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Evaluation of soil and vegetation heat flux predictions using a simple two-source model with radiometric temperatures for partial canopy cover

William P. Kustas[a,*], John M. Norman[b]

[a]United States Department of Agriculture, Agricultural Research Service, Hydrology Lab Building 007, Beltsville Agricultural Research Center, West Beltsville, MD 20705-2350, USA
[b]Department of Soil Science, 1525 Observatory Drive, University of Wisconsin, Madison, WI 53706, USA

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Abstract

A two-source model developed to use radiometric temperature observations for predicting component surface energy fluxes from soil and vegetation was evaluated with data from a row crop (cotton). The total or combined heat fluxes from the soil and vegetation agreed to within 20% of the observed values, on average. Component heat flux predictions from the soil and vegetation indicated that soil evaporation was generally higher than canopy transpiration. This result contradicts an earlier study which showed that soil evaporation was $\sim$1/3 of canopy transpiration rates with a significant source of sensible heat from the soil being advected to the canopy (Kustas, 1990). Moreover, the modeled derived canopy temperatures were $\sim$6 K higher and soil temperatures were $\sim$4 K lower than the radiometric temperature observations. In order to obtain more physically realistic soil and vegetation component heat fluxes and better agreement between the predicted and observed soil and canopy temperatures, two model parameterizations required modification. One adjustment was to the magnitude of the Priestley–Taylor coefficient α_{PT} used in estimating canopy transpiration. The magnitude of α_{PT} was increased by $\approx$50% from its 'universal constant' $\alpha_{PT} \sim 1.3$ to $\alpha_{PT} \sim 2$. The other modification was to the free convective velocity, U_{CV}, defined as constant in the original formulation for estimating soil resistance to sensible heat flux transfer, R_S. The new formulation is based on the recent experimental results from Kondo and Ishida (1997) who found that $U_{CV} \propto \Delta T^{1/3}$ where ΔT is the surface–air temperature difference. Both of these modifications are shown to be supported by observations from the literature and therefore are not considered merely model 'tuning'. Furthermore, component heat fluxes predicted by the model using canopy and soil radiometric temperature observations support the higher α_{PT} value and new free convective formulation for estimating R_S. Two other changes to model algorithms are described which are relevant to all dual-source modeling schemes. One is replacing the commonly used Beer's law type expression for estimating the divergence of net radiation in partial canopy covered surfaces with a more physically-based algorithm. The other is a simple method to address the effects of clumped vegetation (common in row crops and sparse canopies) on radiation divergence and wind speed inside the canopy layer.

Keywords: Remote sensing; Row crop; Surface energy balance; Radiation balance

*Corresponding author. Tel.: +1-301-504-8498; fax: +1-301-504-8931; e-mail: bkustas@hydrolab.arsusda.gov

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1. Introduction

Recent progress in the application of directional radiometric surface temperature observations, $T_R(\phi)$, for estimating surface heat fluxes over partial canopy-covered surfaces has resulted from the development of two-source models which explicitly treat the energy exchanges between the soil and vegetation and the overlying atmosphere. These models are an advancement over single-source models which produce significant errors in predicted heat fluxes when applied to sparsely vegetated surfaces (Verhoef et al., 1997). Such a model developed by Norman et al. (1995) accounts for differences between $T_R(\phi)$ and the so-called 'aerodynamic temperature' T_O which satisfies the transport expression (Norman and Becker, 1995)

$$H = \rho C_P \frac{(T_O - T_A)}{R_{AH}} \tag{1}$$

where H is the sensible heat flux (W m^{-2}), ρC_p is the volumetric heat capacity of air (J m^{-3} K^{-1}), T_A is the air temperature at some reference height above the surface (K) and R_{AH} is the resistance to heat transport (s m^{-1}), which is described in Appendix A (see also Brutsaert, 1982). T_O cannot be measured, so it is often replaced with an observation of $T_R(\phi)$ in Eq. (1). In order to obtain acceptable estimates of H, this has required empirical adjustments to the magnitude of the surface roughness for heat (z_{OH}) for a particular surface, which unfortunately does not seem to be possible a priori and therefore renders the method unsuitable for general applications (Kustas et al., 1996; Verhoef et al., 1997). A recent study using a detailed multilayer energy budget model showed that a single-source approach can predict reliable H values, but it requires $T_R(\phi)$ observations with a viewing angle ϕ of 50° to 70° from nadir (Matsushima and Kondo, 1997).

Comparisons of predicted versus observed turbulent fluxes of sensible (H) and latent heat (LE) using Norman et al. (1995) original two-source model (called herein N95) by Kustas et al. (1996) and Zhan et al. (1996) and revisions to it by Kustas and Norman (1997) to include multi-angle $T_R(\phi)$ observations have all been with the total flux from the combined soil/canopy system. Therefore, it is not known how well the model predicts the H and LE fluxes from the soil and vegetation separately.

In this paper, meteorological, surface energy flux and $T_R(\phi)$ data collected from a furrowed cotton field located in central Arizona are used to evaluate the capability of the N95 model to compute the proper proportion of H and LE contributed by the soil and crop to the total. Although the H and LE from the soil and vegetation were not directly measured, an analysis by Kustas (1990) of the flux observations together with results using a two-source model provides reasonable estimates of the relative contributions from both the soil and vegetation to the total H and LE measured above the surface. Additional verification of appropriate partitioning of component heat fluxes by the model comes from comparing predicted versus observed soil and vegetation temperatures.

2. Model description

A detail description of the original N95 model can be found in Norman et al. (1995). Other versions of the model adapted to use multiple-view angle $T_R(\phi)$ observations is described in Kustas and Norman (1997). A brief description of the model formulations is given in Appendix A, and includes changes to several of the original N95 formulations to account for temporal variations in net radiation divergence through the canopy layer and in the soil heat flux–soil net radiation ratio (Kustas et al., 1998).

In addition, several other modifications to the formulations given in Appendix A will be described below. Two of these changes are general in nature and were not directly influenced by this study. One is replacing the commonly used Beer's law type expression with a more physically-based algorithm for estimating the divergence of net radiation in partial canopy covered surfaces. The other is a simple method to address the effects of clumped vegetation on radiation divergence and wind speed inside the canopy layer. The other two modifications are the direct result of comparing the two-source model output to surface flux measurements, soil and canopy temperature observations, and to previous model results (i.e., Kustas, 1990). One adjustment is to the magnitude of the Priestley–Taylor coefficient α_{PT} used in estimating canopy transpiration. The other is a new formulation for estimating soil resistance to sensible heat flux transfer, R_S.

Experience has revealed that the exponential extinction of net radiation (i.e., Eqs. (A.8) and (A.9)) is only appropriate for canopies of nearly full cover and contains significant systematic errors for sparse canopies with relatively hot soil surfaces. These errors occur because the contribution of soil thermal radiation to net radiation depends on soil surface temperature, which can be more than 20°C above vegetation or air temperature; hence exponential equations such as Eqs. (A.8) and (A.9) do not account for such surface conditions. For a sparse canopy having a leaf area index (LAI) ~0.4 with differences in soil and vegetation temperatures on the order of 20°C, net radiation absorbed by the soil surface and canopy calculated from Eqs. (A.8) and (A.9) can be in error by over 50 W m^{-2} resulting in relative errors of ~15% and ~40% for the soil and canopy, respectively.

In the present analysis, a more physically-based algorithm for estimating the divergence of R_N was constructed, which requires incident solar radiation observations and formulations for the transmission of direct and diffuse shortwave radiation and for the transmission of long-wave radiation through the canopy (Campbell and Norman, 1998). Since the reflection and absorption of radiation in the visible and near-infrared wavelengths is markedly different for vegetation and soils, the visible and near-infrared albedos of the soil and vegetation were evaluated separately before combining to give an overall shortwave albedo. The equations for estimating the transmission and reflection of direct and diffuse shortwave radiation are described in Chapter 15 of Campbell and Norman (1998). The net shortwave radiation balance for the soil ($S_{N,S}$) and canopy ($S_{N,C}$) are computed; then the net long-wave radiation balance for the soil ($L_{N,S}$) and canopy ($L_{N,C}$) are estimated. The long-wave balance for the soil-vegetation-atmosphere system is derived by calculating diffuse radiation transmission to the soil and absorption by the canopy (Ross, 1975). A simpler formulation of the net long-wave radiation balance than described in Ross (1975) was derived where a single exponential equation is used for estimating the transmission for both the soil and canopy,

$$L_{N,S} = \exp(-\kappa_L \mathrm{LAI}) L_{sky} + [1 - \exp(-\kappa_L \mathrm{LAI})] L_C - L_S \tag{2a}$$

$$L_{N,C} = [1 - \exp(-\kappa_L \mathrm{LAI})][L_{sky} + L_S - 2L_C] \tag{2b}$$

where the extinction coefficient, $\kappa_L \approx 0.95$, is similar to the extinction coefficient for diffuse radiation under low vegetation, i.e., LAI ≤ 0.5 (Campbell and Norman, 1998) and L_C, L_S and L_{sky} are the long-wave emissions from the canopy, soil and sky, respectively. L_C, L_S and L_{sky} are computed from the Stefan–Boltzmann equation using canopy temperature, soil temperature and shelter level air temperature and vapor pressure (Brutsaert, 1982). Thus Eqs. (A.8) and (A.9) are replaced by visible and near-infrared radiation penetration equations from Chapter 15 of Campbell and Norman (1998) combined with Eqs. (2a) and (2b) above (i.e., $R_{N,S} = S_{N,S} + L_{N,S}$ and $R_{N,C} = S_{N,C} + L_{N,C}$).

The radiative exchange algorithms used in the model apply to vegetative canopies with leaves randomly distributed over the surface. When the leaves are not randomly distributed over the surface but clumped as in the case of row crops, they may only intercept 70% to 80% of the radiation in comparison to the same crop randomly distributed over the surface (Campbell and Norman, 1998). Models to estimate radiation extinction for row crops have been developed (e.g., Gijzen and Goudriaan, 1989), but are rather complex and require additional information about the surface which will not be available operationally. An alternative is to use the same formulations described above, but with LAI multiplied by a clumping factor Ω, namely ΩLAI, (Chen and Cihlar, 1995). Campbell and Norman (1998) suggest for strongly clumped canopies, Ω is a function of the solar zenith angle, θ_S, and can be estimated by the following expression:

$$\Omega(\theta_S) = \frac{\Omega(0)}{\Omega(0) + [1 - \Omega(0)]\exp[-2.2(\theta_S)^p]} \tag{3}$$

$$p = 3.8 - 0.46D$$

where $\Omega(0)$ is the clumping factor when the canopy is viewed at nadir and D is the ratio of vegetation height versus width. The value of $\Omega(0)$ can be estimated with general knowledge of LAI and the fractional cover of the canopy. For the cotton crop used in this study, LAI ≈ 0.4 and fractional cover, $f_C \approx 0.24$ (see ahead). If the vegetation were randomly distributed and the leaf angle distribution approximated a spherical distribution, the canopy gap fraction from the zenith would be exp(−0.5 LAI) ≈ 0.82. In actuality the vegetation is clumped along the furrows so the field LAI of 0.4 corresponds to a local LAI (LAI_L) within the vegetated region of $LAI_L = LAI/f_C \approx 1.7$. If all the leaves contained within the vegetated region are randomly distributed, then the transmission of this vegetated region is $f_C \exp(-0.5\ LAI_L) + (1 - f_C) \approx 0.86$; therefore $\exp(-0.5\ \Omega\ LAI) \approx 0.86$ so that $\Omega \approx 0.75$. The angular dependence of Ω given by Eq. (3) is reasonable for cross-row directions, but obviously is not representative of the along-row direction.

Clumping of the vegetation will also affect the wind speed inside the canopy layer and above the soil surface, which in turn will affect the magnitude of R_S (see Appendix A). Therefore, $\Omega(0)$ is also included the equations of Goudriaan (1977) for predicting the wind speed above the soil surface (see Appendix B in N95).

3. The data

The data used in the present analysis were collected from a furrowed row crop (cotton, *Gossypium hirsutum* L.) with field dimensions of 1500 m east-west and 300 m north-south located in Maricopa Farms in central Arizona (33.08°N, 111.98°W). The experiment ran from 10 June 1987, day of year (DOY) 161 to 14 June 1987, DOY 165. Detailed description of the micrometeorological instrumentation, agronomic and radiometric temperature measurements made in the cotton field are given by Kustas et al. (1989, 1990).

Agronomic measurements indicated LAI ≈ 0.4, a crop height $h_C \approx 0.32$ m, crop width $w_C \approx 0.26$ m, and row spacing $s_C \approx 1$ m. Furrows ran north-south, having an average depth ≈ 0.17 m. The furrow depth comprised roughly 1/2 the total crop-furrow height dimension yielding a total obstacle height (i.e. furrow plus crop) of ≈0.50 m. This had an effect on the aerodynamic roughness for this surface (see below). The fractional canopy cover was estimated by Kustas et al. (1990) to range between f_C ($=w_C/s_C$) ≈ 0.26 and $f_C \approx 0.22$ from nadir-viewing photographs; hence the average fractional cover or $f_C = 0.24$ was used in the present analysis. The last irrigation, which essentially floods the field filling the furrows, occurred on or about Day 143. Following the irrigation, dry weather persisted for the period leading upto and during the experiment. Hence, at the start of the experiment, the soil surface was relatively dry.

A detailed description of the micrometeorological measurements is in Kustas et al. (1989). Micrometeorological data included wind speed and temperature profiles at five levels above the surface. Surface fluxes were estimated using Bowen ratio/energy balance and eddy covariance techniques. Analysis and interpretation of these data are given in Kustas et al. (1989) and Kustas (1990). The momentum roughness parameters, d_O and z_{OM}, for the furrow-canopy system were determined using the profile data (Kustas et al., 1989). The relatively high roughness values for such a sparsely vegetated surface namely, $d_O \approx 0.3$ m and $z_{OM} \approx 0.07$ m, indicated that furrows and row structure of the vegetation were enhancing turbulent transport. Hatfield et al. (1985) has also reported unusually high z_{OM} values relative to crop height for an incomplete cover cotton row crop.

A thorough discussion and analysis of the ground-based and airborne-based radiometric temperature observations is given by Kustas et al. (1990). The ground-based radiometric temperature observations of sunlit and shaded soil and sunlit canopy were used to derive composite $T_R(\phi)$ values. A single set of measurements consisted of 200 $T_R(\phi)$ observations with the following sequence replicated five times: ten nadir-looking $T_R(0°)$ each across two rows, ten nadir-looking $T_R(0°)$ of the vegetation only, ten off-nadir $T_R(\approx 45°)$ observations (five east- and west-looking) viewing primarily shaded and sunlit soil. A model similar to that of Kimes (1983) for estimating fractional areas of sunlit and shaded soil and sunlit canopy based on row orientation and spacing, height and width of the vegetation was used to weight the various component temperatures. The resulting composite $T_R(\phi)$ values estimated by the model with the ground-based observations agreed to within ± 1.5 K of the aircraft-based composite $T_R(\phi)$ observations at significantly coarser resolution (i.e., ∼40 m diameter pixels) collected over the cotton field. Since only one day of airborne $T_R(\phi)$ data were available, the larger quantity of the ground-based $T_R(\phi)$ observations were used for computing composite $T_R(\phi)$ for the field. This resulted in nineteen observations having all the necessary data for running the two-source model.

Table 1
Micrometerological and $T_R(\phi)$ data from furrowed cotton crop (see Table 1 of Kustas, 1990). The wind speed u and air temperature T_A are from 3 m level

DOY	Time (decimal)	R_N (W m^{-2})	G (W m^{-2})	H (W m^{-2})	LE (W m^{-2})	$T_R(\phi)$ (C)	T_A (C)	u (m s^{-1})
162	10.43	483	121	54	308	42	33	0.9
162	11.52	539	135	111	293	48	35	1.5
162	12.54	597	149	199	249	56	36	1.8
162	14.05	572	143	117	312	51	37	1.6
163	10.11	531	133	82	316	44	34	1.2
163	11.07	593	148	131	314	49	35	1.3
163	12.03	637	159	172	306	55	36	2.4
163	14.02	596	149	167	280	56	38	3.0
163	15.02	514	128	136	250	52	39	2.9
164	9.55	467	117	47	303	41	34	0.4
164	10.5	556	139	104	313	47	36	1.5
164	11.52	610	152	119	339	54	37	1.4
164	12.52	625	156	150	319	59	39	1.5
164	13.55	604	151	155	298	58	40	2.0
164	14.47	548	137	126	285	56	40	1.7
165	9.23	434	108	38	288	39	35	0.7
165	10.31	544	136	47	361	48	37	0.8
165	11.27	595	149	121	325	54	38	1.1
165	12.16	628	157	140	331	57	39	1.8

The surface flux, meteorological and radiometric temperature data used in the present study are listed in Table 1 (see also Kustas, 1990). Most of the data were collected within several hours of solar noon (~1230 local time), so that θ_S typically ranged between 20° and 30° degrees. Winds were generally light and variable and $T_R(\phi) - T_A \approx 14$ K on average. Kustas (1990) identified a reduced data set, 10 out of the 19 observations, that had optimal wind speed and fetch conditions; however, given the relatively small number of data points, all data are used in the present analysis.

At the start of the experiment nearly three weeks had elapsed since the last irrigation, resulting in a relatively dry soil surface. However during the experiment, the average Bowen ratio $B_O = H/\mathrm{LE}$ for the 19 observations was less than 0.4 and the average canopy-air temperature differences $(T_C - T_A) \approx -4$ K indicating that there was adequate moisture in the root zone for the crop to meet atmospheric demand. In fact, with the vapor pressure deficit averaging ≈5 kPa, results from Hatfield et al. (1985) for a cotton crop under partial canopy cover indicate unstressed conditions exist when $(T_C - T_A) \leq -3$ K.

4. Results

4.1. Previous results

Kustas (1990) developed a two-layer model that uses T_C observations and an estimate of the Bowen ratio of the soil surface $B_{O,S}$ for estimating the energy balance of the soil and vegetation. An average value for $B_{O,S}$ for the study period, $\langle B_{O,S}\rangle$, was estimated from studies relating soil-limiting daily evaporation to soil desorption (e.g., Jackson et al., 1976; Parlange et al., 1993). This approach for partitioning the available energy at the soil surface, $(R_{N,S} - G)$, between LE_S and H_S has also been used successfully in other two-source approaches (Massman, 1992; Massman and Ham, 1994). With $\langle B_{O,S}\rangle \sim 3$ (see Appendix in Kustas, 1990), the model indicated a significant H_C component (i.e., $\langle H_C\rangle \sim -100$ W m^{-2}) advected from the surrounding soil which had a significant sensible heat flux $\langle H_S\rangle \sim 250$ W m^{-2}. This resulted in a value for $\langle \mathrm{LE}_S\rangle \sim 75$ W m^{-2}, and $\langle \mathrm{LE}_C\rangle \sim 220$ W m^{-2}. These results from Kustas (1990) suggested a significant interaction between the soil and vegetation existed for this partial canopy cotton crop. This degree of interaction has also been confirmed with actual measurements of soil and vegetation fluxes over a partial canopy cover of cotton with similar row structure but without furrows (Ham et al., 1991). Furthermore, calculations with N95 model using both the 'parallel' and 'series' resistance network (see Appendix A) indicated significantly better agreement with the observations were obtained using the 'series' resistance network which allows for direct interaction between soil and vegetation. Therefore the only results with the 'series' resistance network (cf. Eqs. (A.14)–(A.16)) are presented.

4.2. Assessing model performance

Model performance was quantified via the root-mean-square-difference (RMSD) as suggested by Willmott (1982). In addition, the mean-absolute-percent-difference (MAPD) was computed by taking the absolute difference between a predicted and measured quantity divided by the measured value and multiplying it by 100. Values of MAPD permit comparisons with the typical uncertainties found in the micrometeorological techniques. A final statistic, the mean-bias (MB) was computed by taking the difference between predicted and observed. This statistic will be particularly useful when comparing predicted versus measured component temperatures. A negative (positive) value indicates the model underestimates (overestimates) the observed flux or temperature. Table 2 provides a summary of the main statistical results from Kustas (1990) and the various N95 model predictions discussed below.

4.3. Results with N95 model

The N95 model was first run using the Priestley–Taylor parameter $\alpha_{PT} = 1.26$ and the formulations in Appendix A, except in the calculation of net radiation divergence (i.e., Eqs. (A.8) and (A.9)), which was replaced by the more physically-based algorithm described earlier (cf. Eqs. (2a) and (2b)), and the use of the clumping factor Ω. The performance of the N95 model in predicting the total fluxes for the soil-vegetation system is quite good (see Table 3) with MAPD <5% for R_N, MAPD $\approx$ 10% for G and LE, and MAPD < 20% for H. Bowen ratio/energy balance and eddy covariance techniques for determining the heat fluxes have ~20% uncertainty (Fritschen et al., 1992; Nie et al., 1992; Kustas and Norman, 1997); hence, when discrepancies between model predicted and observed heat fluxes are less than ~20%, the performance of the model is deemed acceptable. A RMSD of 40 W m^{-2} for LE is comparable to the value obtained with the two-source model of Kustas (1990). The N95 model overestimates G and H (i.e., MB $\approx$ 15 W m^{-2}) resulting in a fairly consistent underestimate of LE (i.e., MB ≈ -30 W m^{-2}).

Although the model predictions of the H and LE are reasonable, values of H_C, LE_C, H_S and LE_S indicate

Table 2

Average total and component (i.e., soil and canopy) flux predictions and statistical differences (MAPD values) with observations using model from Kustas (1990) and N95 model with different values of α_{PT} and R_S formulation (i.e., Eq. (A.17) vs. Eq. (5)) as described in the text

Average flux (MAPD) (W m^{-2})/(%)	Model description			
	Kustas (1990)	N95 $\alpha_{PT} = 1.26$ and Eq. (A.17)	N95 $\alpha_{PT} = 2$ and Eq. (5)	N95 T_S and T_C and Eq. (5)
$\langle R_N \rangle$	562	561(3)	567(3)	563(3)
$\langle G \rangle$	140	157(12)	152(8)	148(6)
$\langle H \rangle$	129(38)	130(18)	110(24)	105(30)
$\langle LE \rangle$	293(10)	274(11)	305(10)	310(13)
$\langle R_{N,S} \rangle$	441	450	434	422
$\langle R_{N,C} \rangle$	121	111	133	141
$\langle H_S \rangle$	227	139	194	211
$\langle H_C \rangle$	−98	−9	−84	−106
$\langle LE_S \rangle$	74	154	88	64
$\langle LE_C \rangle$	219	120	217	246

Table 3
Statistical results comparing N95 model predicted vs. observed surface fluxes and soil and canopy temperatures

Flux/Temperature	N95 Results using $\alpha_{PT} = 1.26$ and Eq. (A.17) for estimating R_S		
	RMSD (W m^{-2})/(K)	MAPD (%)/(%)	MB (W m^{-2})/(K)
R_N	19	3	−1
G	18	13	17
H	23	18	13
LE	42	11	−31
T_S	4.2	7	−3.8
T_C	6.4	19	6.4

the model does not correctly partition the heat fluxes between the soil and canopy sources (see Table 2). In contrast to the results of Kustas (1990), values of $\langle H_C \rangle$ and $\langle LE_C \rangle$ computed by the N95 model are ≈ -10 W m^{-2} and 120 W m^{-2}, respectively. For the soil, values of $\langle H_S \rangle$ and $\langle LE_S \rangle$ are $\approx$140 W m^{-2} and 155 W m^{-2}, respectively. This yields a $\langle B_{O,S} \rangle \sim 1$ which is significantly smaller than the value estimated by Kustas (1990) and a ratio of $\langle LE_S \rangle / \langle LE_C \rangle \approx 1.25$ versus the more realistic ratio from Kustas (1990) of $\sim$0.35. MB values of −3.8 and 6.4 K are obtained between predicted and observed T_S and T_C, respectively (Table 3). The significant underestimation of T_S and overestimation of T_C gives added support to the conclusion of incorrect partitioning of the heat fluxes by the N95 model.

This result may not be surprising given the complicated nature of turbulent flow observed in row crops. Indeed, studies indicate airflow and temperature distributions in the canopy-air space for row crops are likely to differ from profiles in vegetation randomly distributed over a surface (Arkin and Perrier, 1974; Graser et al., 1987), especially when the furrow depth/height and plant spacing is significant relative to vegetation height and the amount of cover (Graser et al., 1987; Kustas et al., 1989). For a similar row crop of cotton, but without furrows and higher LAI ($\approx$2), Ham and Heilman (1991) found aerodynamic resistances within and above the canopy were highly variable and not significantly correlated with wind speed. They concluded that approaches using bulk aerodynamic resistances with standard meteorological data are not appropriate for these sparse canopy systems. Moreover, Ham and Heilman (1991) suggest gradient-driven transport, or K-theory, is not applicable within the canopy air-space (e.g., Raupach et al., 1986). However, a number of studies have successfully applied K-theory in sparse canopies (e.g., Dolman and Wallace, 1991; Nichols, 1992; Flerchinger et al., 1998). Therefore, we investigated modifications to several model formulations in order to obtain more appropriate heat flux partitioning between the canopy and soil.

To obtain more realistic partitioning of the heat fluxes for the soil and canopy components, two model formulations were revised. For the canopy, this simply required the value of α_{PT} to be increased by $\approx$50% to $\alpha_{PT} = 2$ in Eq. (A.19), namely the Priestley–Taylor formulation for canopy transpiration. For the soil, the free convection velocity 'constant' a used in the formulation of R_S in Eq. (A.17) was allowed to vary based on the experimental results described by Kondo and Ishida (1997) which show that $a \propto \Delta T^{1/3}$ where ΔT is the surface-air temperature difference (see below).

Values of α_{PT} significantly exceeding its typical value of $\sim$1.3 have been observed for an irrigated closed canopy (i.e., a wheat crop with LAI $\approx$ 3) in an arid climate where $1.5 \leq \alpha_{PT} \leq 2$ (Baldocchi, 1994). In fact, Baldocchi (1994) shows that when the canopy resistance to transpiration is on the order of 10–20 s m^{-1} α_{PT} can lie within the range of $\sim$1.5 to $\sim$1.8 (see Fig. 11 from Baldocchi, 1994). In general, however, the average α_{PT} computed by Baldocchi (1994) was $\approx$1.26.

From numerous experimental studies under free convective conditions, the free convective velocity U_{CV} is related to ΔT (Kondo and Ishida, 1997)

$$U_{CV} = c(T_S - T_A)^{1/3} \quad (4)$$

where Kondo and Ishida's (1997) experimental results indicate that c (m s^{-1} K$^{-1/3}$) ranges from 0.0011 for an aerodynamically smooth surface to 0.0038 for an aerodynamically rough surface. The laboratory and field data from Sauer (1993) indicate that U_{CV} or a (cf. Eq. (A.17)) ≈ 0.004 is applicable to soil surfaces where $\Delta T \sim 3$–5 K. Substituting $\Delta T = 4$ K and $U_{CV} = 0.004$ into Eq. (4) yields $c \approx 0.0025$. This value of c may be more appropriate for soil surfaces associated with cultivated crops. Since the model derives both soil and canopy temperatures, as a first approximation, T_C was substituted for T_A in Eq. (4). Therefore, Eq. (A.17) for estimating R_S was modified and had the following form:

$$R_S = \frac{1}{c(T_S - T_C)^{1/3} + bu_S} \quad (5)$$

with $c = 0.0025$ and $b = 0.012$. The effect on model output using $c = 0.0038$ in Eq. (5) will be discussed. Sauer and Norman (1995) indicate that for rough soil surfaces or higher turbulent intensities in the canopy air space, the magnitude of the coefficient b in Eq. (A.17) for predicting R_S would be larger reaching an upper limit for $b \approx 0.024$. However, there is no direct way to estimate the change in b from routine observations. Furthermore, under the extreme temperature differences between soil and canopy in the present study (i.e., $T_S - T_C \sim 25$ K, on average) and generally light wind conditions, it is the free convective velocity U_{CV} which dominates the heat transfer from the soil surface.

Model performance in predicting the total heat fluxes using $\alpha_{PT} = 2$ and Eq. (5) for estimating R_S is satisfactory (see Table 4), with MAPD $\approx$ 25% for H and $\approx$10% for LE. In addition, MB values for both H and LE are reduced to $\sim$5 W m^{-2}; for LE this is a significant reduction in bias (see also Fig. 1). Furthermore, $\langle H_C \rangle \approx -85$ W m^{-2} and $\langle LE_C \rangle \approx 220$ W m^{-2}, which more closely match the results from Kustas (1990). The agreement with Kustas (1990) is also fairly good for the soil component where values of $\langle H_S \rangle$ and $\langle LE_S \rangle$ are $\approx$195 W m^{-2} and $\approx$90 W m^{-2}, respectively. This yields a $\langle B_{O,S} \rangle \approx 2$, which is closer to the value of $\sim$3, estimated by Kustas (1990); the ratio of $\langle LE_S \rangle / \langle LE_C \rangle \approx 0.4$ is also reasonably close to the value of $\sim$0.35 from Kustas (1990). MB values of -3 and 0.8 K are obtained between predicted and observed T_S and T_C, respectively. Compared to the original N95 model, there is a significant reduction in RMSD and MB for T_C, but still over a 2 K discrepancy in T_S. To reduce the discrepancies in T_S by further adjustments to R_S formulation is not warranted since this would involve essentially 'tuning' the model.

With $T_R(\phi)$ observations at very different view angles (i.e., $\phi \sim 0°$ or nadir and $\phi \sim 55°$) reliable canopy and soil temperatures can be derived (Francois et al., 1997). With estimates of T_S and T_C the N95 model does not require the Priestley–Taylor assumption (Kustas and Norman, 1997). This version of the model was evaluated using observations of T_S and T_C from Kustas et al. (1990).

The utility of the model in predicting H and LE using T_S and T_C observations is comparable to the results using the Priestley–Taylor assumption except that there are generally higher RMSD values (see Table 5). Plots comparing predicted versus observed R_N, G, H and LE (Fig. 2) reveal more scatter in H and LE estimates compared to the version using the Priestley–Taylor assumption, but relatively low MB values. This increase in scatter using T_S and T_C estimates instead of the Priestley–Taylor assumption was also observed by Kustas and Norman (1997). When considering the soil component, the partitioning of the heat fluxes more closely matches the two-source results from Kustas (1990) with values of $\langle H_S \rangle \approx 210$ W m^{-2} and $\langle LE_S \rangle \approx 65$ W m^{-2}, respec-

Table 4
Statistical results comparing N95 model predicted vs. observed surface fluxes and soil and canopy temperatures

Flux/Temperature	N95 Results using $\alpha_{PT} = 2$ and Eq. (5)		
	RMSD (W m^{-2})/(K)	MAPD (%)/(%)	MB (W m^{-2})/(K)
R_N	21	3	5
G	13	8	11
H	25	24	−6
LE	37	10	0
T_S	3.5	5	−3
T_C	1.7	4	0.8

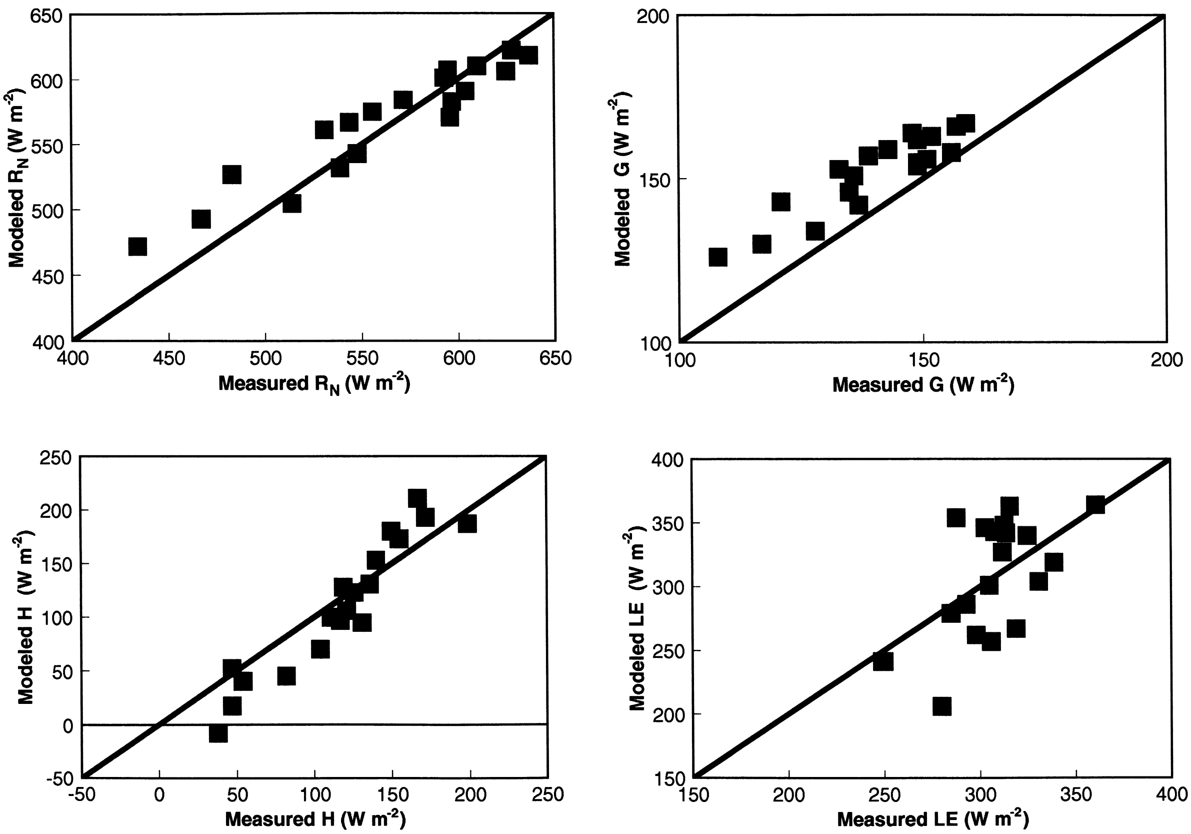

Fig. 1. Comparison of predicted vs. observed surface fluxes using N95 model with Priestley–Taylor parameter $\alpha_{PT} = 2$ and $c = 0.0025$ in Eq. (5) for estimating R_S. The 1 : 1 line represents perfect agreement with the observations.

tively (see Table 2). This yields a $\langle B_{O,S}\rangle \approx 3$, which is the same value derived by Kustas (1990); a ratio of $\langle LE_S\rangle/\langle LE_C\rangle \sim 0.25$ is slightly lower than the value obtained by Kustas (1990).

Part of the reason for discrepancies between Kustas (1990) estimates of the partitioning of the heat fluxes between soil and canopy and N95 model version using T_S and T_C observations is that Kustas (1990) used measured R_N and G whereas in this study they are estimated from incident solar radiation, albedo, sky and surface temperatures. In addition, there are two differences in the method used in estimating R_N divergence through the canopy layer: (1) in the present study LAI is reduced by Ω, ($\sim$0.75); (2) Kustas (1990) used a formulation similar to Eqs. (A.8) and (A.9) whereas the present study uses a more general method

Table 5
Statistical results comparing N95 model predicted vs. observed surface fluxes

Flux	N95 Results using T_S and T_C observations with Eq. (5) for estimating R_S		
	RMSD (W m^{-2})	MAPD (%)	MB (W m^{-2})
R_N	20	3	1
G	10	6	7
H	36	30	−12
LE	47	13	5

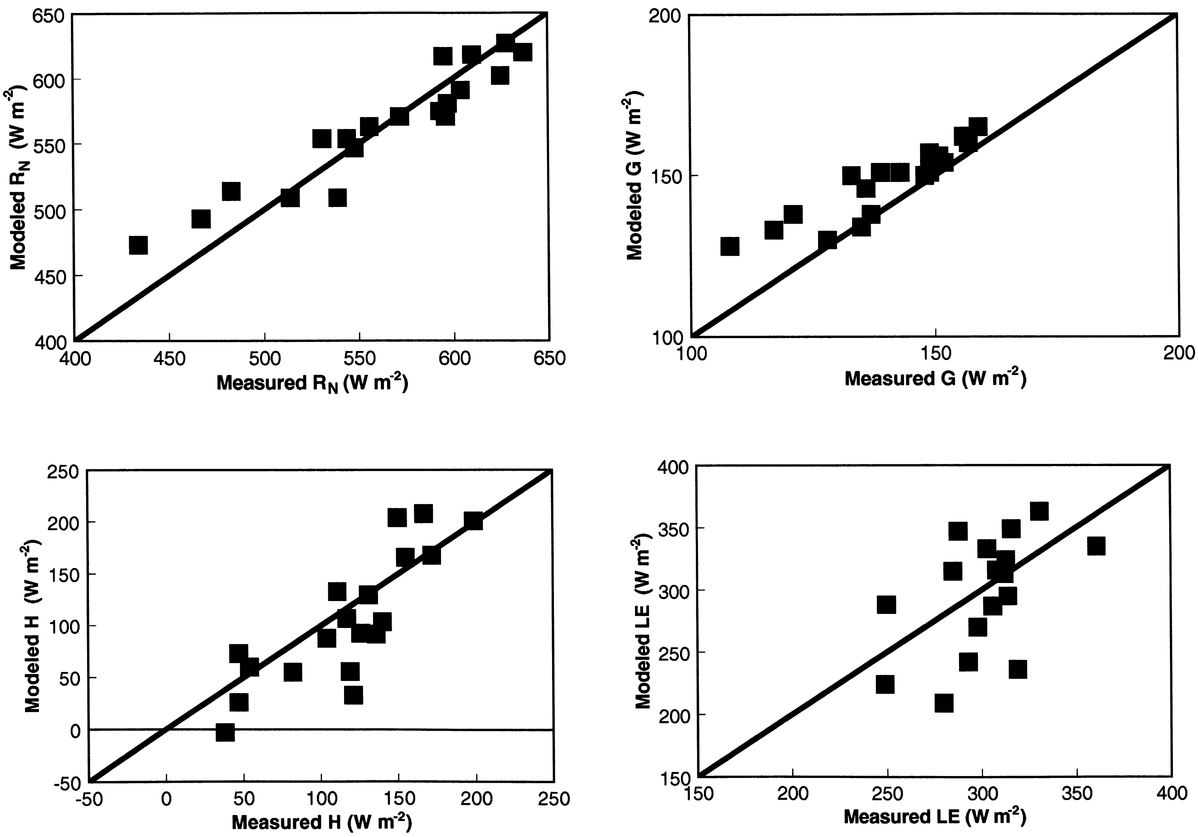

Fig. 2. Comparison of predicted vs. observed surface fluxes using N95 model with T_S and T_C observations and $c = 0.0025$ in Eq. (5) for estimating R_S. The 1 : 1 line represents perfect agreement with the observations.

for estimating net radiation divergence. These two effects nearly cancel so that $\langle R_{N,C}\rangle / \langle R_N\rangle$ from Kustas (1990) is similar to the present method. However in general, the present formulation for partitioning R_N provides more physically realistic values of $R_{N,S}$ and $R_{N,C}$ for clumped vegetation and supports an earlier conclusion by Ham et al. (1991) that simple exponential decay formulations similar to Eqs. (A.8) and (A.9) are not appropriate for predicting net radiation divergence for row crops.

The use of Ω can have a significant effect on the estimation of canopy and soil temperatures from the radiometric temperature observations (cf. Eqs. (A.1) and (A.2)), which in turn affect the model predicted fluxes. For clumped vegetation, $\Omega < 1$; thus for a given LAI, the fraction of the $T_R(\phi)$ observation occupied by soil is greater. In the present study, using $\Omega = 1$ instead of $\Omega = 0.75$ with $\alpha_{PT} = 2$ and $c = 0.0025$ produces larger differences between model predicted and observed H and LE. Compared to the results in Table 4 for H and LE, RMSD values increase from $\approx$25 and 35 W m^{-2} to $\approx$40 and 50 W m^{-2}, and MAPD values increase from $\approx$25 and 10% to $\approx$30 and 15%, respectively. In addition there are larger discrepancies between observed and estimated T_C with RMSD $\approx$3 K compared to $\approx$1.7 K using $\Omega = 0.75$ (see Table 4).

4.4. Sensitivity of N95 results to Priestley–Taylor and soil resistance formulations

A preliminary sensitivity analysis of the impact of the Priestley–Taylor and soil resistance formulations on N95 model output of the heat fluxes was conducted by using values of α_{PT} in Eq. (A.19) and c in Eq. (5) that fall within their likely ranges, namely $\alpha_{PT} = 1.26$

Table 6
Results of sensitivity analysis comparing average total and component (i.e., soil and canopy) flux predictions and statistical differences (MAPD values) with observations using N95 model with $\alpha_{PT} = 1.26$ and Eq. (5) with $c = 0.0025$, $\alpha_{PT} = 2$ and Eq. (5) with $c = 0.0038$ and $\alpha_{PT} = 1.26$ and Eq. (5) with $c = 0.0038$ (see text for details)

Flux/(MAPD) ($W\ m^{-2}$)/(%)	Model description			
	N95 $\alpha_{PT} = 2$ and $c = 0.0025$	N95 $\alpha_{PT} = 2$ and $c = 0.0038$	N95 $\alpha_{PT} = 1.26$ and $c = 0.0025$	N95 $\alpha_{PT} = 1.26$ and $c = 0.0038$
$\langle R_N \rangle$	567(3)	565(3)	561(3)	561(3)
$\langle G \rangle$	152(7)	154(10)	158(13)	158(13)
$\langle H \rangle$	110(24)	154(37)	153(33)	182(58)
$\langle LE \rangle$	305(10)	257(20)	250(19)	220(29)
$\langle R_{N,S} \rangle$	434	439	451	453
$\langle R_{N,C} \rangle$	133	126	110	108
$\langle H_S \rangle$	194	223	162	191
$\langle H_C \rangle$	−84	−69	−9	−9
$\langle LE_S \rangle$	88	62	132	103
$\langle LE_C \rangle$	217	195	118	117

to 2 and $c = 0.0025$ to 0.0038. The N95 model was run using $\alpha_{PT} = 1.26$ and $c = 0.0025$, $\alpha_{PT} = 2$ and $c = 0.0038$, and $\alpha_{PT} = 1.26$ and $c = 0.0038$. In comparison to the base case where $\alpha_{PT} = 2$ and $c = 0.0025$ (see Table 6), all other cases have significant biases in H and LE predictions compared to the observations with MB values ranging from $\sim$+40 to +70 $W\ m^{-2}$ for H and −50 to −90 $W\ m^{-2}$ for LE. This leads to MAPD values of 30–60% for H and 20–30% for LE with the largest discrepancies obtained by using $\alpha_{PT} = 1.26$ and $c = 0.0038$ in Eq. (5). The total heat fluxes are similar for the case where $\alpha_{PT} = 2$ and $c = 0.0038$, and $\alpha_{PT} = 1.26$ and $c = 0.0025$ in Eq. (5), but only the model output using $\alpha_{PT} = 2$ and $c = 0.0038$ is the relative partitioning between $\langle H_S \rangle$ and $\langle LE_S \rangle$, and $\langle H_C \rangle$ and $\langle LE_C \rangle$ similar to Kustas (1990) and the output for the base case (see Table 6). With $c = 0.0038$, R_S values are reduced by. 20%, on average (i.e., from $\langle R_S \rangle \approx 90\ s\ m^{-1}$ to $\langle R_S \rangle \approx 70\ s\ m^{-1}$). This yields higher values of sensible heat fluxes from the soil for the case where $\alpha_{PT} = 2$, but not when $\alpha_{PT} = 1.26$. Clearly the effects of α_{PT} and c on model flux predictions are not independent because the temperature differences in the canopy air space (i.e., $T_S - T_{AC}$ and $T_C - T_{AC}$) are modified by the model in order to obtain physically plausible solutions. The N95 model version using T_S and T_C observations with $c = 0.0038$ gave component heat fluxes (not shown) similar to the predictions with $\alpha_{PT} = 2$ and $c = 0.0038$, but with significantly higher MAPD values for H and LE on the order of 50 and 30%, respectively.

5. Conclusions

A two-source model using radiometric surface temperature (the N95 model) was applied to a sparse canopy cover of irrigated cotton planted in rows. Although the original model formulations compute acceptable estimates of the total heat fluxes, the partitioning of the available energy between soil and canopy latent and sensible heat fluxes are not physically realistic. This conclusion is based on previous results using a different two-source approach (Kustas, 1990) and comparisons between measured and modeled predicted soil and canopy temperatures.

To obtain more realistic partitioning between heat fluxes for the soil and vegetation components, namely between H_S and LE_S, and between H_C and LE_C, Priestley–Taylor parameter α_{PT} had to be increased from $\sim$1.3 to 2 and the 'constant' a in Eq. (A.17) for estimating R_S, which is actually the free convective velocity, U_{CV}, was allowed to vary as a function of $(T_S - T_C)^{1/3}$ via Eq. (5). This causes the overall performance of the model to improve with the bias between measured and modeled predicted soil and canopy temperatures and fluxes greatly reduced.

The model was also run using radiometric observations of canopy and soil temperatures, thus eliminating the need for the Priestley–Taylor assumption. Results were similar, further supporting the idea that α_{PT} must be significantly higher for conditions where sensible heat is being advected from a significant bare soil source. A significant source of energy advected from a hot dry soil to actively transpiring vegetation will most likely occur in agricultural field settings in arid climates. This phenomenon, however, has also been observed at significantly larger scales in natural open forested areas in the Sahel, where clumps of natural vegetation and continuous patches of bare soil have typical length scales on the order of 50 m (Blyth and Harding, 1995). Baldocchi (1997) show a significant relationship between α_{PT} and the canopy resistance to transpiration. However, much of these data are for open canopies so that the bare soil/substrate has an influence on the magnitude of α_{PT} and the canopy resistance and hence the canopy resistance–α_{PT} relationship.

The new formulation for R_S is derived from model output of canopy and soil temperatures, hence no additional information is required. However, a sensitivity analysis shows that using the upper limit in the magnitude of the coefficient c can cause a significant deterioration in model performance. On the other hand, the results of Sauer (1993) and Sauer and Norman (1995) suggest that for soils associated with cultivated crops $c \sim 0.0025$. Further experimental and theoretical studies should be conducted for different soil surface conditions in order to know the likely range in magnitude for this coefficient.

Row structure has been shown to significantly influence flow patterns (e.g., Arkin and Perrier, 1974). Moreover observations from Ham and Heilman (1991) indicate that soil and canopy aerodynamic resistances are not significantly related to meteorological conditions above the canopy. By using physical principles and experimental results, this study was able to modify the soil aerodynamic resistance formulation to accommodate the highly convective case.

To more fully understand the utility of the two-source model in providing reliable component flux estimation from the soil and vegetation, observations of both soil and vegetation heat fluxes are required. These observations are difficult to make (Ham et al., 1991). An alternative is to extract soil and vegetation temperatures using very different radiometric temperature view angles (Francois et al., 1997) and compute fluxes using the N95 model version with T_C and T_S. Although such an approach generally yields considerable scatter with observations (Kustas and Norman, 1997), on average these flux predictions, particularly the estimates of the soil and canopy components ($\langle H_S \rangle$ and $\langle H_C \rangle$ and $\langle LE_S \rangle$ and $\langle LE_C \rangle$) will indicate if the partitioning is physically realistic for the value assumed for α_{PT} in the Priestley–Taylor formulation.

An example of how this approach might be used is illustrated in the present study by comparing the mean output of component fluxes in Table 6 using $\alpha_{PT} = 1.26$ (with $c = 0.0025$ in Eq. (5)) versus the same output in Table 2 using T_C and T_S observations. The differences, especially in the magnitude of $\langle H_C \rangle$, suggest that one needs to increase the value of α_{PT} in order to account for the advection of heat towards the vegetation. Thus in practice α_{PT} could be adjusted until component fluxes agreed (on average) with those derived using estimates of T_C and T_S from dual-angle $T_R(\phi)$ observations. This may be one way of determining the variability in α_{PT} for different ecosystems as long as the coefficients in Eq. (5) for estimating R_S are known with some reasonable degree of certainty. For example, when $c = 0.0038$ in Eq. (5), using $\alpha_{PT} = 2$ yields similar partitioning in the soil and canopy heat fluxes to Kustas (1990) and the base case ($\alpha_{PT} = 2$ and $c = 0.0025$), but the total heat flux predictions deviate significantly from the observed (Table 6). This is the same result obtained with the N95 model version using T_C and T_S with $c = 0.0038$. Consequently, if the magnitude of c is highly variable, it may be difficult to derive appropriate α_{PT} values and reliable fluxes from using estimates of T_S and T_C with dual-angle $T_R(\phi)$ observations.

It is likely that the magnitude of α_{PT} will vary significantly from its typical value of $\sim$1.3 when vegetation is under unique environmental conditions (such as in the present study; see also Baldocchi, 1997). In addition for different vegetation types, for example most woody vegetation, such as deciduous and coniferous trees, the stomatal resistance is significantly higher than grasses and crops resulting in a significant decrease in α_{PT} (Jarvis and McNaughton, 1986). However, the N95 model can override the Priestley–Taylor parameterization when transpiration is less than potential (Norman et al., 1995). Therefore, it appears that it may be the upper limit in canopy transpiration that may be more difficult to estimate for different vegetation types.

Based on the results of this study, the original two-source equations of Norman et al. (1995) have been modified in four ways: (1) net radiation divergence of the canopy and net radiation at the soil surface are no longer calculated using Eqs. (A.8) and (A.9); instead visible and near-infrared equations from Campbell and Norman (1998) are combined with Eqs. (2a) and (2b); (2) the soil surface resistance R_S is no longer calculated from Eq. (A.17) but from Eq. (5); (3) the clumping factor Ω is recommended to address the effects of clumped vegetation on radiation divergence and wind speed inside the canopy layer; and (4) since the model can override the Priestley–Taylor approximation when transpiration is less than potential, it is recommended that $\alpha_{PT}=2$ under sparse canopy cover conditions where a significant source of heat can be advected from hot bare soil surfaces.

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Appendix A

Overview of N95 model

With the use of a single emissivity to represent the combined soil and vegetation, the ensemble directional radiometric temperature, $T_R(\phi)$, is related to the fraction of the radiometer view occupied by soil versus vegetation expressed as

$$T_R(\phi) \approx [f(\phi)T_C^n + (1-f(\phi))T_S^n]^{1/n} \qquad (A.1)$$

where T_C and T_S are the thermodynamic temperatures of the vegetation canopy and soil surface, respectively, and are assumed to represent spatially weighted averages of the sunlit and shaded portions of the canopy and soil, respectively, and $n\sim 4$ (Becker and Li, 1990). The fraction of the field of view of the infrared radiometer occupied by canopy, $f(\phi)$, depends upon the view zenith angle, ϕ, canopy type and fraction of vegetative cover, f_C. For many vegetated surfaces, assuming a random canopy with a spherical leaf angle distribution is reasonable so that

$$f(\phi) = 1-\exp\left(\frac{-0.5\,\mathrm{LAI}}{\cos\phi}\right) \qquad (A.2)$$

The use of $T_R(\phi)$ in a convective heat flux equation frequently involves the controversial assumption that $T_R(\phi)$ is equivalent to the so-called 'aerodynamic temperature', T_O, of the surface. T_O is the temperature that satisfies the bulk transport expression having the form

$$H = \rho C_P \frac{(T_O - T_A)}{R_{AH}} \qquad (A.3)$$

where H is the sensible heat flux (W m^{-2}), ρC_P is the volumetric heat capacity of air (J m^{-3} K^{-1}), T_A is the air temperature at some reference height above the surface (K) and R_{AH} is the resistance to heat transport (s m^{-1}), which has the following form in the surface layer (Brutsaert, 1982):

$$R_{AH} = \frac{[\ln(z_U - d_O/z_{OM}) - \Psi_M][\ln(z_T - d_O/z_{OH}) - \Psi_H]}{k^2 u} \qquad (A.4)$$

In this equation d_O is the displacement height (m), u is the wind speed (m s^{-1}) measured at height z_U (m), k is von Karman's constant ($\approx$0.4), z_T is the height (m) of the T_A measurement, Ψ_M and Ψ_H are the Monin–Obukhov stability functions for momentum and heat, respectively, and are functions of $(z-d_O)/L$ (see Brutsaert, 1982) where $L=-u_*^3/[k(g/T_A)(H_V/\rho C_P)]$ is the Monin–Obukhov length (m), u_* is the friction velocity (m s^{-1}), g is the acceleration of gravity (m s^{-2}), $H_V = (H + 0.61\,T_A C_P E)$ is the virtual sensible heat flux (W m^{-2}), and E is the rate of surface evaporation (kg m^{-2} s^{-1}). The roughness parameter z_{OM} is the local roughness length (m) for momentum transport and z_{OH} is the local roughness length (m) for heat transport. T_O cannot be measured, so it is often replaced with an observation of $T_R(\phi)$ in Eq. (A.3).

The net energy balance of the soil–canopy system is given by (neglecting photosynthesis)

$$R_N = H + \mathrm{LE} + G \qquad (A.5)$$

The system of equations for computing fluxes from the soil and canopy components, denoted by subscripts s and c, respectively, are listed below and will be used by all versions of the model. The energy budgets for the soil and vegetation are given by

$$R_{N,S} = H_S + LE_S + G \tag{A.6}$$

$$R_{N,C} = H_C + LE_C \tag{A.7}$$

with $R_N = R_{N,S} + R_{N,C}$. Similar to Eq. (A.1) for estimating the contribution of soil and canopy temperatures to the observed radiometric temperature, Eqs. (A.8) and (A.9) are used for partitioning net radiation, R_N, between the soil and vegetation in order to properly weight the contributions of sensible, H, and latent heat flux, LE, from the soil and vegetation, and estimate the soil heat flux, G

$$R_{N,S} = R_N \exp\left(-\kappa \mathrm{LAI}/\sqrt{2\cos(\theta_S)}\right) \tag{A.8}$$

$$R_{N,C} = R_N\left[1 - \exp\left(-\kappa \mathrm{LAI}/\sqrt{2\cos(\theta_S)}\right)\right] \tag{A.9}$$

Eqs. (A.8) and (A.9) are modifications from the original N95 formulations (where $\sqrt{2\cos(\theta_s)} = 1$ and $\kappa = 0.45$) proposed by Anderson et al. (1997) based on simulations with a detailed soil–plant–atmosphere model, Cupid (Norman and Campbell, 1983) where the net radiation divergence is found to be a function of the solar zenith angle θ_S. The value of $\kappa = 0.6$ is used in order that at low solar zenith angles elevations (i.e., $\theta_S < 30°$) the quantity $\kappa/\sqrt{2\cos(\theta_S)}$ will have a value of $\approx$0.45 which is midway between its likely limits of 0.3 to 0.6 (Ross, 1981).

For computing G, the original formulation from N95 was simply

$$G = c_G R_{N,S} \tag{A.10}$$

where the value of $c_G \approx 0.35$ (Choudhury et al., 1987). However c_G is constant only for several hours around solar noon (Kustas and Daughtry, 1990). Friedl (1996) included the effects of a temporally varying c_G by multiplying Eq. (A.10) by $\cos(\theta_S)$. Another approach developed by Kustas et al. (1998) is based on time differences with the local solar noon quantified by the following nondimensional time parameter, t_N,

$$t_N = \frac{|t_i - t_{SN}|}{t_{SN}} \tag{A.11}$$

where t_i is the time nominally ±5 h of the local time of solar noon, t_{SN}, and the || represents the absolute value of the difference. Using experimental data to compute $G/R_{N,S}$ or c_G as a function of time t_i, an empirical function was fit between $G/R_{N,S}$ and t_N. The results indicated that a constant $G/R_{N,S}$ could be used for $t_N < 0.3$ (i.e., several hours around solar noon) and linear least squares regression equation between $G/R_{N,S}$ and t_N was needed for $t_N > 0.3$. Neither Eq. (A.11) nor the approach suggested by Friedl (1996), however, considers the fact that G and R_N are not in phase, and hence the temporal change in the ratio $G/R_{N,S}$ will not be the same between the morning and afternoon. In addition, these approaches also do not account for possible variations in c_G due to soil moisture conditions (e.g., Friedl, 1996).

With $H = H_S + H_C$ and with the soil and vegetation taken in 'parallel' (i.e., the resistance network does not make allowance for interaction between scalar fluxes from the soil and vegetative canopy), the heat fluxes from the soil and vegetation are computed by

$$H_S = \rho C_P \frac{T_S - T_A}{R_{AH} + R_S} \tag{A.12}$$

$$H_C = \rho C_P \frac{T_C - T_A}{R_{AH}} \tag{A.13}$$

With H_C and H_S taken in 'series' (i.e., the resistance network permits interaction between the soil and vegetation heat fluxes, thus influencing the temperature in the canopy air space) yields

$$H_S = \rho C_p \frac{T_S - T_{AC}}{R_S} \tag{A.14}$$

$$H_C = \rho C_p \frac{T_C - T_{AC}}{R_X} \tag{A.15}$$

where T_{AC} is related to T_O in Eq. (A.3), namely,

$$H = \rho C_p \frac{T_{AC} - T_A}{R_A} \tag{A.16}$$

See Figs. 1 and 11 in N95 illustrating the 'parallel' and 'series' resistance network.

R_S is the resistance to heat flow in the boundary layer immediately above the soil surface and is estimated from an empirical expression developed by Sauer et al. (1995) from extensive studies of this soil-surface resistance in a wind tunnel and beneath a corn canopy. R_X is the total boundary layer resistance of the complete canopy of leaves (see Appendix B in N95) estimated with the wind speed in the canopy air space computed from the equations of Goudriaan (1977). R_{AH} is estimated via Eq. (A.4) with local d_O and z_{OM} estimated as a fraction of canopy height, h_C, (i.e., $d_O \approx 0.65$ h_C; $z_{OM} \approx 0.13$ h_C; see Brutsaert, 1982) and z_{OH} is estimated as a fraction of z_{OM} as postulated by Garratt and Hicks (1973), namely $z_{OH} \approx z_{OM}/7$ or $kB^{-1} \approx 2$. R_A is computed from Eq. (A.4) with $z_{OH} = z_{OM}$. T_{AC} is the momentum aerodynamic temperature and only approximates the temperature in the canopy air space (see Appendix A in N95).

Although soil-surface resistances depend on many factors, a reasonable, simplified equation has been developed where

$$R_S = \frac{1}{a + bu_S} \tag{A.17}$$

In Eq. (A.17), $a \simeq 0.004$ m s^{-1} is the free convective velocity 'constant', $b \simeq 0.012$, and u_S is the wind speed at a height above the soil surface where the effect of the soil surface roughness is minimal; typically 0.05 to 0.2 m; u_S is determined assuming an exponential wind profile in the canopy air space with formulations given by Goudriaan (1977), and are summarized in Appendix B of N95. The coefficients in Eq. (A.17) depend on turbulent length scale in the canopy, soil-surface roughness and turbulence intensity in the canopy and are discussed by Sauer et al. (1995). The numerical value for the coefficient a was taken from data presented in Sauer (1993) as the mean intercept of plots of soil surface transfer coefficients versus wind speed in the canopy. For the smooth aluminum plates used by Sauer (1993) the value of the parameter b was measured to be 0.007. The value of 0.012 for b used in Eq. (A.17) was estimated from a combination of wind tunnel data for surfaces of various roughnesses and the field data on smooth plates to represent the more typical roughness that soil surfaces have.

Finally, for $LE = LE_S + LE_C$ the fluxes are estimated by the following expressions:

$$LE_S = R_{N,S} - G - H_S \tag{A.18}$$

$$LE_C = \alpha_{PT} f_G \frac{\Delta}{\Delta + \gamma} R_{N,C} \tag{A.19}$$

The Priestley–Taylor parameter, α_{PT}, is set equal to 1.26 (Priestley and Taylor, 1972) for the green part of the canopy, Δ is the slope of the saturation vapor pressure-temperature curve at T_C (Pa K^{-1}) and γ is the psychrometric constant ($\approx$66 Pa K^{-1}). The fraction of LAI that is 'green' or actively transpiring, f_G, may be obtained from knowledge of the phenology of the vegetation. If no information is available for estimating f_G, then it is assumed to equal unity.

Eq. (A.19) only provides an initial calculation of LE_S, and it can be overridden if the temperature difference between the soil-canopy system and the atmosphere is large causing erroneous flux estimates, such as negative LE_S or condensation during the daytime period. If the estimated radiometric temperature from Eq. (A.1) is less than the measured $T_R(\phi)$, then the Priestley–Taylor approximation in Eq. (A.19) will tend to overestimate the canopy transpiration rate because the water supply in the root zone is inadequate. Therefore an iteration procedure will compute LE_C values below estimates given by Eq. (A.19) until values of T_C and T_S used in Eq. (A.1) agree with the measured $T_R(\phi)$. Further details concerning model convergence issues for the energy budgets of the soil and vegetation in later iterations and the justification for the Priestley–Taylor assumption used in Eq. (A.19) are given in N95.

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