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Two-source energy balance model estimates of evapotranspiration using component and composite surface temperatures ☆

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ABSTRACT

The two source energy balance model (TSEB) can estimate evaporation (*E*), transpiration (*T*), and evapotranspiration (*ET*) of vegetated surfaces, which has important applications in water resources management for irrigated crops. The TSEB requires soil (T_S) and canopy (T_C) surface temperatures to solve the energy budgets of these layers separately. Operationally, usually only composite surface temperature (T_R) measurements are available at a single view angle. For surfaces with nonrandom spatial distribution of vegetation such as row crops, T_R often includes both soil and vegetation, which may have vastly different temperatures. Therefore, T_S and T_C must be derived from a single T_R measurement using simple linear mixing, where an initial estimate of T_C is calculated, and the temperature – resistance network is solved iteratively until energy balance closure is reached. Two versions of the TSEB were evaluated, where a single T_R measurement was used (TSEB-T_R) and separate measurements of T_S and T_C were used (TSEB-T_C–T_S). All surface temperatures (T_S, T_C, and T_R) were measured by stationary infrared thermometers that viewed an irrigated cotton (*Gossypium hirsutum L.*) crop. The TSEB-T_R version used a Penman–Monteith approximation for T_C, rather than the Priestley-Taylor-based formulation used in the original TSEB version, because this has been found to result in more accurate partitioning of E and T under conditions of strong advection. Calculations of *E*, *T*, and *ET* by both model versions were compared with measurements using microlysimeters, sap flow gauges, and large monolythic weighing lysimeters, respectively. The TSEB-T_R version resulted in similar overall agreement with the TSEB-T_C–T_S version for calculated and measured *E* (*RMSE* = 0.7 mm d^{-1}) and better overall agreement for *T* (*RMSE* = 0.9 vs. 1.9 mm d^{-1}), and *ET* (*RMSE* = 0.6 vs. 1.1 mm d^{-1}). The TSEB-T_C–T_S version calculated daily *ET* up to 1.6 mm d^{-1} (15%) less early in the season and up to 2.0 mm d^{-1} (44%) greater later in the season compared with lysimeter measurements. The TSEB-T_R also calculated larger *ET* later in the season but only up to 1.4 mm d^{-1} (20%). *ET* underestimates by the TSEB-T_C–T_S version may have been related to limitations in measuring T_C early in the season when the canopy was sparse. *ET* overestimates later in the season by both versions may have been related to a greater proportion of non-transpiring canopy elements (flowers, bolls, and senesced leaves) being out of the T_C and T_R measurement view.

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1. Introduction

Quantification and management of evapotranspiration (*ET*) and its components, evaporation (*E*) and transpiration (*T*), are some of several strategies being sought to increase crop water use efficiency (*WUE*, defined as economic yield per unit water used). In most cropping systems, *E* is considered a loss because it does not contribute directly to biomass or yield production, but it may contribute to crop production indirectly if it can reduce *T* by modifying the microclimate of the crop canopy [1]. Although *E* may originate from either the soil or canopy surfaces (where the latter is from intercepted rain or irrigation water evaporating from the plant and not taken up by roots), the water storage capacity of the soil top layer (where *E* occurs) is usually much greater compared with

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the canopy, hence most E is considered to be from the soil. Therefore, considerable emphasis has been placed on investigating crop management strategies thought to influence soil E; examples include residue management [2,3], crop row orientation, row spacing, plant spacing and population [4–6] and irrigation system comparison [7]. A number of studies have investigated the energy balance of the soil and canopy of row crops, which included measurements of E (e.g. [2,3,8]) and T (e.g. [1,6,9–12]) in addition to estimates to estimate ET. However, separate measurements of E and T entail much greater difficulty compared with ET ([13], 2012). Consequently, the impact of various management strategies on E and T, and their partitioning in total ET, must often be inferred. This has limited the understanding of the physical processes involved, and has also likely limited our ability to exploit methods to increase WUE [14]. Even if E and T measurements were routinely available, it is well recognized that accurate simulation models are needed to supplement experimentation. Hence simulation models that calculate E, T, and ET, while not a substitute for field measurements, will have increasing impacts in finding practical ways to reduce E and increase WUE.

Calculations of E, T, and ET commonly use the gradient – resistance principle to model the energy exchange of the soil–plant-atmosphere continuum, such as described by Shuttleworth and Wallace [15] and Shuttleworth and Gurney [16]. Several studies have applied the Shuttleworth and Wallace [15] approach to model the soil and canopy energy budgets separately (e.g. [8,12,21,22]); however, these often used detailed measurements of micrometeorological variables in the soil, canopy, and boundary layer space, which are not routinely available. Since radiometric surface temperature (T_R) can be measured over areas at various spatial scales noninvasively, T_R can be used as a convenient driver for remote sensing-based surface energy balance models where temperature is the primary gradient [17–19]. Most annual crops will contain partial canopy cover during the early part of the growing season, and possibly throughout the season. Therefore, T_R is often a composite of canopy (T_C) and soil (T_S) component temperatures, especially for dryland or deficit-irrigated crops in non-humid regions where water is limited. Separate measurements of T_C and T_S are seldom available in practice. Although it may be possible to extract T_C and T_S from multiple view angles of T_R [20], Chehbouni et al. [21] and Merlin and Chehbouni [22] showed that T_C and T_S retrievals are sensitive to errors in T_R measurements, and more importantly, T_R is usually available at only one view angle.

Norman et al. [23] described a two-source energy balance (TSEB) model (i.e., two-layer soil+canopy) where sensible (H) and latent heat flux (LE) for both the soil and canopy sources can be calculated separately using a single measurement of T_R (i.e., one view angle), meteorological variables normally used to calculate ET (air temperature, vapor pressure deficit, wind speed, and solar irradiance), and ancillary information about the vegetation that is either readily available or can be reasonably estimated for common crops (leaf area index, crop height, row spacing, etc.). The T_R, T_C, and T_S components are assumed related by simple linear mixing based on the Stephan–Boltzmann relationship between radiation and temperature:

$$T_R^4 = f_{VR}T_C^4 + (1 - f_{VR})T_S^4 \tag{1}$$

where f_{VR} is the fraction of vegetation appearing in the radiometer field of view (i.e., the vegetation view factor). With T_R measured, an initial calculation of T_C is made assuming non-water-stressed conditions, T_S is calculated using Eq. (1), and the energy balance of the soil and canopy is calculated. If the calculated (non-water-stressed) T_C does not result in a plausible energy balance closure (e.g., resulting in condensation on the soil during the daytime), T_C, T_S, and resistances are recalculated until a realistic energy balance is obtained; additional details are contained in the forthcoming section.

The Norman et al. [23] TSEB approach generally does not require any additional information beyond that required for simpler (single layer) energy balance models and can use a single measurement of T_R. Consequently, it and subsequent refinements [24–26] have been found practical for estimating surface energy fluxes for a wide variety of vegetation, vegetation cover, climates, and spatial scales where T_R was obtained from ground-based, airborne, and satellite instruments. Studies included grass and desert shrubs near Tombstone, Arizona [23]; prairie grass near Manhattan, Kansas [23]; irrigated cotton near Maricopa, Arizona [23,27,28]; rangeland, pasture, and bare soil near El Reno, Oklahoma [29]; riparian zone along the Rio Grande in the Bosque Del Apache National Wildlife Refuge in Central New Mexico [29]; corn (*Zea mays* L.), soybean (*Glycine max* L.), and bare soil near Ames, Iowa [25,30]; and irrigated spring wheat (*Triticum aestivum L.*) near Maricopa, Arizona [31]. In addition, several studies compared the TSEB with single-layer or vegetation index – temperature approaches, with the TSEB generally giving the best agreement with H and LE estimates [32–35]. Most of these studies evaluated the TSEB model in terms of total (soil+canopy) H, LE, or ET, where calculated variables were compared to measurements using Bowen ratio, eddy covariance, or meteorological flux tower techniques. However, French et al. [31] derived ET from neutron probe measurements and a soil water balance, and Tang et al. [35] used large aperture scintillometers for independent estimates of turbulent fluxes.

Because of the paucity of separate E and T measurements, relatively few studies have considered how well the TSEB partitions these components, which may be prone to greater error compared with total LE or ET [24,36]. Furthermore, relatively few studies included separate measurements of T_C and T_S, which would allow more direct calculation of E and T without using the assumptions associated with Eq. (1) (described in more detail shortly), and which are otherwise used if only a single T_R measurement is available. Sánchez et al. [37] tested a simplified version of the TSEB that used separate measurements of T_C and T_S for corn over a wide range of canopy cover; however, only flux tower estimates of total (soil+canopy) H and LE were available for that study. With accurate calculations of E and T urgently needed to evaluate techniques that impact WUE, a pertinent question is whether separate measurements of T_C and T_S would be advantageous over T_R, and if greater efforts should be directed accordingly.

In addition to the need to consider separate measurements of E, T, T_S, and T_C, relatively few studies have compared ET calculated by the TSEB to ET measured by monolythic weighing lysimeters, or at locations having strong regional advection, such as the US Southern High Plains. Weighing lysimeters are presently the most accurate method to measure ET, and can be automated to provide nearly continuous measurements [38,39]. Although the Bowen ratio and eddy covariance measurement techniques have been widely used to evaluate the TSEB for their relative ease of deployment, they are known to suffer from measurement issues and assumptions, particularly when advection is present [40–42]. The neutron probe has been shown to be the most accurate method to measure soil water throughout the profile [43], and can estimate crop water use by calculating the soil water balance ([44], 2012). However, the neutron probe cannot be operated unattended because it is a radioactive device, and so cannot feasibly provide ET over hourly or shorter intervals or on larger spatial scales easily. Furthermore, the soil water balance may be subject to some uncertainty if deep percolation or runoff occur, but these can be minimized with irrigation management ([44], 2012).

The objectives of this paper are to compare measurements of E, T, and ET with those calculated by the TSEB using (1) a single view angle measurement of T_R (termed the TSEB-T_R model version), and

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