance to heat transfer from eight semiarid sites was investigated. The sensible heat flux, meteorological, and remotely sensed data were collected from ground-based stations. An empirical correction to the standard formula was computed for each site.

2. Site characteristics

During the last few years a number of multidisciplinary projects have taken place. Their general aim has been to quantify and understand the fluxes from areas of sparse natural vegetation. Additionally, these projects collected data to enable development and validation of remote sensing algorithms. The data from six of these projects are used in this analysis; these were the SEBEX (Sahelian Energy Balance Experiment), La Crau, MONSOON 90, Owens Valley, Smith Creek Valley, and Smoke Creek Desert projects. During some of these projects, measurements were made over more than one type of vegetation. Table 1 gives the location, vegetation classification, and the average annual precipitation for each of the sites. Details of the sites are given by Wallace et al. (1991), Kohsiek et al. (1993), Kustas et al. (1991), Kustas et al. (1989), and Nichols (1992), respectively.

Table 2 gives the proportions of the surface cover and the aerodynamic characteristics for each site. Values of z_{0m} and d_0 for each site had been derived from eddy correlation measurements of u_* (Kohsiek et al. 1993; Lloyd et al. 1992), estimated from empirical formulas that use canopy height and density (Kustas et al. 1989; Nichols 1992), or determined by applying surface similarity theory to vertical velocity fluctuations (Kustas et al. 1994). The data collected do not suggest that the measurements were taken within the roughness sublayer. At these sites the height of the grass was typically 0.1 to 0.3 m; shrubs were 0.5 to 2.5 m tall, and trees were 3 to 5 m tall.

3. Measurements

In the SEBEX project the surface temperature was measured by infrared thermometers (model 4000) manufactured by Everest Interscience.[1] They had a field

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[1] Trade and company names are given for the benefit of the reader and imply no endorsement by the United States government.

TABLE 2. Proportions of the components of the surface cover and the aerodynamic characteristics—roughness length z_{0m} and zero plane displacement d_0—for the eight sites.

		Surface cover (%)			Aerodynamic characteristics (m)	
Project	Surface	Bare soil	Grass Forbes	Shrubs trees	z_{0m}	d_0
SEBEX	Savanna	3	78	19	0.17	0.93
SEBEX	Open forest	67		33	0.4	2.0
MONSOON 90	Grass	60	36	4	0.01	0.3
MONSOON 90	Shrubs	74		26	0.04	0.5
Owens Valley	Shrubs	70		30	0.1	0.7
Smith Creek Valley	Shrubs	75	2	23	0.06	0.375
Smoke Creek Desert	Shrubs	70		30	0.04	0.25
La Crau	Stones/grass	95	5		0.013	

of view of 15°. To obtain an areal average the measurements were replicated. The number used and the height of the mountings is given in Table 3. The sensors were positioned so that they sampled the various components of the land cover. The individual measurements were weighted by the average proportion of the vegetation over the areas. The air temperature was measured by an automatic weather station manufactured by Campbell Scientific Inc., and the data integrated over an hour. The hourly measurements of the sensible heat flux were made by the Institute of Hydrology Mk2 Hydra, an eddy correlation system using a vertical sonic anemometer and fine-wire thermocouple (Shuttleworth et al. 1988).

In the MONSOON 90 project, the sensible heat flux was estimated using both eddy correlation and temperature variance techniques. The variance technique is described in Wesely (1988), while the eddy correlation methods used at these sites are described in Blanford and Stannard (1991) and Stannard et al. (1994). Comparison of sensible heat fluxes by the eddy correlation and variance technique was satisfactory (Kustas et al. 1991; Kustas et al. 1994). Since the variance data allowed for a nearly continuous set of local sensible heat flux estimates at both sites, these fluxes were used in the present study. Measurements of wind speed and direction and air temperature were made by an R. M. Young Wind Sentry (model 3001-5) and a Campbell Scientific fine-wire chromel constantan thermocouple. Twenty-minute averages were recorded. For more details about the field sites and measurements, see Kustas et al. (1991) and Kustas and Goodrich (1994).

Continuous thermal infrared observations were made at the two Walnut Gulch sites using Everest Interscience (model 110) infrared thermometers having a 3° field of view. One sensor viewed the soil surface while the other viewed the vegetation. Sensors were positioned 2 m above the soil surface at the Lucky Hills site and 1 m above the soil surface at the Kendall site. Periodically, ground-based transects with a nadir-viewing thermal IR sensor mounted on a yoke appa-

TABLE 3. Number of infrared thermometers and height of sensible heat flux, wind speed, and surface and air temperature sensors.

		Surface temperature (number) height (m)		Height (m)		
Project/site	Period	Grass/soil	Shrubs	Wind speed	Air temperature	Sensible heat flux
SEBEX Fallow/savanna	7 Oct–4 Dec 1989 11 May–7 Jun 1990	(3) 3.5 (2) 6.0	(3) 3.5 (4) 3.5	10.3 10.3	10.3 10.3	12.3 12.3
SEBEX Natural open forest	7 Oct 1989–30 Sep 1990	(3) 3.5	(3) 9.5	12.1	12.1	15.9
MONSOON 90 Shrub	28 Jul–10 Aug 1990	(1) 2	(1) 2	4.3	4.0	4.0
MONSOON 90 Grass	28 Jul–10 Aug 1990	(1) 1	(1) 1	4.3	4.0	4.0
Owens Valley	2–5 Jun 1986	(1) 150*	(1) 150*	2.0	2.0	2.0
Smith Creek Valley	23 Jul–3 Aug 1989	(1) 2	(1) 2	2.25	2.25	1.75
Smoke Creek Desert	23–31 Jul 1989	(1) 2	(1) 2	2.0	2.0	1.5
La Crau	2–23 Jun 1987	(1) 1.5		10.5	1.9	11.0

* Composite temperature obtained from aircraft platform (see text).

ratus were collected near the flux stations. The composite surface temperature from these ground-based transects were in close agreement with low-altitude aircraft observations having a much larger sensor footprint (Moran et al. 1991). Therefore, reliable estimates of the composite surface temperature with the continuous thermal IR observations were obtained by a least-squares regression. The one sensor viewing the soil and the other viewing the vegetation were the independent variables, and the composite temperatures from the yoke transects were the dependent variable. For the Lucky Hills and Kendall sites the root-mean-square error between predicted and actual composite temperature was about 0.9°C and 1.1°C, respectively.

In Owens Valley, measurements of the surface energy balance were made by the Bowen ratio energy balance approach and eddy correlation method. For a description of the Bowen ratio systems see Gay (1988) and Stannard (1985), and for the eddy correlation systems see Tanner et al. (1985). In general, the agreement between the two techniques was satisfactory (Weaver 1992). Estimates of the surface energy balance components were adopted for the analysis from Kustas et al. (1989). Wind speed and air temperature were measured by a portable meteorological station nearby the flux sites. Wind speed was measured by an R. M. Young three-cup anemometer (model 12002), and air temperature was measured with a shielded and aspirated copper constantan thermocouple manufactured by the U.S. Department of Agriculture–Agricultural Research Service (USDA-ARS), U.S. Water Conservation Laboratory.

Remote sensing data were collected over Owens Valley using an Exotech four-band radiometer and an Everest Interscience (model 110) infrared thermometer mounted on an aircraft platform. Observations were made for several clear days in the late morning and early afternoon. The aircraft flew at an altitude of 150 m above ground level. The nadir-looking instrument had a nominal 15° field of view, which resulted in a 40-m-diameter footprint at the surface. For further details concerning the micrometeorological and remote sensing measurements, see Kustas et al. (1989) and Wilson et al. (1992).

Sensible heat fluxes at Smith Creek Valley and Smoke Creek Desert were evaluated with the Bowen ratio–energy balance approach. Gradients of temperature and vapor pressure above the canopy were determined by measurements at two heights of air and dewpoint temperatures. The air temperatures were measured using fine-wire thermocouples, and dewpoint temperatures were measured with a single cooled-mirror hygrometer. The Bowen ratio system was designed and manufactured by Campbell Scientific (Tanner et al. 1987).

Continuous thermal infrared observations of bare soil temperatures were made at both sites using an Everest Interscience (model 4000) infrared thermometer with a 15° field of view mounted approximately 2 m above the soil surface. Canopy temperatures were measured with an Everest Interscience (model 110) infrared thermometer with a 3° field of view mounted 2 m above the soil surface. Wind speeds were measured with R. M. Young photochopper anemometers with a threshold of 0.2 m s^{-1}. For more details concerning the micrometeorological and remote sensing measurements, see Nichols (1992).

Measurements for the La Crau experiment were made in June 1987 in the La Crau region of southern France, a dry flat area of about 150 km^2 covered with pebbles and stones up to 15 cm high and a very sparse vegetation cover of grasses and herbs. Apart from synoptic observations (wind, temperature, humidity, pressure, precipitation, and radiation), profile measurements (wind, temperature, and humidity) of the vertical fluxes of sensible heat, momentum, and water vapor were measured with the eddy correlation method (3D sonic anemometer, fast-response thermometer, and hygrometer). Also, surface temperature measurements were made with a Hermann KT24 infrared thermometer, which was looking south with an angle of 45°. To adjust for this view angle a correction has been applied of 0.001 times the incoming solar radiation (W m^{-2}). For more detailed information on the site and measurements see Kohsiek et al. (1993).

All the infrared thermometers operated in the 8–14-μm band. Since the surface emissivity of most of the sites was not determined and reliable estimates of the atmospheric longwave radiation were not available, the radiometric surface temperatures were derived from the infrared thermometer measurements assuming an emissivity of unity.

4. Methodology

The turbulent transfer of sensible heat from a surface can be parameterized by a resistance-type formulation using the difference between the radiometric surface temperature T_S^R and air temperature T_a, typically measured several meters above the surface:

$$H = \frac{\rho c_p (T_S^R - T_a)}{r_h}, \tag{1}$$

where r_h is the resistance to heat transfer from a surface at T_S^R, ρ is the density, and c_p is the specific heat of air at constant pressure. This is analogous to the equation involving the aerodynamic surface temperature T_S^A, which replaces T_S^R in (1), and the resistance is defined by the classical aerodynamic resistance to heat transfer r_{ah} (Verma 1989):

$$r_{ah} = \frac{1}{k u_*}\left[\ln\left(\frac{z_r - d_0}{z_{0m}}\right) + \ln\left(\frac{z_{0m}}{z_{0h}}\right) - \Psi_h\left(\frac{z_r - d_0}{L}\right)\right] \tag{2}$$

TABLE 4. The average (avg) and standard deviation (std) of the quantity kB^{-1} and the average resistances computed by Eqs. (1), (2), and (5) derived from the measurements of the sensible heat flux, radiometric surface–air temperature difference, and wind speed for each site.

Project	Surface	Number of hours of observation	kB^{-1} (avg)	kB^{-1} (std)	Resistances (s m^{-1}) r_{ah}	r_r	r_h
SEBEX	Savanna	507	5.8	2.9	17	38	55
SEBEX	Open forest	1142	8.3	3.3	12	48	60
MONSOON 90	Grass	95	3.8	2.8	44	31	75
MONSOON 90	Shrubs	98	5.6	2.8	30	38	68
Owens Valley	Shrubs	22	8.0	3.8	22	55	77
Smith Creek Valley	Shrubs	69	12.4	5.9	24	73	97
Smoke Creek Desert	Shrubs	79	8.4	4.9	31	69	100
La Crau	Stones/grass	40	4.5	2.1	31	22	53

where u_* is the friction velocity defined by

$$u_* = ku\left[\ln\left(\frac{z_r - d_0}{z_{0m}}\right) - \Psi_m\left(\frac{z_r - d_0}{L}\right)\right]^{-1}. \quad (3)$$

The symbol d_0 is the displacement height; z_{0m} is the momentum roughness length; z_{0h} is the roughness length for heat; z_r is the level above the surface where wind speed, u, and T_a are measured; k is von Kármán's constant ($\sim$0.4); and Ψ_h and Ψ_m are stability correction functions for heat and momentum, respectively, as a function of L, the Monin–Obukhov length. See Brutsaert (1982) for details concerning the stability correction functions of wind speed and temperature in the surface layer. Mathematically, r_{ah} is the resistance from a height $z_{0h} + d_0$ having an aerodynamic temperature T_S^A to the height z_r in the lower atmosphere.

Under unstable conditions the value of T_S^R is frequently higher than T_S^A, and as a result, this requires that $r_h > r_{ah}$. This can be represented algebraically by adding an excess resistance to r_{ah}—namely,

$$r_h = r_{ah} + r_r, \quad (4)$$

where r_r is the excess resistance required to satisfy (1) given an estimate of r_{ah} computed from (2) and (3). Since the roughness length for momentum has been related to mean obstacle height and density (Brutsaert 1982), it can be estimated from land use information. However, the roughness length for heat over different surfaces is not well known. Therefore, the term involving z_{0h} in (2) is often neglected when r_{ah} is calculated. When this is done, the excess resistance r_r in (4) also includes differences between z_{0m} and z_{0h}.

Previous work has shown that momentum and heat transfer from vegetation and rigid obstacles are significantly different and have been quantified by the quantity B^{-1} [$=k^{-1}\ln(z_{0m}/z_{0h})$] proposed by Owen and Thompson (1963) and Chamberlain (1966). It can be shown (e.g., Verma 1989) that B^{-1} is related to r_r by the following relationship:

$$r_r = B^{-1}u_*^{-1}. \quad (5)$$

The value more often reported in the literature is kB^{-1} (Brutsaert 1982), which is the $\ln(z_{0m}/z_{0h})$ term in (2) and is the quantity calculated here from each set of hourly measurements used in (1) for the eight sites.

The wind speed and air temperature data were extrapolated to $z_r = 10$ m for all sites using the Businger–Dyer surface-layer stability correction formulations for unstable conditions (Brutsaert 1982). This was performed in order to have consistency in the calculation of resistances among the sites. The height $z_r = 10$ m is the measurement height for wind speed recommended by the World Meteorological Organization.

5. Results

Values of kB^{-1} were derived from (1), (2), and (3) using measurements of H, T_S^R, and u. For each site the average and standard deviation of kB^{-1} derived from all the hours of measurements is presented in Table 4 with the number of hours used. For most sites, the standard deviation is relatively high, with the coefficient of variation being greater than or equal to 0.5. There is a range in kB^{-1} for the different sites of over 3 to 1; however, the range in the total resistance r_h (the sum of the aerodynamic and excess resistances) is considerably smaller. In addition the "excess resistance" r_r is typically larger than r_{ah}. Figure 1 shows kB^{-1} plotted against the roughness Reynolds number Re* with the curves for surfaces with bluff rough and permeable rough elements also shown. The present results show that the values of kB^{-1} range between and beyond these two theoretical curves. This is in contrast to previous results [see the summary by Brutsaert (1982)], which were close to the permeable rough region except for well-spaced roughness elements like a vineyard (Garrett and Hicks 1973). Negative values of kB^{-1} shown in Fig. 1 are probably due to a combination of errors in the measurement of H and T_S^R. Assuming that emissivity is unity causes T_S^R to be underestimated because the emissivity is generally less than unity for sparse vegetation cover (e.g., Hipps 1989; Van de Griend et al. 1991). As a result, kB^{-1} will be underestimated (e.g., Kohsiek et al. 1993).

TABLE 5. Mean sensible heat flux of all observations at each site estimated without an excess resistance ($\bar{H}_0$), estimated using the average value of kB^{-1} to compute the excess resistance ($\bar{H}_e$), and measured ($\bar{H}_m$).

Project/site	$\bar{H}_m$ (W m^{-2})	$\bar{H}_0$ (W m^{-2})	Difference (W m^{-2})	$\bar{H}_e$ (W m^{-2})	Difference (W m^{-2})
SEBEX Fallow/Savanna	212	623	411	186	−26
SEBEX Natural open forest	169	862	693	192	23
MONSOON 90 Shrub	147	474	327	128	−19
MONSOON 90 Grass	139	291	152	103	−36
Owens Valley Shrub	239	1966	1727	264	25
Smith Creek Valley Shrub	146	960	814	203	57
Smoke Creek Desert Shrub	203	1214	1011	225	22
La Crau Stones/grass	211	426	215	153	−58

As a preliminary assessment of the improvement due to using an excess resistance, sensible heat fluxes for the individual sites were determined from measurements of T_S^R using a value of kB^{-1} derived by averaging all the values of kB^{-1}, yielding a value of 7.0. For comparison, the sensible heat fluxes were also determined without the use of an excess resistance or $kB^{-1} = 0$. Table 5 lists the estimate of the sensible heat flux, averaged over all hours, using the average kB^{-1} for all sites ($\bar{H}_e$) and using no excess resistance ($\bar{H}_0$) compared to the average measured value ($\bar{H}_m$) for each site. The table also gives the differences between the estimated and measured fluxes. It is immediately obvious that the omission of an excess resistance results in gross overestimates of the sensible heat fluxes for these semiarid sites. In contrast, the use of an average value of kB^{-1} to calculate the excess resistance significantly reduced the differences in the average sensible heat flux between measured and modeled. The percent difference between $\bar{H}_e$ and $\bar{H}_m$ varied from 10% to 40%, with an average for all sites of about 20%. Although using mean values in Table 5 considerably reduces variability, these results are intended to illustrate the main point of this study—namely, that using infrared temperature with (1) for computing fluxes in semiarid environments will require an estimate of the "excess" resistance.

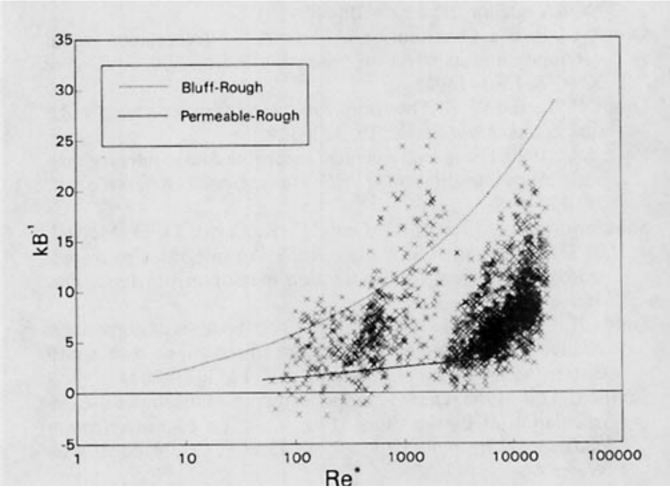

FIG. 1. The relationship between kB^{-1} and the roughness Reynolds number Re* ($= z_{0m}u_*/\nu$, where ν is the kinematic viscosity of air) for the eight semiarid sites. The values were computed from the hourly data. The two curves from Brutsaert (1982) represent the behavior of kB^{-1} for bluff rough and permeable rough elements.

6. Concluding remarks

The present analysis has confirmed that the data from these sites show large differences between radiometric and aerodynamic surface temperatures. Therefore, the use of the standard aerodynamic formula to determine sensible heat fluxes from radiometric surface–air temperature differences results in large overestimates of the fluxes. On the other hand, this preliminary study supports the use of a resistance-type formulation for the estimation of sensible heat flux over semiarid areas as long as one accounts for the significant "excess" resistance term.

In future analyses, practical methods for determining the appropriate magnitude of kB^{-1} or r_r will be explored. This will involve developing techniques that make use of meteorological and remotely sensed data that are readily available on a regional scale. For example, global maps of vegetation index are available from the National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer data (Ohring et al. 1989). Vegetation indices have been related to vegetation cover (Ormsby et al. 1987) and surface temperature (Price 1990). These relationships may provide operational methods for estimating regional values of kB^{-1}.

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