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Evaluating the two-source energy balance model using local thermal and surface flux observations in a strongly advective irrigated agricultural area

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ABSTRACT

Application and validation of many thermal remote sensing-based energy balance models involve the use of local meteorological inputs of incoming solar radiation, wind speed and air temperature as well as accurate land surface temperature (LST), vegetation cover and surface flux measurements. For operational applications at large scales, such local information is not routinely available. In addition, the uncertainty in LST estimates can be several degrees due to sensor calibration issues, atmospheric effects and spatial variations in surface emissivity. Time differencing techniques using multi-temporal thermal remote sensing observations have been developed to reduce errors associated with deriving the surface-air temperature gradient, particularly in complex landscapes. The Dual-Temperature-Difference (DTD) method addresses these issues by utilizing the Two-Source Energy Balance (TSEB) model of Norman et al. (1995) [1], and is a relatively simple scheme requiring meteorological input from standard synoptic weather station networks or mesoscale modeling. A comparison of the TSEB and DTD schemes is performed using LST and flux observations from eddy covariance (EC) flux towers and large weighing lysimeters (LYs) in irrigated cotton fields collected during BEAREX08, a large-scale field experiment conducted in the semi-arid climate of the Texas High Plains as described by Evett et al. (2012) [2]. Model output of the energy fluxes (i.e., net radiation, soil heat flux, sensible and latent heat flux) generated with DTD and TSEB using local and remote meteorological observations are compared with EC and LY observations. The DTD method is found to be significantly more robust in flux estimation compared to the TSEB using the remote meteorological observations. However, discrepancies between model and measured fluxes are also found to be significantly affected by the local inputs of LST and vegetation cover and the representativeness of the remote sensing observations with the local flux measurement footprint.

1. Introduction

The energy balance at the land surface, and in particular the partitioning of the available energy ($R_N - G$) into sensible (H) and latent heat flux (LE), significantly affects important hydrologic and atmospheric processes and is a key indicator of the surface moisture status. For irrigated agriculture, the latent heat flux (or evapotranspiration (ET) when expressed as rate of water loss) is tied to crop water requirements, irrigation applications, and vegetation stress. Land surface temperature (LST) is a fundamental surface state variable that is strongly coupled to the surface energy balance and ET [3]. For this reason, studies have evaluated the utility of LST as a key boundary condition and metric for modeling water use and availability, which is tied to plant growth and carbon assimilation (e.g., [4]). Consequently, LST provides a means for monitoring crop water use, stress and ultimately yield (e.g., [5,6]). Kalma et al. [7] review land surface schemes of varying degrees of complexity that involve the use of LST for estimating the surface energy balance and the relative partitioning of the available energy ($R_N - G$) at the land surface between H and LE.

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While LST is a useful controlling variable in energy balance modeling, uncertainties in accounting for variations in thermal emissivity, atmospheric corrections, radiometer viewing angle, and sensor calibration can significantly degrade the accuracy of LST retrievals from remotely sensed brightness temperatures [8]. Another complicating factor is the need for specifying surface layer atmospheric properties (principally wind speed and air temperature) over the modeled landscape. Errors in LST and meteorological boundary conditions can render many approaches that rely on surface-air temperature differences to be rather tenuous when applied to heterogeneous landscape conditions [9].

Anderson et al. [10] describes remote sensing techniques that have been developed which attempt to minimize the impacts of many of the uncertainties in LST and meteorological forcing variables. One approach uses maximum and minimum LST from remotely sensed temperatures along with energy balance constraints to define model variables. Another methodology uses time-differencing techniques to reduce the sensitivity to the requirement of an absolute LST-air temperature difference. A simplified form of a temperature-differencing approach, called the Dual-Temperature-Difference (DTD) scheme, was developed for routine applications using continuous ground-based or geostationary satellite observations of LST [11,12]. The land-surface scheme in the DTD is based on the Two-Source Energy Balance (TSEB) model framework of Norman et al. [1], which accounts for the main physical factors causing differences between aerodynamic temperature and radiometric LST [13].

For irrigated croplands in strongly advective environments, there are likely to be significant variations in near surface/screen level (~2 m) atmospheric properties used as upper boundary conditions in model implementations. As a result, direct applications of a land-surface model like TSEB at large scales are questionable in the absence of a relatively dense network of weather station observations. The DTD, however, is less sensitive to errors in air temperature boundary conditions, and may be more accurate for regional applications. In this study, the relative utility of the TSEB and DTD formulations were evaluated using local LST observations from several locations within an irrigated cotton field collected during the 2008 Bushland Evapotranspiration and Agricultural Remote sensing EXperiment (BEAREX-08) at the USDA-ARS Conservation and Production Research Laboratory at Bushland, Texas. Both local meteorological observations collected within the field site and remote observations obtained from the regional airport in Amarillo, TX approximately 35 km from the BEAREX08 study site were used in the TSEB and DTD model computations to assess sensitivity to input errors. Model surface flux output, using both local and remote inputs, is compared to eddy covariance and lysimeter measurements collected during BEAREX08.

This study also looks in detail at the importance of using LST and vegetation inputs that are spatially consistent with the surface footprint sampled by the flux instrumentation used for model evaluation. Proper selection of model inputs in relationship to the validation dataset is essential for isolating model errors from input errors over strongly heterogeneous landscapes. An example is provided for a case where model-measurement differences are exacerbated due to a mismatch in remotely-sensed surface boundary conditions and source area contributing to the flux measurement for a strongly advective environment.

2. Model overview

2.1. Two-source energy balance (TSEB) model formulation

The TSEB scheme originally proposed by Norman et al. [1] has gone through several revisions, improving the representation of shortwave and longwave radiation exchange within the soil-canopy system as well as soil-canopy interactions [14,15–17]. In TSEB, the satellite-derived directional radiometric surface radiometric temperature at viewing angle ϕ, $T_R(\phi)$, is considered to be a composite of the soil surface and canopy temperatures, expressed as:

$$T_R(\phi) \approx [f_C(\phi)T_C^4 + (1 - f_C(\phi))T_S^4]^{1/4} \quad (1)$$

where T_C is canopy temperature, T_S is soil surface temperature, and $f_C(\phi)$ is the fractional vegetation cover observed at the radiometer view angle ϕ. For a canopy with a spherical leaf angle distribution and leaf area index LAI, $f_C(\phi)$ can be expressed as

$$f_C(\phi) = 1 - \exp\left(\frac{-0.5\Omega LAI}{\cos\phi}\right) \quad (2)$$

where the factor Ω indicates the degree to which vegetation is clumped, as in row crops or sparse shrubland canopies [14,17]. Recent modifications for computing Ω for row crops suggested by Anderson et al. [18] and Colaizzi et al. [19] were used in this study and yielded Ω values ranging from 0.5 to 0.9 as the canopy fractional cover and LAI varied over the study period. The T_C and T_S are used to compute the surface energy balance for the canopy and soil components of the composite land-surface system:

$$R_{NS} = H_S + LE_S + G \quad (3)$$

$$R_{NC} = H_C + LE_C \quad (4)$$

where R_{NS} is net radiation at the soil surface and R_{NC} is net radiation divergence in the vegetated canopy layer, H_C and H_S are the canopy and soil sensible heat fluxes, respectively, LE_C is the canopy transpiration rate, LE_S is soil evaporation, and G is the soil heat flux.

By permitting the soil and vegetated canopy fluxes to interact with each other, Norman et al. [1] derived expressions for H_C and H_S as a function of temperature differences, with:

$$H_C = \rho C_P \frac{T_C - T_{AC}}{R_X} \quad (5)$$

and

$$H_S = \rho C_P \frac{T_S - T_{AC}}{R_S} \quad (6)$$

so that the total sensible heat flux, $H = H_C + H_S$, is equal to

$$H = \rho C_P \frac{T_{AC} - T_A}{R_A} \quad (7)$$

where ρ is the density of air (kg m^{-3}), C_P is the specific heat of air (~1000 J kg^{-1} K^{-1}), T_{AC} is an air temperature in the canopy air layer (°C) closely related to the aerodynamic temperature, R_X is the total boundary layer resistance (s m^{-1}) of the complete canopy of leaves, R_S is the resistance (s m^{-1}) to sensible heat exchange from the soil surface, and R_A is aerodynamic resistance (s m^{-1}). Resistance terms are defined in Norman et al. [1] with recent revisions described in Kustas and Norman [14–17]. Weighting of the heat flux contributions from the canopy and soil components is performed indirectly by the partitioning of the net radiation between soil and canopy and via the impact on resistance terms by the fractional amount and type of canopy cover [see 15]. The resistances R_X and R_S effectively account for the excess resistance parameterizations in one-source energy balance (OSEB) modeling approaches where this additional resistance is introduced typically *ad-hoc* in OSEB formulations to account for the less efficient transport of heat relative to momentum transport near the surface elements [3]. With resistance formulations for heat transfer from the soil and canopy elements, this results in a more realistic representation of the soil and vegetation influence on the rate of (or resistance to) turbulent heat exchange with the overlying atmosphere and a physically-based means of relating soil and canopy temperatures to the radiometric surface