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Application of remote sensing-based two-source energy balance model for mapping field surface fluxes with composite and component surface temperatures

Lisheng Song[a,b], Shaomin Liu[a,*], William P. Kustas[b,**], Ji Zhou[c], Ziwei Xu[a], Ting Xia[d,b], Mingsong Li[c]

[a] State Key Laboratory of Remote Sensing Science, School of Geography, Beijing Normal University, Beijing 100875, China
[b] U.S. Department of Agricultural, Agricultural Research Service, Hydrology and Remote Sensing Lab, Beltsville, MD 20705, USA
[c] School of Resources and Environment, University of Electronic Science and Technology of China, Chengdu 611731, China
[d] Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China

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ABSTRACT

Operational application of a remote sensing-based two source energy balance model (TSEB) to estimate evaportranspiration (*ET*) and the components evaporation (*E*), transpiration (*T*) at a range of space and time scales is very useful for managing water resources in arid and semiarid watersheds. The TSEB model uses composite land surface temperature as input and applies a simplified Priestley–Taylor formulation to partition this temperature into soil and vegetation component temperatures and then computes subsequent component energy fluxes. The remote sensing-based TSEB model using component temperatures of the soil and canopy has not been adequately evaluated due to a dearth of reliable observations. In this study, soil and vegetation component temperatures partitioned from visible and near infrared and thermal remote sensing data supplied by advanced scanning thermal emission and reflection radiometer (ASTER) are applied as model inputs ($TSEB_{CT}$) to assess and refine the subsequent component energy fluxes estimation in TSEB scheme under heterogeneous land surface conditions in an advective environment. The model outputs including sensible heat flux (*H*), latent heat flux (*LE*), component *LE* from soil and canopy from the $TSEB_{CT}$ and original model ($TSEB_{PT}$) are compared with ground measurements from eddy covariance (EC) and larger aperture scintillometers (LAS) technique, and stable isotopic method. Both model versions yield errors of about 10% with *LE* observations. However, the $TSEB_{CT}$ model output of *H* and *LE* are in closer agreement with the observations and is found to be generally more robust in component flux estimation compared to the $TSEB_{PT}$ using the ASTER data in this heterogeneous advective environment. Thus given accurate soil and canopy temperatures, $TSEB_{CT}$ may provide more reliable estimates of plant water use and values of water use efficiency at large scales for water resource management in arid and semiarid landscapes.

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1. Introduction

Accurate estimates of evapotranspiration (ET) have a wide range of applications in hydrology, climate, weather and crop yield forecasting, drought monitoring, and water resource management. What's more, accurate partitioning of *ET* into evaporation (*E*) and transpiration (*T*), permits the evaluation of how much irrigated water is beneficial to the plants growth compared with non-beneficial water loss from the surface soil (Pereira et al., 2015). Knowledge of this partitioning can foster the development of more efficient irrigation management practices and engineering designs. Ground-based measurements from lysimeters or from eddy covariance flux tower observations can provide representative values of *ET* at field scale and with high frequency eddy covariance data it's partitioning into *E* and *T* under certain environmental conditions (Scanlon and Kustas, 2012). But such local *ET* observations are difficult to scale up to watershed, and regional scales, due to natural variability at the landscape scale of soil properties and vegetation type, as well as hydrometeorological conditions which includes local weather, and soil moisture conditions (Choi et al., 2009).

* Corresponding author. Tel.: +86 10 58802240; fax: +86 10 58805274.
** Corresponding author. Tel.: +1 301 504 8498; fax: +1 301 504 8931.
E-mail addresses: smliu@bnu.edu.cn (S. Liu), Bill.Kustas@ars.usda.gov (W.P. Kustas).

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To address the need for large scale spatially distributed *ET*, several remote sensing based approaches using the satellite-based thermal infrared (TIR) and visible and near infrared (VNIR) imagery have been developed and refined in recent years (Kustas and Anderson, 2009). One set of approaches involve one-source models (OSM) applied in contextual approach with remote sensing imagery to define hydrologic extremes (wet/cool and hot/dry conditions) (Allen et al., 2007; Bastiaanssen et al., 1998; Su, 2002). Compared with the OSM-contextual based approaches, the two-source energy balance model (TSEB) is more physical-based since the parameterizations explicitly treat the radiative temperature and energy exchanges between soil and vegetation, and soil-vegetation-atmosphere interface (Kustas and Norman, 1999; Norman et al., 1995). The TSEB model partitions the composite surface radiometric temperature and energy fluxes into soil and vegetation temperatures and fluxes. It not only can produce more reliable flux estimates than OSM techniques, particularly for heterogeneous surfaces with partial vegetation cover, but also TSEB partitions the fluxes and *ET* in particular into soil (*E*) and vegetation (*T*) components which is useful information for identifying plant stress from changes in *T* than changes in surface moisture affecting only *E* (Kustas and Anderson, 2009).

There have been great advances in the application of thermal infrared remote sensing for using the TSEB model to estimate land surface *ET* and its component of *E* and *T*. However, errors in estimation of land surface temperature and near surface air temperature can significantly degrade the accuracy of the TSEB model which is quite sensitive to uncertainty in surface-air temperature differences. To address this limitation, several time-differencing techniques such as ALEXI (Atmosphere-Land Exchange Inverse) (Anderson et al., 1997), DisALEXI (an ALEXI flux disaggregation approach) (Norman et al., 2003) and DTD (Dual-Temperature Difference) (Norman et al., 2000) models based on the TSEB model framework, have been shown to minimize the impacts of inevitable uncertainties in the land surface and air temperatures (Kustas and Anderson, 2009). The TSEB modeling framework in addition applies the Priestley–Taylor equation with the coefficient α usually assumed to have a value ~1.3 to initially estimate vegetation temperature. There is a iteration procedure to adjust the value of α in cases where estimated $E<0$ under daytime conditions due to an overestimated soil surface temperature indicating plants are likely under water stress and should have an elevated canopy temperature. However, under well watered and in strongly advective conditions where a higher value of α may be more appropriate, this cannot be derived a priori (Kustas and Norman, 1999). Refinements to the TSEB modeling parameterizations such as using Penman–Monteith formulation for estimating the vegetation temperature have been proposed (Colaizzi et al., 2012a), which can provide a more accurate partitioning between soil *E* and canopy *T* than in the original TSEB model, but requiring near-surface vapor pressure and knowledge of stomatal resistance makes it difficult to be applied operationally at large scales using satellite data.

Although the TSEB model and refinements to it have been applied and evaluated under a wide variety of vegetation types, vegetation coverage, climates and spatial scales (Colaizzi et al., 2012a), there have been very few studies that have evaluated the TSEB model using the component soil and vegetation temperatures from the infrared radiometers (Colaizzi et al., 2012a; Sánchez et al., 2008, 2015) and also the partitioned fluxes *E* and *T* (Colaizzi et al., 2012a; Agam et al., 2012). A major reason for the lack of such studies is the difficulty in obtaining reliable soil and vegetation temperatures (accounting for both shaded and sunlit soil and vegetation temperatures) and in measuring *E* and *T* that are representative at the micrometeorological scale (Colaizzi et al., 2012a; Song et al., 2015a).

In this paper, the remote sensing based TSEB model is evaluated with composite and component temperatures as input. The modeled *ET* and its component *E* and *T* are evaluated with tower measurements from the eddy covariance system and the stable oxygen and hydrogen isotopes approach. Additionally, the model output of sensible heat flux was assessed under heterogeneous land surface conditions using Large Aperture Scintillometers (LAS) measurements. In this paper, evaluation of *ET* and *T* and *E* and *H* output from TSEB model is performed during a growing season, in an irrigated semiarid agricultural location, under strongly advective conditions. This provides greater insight into the capability of the TSEB to accurately partition *ET* into its soil and plant canopy contributions under such conditions.

2. Methodology

The key boundary condition for remote sensing based TSEB model is the land surface temperatures (Kustas and Anderson, 2009). The model originally proposed by Norman et al. (1995) has undergone several refinements which include improving net radiation partitioning between soil and canopy elements and soil surface resistance formulation (Colaizzi et al., 2012b, 2012c; Kustas and Norman, 1999, 2000), the reference air temperature estimation at the regional scale(Anderson et al., 1997; Norman et al., 2000; Cammalleri et al., 2012), the temperature partitioning between soil and canopy and use of the Penman–Monteith as opposed to the Priestley–Taylor formulation for *T* (Colaizzi et al., 2012a). In the TSEB model the satellite derived directional surface temperature, $T_R(\theta)$ is related to the soil and vegetation component temperatures, based on the fraction of vegetation cover viewed by the radiometer at viewing angle θ (Kustas and Anderson, 2009), expressed as

$$T_R\left(\theta\right) \approx \left[f_c\left(\theta\right)T_c^4 + \left(1 - f_c\left(\theta\right)\right)T_s^4\right]^{1/4} \quad (1)$$

where T_c and T_s are component temperatures (K) in the pixel, and $f_c(\theta)$ is the fraction of vegetation coverage observed at the view zenith angle (θ) by the thermal sensor. These component temperatures when combined with the available energy for the soil and canopy system compute the relevant turbulent fluxes from the soil and canopy elements (Colaizzi et al., 2012a, 2012b; Kustas and Anderson, 2009):

$$Rn_s = H_s + LE_s + G_0 \quad (2)$$

$$Rn_c = H_c + LE_c \quad (3)$$

$$Rn_s = \tau_{\text{longwave}}L_\downarrow + \left(1 - \tau_{\text{longwave}}\right)\varepsilon_c\sigma T_c^4 - \varepsilon_s\sigma {T_s}^4 + \tau_{\text{solar}}\left(1 - \alpha_s\right)S_\downarrow \quad (4)$$

$$Rn_c = \left(1 - \tau_{\text{longwave}}\right)\left(L_\downarrow + \varepsilon_s\sigma {T_s}^4 - 2\varepsilon_c\sigma T_c^4\right) + \left(1 - \tau_{\text{solar}}\right)\left(1 - \alpha_c\right)S_\downarrow \quad (5)$$

where Rn is net radiation (W m^{-2}), G_0 is surface soil heat flux (W m^{-2}), and H and LE are the sensible and latent heat fluxes (W m^{-2}), ε, α, are the emissivity and albedo, respectively; the subscripts *c* and *s* refer to the canopy and soil, respectively. $S_\downarrow$ and $L_\downarrow$ are the incoming shortwave and longwave radiation (W m^{-2}) from the sky, τ_{longwave} and τ_{solar} are the longwave and shortwave radiation transmittances through the canopy, respectively.

By allowing the interaction between the soil and vegetation fluxes in the soil and vegetation combined system, the series version of TSEB model proposed by Norman et al. (1995) is a more realistic parameterization of the energy exchange between the soil and canopy components. The model expresses H_s and H_c as a

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