An Evaluation of Two Models for Estimation of the Roughness Height for Heat Transfer between the Land Surface and the Atmosphere

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ABSTRACT

Roughness height for heat transfer is a crucial parameter in estimation of heat transfer between the land surface and the atmosphere. Although many empirical formulations have been proposed over the past few decades, the uncertainties associated with these formulations are shown to be large, especially over sparse canopies. In this contribution, a simple physically based model is derived for the estimation of the roughness height for heat transfer. This model is derived from a complex physical model based on the ''localized near-field'' Lagrangian theory. This model (called Massman's model) and another recently proposed model derived by fitting simulation results of a simple multisource bulk transfer model (termed Blümel's model) are evaluated using three experimental datasets. The results of the model performances are judged by using the derived roughness values to compute sensible heat fluxes with the bulk transfer formulation and comparing these computed fluxes to the observed sensible heat fluxes. It is concluded, on the basis of comparison of calculated versus observed sensible heat fluxes, that both the current model and Blümel's model provide reliable estimates of the roughness heights for heat transfer. The current model is further shown to be able to explain the diurnal variation in the roughness height for heat transfer. On the basis of a sensitivity analysis, it is suggested that, although demanding, most of the information needed for both models is amendable by satellite remote sensing such that their global incorporation into large-scale atmospheric models for both numerical weather prediction and climate research merits further investigation.

1. Introduction

Models of energy and mass transfer between the land surface and the atmosphere, especially those designed for numerical weather prediction or for climate studies, usually use a bulk parameterization based on Monin–Obukhov similarity (MOS) theory. In remote sensing of surface energy balance, the bulk formulation has been also the most widely used method. As pointed out recently by Brutsaert (1998), unless there is a major breakthrough for the description of the turbulence at and near the land surface, similarity is likely to remain the main, if not the only, practical approach for the estimation of energy and mass transfer between the land surface and the atmosphere in the near future. Other formulations based on surface bulk transfer coefficients or the various resistances and conductance parameters are in fact also based on similarity. MOS relates surface fluxes to surface variables and variables in the atmospheric surface layer (ASL); the bulk atmospheric boundary layer similarity (BAS) proposed by Brutsaert (1982, 1999) relates surface fluxes to surface variables and the mixed layer atmospheric variables. To calculate accurately the sensible heat flux by means of similarity theory, the roughness height for heat transfer must be accurately determined. The primary objective of this study is to search for a method to determine independently the roughness height for heat transfer.

In the ASL, the similarity relationships for the profiles of the mean wind speed u and the mean temperature difference $\theta_0 - \theta_a$ are usually written as

$$u = \frac{u_*}{k}\left[\ln\left(\frac{z-d}{z_{0m}}\right) - \Psi_m\left(\frac{z-d}{L}\right) + \Psi_m\left(\frac{z_{0m}}{L}\right)\right] \quad (1)$$

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$$\theta_0 - \theta_a = \frac{H}{ku_*\rho C_p}\left[\ln\left(\frac{z-d}{z_{0h}}\right) - \Psi_h\left(\frac{z-d}{L}\right) + \Psi_h\left(\frac{z_{0h}}{L}\right)\right], \quad (2)$$

where height z is measured above the surface, $u_* = (\tau_0/\rho)^{1/2}$ is the friction velocity, τ_0 is the surface shear stress, ρ is the density of air, $k = 0.4$ is von Kármán's constant, d is the zero plane displacement height, z_{0m} is the roughness height for momentum transfer, θ_0 is the potential temperature at the surface, θ_a is the potential air temperature at height z, H is the sensible heat flux, z_{0h} is the scalar roughness height for heat transfer, Ψ_m and Ψ_h are the stability correction functions for momentum and sensible heat transfer, respectively, and L is the Obukhov length defined as

$$L = -\frac{\rho C_p u_*^3 \theta_v}{kgH}, \quad (3)$$

where g is the acceleration due to gravity and θ_v is the potential virtual temperature near the surface. In this study, we adopt the criteria proposed by Brutsaert (1999) to decide if the MOS or the BAS stability corrections should be used. Because the measurements in all three datasets were performed at a height of a few meters above ground, all calculations use the MOS functions given by Brutsaert (1999).

The scalar roughness height z_{0h} for heat transfer can be derived from

$$z_{0h} = z_{0m}/\exp(kB^{-1}), \quad (4)$$

where B^{-1} is the inverse Stanton number, a dimensionless heat transfer coefficient. Although values of kB^{-1} of less than 0 have been reported, z_{0h} is usually smaller than z_{0m} and kB^{-1} of greater than 0 is more common. This difference is caused by different physical processes in momentum transport and in heat transport between the surface and the atmosphere. The former occurs by form drag and related pressure forces, whereas the latter is ultimately controlled by molecular diffusion. The major difficulty in determination of z_{0h} arises because it cannot be experimentally measured. Instead, its value must be derived from Eqs. (1)–(3), which involve both aerodynamic and thermal dynamic variables. Any errors in the measurements of these variables will contribute to uncertainties of z_{0h} values.

The quantity kB^{-1} has been the subject of numerous studies. For example, see Brutsaert (1982), Beljaars and Holtslag (1991), Blyth and Dolman (1995), Verhoef et al. (1997), Massman (1999a), and Blümel (1999) for detailed reviews on kB^{-1}. The range of observed kB^{-1} values is large, varying from close to zero ($kB^{-1} = -0.0953$) for a dense forest with a leaf area index of 10 (Bosveld 1999) to as high as 24 for miscellaneous grass coverage as summarized by Massman (1999a). For a smooth bare soil surface, values of kB^{-1} from -7.0 to 7.0 have been reported by Verhoef et al. (1997). After evaluating various semiempirical formulas for calculation of kB^{-1} for a savanna, a vineyard, and bare soil, Verhoef et al. (1997) have concluded that 1) most of the formulas apply either to bare soil (bluff–rough) or vegetation (permeable–rough) surfaces but all fail to compute correct kB^{-1} for savanna, which falls between the two surfaces, and 2) none of the formulas is able to describe the observed diurnal variation in kB^{-1}. As a result, they suggest that the concept of kB^{-1} is questionable and should be avoided in meteorological models. However, the alternative approach suggested by them, that is, canopy boundary layer resistance, has been shown to be in fact also based on similarity by Brutsaert (1999). This debate forms one chief motivation for this study.

In practice, one fundamental issue arises from the fact that kB^{-1} values cannot be measured directly but are derived from the bulk transfer formulation using measurements of other quantities, given in Eqs. (1)–(2). Any uncertainties associated with such measurements will be carried over to the uncertainties in the estimated kB^{-1} values. In particular, the needed surface potential temperature in Eq. (2) is usually determined using a radiometer with a limited field of view. Although only a small portion of the area (the so-called fetch) affecting the momentum exchange between land surface and the atmosphere [Eq. (2)] is actually measured, an assumption is usually made to regard this temperature as representative of the whole fetch area. A second problem with this measurement arises from the difficulty of accurate determination of the surface emissivity, which is needed to convert the radiometric temperature to physical temperature. As an indication, a 1% difference in surface emissivity will result in a difference of 0.6 K in the derived physical temperature. These uncertainties are certainly important factors that contribute to the observed uncertainties in the reported kB^{-1} values. As a consequence of these combined uncertainties, the physical meaning of kB^{-1} as well as the associated accuracy to be expected have not been clearly defined.

More recently, two models, one developed by Massman (1999a) and the other developed by Blümel (1999), have been reported. The model of Massman (1999a) is constructed using Raupach's (1989) ''localized near-field'' (LNF) Lagrangian theory. The model includes a within-canopy turbulence model of Massman and Weil (1999) that can easily incorporate the vertical distribution of foliage. The model is complex and requires many variables. Some of these variables characterize the microscale properties of the canopy, others characterize the macroscale properties of the site, and some others characterize the interaction between the airflow and the canopy. The model has been used successfully to explain the behavior and the ranges in observed kB^{-1} values over various surfaces.

In contrast to Massman's (1999a) approach, Blümel

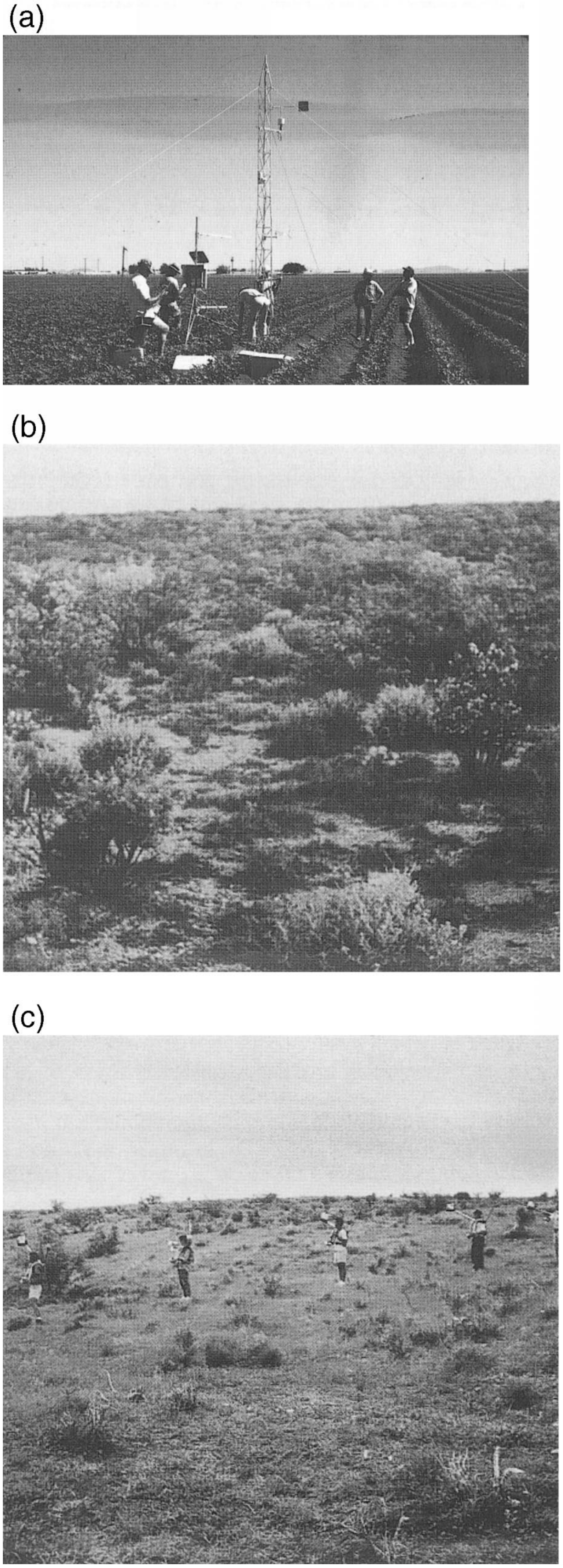

FIG. 1. Ground cover photographs of (a) cotton, (b) shrubs, and (c) grass.

(1999) derived his model by fitting simulation results of a simple multisource bulk transfer model. First of all, Blümel (1999) developed a simple multisource transfer model with prescribed temperatures of the soil and vegetation and of the air at a reference level to simulate the total sensible heat flux and the momentum flux for different surface types. The simulation results are then used to derive a functional relationship for determining the kB^{-1} value of a given fractional canopy coverage, using the limiting values of bare soil and full canopy coverage.

The main difference between these two approaches is that Blümel (1999) model uses a ''bulk'' approach to scale the soil and plant boundary layers resistances, whereas Massman's (1999a) ''Lagrangian'' approach uses microscale physics and scales from the microscale to the bulk scale. Massman's (1999a) Lagrangian approach is shown to be consistent with the observed within-canopy countergradient canopy flow.

In the following, we will first derive a simple physically based kB^{-1} model synthesized from Massman's (1999a) model. We choose to proceed this way because of the desire to retain as much as possible the physics of Massman's (1999a) model and to avoid as much as possible complexities in model parameters that may be difficult to determine in applications to different surfaces. For this reason, we will call this model the Massman's (1999a) kB^{-1} model. This model and Blümel's (1999) model will be evaluated using three experimental datasets to be discussed below. Equations (1)–(3) will be used to calculate the sensible heat fluxes together with the z_{0h} values determined by these two models [Eq. (4)]. The calculated sensible heat fluxes will be compared with the measured ones. A simple sensitivity analysis will be performed to determine the most important parameters and to investigate whether these parameters are amendable through satellite remote sensing. Last, the model will be used to explain the reported diurnal variations in kB^{-1} values and kB^{-1} values at limiting cases.

2. Two kB^{-1} models

a. Massman's (1999a) kB^{-1} model

To estimate H from Eqs. (1)–(3), the parameters d, z_{0m}, and z_{0h} must also be known in addition to the atmospheric flow and surface thermodynamic variables. The canopy momentum transfer model of Massman (1997) is used to estimate d and z_{0m}. In this model, the within-canopy horizontal wind speed $u(z)$ is modeled as

$$u(z)/u(h) = e^{-n[1-\zeta(z)/\zeta(h)]}, \qquad (5)$$

where h is the canopy height. The within-canopy wind speed profile extinction coefficient n is formulated as a function of the cumulative leaf drag area per unit planform area $\zeta(z)$ evaluated at $z = h$:

$$n = \frac{\zeta(h)}{2u_*^2/u(h)^2}, \quad (6)$$

$$\zeta(z) = \int_0^z [C_d(z')\alpha(z')/P_m(z')]\, dz', \quad (7)$$

where C_d is the drag coefficient of the foliage elements, α is the vertical leaf area density function, and P_m is the momentum shelter factor. The ratio $u_*/u(h)$ is parameterized as

$$u_*/u(h) = c_1 - c_2 e^{-c_3\zeta(h)}, \quad (8)$$

where c_1 (=0.320), c_2 (=0.264), and c_3 (=15.1) are model constants related to the bulk surface drag coefficient $[2u_*^2/u(h)^2]$ and to the substrate or soil drag coefficient c_s as discussed by Massman (1997). In a physical sense, c_1 is the full canopy limit for $u_*/u(h)$, c_2 is a linear combination of c_1 and $\sqrt{c_s}$, and c_3 is related to the value of $\zeta(h)$ that distinguishes full canopy cover from partial canopy cover. A full canopy cover is defined as the situation in which $u_*/u(h)$ no longer varies greatly with $\zeta(h)$.

By assuming that the displacement height d is the effective level of mean drag on the canopy elements and by including the drag correction associated with the substrate or soil surface, d can be derived as

$$\frac{d}{h} = 1 - \int_0^1 e^{-2n[1-\zeta(z)/\zeta(h)]}\, d\xi, \quad (9)$$

with $\xi = z/h$, and similarly by assuming a roughness sublayer above the canopy and a logarithmic wind profile from the canopy top to the top of the surface layer, the roughness height z_0 for momentum transfer is given by

$$\frac{z_{0m}}{h} = \left(1 - \frac{d}{h}\right) e^{-ku(h)/u_*}. \quad (10)$$

Full discussions on the constants and parameters are given in Massman (1997, 1999a).

The vertical leaf area density function α is described by a modified Beta function proposed by Massman (1999a):

$$\alpha(z) = \frac{\mathrm{LAI}}{h} \frac{\beta(\xi)}{\int_0^1 \beta(\xi)\, d\xi}, \quad (11)$$

where LAI is the one-sided leaf area index over the whole area, $0 \le \xi = z/h \le 1$, and $\beta(\xi) = (a_1 - \xi)^{a_2}(a_3 + \xi)^{a_4}$, with $a_1 \ge 1$, $a_2 > 0$, $a_3 \ge 0$, and $a_4 > 0$ as adjustable model parameters. Further, it can be shown that setting $\xi = \xi_m = (a_4 a_1 - a_2 a_3)/(a_2 + a_4)$ produces a maximum in $\beta(\xi)$ that corresponds to the maximum leaf area density.

The full LNF model for kB^{-1} is then described by combining a far-field and a near-field temperature profile (Raupach 1989), with a canopy source function and leaf boundary layer resistance, the canopy momentum transfer model as discussed above (Massman 1997), a canopy turbulence model (Massman and Weil 1999), and the soil boundary layer resistance (Sauer and Norman 1995). The LNF model's results compare favorably with simpler models developed by Choudhury and Monteith (1988) and McNaughton and van den Hurk (1995) for canopy leaf only. It is also able to reproduce the most-observed variability synthesized from many field studies of kB^{-1} (Massman 1999a). Although the full LNF model provides significant insights into the physical processes of heat transfer between the land surface and the atmosphere, its input variables are also demanding. For practical purposes, Massman (1999a) then proposed a simpler alternative to describe the combined effects of canopy and soil boundary layer on kB^{-1} by simplifying the model of Choudhury and Monteith (1988) for canopy and the soil boundary layer resistance formulation based on Sauer and Norman (1995) and retaining the weighting factors of the full LNF model.

Based on the same strategy, a simple physically based model is derived in this study for the estimation of the roughness height for heat transfer. This model retains the approach of Massman (1999a) but differs from the formulation of the first and third terms of his simplified alternative and the weighting factors. The first term follows the full canopy-only model of Choudhury and Monteith (1988), and the third term is that of Brutsaert (1982) for bare soil surface. By adopting a quadratic weighting based on the fractional canopy coverage, the empirical factors used by Massman (1999a) are no longer necessary. We will call the current formulation Massman's (1999a) kB^{-1} model in the rest of this work. It is given as follows:

$$kB^{-1} = \frac{kC_d}{4C_t \dfrac{u_*}{u(h)}(1 - e^{-n/2})} f_c^2 + \frac{k\dfrac{u_*}{u(h)}\dfrac{z_{0m}}{h}}{C_t^*} f_c^2 f_s^2 + kB_s^{-1} f_s^2, \quad (12)$$

where f_c is the fractional canopy coverage and f_s is its compliment. Here, C_t is the heat transfer coefficient of the leaf. For most canopies and environmental conditions, C_t is bounded as $0.005N \le C_t \le 0.075N$ (N is number of sides of a leaf to participate in heat exchange). The heat transfer coefficient of the soil is given by $C_t^* = \mathrm{Pr}^{-2/3}\mathrm{Re}_*^{-1/2}$, where Pr is the Prandtl number (0.71; Massman 1999b) and the roughness Reynolds number $\mathrm{Re}_* = h_s u_*/\nu$, with h_s being the roughness height of the soil. The kinematic viscosity of the air is given by $\nu = 1.327 \times 10^{-5}(p_0/p)(T/T_0)^{1.81}$ (Massman 1999b), with p and T being the ambient pressure and temperature, $p_0 = 101.3$ kPa, and $T_0 = 273.15$ K. For bare soil surface, kB_s^{-1} is calculated according to Brutsaert (1982) as

$$kB_s^{-1} = 2.46(\mathrm{Re}_*)^{1/4} - \ln(7.4). \quad (13)$$

According to this formulation, the three terms on the right-hand side of Eq. (12) represent the contributions of canopy only, canopy–soil interaction, and soil only, respectively. Equation (12) reduces to limiting cases of canopy only, for $f_c = 1$, and soil surface only, for $f_s = 1$.

b. Blümel's (1999) kB^{-1} model

Blümel's (1999) kB^{-1} model is derived by fitting simulation results of a simple multisource bulk transfer model. First of all, Blümel (1999) developed a simple multisource transfer model with prescribed temperatures of the soil and vegetation, and of the air at a reference level to simulate the total sensible heat flux and the momentum flux for different surface types without explicit knowledge of the roughness lengths for momentum and heat transfer. The simulation results are then used to derive a functional relationship for determining the kB^{-1} value of a given fractional canopy coverage, using the limiting values of bare soil and full canopy coverage.

For a given fractional canopy coverage f_c, Eq. (4) is rewritten as

$$kB^{-1}(f_c) = \frac{C(f_c)}{\ln(z_{\mathrm{eff}}/z_{0m\mathrm{eff}})} - \ln\left(\frac{z_{\mathrm{eff}}}{z_{0m\mathrm{eff}}}\right), \qquad (14)$$

where the subscript eff refers to an effective value either measured or estimated taking into account f_c. In the latter case, $z_{\mathrm{eff}} = z - f_c d$, $z_{0m\mathrm{eff}} = z_{\mathrm{eff}} \exp(-k/C_{DM\mathrm{eff}}^{1/2})$, and $C_{DM\mathrm{eff}} = g(f_c)C_{DMc} + [1 - g(f_c)]C_{DMs}$. The neutral transfer coefficients are given as $C_{DMs} = [k/\ln(z/z_{0ms})]^2$ for bare soil and $C_{DMc} = \{k/\ln[(z - d)/z_{0mc}]\}^2$ for canopy. Here, $z_{0ms} \equiv h_s$ is the roughness height of the soil, d is calculated with Eq. (9), and $z_{0mc} \equiv z_{0m}$ is given by Eq. (10). The $g(f_c)$ is an empirical weighting function given as $g(f_c) = f_c^{\gamma_f} + f_c(1 - f_c)\zeta_f$, with $0.5 \le \gamma_f \le 1.0$ and $0.0 \le \zeta_f \le 1.0$ prescribed to determine the influence of stand geometry for the momentum flux. In the later calculations, we use $\gamma_f = 0.5$ and $\zeta_f = 1.0$, implying a maximum of $g(0.78) = 1.055$. Details on these parameters can be found in Blümel (1999). The function $C(f_c)$ is defined as

$$C(f_c) = \ln(z_{\mathrm{eff}}/z_{0m\mathrm{eff}}) \ln(z_{\mathrm{eff}}/z_{0h\mathrm{eff}}). \qquad (15)$$

The limiting value of $C(f_c)$ for bare soil is determined as follows:

$$C_s = \ln\left(\frac{z}{z_{0ms}}\right) \ln\left(\frac{z}{z_{0hs}}\right) = \ln\left(\frac{z}{z_{0ms}}\right)\left[\ln\left(\frac{z}{z_{0ms}}\right) + kB_s^{-1}\right], \qquad (16)$$

where kB_s^{-1} is given by Eq. (13).

For full canopy coverage the following relationships are given similarly as

$$C_c = \ln\left(\frac{z - d}{z_{0mc}}\right)\left[\ln\left(\frac{z - d}{z_{0mc}}\right) + kB_c^{-1}\right] \quad \text{and} \qquad (17)$$

$$kB_c^{-1} = C_k(\sigma_\alpha \mathrm{LSAI}^3)^{-1/4}\left[D_l u \Big/ \ln\left(\frac{z - d}{z_{0mc}}\right)\right]^{1/2}, \qquad (18)$$

where $C_k = 16.4\ \mathrm{m}^{-1}\ \mathrm{s}^{1/2}$, σ_α is a momentum partition factor given as

$$\sigma_\alpha = 1 - \frac{0.5}{0.5 + \mathrm{LSAI}} \exp\left(-\frac{\mathrm{LSAI}^2}{8}\right),$$

LSAI is the leaf and stem area index of the canopy covered area only, and D_l is the typical leaf dimension. If information on LSAI is not available, $(\sigma_\alpha \mathrm{LSAI}^3)^{-1/4} = 0.4$, for LSAI greater than 4. For the datasets used in the study, we assume $\mathrm{LSAI} = (1.1\mathrm{LAI})/f_c$, because only measurements for LAI and f_c are available [here LAI must be divided by f_c, because LAI is defined for the whole area in this study and LSAI in Blümel (1999) is defined for the canopy-covered area only]. Last, instead of through Eq. (15), $C(f_c)$ is obtained by fitting an empirical relation to simulation results as follows:

$$C(f_c) = A \exp(-a_1 f_c) + B, \qquad (19)$$

with fitting parameters $A = (C_s - C_c)/[1 - \exp(-a_1)]$, $B = C_s - A$, and $a_1 = 2.6\ (10\ h/z)^{0.355}$ determined from the simulation results of the multisource model.

In summary, in Blümel's (1999) kB^{-1} model, the kB^{-1} value of any surface with a fractional canopy coverage f_c can be obtained from Eq. (14), with Eq. (19) to interpolate between the soil limit given by Eq. (16) with Eq. (13) and the full canopy limit given by Eq. (17) with Eq. (18). In the original application, Blümel (1999) used the empirical relations proposed by Brutsaert (1982) to estimate the aerodynamic parameters d and z_{0m} using the mean vegetation height. In our analysis, we use the values calculated from Eqs. (9)–(10) for consistency [these values and those calculated from the relations proposed by Brutsaert (1982) give comparable values for the datasets used].

3. A simple energy balance model

To assess the suitability of the two kB^{-1} models in applications to energy balance calculation, the latent heat flux is calculated using the energy balance residual method, with other energy balance terms (net radiation and soil heat flux) calculated independently.

The equation to calculate the net radiation is given by

$$R_n = (1 - \alpha)R_{\mathrm{swd}} + \varepsilon R_{\mathrm{lwd}} - \varepsilon\sigma T_0^4, \qquad (20)$$

where α is the albedo, R_{swd} is the downward solar radiation, R_{lwd} is the downward longwave radiation, ε is the emissivity of the surface, σ is the Stefan–Bolzmann constant, and T_0 is the surface temperature.

The equation to calculate soil heat flux is parameterized as

$$G_0 = R_n[\Gamma_c + (1 - f_c)(\Gamma_s - \Gamma_c)], \qquad (21)$$

in which we assume the ratio of soil heat flux to net radiation $\Gamma_c = 0.05$ for full vegetation canopy (Monteith 1973) and $\Gamma_s = 0.315$ for bare soil (Kustas and Daughtry 1989). An interpolation is then performed between these limiting cases using the fractional canopy coverage f_c.

After computing the sensible heat flux from Eqs. (1)–(3) and the net radiation and soil heat flux with Eqs. (20) and (21), the latent heat flux can be derived as an energy balance residual:

$$\lambda E = R_n - G_0 - H. \qquad (22)$$

In the following section, we will first describe the datasets to be used and then assess the suitability of the two kB^{-1} models, judged by their performance in computing sensible heat fluxes.

4. Datasets

Three datasets with most of the information required by the models are used in this study. These datasets have been used extensively for validation purposes (e.g., Norman et al. 1995; Zhan et al. 1996; Flerchinger et al. 1998; Kustas and Norman 1999).

a. Cotton data

The first dataset was collected over a cotton field in Maricopa Farms in central Arizona from 10 June 1987, day-of-year (DOY) 161, to 14 June 1987, DOY 165 (henceforth termed cotton data). The field is 1500 m east–west by 300 m north–south in size, with cotton rows 0.2 m in width and spaced 1 m apart, running north–south. The cotton is 0.32 m high on top of a 0.17 m high furrow. Profile measurements of wind and temperature at five levels were used to derive the zero plane displacement and the roughness height for momentum (these values are regarded as experimental estimates). Sensible and latent heat fluxes were measured by the Bowen ratio and eddy correlation method. The measurements of the latter are used in this study for comparison. Complete descriptions on this dataset are given by Kustas et al. (1989a,b) and Kustas and Daughtry (1989) and Kustas (1990), for the instrumentation, the agronomic measurements, the derivation of aerodynamic roughness parameters, the determination of the composite surface radiometric temperature, the determination of the soil heat flux, and the modeling of the heat fluxes with a one- and two-layer model. The total height of the cotton canopy is determined as the sum of the cotton plant height, 0.32 m, and the height of furrow, 0.17 m. Other agronomic and aerodynamic information relevant for this study is listed in Tables 1–4 and 8. The composite surface radiometric temperature is derived by weighting the measured radiometric temperatures of the shaded soil, sunlit soil, and vegetation with the actual areas covered by these portions (Kustas and Daughtry 1989). Figure 1a shows the surface condition during the measurements.

b. Shrub data

The second dataset was collected during the ''MONSOON'90'' multidisciplinary experiment conducted over the U.S. Department of Agriculture Agricultural Research Service Walnut Gulch experimental watershed in southeastern Arizona during June–September 1990 (Kustas and Goodrich 1994). This dataset was collected in the Lucky Hills study area, which is a shrub-dominated ecosystem (henceforth shrub data). Data from the second observation period from mid-July to early August (20 days in total, the longest of the three observation periods) are used in this study. These include ground-based continuous measurements of meteorological conditions at screen heights, near-surface soil temperature and soil moisture, surface temperature, incoming solar and net radiation, soil heat flux, and indirect determination of sensible and latent heat fluxes (Kustas et al. 1994a,b). Detailed measurements on vegetation type, height, and fractional cover and surface soil properties were made at each site (Weltz et al. 1994). For the shrub site, there are large and small shrubs as can be observed in Fig. 1b. The height of large shrubs is determined as 0.5 m, and the averaged height is 0.27 m. The former is used in the calculation because of its more obvious influence on the airflow.

c. Grass data

The third dataset was collected during the MONSOON'90 multidisciplinary experiment in the Kendall study area, a grass-dominated ecosystem (henceforth grass data). All the measurements are similar to the shrub data. At the grass site, the surface is also complex (Fig. 1c), consisting of shrubs, tall grass, and low grass. The height of the shrubs is determined as 0.27 m, tall-grass height is determined as 0.2 m, and averaged grass height is estimated as 0.1 m. For the same reason as for the shrub data, the maximum height used in the calculation is set as 0.27 m. Other parameters used in this study are also listed in Tables 1–4 and 8.

5. Results and discussion

a. Estimates of d, z_{0m} values

Figure 1 shows the photographs of the surfaces of the three datasets studied, from which it is immediately obvious that all the three surfaces are complex. All three surfaces consist of bare soil and vegetation of different fractional coverage and different height. The cotton field has both sunlit and shaded soil as well as sunlit and shaded leaves (Fig. 1a). The shrub surface is covered

TABLE 1. Input requirements for the kB^{-1} models and the parameters used for each of the three datasets.

Symbol (unit)	Variables and parameters	Cotton data	Shrub data	Grass data
u (m s^{-1})	Wind speed at reference height	Actual measurements	Actual measurements	Actual measurements
T_a (°C)	Air temperature at reference height	Actual measurements	Actual measurements	Actual measurements
p_a (Pa)	Surface pressure	96 500.0	86 500.0	85 000.0
h (m)	Total height of vegetation	0.49	0.5	0.27
z (m)	Reference (measurement) height	3.0	4.3	4.3
LAI	Leaf area index per total area	0.4	0.5	0.8
f_c	Fractional foliage coverage	0.24	0.26	0.44
D_l (m)	Leaf width	0.05	0.01	0.005
ξ_m	Position of maximum foliage density	0.5	0.35	0.5

by tall shrubs, short shrubs, and patched bare soil with both sunlit and shaded portions (Fig. 1b). The grass surface has bare soil, short grass, and long grass as well as short and tall shrubs interspersed among one another (Fig. 1c). As such, all three surfaces will be expected to have different surface temperature components and complex aerodynamic characteristics. It is also easily appreciated that the description of the surfaces likely will require multiscales, owing to the multiscale nature of the surfaces themselves.

This study is meant to evaluate the robustness of the two models for applications to complex surfaces. Rather than retrieving a set of optimal parameters (that when used in heat flux calculation might give a best fit to measured values) for the particular datasets studied, we will restrain our effort to searching for the best strategies using as little information as possible. To this end, the input parameters for the models as listed in Table 1 are either directly measurable (e.g., the heights and leaf area indices of different vegetation species) or can be estimated either by field survey or by remote sensing means (e.g., the fractional coverage and, in certain cases, also LAI). The parameters that are more difficult to measure are assigned some reasonable values based on literature recommendations (e.g., leaf drag and heat transfer coefficients).

The vertical foliage density distribution can be measured relatively easily for uniform canopy, but such measurements are much more difficult for complex canopies such as are studied here. At any rate, because such information is not available for this study, we have decided to use the same set of parameters in the modified beta function except for the level of the maximum foliage density. By adjusting this one parameter, we try to cope with the complexity encountered while maintaining the required information, not available otherwise, to a minimum.

The parameters of the modified beta function in Eq. (11) are given as follows: $a_1 = 1.0500$, $a_2 = 2.0000$, and $a_3 = 0.1000$. The parameter a_4 is derived using the relation $\xi_m = (a_4 a_1 - a_2 a_3)/(a_2 + a_4)$ with ξ_m, the level of maximum density, as the only adjustable model parameter. Here, ξ_m is determined chiefly by inspecting the field photographs taken at the time of the data collection. For each uniform canopy, we simply assume a bell-shaped density distribution with maximum foliage density around the middle to upper three-quarters (0.5–0.75) of the normalized height dependent on the actual canopy type, and a superposition is applied to multiple species. For the cotton data, a value of 0.5 is assigned using the total height as the sum of the cotton and furrow height. For the shrub data, the total height is that of the large shrubs, and a superposition of the large and small shrubs gives a maximum foliage density of about 0.35. For the grass data, a superposition of short grass, tall grass, and shrubs (as can be seen from Fig. 1c) similarly gives a value of 0.5 as the level of maximum foliage density. These values, as already stated, must be seen as reasonable estimates and may actually differ to large or small extent when actual measurements are carried out. However, it may be argued that even if real measurements may be feasible despite the apparent difficulty involved for such complex canopies, they may not necessarily represent the aerodynamic density distribution, simply because the sheltering effects that vary with the actual wind cannot be easily measured in a natural environment. The actual shapes of the foliage distributions are plotted in Fig. 2.

Other parameters, such as the reference height and the surface pressure, are measured values in the datasets. The roughness height h_s of the soil is usually not available, but field measurements performed by Su et al. (1997) showed a lower bound of 0.009 m for most agricultural fields. This value is used for this study. Other parameters that are not available in the measurements are set to literature values: that is, the drag coefficient of the foliage elements $C_d = 0.2$, the momentum shelter factor $P_m = 1.0$, and the heat transfer coefficient C_t of the leaf = 0.01.

The estimates of the aerodynamic parameters from experimental data are listed in Tables 2–4. In the following we will discuss each of the three datasets separately.

1) ESTIMATES OF d, z_{0m} VALUES FOR COTTON DATA

For the cotton data, the model estimates fall within the range of experimentally estimated values of d and z_{0m} and are therefore deemed satisfactory. From Table 2, it is also obvious that it is a difficult task to determine

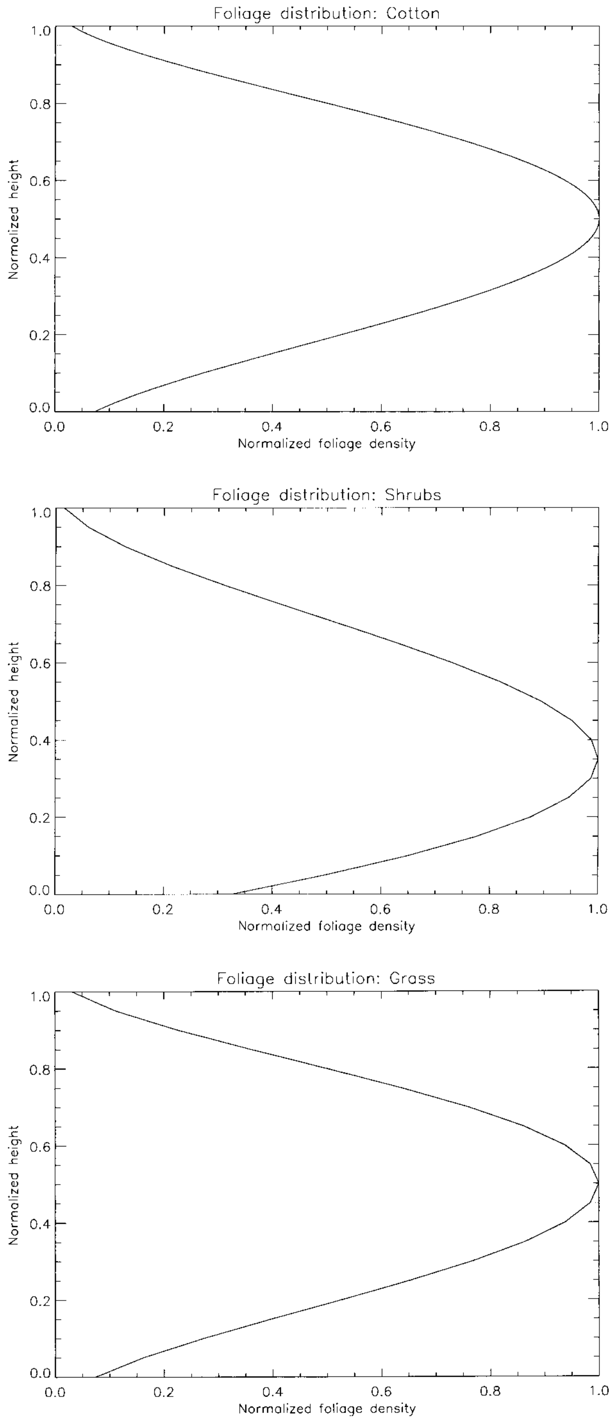

FIG. 2. Foliage distribution of (top) cotton, (middle) shrubs, and (bottom) grass.

the aerodynamic parameters experimentally even with detailed profile measurements. This is due to the fact that on one hand neutral conditions are needed to use the commonly applied logarithmic profiles and on the other the parameters of d and z_{0m} are interlinked (through the profile relationship) so that changes in one will result necessarily in changes in the other. Note also that true neutral conditions are rare and some approximations are always necessary, which may actually result in large uncertainty. This uncertainty is amply demonstrated in the five estimated values of d and z_{0m} (Kustas et al. 1989b) as recaptured in Tables 2–4. The presently estimated values fall comfortably within the range of the median values.

2) ESTIMATES OF d, z_{0m} VALUES FOR SHRUB DATA

The results for the shrub data are listed in Table 3. The comparison with the experimental estimates is also favorable. However, it is also clear that the uncertainties in the experimental estimates are large, because values determined with different methods resulted in big differences (Table 3).

3) ESTIMATES OF d, z_{0m} VALUES FOR GRASS DATA

The results for the grass data are listed in Table 4. The comparison with the experimental estimates is less favorable, which may be due to the extreme complexity of the surface concerned. Again, it is clear that the uncertainties in the experimental estimates are large, because values determined with different methods resulted in big differences (Table 4).

In summary, when compared with observed values of d and z_{0m}, these parameters likely are underestimated by the model. However, as Tables 2–4 indicate, the observed values are uncertain. For this study we do not find the differences between these modeled and observed values to be significant, but the issue may warrant closer examination in other studies. A striking feature for the shrub and grass data as compared with the cotton is the large zero plane displacement heights with reference to the mean vegetation heights. As a matter of fact, for both datasets, d values are larger than typical heights of the taller shrubs measured within 50 m of the towers (Weltz et al. 1994), which is direct evidence of the obvious important influence of topography and of riparian vegetation hundreds of meters upwind (Kustas et al. 1994a). This makes the application of empirical methods using vegetation height (e.g., Brutsaert 1982) tenuous. In a similar way, the momentum transfer model of Massman (1997) also does not include explicitly such fetch effects or in the case of the cotton the observed influence of the furrows on d (Kustas 1990). In a study for updating numerical weather predictions using remotely sensed land surface heat fluxes, Su et al. (1998) employed a digital elevation model to calculate the roughness parameters due to topographic effects. Such a method is also applicable for this study, but we did not have a digital elevation model available.

b. Estimates of kB^{-1} values and sensible heat fluxes

The estimation of kB^{-1} values using experimental data involves sensible heat flux, wind speed, and tem-

TABLE 2. Estimates of aerodynamic parameters with Massman's (1997) momentum transfer model and estimates from profile data under neutral conditions for the cotton data. Standard error is given in parentheses when available.

d (m)	z_{0m} (m)	Time (h)	Source and remarks
0.41 (0.17)	0.043 (0.020)	2300	Measurements at different times from DOY 163–164 [Table 3 of Kustas et al. (1989b)]
0.45 (0.27)	0.040 (0.038)	2340	
0.42 (0.10)	0.040 (0.013)	2400	
0.30 (0.22)	0.065 (0.040)	0020	
0.00 (0.13)	0.14 (0.035)	0040	
0.41 (0.17)	0.040 (0.035)		Median values of all time intervals
0.299	0.033		Estimates of current study

TABLE 3. Estimates of aerodynamic parameters with Massman's (1997) momentum transfer model and other estimates from the literature for the shrub data. Standard error is given in parentheses when available.

d (m)	z_{0m} (m)	Sources and remarks
0.5	0.04	Used in model calculation, Table 4 of Kustas et al. (1994b)
0.60 (0.32)	0.08 (0.06)	Estimated from near-neutral wind profile [Table 4 of Kustas et al. (1994a)]
0.3	0.04	Eqs. (3) and (5), and Table 4 of Kustas et al. (1994a)
0.5	0.03	Eqs. (2), (3), (6) and (7), and Table 4 of Kustas et al. (1994b)
—	0.07	Estimated from laser profile [Table 3 of Menenti and Ritchie (1994)]
0.5	0.05	Table 3 of Moran et al. (1994)
0.281	0.0487	Estimates of current study

perature (composite temperature), as required in Eqs. (1)–(3). Each of these required quantities is measured with some errors. Especially in the measurement of temperature, usually a radiometer with a certain field of view is pointed to the target area. Dependent on the angle of the observation, the resultant temperature can be very different, given that the temperatures of sunlit soil, shaded soil, and vegetation are likely very different during sunshine hours. As a consequence, to obtain a good composite temperature of the source area representative of the sensible heat measurement, a large number of temperature measurements and delicate weighting procedures must be used (Kustas et al. 1989a). Failure to do so will introduce large errors in calculated sensible heat flux. If such a temperature, the measured sensible heat flux, and the wind speed are used together to estimate kB^{-1} values, the uncertainty in temperature will be carried over to and amplified in the estimated kB^{-1} values. The often reported large variations in estimated kB^{-1} values (orders of magnitude sometimes) are probably consequences of such a practice. It has been demonstrated recently by Jacobs and Brutsaert (1998) that using off-nadir instead of nadir view angle in measuring surface temperature with infrared thermometers results in a nearly twofold variation of z_{0h} (0.0038 and 0.0021 m for the off-nadir and the nadir viewing angles, respectively). Their findings provide evidence for the above argument.

In both of the models examined, because the surface temperature (or the temperature gradient between surface and the air at the reference height) is not directly employed in calculating kB^{-1}, errors in surface temperature measurements will not contaminate the estimated kB^{-1} values. This fact can be seen by the small standard deviation of the estimated kB^{-1} values for all three datasets (Tables 5–7). The results of the model performances will be judged by using the derived roughness values to compute sensible heat fluxes with the bulk transfer formulation and comparing these computed fluxes to the observed sensible heat fluxes. To do so, we first compute the kB^{-1} values [or rather the z_{0h} values through Eq. (4)], then the sensible heat fluxes are obtained by solving the system of nonlinear Eqs. (1)–(3) using the method of Broyden (Press et al. 1997). Last, the computed fluxes will be compared with the observed sensible heat fluxes.

TABLE 4. Same as Table 3 but for the grass data.

d (m)	z_{0m}	Sources and remarks
0.3	0.01	Used in model calculation, Table 4 of Kustas et al. (1994b)
0.54 (0.14)	0.01 (0.009)	Estimated from near-neutral wind profile [Table 4 of Kustas et al. (1994a)]
0.3	0.004	Eqs. (3) and (5), and Table 4 of Kustas et al. (1994a)
0.5	0.01	Eqs. (2), (3), (6) and (7), and Table 4 of Kustas et al. (1994b)
—	0.02	Estimated from laser profile [Table 3 of Menenti and Ritchie (1994)]
0.5	0.01	Table 3 of Moran et al. (1994)
0.171	0.0226	Estimates of current study

TABLE 5. Statistics of model calculation compared with observed heat fluxes of the cotton dataset (MAD: mean absolute deviation; rmse: root-mean-square error; R2: coefficient of determination).

Massman's (1999a) kB^{-1} model
$kB^{-1} = 4.420$ (± 0.449), $z_{0h} = 4.39 \times 10^{-4}$ ($\pm 2.29 \times 10^{-4}$) (m)
Energy balance terms (W m^{-2})

Variable	Measured Mean	Measured Std dev	Calculated Mean	Calculated Std dev
R_n	561.74	57.03	555.21	39.54
G_0	140.37	14.23	139.58	9.94
H	116.63	45.59	112.80	57.84
λE	304.74	27.45	302.83	45.69

No. of data points used 19
Statistics (calculated vs measured)

	R_n	G_0	H	λE
MAD (W m^{-2})	19.12	4.51	18.73	28.81
Rmse (W m^{-2})	22.82	5.42	22.19	33.37
R2	0.91	0.92	0.87	0.44

Blümel's (1999) kB^{-1} model
$kB^{-1} = 4.100$ (± 0.628), $z_{0h} = 6.69 \times 10^{-4}$ ($\pm 5.06 \times 10^{-4}$) (m)
Energy balance terms (W m^{-2})

Variable	Measured Mean	Measured Std dev	Calculated Mean	Calculated Std dev
R_n	561.74	57.03	555.21	39.54
G_0	140.37	14.23	139.58	9.94
H	116.63	45.59	116.84	57.66
λE	304.74	27.45	298.79	44.87

No. of data points used 19
Statistics (calculated vs measured)

	R_n	G_0	H	λE
MAD (W m^{-2})	19.12	4.51	18.25	28.41
Rmse (W m^{-2})	22.82	5.42	21.07	33.55
R2	0.91	0.92	0.88	0.43

TABLE 6. Same as Table 5 but for the shrub dataset.

Massman's (1999a) kB^{-1} model
$kB^{-1} = 6.53$ (± 0.298), $z_{0h} = 3.43 \times 10^{-5}$ ($\pm 1.01 \times 10^{-5}$) (m)
Energy balance terms (W m^{-2})

Variable	Measured Mean	Measured Std dev	Calculated Mean	Calculated Std dev
R_n	425.77	135.15	434.78	149.94
G_0	121.54	56.46	107.00	36.90
H	134.14	57.03	118.88	76.49
λE	169.87	60.14	208.90	94.94

No. of data points used 111
Statistics (calculated vs measured)

	R_n	G_0	H	λE
MAD (W m^{-2})	24.36	27.17	35.34	61.86
Rmse (W m^{-2})	30.86	32.31	42.75	76.44
R2	0.97	0.79	0.74	0.52

Blümel's (1999a) kB^{-1} model
$kB^{-1} = 3.21$ (± 0.450), $z_{0h} = 1.01 \times 10^{-3}$ ($\pm 4.45 \times 10^{-4}$) (m)
Energy balance terms (W m^{-2})

Variable	Measured Mean	Measured Std dev	Calculated Mean	Calculated Std dev
R_n	425.77	135.15	434.78	149.94
G_0	121.54	56.46	107.00	36.90
H	134.14	57.03	115.89	73.88
λE	169.87	60.14	211.89	94.37

No. of data points used 111
Statistics (calculated vs measured)

	R_n	G_0	H	λE
MAD (W m^{-2})	24.36	27.17	34.77	62.36
Rmse (W m^{-2})	30.86	32.31	41.88	77.06
R2	0.97	0.79	0.75	0.54

The model-estimated values of kB^{-1} (and values of z_{0h}) are given in Tables 5–7. From these tables, it appears that both models give comparable values of kB^{-1} (both mean and standard deviation) for the cotton (Table 5) and the grass datasets (Table 7). For the shrub dataset (Table 6), Massman's (1999a) model doubles that of Blümel's (1999) and will be discussed later in the pages.

Results for the cotton, shrub, and grass sites are illustrated in Figs. 3, 5, and 6, respectively. The statistics of the predicted versus observed heat fluxes are tabulated in Tables 5–7 for each of the datasets and for both models.

1) ESTIMATES OF SENSIBLE HEAT FLUX FOR COTTON DATA

As can be seen from Table 5 and Fig. 3, the estimated sensible heat fluxes from both models are in good agreement with measured values. Both the mean absolute difference (MAD) and the root-mean-square error (rmse) are on the order of 20 W m^{-2}, and the coefficient of determination R^2 is near 0.87, which are comparable to previous modeling studies (Kustas 1990; Kustas and Norman 1999).

From Fig. 3, both models tend to overestimate the sensible heat flux at high values and underestimate it at lower ones. From plotting predicted and measured sensible heat flux as a function of the observed wind speed (Fig. 4), it becomes clear that at higher wind speed ($>$2.0 m s^{-1}) overestimation occurs and at low wind speed ($\sim$0.5 m s^{-1}) underestimation occurs, in between no systematic feature is obvious.

From the data description, it was known that in the east–west direction the fetch for the flux measurement is adequate, but for the north–south direction the fetch is significantly smaller (Kustas et al. 1989b). Although the winds from southwesterly to northwesterly direction were dominant, there were some winds coming from north–northeast directions associated with low winds. This inadequate fetch may actually introduce some uncertainty into the measurements of sensible heat flux. No systematic errors are found to be associated with wind directions. However, a more serious uncertainty might be due to the use of the logarithmic wind profile, given that it is known both theoretically (Massman 1987) and experimentally (Mihailović et al. 1999) that the logarithmic relationship overestimates wind speed in the roughness sublayer. Because in the evaluations of this paper the wind speed is measured and the friction velocity is computed from the logarithmic relationship, u_* is underestimated. From Eqs. (2) and (12), it can be observed that the relationship between u_* and H is nonlinear. The actual influence of u_* on H will depend strongly on value of f_c. From Eq. (2), an underestimation of u_* would result in a smaller H, if the dependence of z_{0h} on u_* through Eq. (12) is neglected. However, when the dependence of z_{0h} on u_* is taken into account, a bigger H may result, depending on the value of f_c. For the current dataset, $f_c < f_s$ or $f_c < 0.5$, an underestimation of u_* at larger wind speed will consequently give larger heat flux estimates. This result explains the bigger discrepancy at strong winds for which the underestimations of u_* are more pronounced. For the low wind speeds around the stall speed of the anemometers, the uncertainties in the measurements may actually contribute to the discrepancy in the lower-heat-flux case.

2) ESTIMATES OF SENSIBLE HEAT FLUX FOR SHRUB DATA

For the shrub data, both the MAD and rmse are larger and the R^2 is smaller than for the cotton data, indicating less agreement between estimated and measured sensible heat fluxes (Table 6 and Fig. 5). With the Massman's (1999a) model, the MAD and the rmse of the sensible heat flux are 35 and 43 W m^{-2}, respectively, with $R^2 = 0.74$. With the Blümel's (1999) model, the MAD and the rmse of the sensible heat flux are 35 and 42 W m^{-2}, respectively, with $R^2 = 0.75$. Thus the model results are practically the same. However, because of the underlying terrain and heterogeneous nature of the vegetation cover for these two sites, the larger uncertainties in model parameters are likely to cause greater discrepancies with the observations. The tendency of the models to overestimate at higher wind speeds and to underestimate at lower wind speeds is similar to the results with the cotton data, suggesting roughness sublayer effects may be the factor.

Note also that the estimated mean value of kB^{-1} of Massman's (1999) model doubles that of Blümel's (1999) model. However, because the statistics of the estimated sensible heat fluxes using both models are similar, the only valid conclusion is that in this case the estimated sensible heat flux is less sensitive to the particular kB^{-1} value. This result is likely due to the special combination of the reference height, the roughness height for momentum, the roughness height for heat transfer, and the stability corrections.

3) ESTIMATES OF SENSIBLE HEAT FLUX FOR GRASS DATA

For the grass data, similar to the shrub data, both the MAD and rmse are larger and the R^2 is smaller than for the cotton data, indicating again less agreement between estimated and measured sensible heat fluxes (Table 7 and Fig. 6). With the Massman's (1999a) model, the MAD and the rmse of the sensible heat flux are 36 and 46 W m^{-2}, respectively, with $R^2 = 0.68$. With the Blümel's (1999) model, the MAD and the rmse of the sensible heat flux are 49 and 59 W m^{-2}, respectively, with $R^2 = 0.69$. Here the Massman's (1999a) model outperformed the Blümel's (1999) model judged by these statistics. Note also that when the mean values of the estimated sensible heat fluxes are compared, the performance of the Blümel's (1999) model is better, but when the standard deviation is compared, the performance of the Blümel's (1999) model is again less favorable. As for the shrub data, because of the underlying terrain and heterogeneous nature of the vegetation cover for these two sites, the larger uncertainties in model parameters are likely to cause greater discrepancies with the observations. Again, the tendency of the models to overestimate at higher wind speeds and to underestimate at lower wind speeds is similar to the results with the cotton data, suggesting roughness sublayer effects may be the factor.

TABLE 7. Same as Table 5 but for the grass dataset.

Massman's (1999a) kB^{-1} model
$kB^{-1} = 4.85$ (± 0.542), $z_{0h} = 4.50 \times 10^{-4}$ ($\pm 3.08 \times 10^{-4}$) (m)
Energy balance terms (W m^{-2})

Variable	Measured Mean	Measured Std dev	Calculated Mean	Calculated Std dev
R_n	434.71	163.91	426.71	168.31
G_0	100.87	51.76	84.66	33.39
H	131.49	51.56	104.59	65.92
λE	202.27	94.55	237.46	106.08

No. of data points used 108
Statistics (calculated vs measured)

	R_n	G_0	H	λE
MAD (W m^{-2})	21.01	25.49	35.54	44.49
Rmse (W m^{-2})	24.72	33.62	46.10	56.51
R2	0.98	0.71	0.68	0.82

Blümel's (1999) kB^{-1} model
$kB^{-1} = 5.03$ (± 0.703), $z_{0h} = 4.22 \times 10^{-4}$ ($\pm 3.97 \times 10^{-4}$) (m)
Energy balance terms (W m^{-2})

Variable	Measured Mean	Measured Std dev	Calculated Mean	Calculated Std dev
R_n	434.71	163.91	426.71	168.31
G_0	100.89	51.76	84.66	33.39
H	131.49	51.56	148.05	91.99
λE	202.27	94.55	194.00	103.64

No. of data points used 108
Statistics (calculated vs measured)

	R_n	G_0	H	λE
MAD (W m^{-2})	21.01	25.49	48.53	46.00
Rmse (W m^{-2})	24.72	33.62	59.12	56.34
R2	0.98	0.71	0.69	0.71

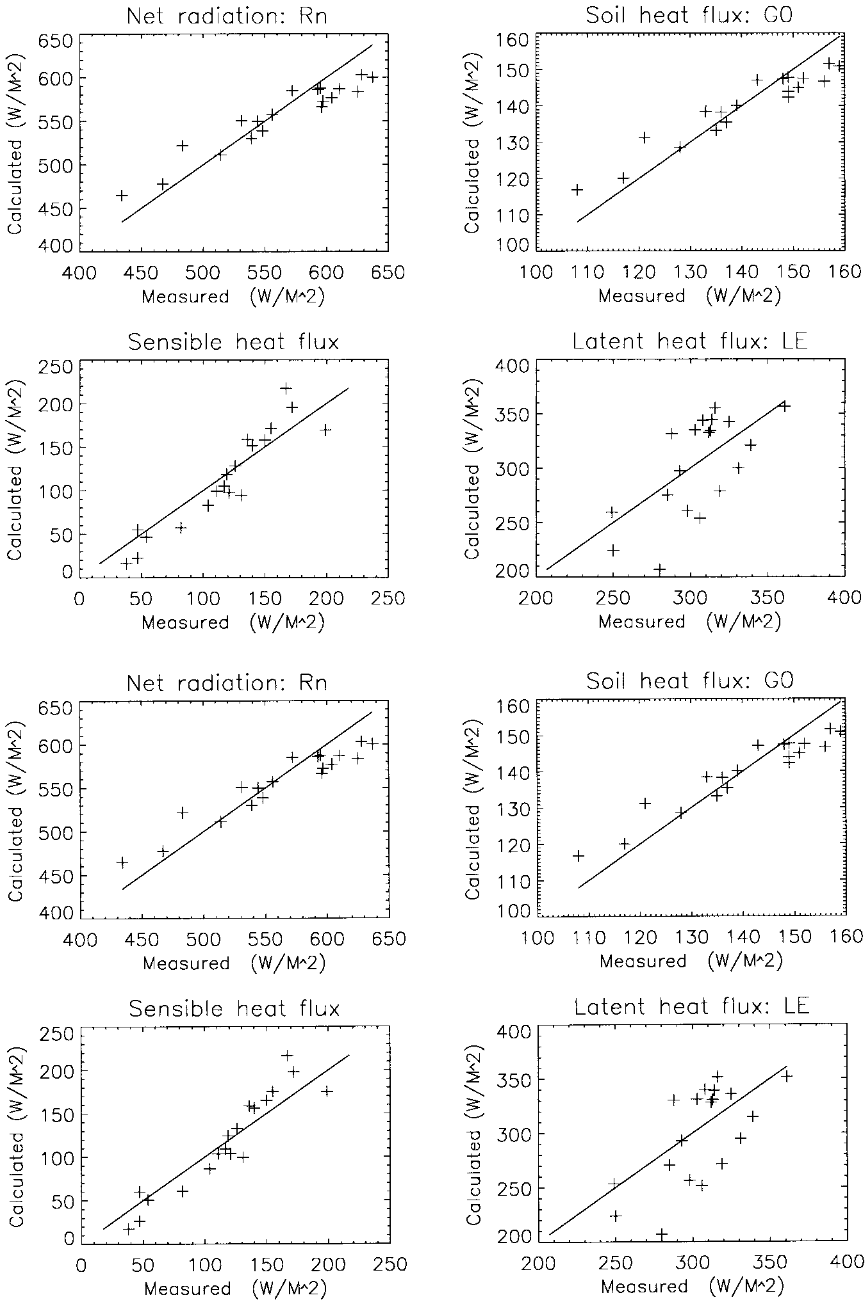

FIG. 3. Calculated vs measured surface energy balance terms for cotton data for (top) Massman's (1999a) model and (bottom) Blümel's (1999) model.

c. Estimates of other components of energy balances

To assess the influence of the z_{0h} values on the latent heat flux, the latent heat flux is calculated using the energy balance residual method, with other energy balance terms (net radiation and soil heat flux) calculated independently. The input parameters for this numerical approach are listed in Table 8. The aerodynamic parameters are the model estimates as discussed previously. All the other input variables are measured except the downward longwave radiation that is estimated with the Stefan–Boltzmann radiation equation with the measured air temperature at the reference height. The emissivity of the air is estimated using the formula of Swinbank (Campbell and Norman 1998, p. 164), which requires only air temperature. Brutsaert's (1982) formula has a better theoretical justification but requires vapor pressure in addition to temperature. In the cotton

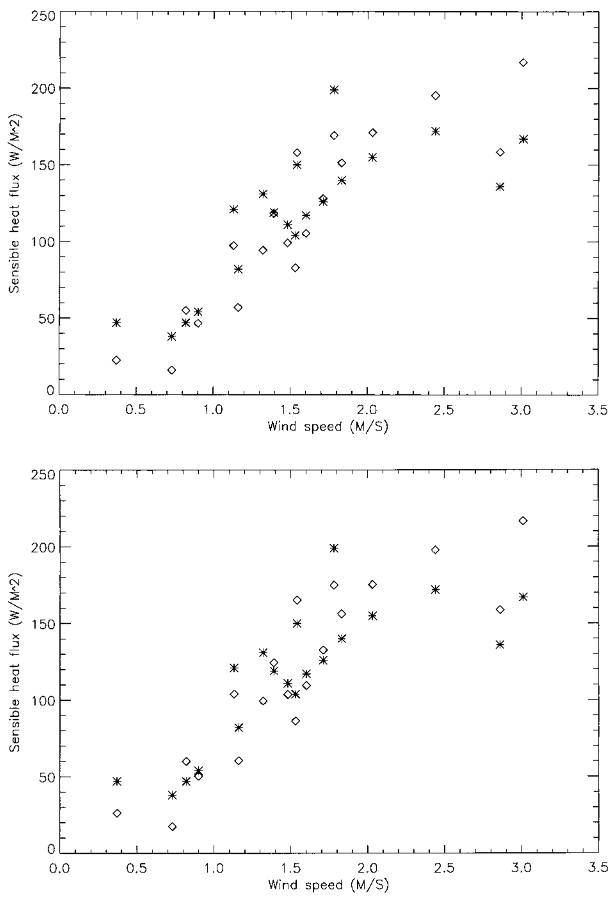

FIG. 4. Calculated (◇) and measured (*) sensible heat fluxes vs wind speed for cotton data for (top) Massman's (1999a) and (bottom) Blümel's (1999) model.

dataset there appears to be some error in the measured vapor pressure; therefore we choose to use Swinbank's formula for all three datasets for the sake of consistency.

The measured albedo values are not available so we have chosen a value for each dataset that keeps the radiation terms in balance. To estimate the soil heat flux, a most simple parameterization is used, in which a ratio of soil heat flux to net radiation is defined as 0.315 for bare soil and 0.05 for full canopy coverage (Kustas and Daughtry 1989) and a linear interpolation is used according to the actual fractional coverage. The surface emissivity values are measured (Kustas et al. 1989a; Humes et al. 1994). Last, a simple energy balance equation is used to estimate the latent heat flux as the residual. Note that the energy balance calculation is just for the purpose of illustrating the possible errors in the latent heat estimation using the current approach of estimation of the sensible heat flux.

Despite the simple parameterizations used in estimating the net radiation and soil heat flux, the estimated energy balance components given in Tables 5–7, including latent heat flux, are in reasonably good agreement with the observations. From the comparisons, we conclude that the current simple parameterizations for net radiation and soil heat flux are adequate. The comparisons also indicate that when the currently evaluated kB^{-1} models are used to estimate the sensible heat flux, the latent heat flux can then be derived from a simple energy balance consideration. This approach eliminates the need to parameterize the canopy stomatal resistance in direct evaluation of the latent heat flux. The implication of such a success is that remotely sensed surface temperature can be used directly in estimation of surface energy balance terms for large areas. On the other hand, by incorporating the current kB^{-1} models, meteorological models will be able to take advantage of the remotely sensed surface temperature directly. This can be done either by evaluating model prognostic surface temperature or by updating other model prognostic variables using the surface temperatures. Until now, atmospheric models have not been able to use remotely sensed surface temperatures over land, because the model parameterization is not compatible with the remotely sensed information (e.g., van den Hurk 2001).

Note also that although an explicit sensitivity analysis for the kB^{-1} is not yet carried out, such an analysis is actually implicit. This is due to the fact that we have used one single set of parameters to characterize the vertical vegetation structure and by adjusting only the level of the maximum density we have been able to cope with the actual complexity involved. Hence the difference between the kB^{-1} values predicted by Massman's (1999a) and Blümel's (1999) kB^{-1} model and the associated sensible heat flux estimated using Eqs. (1)–(3) for the three datasets demonstrate the variability that can be expected. For the cotton data, a 10% difference between the kB^{-1} values resulted in negligible difference in sensible heat fluxes. A similar conclusion holds for the shrub site. For the grass site, apparently because of the extreme difficulty encountered in describing the vertical structure, the resulting kB^{-1} values differ by 75%. The statistics in the estimated sensible heat fluxes are more favorable when using the Massman's (1999a) kB^{-1} model than using the Blümel's (1999) kB^{-1} model. This result may be due to the fact that, in the original simulations used to derive the fitting function in Blümel's (1999) kB^{-1} model, this complexity was not captured adequately.

The current ''single-source'' approaches treat the soil and vegetation components as a composite surface having a single effective surface temperature. Past studies have suggested that single-source approaches are in general unreliable because of uncertainty in the parameterization for the scalar roughness and have advocated the use of ''dual-source'' modeling schemes, in which explicit formulations exist for the radiative and convective exchanges of the soil and vegetation components (e.g., Zhan et al. 1996). The current single-source approaches, however, appear to address this limitation,

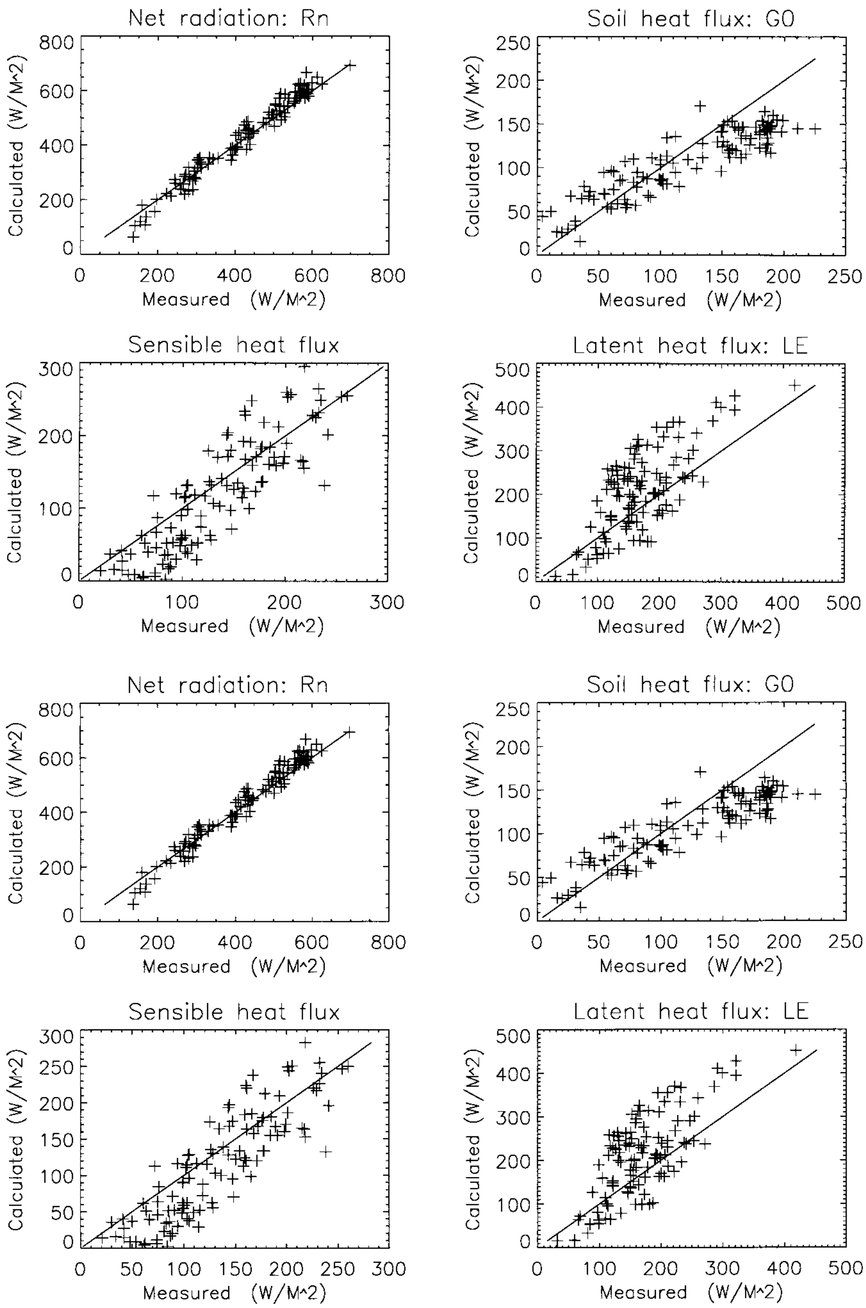

FIG. 5. Same as Fig. 3 but for shrub data.

yielding results comparable to a dual-source scheme applied to the shrub and grass sites (Norman et al. 1995) and the cotton site (Kustas and Norman 1999). Nevertheless, dual-source models can compute both soil and canopy heat fluxes and temperatures and thus can provide estimates of plant stress and water use, whereas the single approaches cannot separate soil and canopy temperatures and can only provide composite or total heat fluxes.

d. Sensitivity of sensible heat flux to parameters in Massman's (1999a) kB^{-1} model

Because Blümel (1999) has done a sensitivity analysis for his model, we will focus on only the Massman's (1999a) kB^{-1} model in this section. Using Eq. (2), the sensitivity of H to kB^{-1} can be quantified as

$$\Delta H = \frac{-H^2}{ku_* \rho C_p(\theta_0 - \theta_a)} \Delta kB^{-1}, \qquad (23)$$

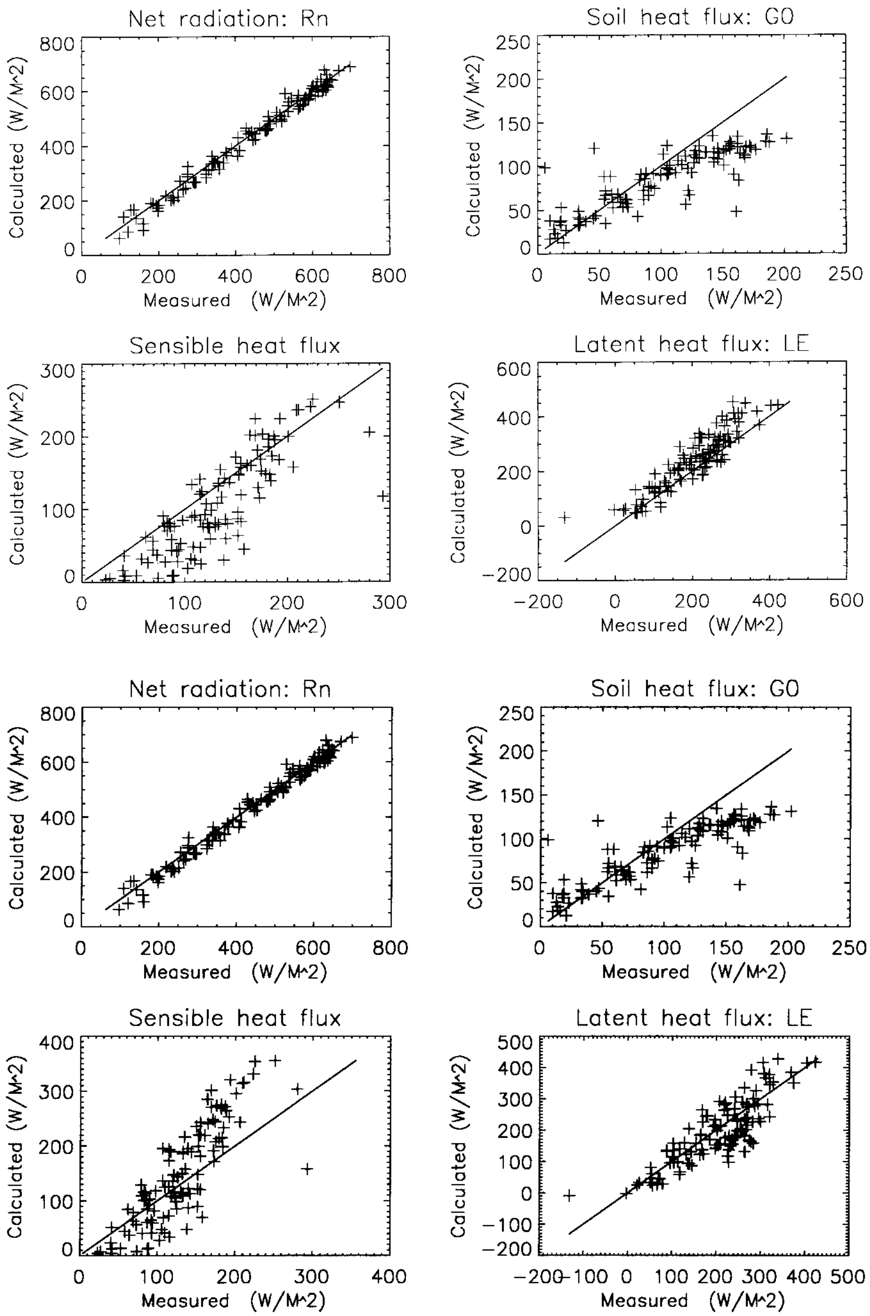

FIG. 6. Same as Fig. 3 but for grass data.

where ΔH (W m^{-2}) refers to unit change in H due to unit change in kB^{-1} (ΔkB^{-1}). Inserting the range of values from the cotton data, that is, $H = 50$–200 W m^{-2}, $u_* = 0.05$–0.3 m s^{-1}, and $(\theta_0 - \theta_a) = 5$–$20$ K, we arrive at $\Delta H = (-24 \text{ to } +10)\ \Delta kB^{-1}$, which means that every unit change of kB^{-1} value may result in as large as 50% changes in H. The sensitivity can be even larger than the values given, depending on the actual combination of surface and meteorological conditions.

Further, be means of an order-of-magnitude analysis, the Massman's (1999a) kB^{-1} model can be approximated, by neglecting terms that contribute less than one order of magnitude to total kB^{-1} value, as

$$\langle kB^{-1} \rangle = \frac{kC_d}{4C_t \dfrac{u_*}{u(h)}} f_c^2 + kB_s^{-1}(1 - f_c)^2, \qquad (24)$$

where $\langle kB^{-1} \rangle$ refers to an estimate of kB^{-1}.

From Eq. (24), with Eqs. (8), (7), (11), and (13), as

TABLE 8. Input parameters and variables used for energy balance calculations.

Symbol (unit)	Variables and parameters	Cotton data	Shrub data	Grass data
z (m)	Reference (measurement) height	3.0	4.3	4.3
d (m)	Displacement height	0.299	0.281	0.171
z_{0m} (m)	Roughness height for momentum transfer	0.033	0.0487	0.0226
z_{0h} (m)	Roughness height for heat transfer	Variable model estimates	Variable model estimates	Variable model estimates
f_c	Fractional canopy coverage	0.24	0.26	0.44
u (m s^{-1})	Wind speed at reference height	Actual measurements	Actual measurements	Actual measurements
T_0 (°C)	Surface temperature	Actual measurements	Actual measurements	Actual measurements
q (kg kg^{-1})	Specific humidity at reference height	Actual measurements	Actual measurements	Actual measurements
p_a (Pa)	Surface pressure	96 500.0	86 500.0	85 000.0
T_a (°C)	Air temperature at reference height	Actual measurements	Actual measurements	Actual measurements
R_{swd} (W m^{-2})	Downward solar radiation	Actual measurements	Actual measurements	Actual measurements
α	Surface albedo	0.22	0.20	0.15
ε	Surface emissivity	0.970	0.979	0.984

well as the definition of the roughness Reynolds number [given in the text under Eq. (12)], the relevant parameters that influence the value of $\langle kB^{-1}\rangle$ can be seen as

$$\langle kB^{-1}\rangle = F\{u, C_d, C_t, h, z, \mathrm{LAI}, f_c\} \qquad (25)$$

with $F\{\ \}$ indicating a functional relation. The sensitivity of $\langle kB^{-1}\rangle$ to the individual parameters in $F\{\ \}$ can be determined similarly as

$$\Delta\langle kB^{-1}\rangle = \frac{\partial F}{\partial x}\Delta x, \qquad (26)$$

where x is a generic parameter.

In Table 9, the reference parameters used in the sensitivity analysis are given for the cotton data. Except that the total height used here is the height of cotton plant, all other parameters remain the same as in previous calculations. The reason for the change of reference height is the fact that, in Eq. (24), the parameterization of vertical structure of the canopy is removed so that the reference is made to the top of the furrow. Using the simplification as given in Eq. (24), the rmse of H calculated for the cotton data is 27.29 W m^{-2} [cf. rmse = 22.19 W m^{-2} when using Eq. (12)]. This result indicates that the simplification is acceptable when judged by the mean measured H of 116.63 (W m^{-2}).

The actual calculations to obtain the sensitivity values in Table 9 are carried out by using 50% and 150% of the reference values, respectively. The sensitivity of $\langle kB^{-1}\rangle$ to all the parameters, except to the vegetation height, is comparable. The errors in the computed H are bounded by 37% relative to the mean measured H. The sensitivity of H to the vegetation height approaches 46% of the mean measured H. Because the chosen lower and upper values probably cover the extreme situations for the parameters needed, it can be concluded that the Massman's (1999a) kB^{-1} model can be confidently used in bulk transfer formulations of sensible heat flux. In large-scale meteorological models and remote sensing algorithms, in which the parameter estimation is usually difficult, the Massman's (1999a) kB^{-1} model should also provide reliable kB^{-1} values as long as the used parameters are accurate to within 50% of their actual values. Recent progress in large-scale remote sensing of land use and vegetation parameters (e.g., Verhoef 1998; Su 2000) has made estimation of some of the necessary parameters possible over large areas on a pixel scale. Among the parameter set $\{u, C_d, C_t, h, z, \mathrm{LAI}, f_c\}$, LAI and f_c can be determined certainly to much better than 50%. With a detailed land use map, the vegetation height h can also be inferred for each land use class or biome (if information on phenology is available, the accuracy can be improved further). The parameters u and z are determined by actual measurements (or by model settings when applied in combination with meteorological models). Their accuracy should be reliable in general. Only the parameters C_d and C_t are truly literature values.

TABLE 9. Sensitivity of the computed sensible heat flux to input parameters in calculating kB^{-1} values using Massman's (1999a) model, evaluated on basis of the cotton data (rmse: root-mean-square error is shown; for the reference values used, rmse = 27.29 W m^{-2}).

Symbol (unit)	Variables and parameters	Rmse (W m^{-2}) (result from using 50% of a reference value)	Reference value	Rmse (W m^{-2}) (result from using 150% of a reference value)
u (m s^{-1})	Wind speed at reference height	36.89	Actual measurements	23.46
C_d	Drag coefficient of the foliage	33.28	0.2	24.77
C_t	Heat transfer coefficient of the leaf	24.50	0.01	34.62
h (m)	Total height	24.98	0.32	45.51
z (m)	Reference (measurement) height	25.90	3.0	28.09
LAI	Leaf area index per total area	22.83	0.4	31.65
f_c	Fractional foliage coverage	29.15	0.24	23.91

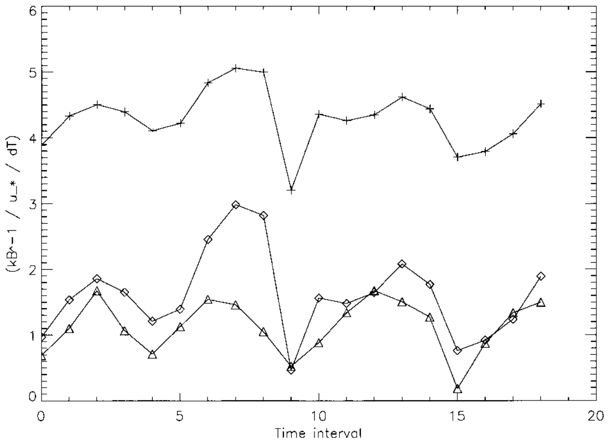

FIG. 7. Calculated kB^{-1} (+) for four days (DOY 162–165). The diurnal variation kB^{-1} values is clearly shown. The variables u_*/0.1 (m s^{-1}; ◇) and $(\theta_0 - \theta_a)$/10.0. (K; △) are also plotted (the scaling factors are chosen to facilitate the comparison of the three displayed quantities).

From the above sensitivity analysis, these literature values are shown to be adequate. Nevertheless, if these parameters can be calculated directly from other measurements, the accuracy of the computed H can be improved further.

e. Diurnal variation of kB^{-1} values and kB^{-1} values at limiting cases

1) DIURNAL VARIATION OF kB^{-1} VALUES

As indicated in the introduction section, none of the formulas evaluated by Verhoef et al. (1997) was able to describe the observed diurnal variation in kB^{-1}. We shall give such an explanation using the Massman's (1999a) kB^{-1} model. Further, this model will be shown to be applicable to all conditions from permeable–rough (dense vegetation) to bluff–rough (bare soil).

Figure 7 shows the plot of the calculated kB^{-1} for four days (DOY 162–165). The diurnal variation of kB^{-1} values is clearly shown. To determine what causes such a diurnal variation, the variables u_* and $(\theta_0 - \theta_a)$ are also plotted on the same figure. By comparing the correspondence between the three curves, it can be concluded that the diurnal variation of kB^{-1} is primarily caused by the diurnal variation in wind speed expressed here by u_* (which also includes the influence of d and z_{0m} and the stability of the atmosphere, described by Ψ_m). This variation clearly can be explained in terms of forced convection in which the resistance for heat transfer is usually smaller than that for momentum transfer (i.e., heat transfer is more efficient under forced convection or the surface cools quicker).

2) PREDICTION OF kB^{-1} VALUES AT LIMITING CASES

In this section, we will investigate if the Massman's (1999a) kB^{-1} model can be used to predict kB^{-1} values at limiting cases for canopy only and for bare soil only. For canopy only, $f_c = 1.0$, Eq. (12) retains only the first term. For the dense Douglas fir forest reported by Bosveld (1999), using values $f_c = 1.0$, LAI = 10, $u_* = 0.5$–1.0 m s^{-1}, we arrive at an estimate of kB^{-1} = about 0.667 for $C_t = 0.15$ (here we assume that the forest leaves/needles have higher heat transfer coefficient than the low vegetation to keep their temperature close to air temperature with limited transpiration). This predicted value is higher but not significantly higher than the one estimated from the experimental data (close to zero). It is unfortunate that the heat transfer coefficient of the leaves/needles was not reported in Bosveld (1999) so that no further analysis can be performed. From the definition given in Eq. (4) using the Stanton number, negative values of kB^{-1} are not permitted, so experimental results of negative values of kB^{-1} may well be caused by errors in the various measured variables used to derive the kB^{-1} values. On the other hand, the definition given in Eq. (4) is just a simple parameterization of a very complex physical process. For canopies with complicated structures, this may be an oversimplification.

For bare soil only, Eq. (12) reduces to Eq. (13), which has been shown to be able to predict the kB^{-1} values for a smooth bare soil surface by Verhoef et al. (1997). Similarly, negative values of kB^{-1} are also not permitted for bare soil, because the original equation of Brutsaert (1982) was derived for roughness surface under non-wind-still condition (requiring $u_* > 0.000\,755$). This again suggests that experimental results of negative values of kB^{-1} for the bare soil reported by Verhoef et al. (1997) may also be caused by errors in the various measured variables used to derive the kB^{-1} values. It may be claimed that without direct measurements of the values of kB^{-1}, the controversy around the kB^{-1} values is not likely to be settled easily. Nevertheless, it is desirable to validate the current model for both dense high vegetation and bare soils using independent datasets.

6. Conclusions

A simple physically based model is derived for the estimation of the roughness height for heat transfer between the land surface and the atmosphere. This model is derived from a complex physical model of Massman (1999a) based on the localized near-field Lagrangian theory. This model (called Massman's model) and another recently proposed model derived by fitting simulation results of a simple multisource bulk transfer model (Blümel 1999) are evaluated using three experimental datasets. The results of the model performances are judged by using the derived roughness values to compute sensible heat fluxes with the bulk transfer formulation and comparing these computed fluxes to the observed sensible heat fluxes. It is concluded, on the basis of comparison of calculated versus observed sensible heat fluxes, that both the current model and Blümel's model provide reliable estimates of the roughness heights for heat transfer for the cotton data and shrub data. For the grass data, the statistics in the estimated sensible heat fluxes are more favorable when using the Massman's (1999a) kB^{-1} model than when using the Blümel's (1999) kB^{-1} model.

The main difference between the two models is that Massman's (1999a) Lagrangian approach uses microscale physics and scales from the microscale to the bulk scale, whereas Blümel's (1999) kB^{-1} model uses a bulk approach to scale the soil and plant boundary layer resistances. As such, the Massman's (1999a) model may provide some explicit physical explanations for observed phenomena. One such application is to explain the diurnal variation in the roughness height for heat transfer in terms of forced convection.

A thorough sensitivity analysis has been performed for the Massman's (1999a) kB^{-1} model. Using parameters values corresponding to 50% and 150% of the reference values, respectively, the errors in the computed H are bounded by 37% relative to the mean measured H for all parameters but the vegetation height, the error of which approaches 46% of the mean measured H. Because the chosen lower and upper values probably cover the extreme situations for the parameters needed, it is suggested that, although demanding, most of the information needed for the current model and Blümel's (1999) model is amendable by satellite remote sensing such that their global incorporation into large-scale atmospheric models for both numerical weather prediction and climate research merits further investigation. For regional applications, the likely uncertainty in the vegetation height information will be significant, but a detailed land use classification combined with phenological data may act as a surrogate.

In addition, simple parameterizations are proposed to estimate the net radiation, soil heat flux, and latent heat flux by means of an energy balance consideration after the sensible heat flux is estimated as described above. From the comparisons with measurements, we conclude that the current simple parameterizations for net radiation and soil heat flux are adequate. The comparisons also indicate that when the currently evaluated kB^{-1} models are used to estimate the sensible heat flux, the latent heat flux can then be derived from simple energy balance consideration, which eliminates the need to parameterize the canopy stomatal resistance in direct evaluation of the latent heat flux.

Since the evaluated parameters are needed in models for heat transfer estimations, it can be expected that integration of the Massman's (1999a) kB^{-1} model and the Blümel's (1999) model will improve the model estimations of sensible heat flux, as shown by the sensitivity analysis. This should be especially true for models of energy and mass transfer between the land surface and the atmosphere designed for numerical weather prediction or for climate studies, given that the current practice in these models is to prescribe the kB^{-1} values empirically. By incorporating these kB^{-1} models, meteorological models will be able to take advantage of the remotely sensed surface temperature directly. This can be done either by evaluating model prognostic surface temperature or by updating other model prognostic variables using the surface temperatures.

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