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Applications of a thermal-based two-source energy balance model using Priestley-Taylor approach for surface temperature partitioning under advective conditions

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In this study ground measured soil and vegetation component temperatures and composite temperature from a high spatial resolution thermal camera and a network of thermal-IR sensors collected in an irrigated maize field and in an irrigated cotton field are used to assess and refine the component temperature partitioning approach in the Two-Source Energy Balance (TSEB) model. A refinement to TSEB using a non-iterative approach based on the application of the Priestley-Taylor formulation for surface temperature partitioning and estimating soil evaporation from soil moisture observations under advective conditions (TSEB-A) was developed. This modified TSEB formulation improved the agreement between observed and modeled soil and vegetation temperatures. In addition, the TSEB-A model output of evapotranspiration (*ET*) and the components evaporation (*E*), transpiration (*T*) when compared to ground observations using the stable isotopic method and eddy covariance (*EC*) technique from the HiWATER experiment and with microlysimeters and a large monolithic weighing lysimeter from the BEAREX08 experiment showed good agreement. Difference between the modeled and measured *ET* measurements were less than 10% and 20% on a daytime basis for HiWATER and BEAREX08 data sets, respectively. The TSEB-A model was found to accurately reproduce the temporal dynamics of *E*, *T* and *ET* over a full growing season under the advective conditions existing for these irrigated crops located in arid/semi-arid climates. With satellite data this TSEB-A modeling framework could potentially be used as a tool for improving water use efficiency and conservation practices in water limited regions. However, TSEB-A requires soil moisture information which is not currently available routinely from satellite at the field scale.

1. Introduction

Evapotranspiration (*ET*) and its partitioning between evaporation (*E*) and transpiration (*T*) is a significant component of the water and energy cycle at all scales, from field and watershed to regional and global, and is essential to many applications in climate, weather, hydrology, and ecology (Seneviratne et al., 2010). Research suggests that *T* is likely to account for about 65% of continental *ET* (including rainfall interception by the vegetation) (Good et al., 2015; Zhang et al., 2016), in order to maintain a mass balance between plant transpiration and CO_2 uptake (Jasechko et al., 2013). In irrigated agriculture, quantification and management of *ET* and its components, *E* and *T*, is essential for reliable irrigation scheduling, quantifying recharge and drainage, and yield forecasting (Zhu et al., 2014). However, validation of models computing relative contributions of *E* and *T* is rare owing to the difficulties in measuring *E* and *T* even at the field scale (Agam et al., 2012; Colaizzi et al., 2012a; Jasechko et al., 2013).

Norman et al. (1995) and Kustas and Norman (1999) developed a two-source energy balance model (TSEB) using land surface

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temperature as a key boundary condition for computing reliable daytime sensible and latent heat fluxes of the soil and canopy elements for partially-vegetated land surfaces. In the original TSEB formulation of Norman et al. (1995), both a series resistance and a parallel resistance approach were derived. However the series resistance approach is often used instead of the parallel approach, since the former allows for interaction between the soil and the canopy and is generally found to be more robust (Song et al., 2015).

In the TSEB scheme, the canopy transpiration component of the latent heat flux is approximated using the modified form of the Priestley-Taylor approach. This is motivated by its simplicity for large scale operational applications and the apparent robustness of its prediction. Then combining a simple linear unmixing method based on the Stefan–Boltzmann law between the emitted blackbody radiation and temperature, the canopy and soil component temperatures are separated from the composite radiometric temperature observation. Finally, the latent heat fluxes from soil and canopy elements are derived using the flux-gradient analogy to Ohm's law and energy conservation principles for the soil-plant-atmosphere continuum.

The TSEB model and its revisions have been integrated into a regional modeling system for computing surface energy fluxes operationally over a wide variety of vegetation, and climates using satellite data (Anderson et al., 2011). In the TSEB scheme, the Priestley-Taylor coefficient α_{PT} for the vegetated canopy is normally set to an initial value of $\alpha_{PT} \sim 1.26$, but is incrementally reduced to account for water-limited conditions. Briefly, when negative soil evaporation results, then the α_{PT} value is reduced and fluxes and temperatures are recomputed in an iterative procedure until a soil latent heat flux value greater than zero is computed (Anderson et al., 2012; Kustas et al., 2012). However, increasing α_{PT} under well-watered advective conditions cannot be done iteratively based on model solutions for the soil and canopy latent heat (*LE*) fluxes or temperatures (Kustas and Norman, 1999; Agam et al., 2010) and so there is no direct way of accounting for strongly advective conditions *a priori* with this type of formulation. Even without advection, semiarid and arid climates typically have large diurnal variation in vapor pressure deficit, which is not accounted for using a constant α_{PT} value (Long and Singh, 2012). This may result in *T* being underestimated, forcing E/ET to be overestimated, because initial estimates of canopy and soil temperature are over- and underestimated, respectively. Colaizzi et al. (2012a, 2014) showed that this could be mitigated by replacing the Priestley-Taylor with the Penman-Monteith formulation in TSEB. However, the Penman-Monteith formulation requires accurate humidity measurements (to calculate vapor pressure deficit), which are not always available at large scales or where vegetation is heterogeneous. Consequently, more comprehensive validation studies of soil and vegetation temperatures and *E* and *T* are needed at the field scale in order to assess current and any future refinements to the TSEB formulations.

How accurately the current version of TSEB model partitions *E* and *T* from *ET* under different environmental conditions requires validation with ground measurements of *E* and/or *T*, while the paucity of datasets having component fluxes and temperature measurements hinders the assessment of TSEB for *ET* partitioning (Song et al., 2015, 2016; Yang et al., 2013a, 2015). The errors in *E* and *T* may be compensating so that discrepancies in the total *LE* or *ET* are minor in comparison (Colaizzi et al., 2012a). A few studies have estimated *T* from sap-flow measurements (Wu et al., 2006); however, this method can only provide daily transpiration estimates (Yang et al., 2013b) and measurements are limited to the scale of individual plants, which imposes limitations in upscaling to the field level because spatial variability is likely in vegetation and soil conditions. *E* can be measured using microlysimeters where the average weight losses are directly proportional to evaporation (Colaizzi et al., 2012a; Song et al., 2015).

Another approach, a novel flux partitioning approach, that requires only standard eddy covariance instrumentation and relies upon a limited number of assumptions for its theoretical development has been proposed (the correlation-based partitioning approach: (Scanlon and Kustas, 2010, 2012)). However, independent *E* and *T* measurements are needed in concert with the eddy covariance measurements to rigorously validate this method.

Recently, based on the theory of that *E* from soil and *T* from plants each contribute unique isotopic signals to water vapor within the ecosystem boundary layer (Williams et al., 2004), some studies have partitioned *E* and *T* by measurements of the isotopic composition of oxygen in soil, plants and atmospheric water vapor (Kool et al., 2014). This method has been implemented successfully not only at canopy scale but also at catchment scale (Hu et al., 2014; Jasechko et al., 2013; Williams et al., 2004; Zhang et al., 2011). However it also has limitations, such as uncertainty in the measurement of the isotopic signals of *ET*, *T* and *E*, which can produce a ten-fold level of uncertainty in *T*/*ET* values (Hu et al., 2014; Wen et al., 2016).

The objective of this study is to modify the TSEB model to account for the advection without tuning Priestley-Taylor parameter for partitioning soil and vegetation temperatures from a composite radiometric surface temperature, to estimate *ET* and its partitioning *E* and *T* under significant advective conditions. This modified TSEB model for advective conditions (TSEB-A) avoids the need to adjust α_{PT} parameter for the canopy elements under high vapor pressure deficit (VPD) conditions, but where sufficient available water is present in the soil profile. We hypothesize that this approach may also reduce the errors in estimating canopy and soil temperatures, and consequently estimates of *E* and *T*.

2. Methodology

2.1. Two-source energy balance model (TSEB)

The TSEB modeling scheme originally proposed by Norman et al. (1995) has undergone several revisions, improving the radiation partitioning between the soil and canopy (Colaizzi et al., 2012a, 2012b), the soil surface aerodynamic resistance to heat transport, the effect of vegetation clumping on resistances and radiation divergence (Kustas and Norman, 1999), or the replacement of Priestley-Taylor with the Penman-Monteith formulation (if humidity measurements are available) (Colaizzi et al., 2014). The TSEB model partitions the composite surface radiometric temperature, measured by a sensor viewing at an angle θ, into soil and canopy component temperatures, T_s and T_c, based on the fraction of vegetation cover $f_c(\theta)$ observed by the sensor, using the Stefan-Boltzmann law, which relates a blackbody temperature to radiance emission (Kustas and Norman, 1999; Norman et al., 1995). Then the derived T_s and T_c are used to calculate the surface energy balance for the soil and canopy components of the composite land-surface system (Kustas et al., 2012).

The soil and vegetation net radiation R_{ns} and R_{nc}, respectively, are estimated using the method proposed by Kustas and Norman (1999). Their formulations are as follows:

$$Rn_s = \tau_{longwave} L_{\downarrow} + (1-\tau_{longwave})\varepsilon_c \sigma T_c^4 - \varepsilon_s \sigma T_s^4 + \tau_{solar}(1-a_s)S_{\downarrow} \tag{1}$$

$$Rn_c = (1-\tau_{longwave})(L_{\downarrow} + \varepsilon_s \sigma T_s^4 - 2\varepsilon_c \sigma T_c^4) + (1-\tau_{solar})(1-a_c)S_{\downarrow}. \tag{2}$$

where $S_{\downarrow}$ and $L_{\downarrow}$ are the incoming shortwave and longwave radiation from the sky, respectively, in W m^{-2}; a_s and a_c are the soil and vegetation albedo, respectively. Furthermore, $\tau_{longwave}$ and τ_{solar} are the longwave and shortwave radiation transmittances through the