An enhanced two-source evapotranspiration model for land (ETEML): Algorithm and evaluation

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ABSTRACT

Satellite remote sensing provides a promising way to estimate regional evapotranspiration (ET) in a spatially distributed manner. In this study, an enhanced two-source evapotranspiration model for land (ETEML) is proposed based on a trapezoid framework of the vegetation fractional cover and land surface temperature (VFC/LST) space. In ETEML, a VFC/LST trapezoid space is theoretically defined for each pixel, and a pixel-wise mixed surface temperature decomposition method is proposed. ETEML is based on a two-source scheme, and the crop water stress index (CWSI) concept is applied to parameterize the soil evaporation and the vegetation transpiration separately. The proposed model was applied to the Soil Moisture–Atmosphere Coupling Experiment (SMACEX) site in central Iowa, USA. Evaluation with a remotely sensed dataset from Landsat was carried out to assess the performance of ETEML. Compared with the tower observations, the mean absolute deviation (MAD) and the root mean square deviation (RMSD) for the ETEML estimated latent heat flux (LE) are, respectively, 49 W/m² and 59 W/m², comparable to retrieval accuracies published in other studies. Comparison between ETEML and variations on a simpler trapezoid interpolation model (TIM1 and TIM2) indicates that ETEML reduces the subjectivity and uncertainties involved in TIM1 and TIM2. Overall, the results suggest that ETEML is promising and can expand the application of the trapezoid framework-based ET modeling approaches to heterogeneous surfaces.

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1. Introduction

Evapotranspiration (ET) is an important process that drives energy and water exchanges between the hydrosphere, atmosphere, and biosphere (Brutsaert, 2005; Eagleson, 2002; Kabat, 2004; Katul, Oren, Manzoni, Higgins, & Parlange, 2012; Priestley & Taylor, 1972). The accurate observation and estimation of ET is extremely important to further our understanding of the global climate change, land–atmosphere interaction, water cycle, and ecological studies (Glenn, Huete, Nagler, Hirschboeck, & Brown, 2007; Kustas & Anderson, 2009; Sellers et al., 1997; Shuttleworth, 2007; Wang & Dickinson, 2012). Recent advances in retrieval algorithms and satellite remote sensing technology enable large-scale mapping of ET (Kalma, McVicar, & McCabe, 2008; Kustas & Anderson, 2009; Li et al., 2009; Moran et al., 1996). Several global multi-year ET datasets have been derived (Mu, Heinsch, Zhao, & Running, 2007; Mu, Zhao, & Running, 2011; Mueller et al., 2011; Zhang et al., 2012). Jiménez et al. (2011) compared 12 monthly mean land surface heat flux products for the period 1993–1995 and found

the seasonality was well captured by all products, but large differences in the flux partitioning were observed. Mueller et al. (2013) presented a monthly global ET synthesis product merged from several global data.

Land surface temperature (LST) is widely used in ET modeling and is a key variable for partitioning available energy into a sensible heat flux (H) and latent heat flux (LE) (Anderson, Norman, Mecikalski, Otkin, & Kustas, 2007a,b; Kalma et al., 2008; Kustas & Anderson, 2009; Kustas et al., 1989). Single-source models often use LST and empirical resistance corrections to estimate surface heat fluxes. However, due to its highly empirical dependency, this approach would produce significant errors when applied to partially vegetated landscapes (Norman, Kustas, & Humes, 1995; Timmermans, Kustas, Anderson, & French, 2007). To overcome these limitations associated with one-source models, two-source models were developed to make use of remotely sensed radiometric surface temperature directly and are preferable over heterogeneous surfaces (Kustas & Norman, 2000). Accurately decomposing the surface temperature of a mixed pixel into soil and canopy component temperatures is the core of the two-source modeling approach. The two-source energy balance model (TSEB) was proposed by Norman et al. (1995) to estimate H and LE for the soil and canopy separately using a single measurement of the radiometric surface temperature.

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The spatial contextual models based on the vegetation fractional cover and land surface temperature (VFC/LST) space are an important modeling scheme. A key advantage of this group of approaches is its relative independence from site-specific tuning of model parameters (Carlson, 2007; Petropoulos, Carlson, Wooster, & Islam, 2009). Such models are collectively referred to here as “trapezoid interpolation models (TIMs).” Related research includes the works by Moran, Clarke, Inoue, and Vidal (1994), Jiang and Islam (2001, 2003), Zhang et al. (2005), Zhang et al. (2008), Wang, Li, and Cribb (2006), Stisen, Sandholt, Norgaard, Fensholt, and Jensen (2008), and Shu, Stisen, Jensen, and Sandholt (2011). Recently, a novel two-source model called the pixel component arranging and comparing algorithm (PCACA) was presented by Zhang et al. (2005) and Zhang (2009) to estimate soil evaporation and vegetation transpiration separately. Most importantly, a new operational way to retrieve land surface component temperatures was proposed by Zhang et al. (2005) and Zhang (2009) based on the interpretation of the pixel distribution in the VFC/LST space (Carlson, 2007; Moran et al., 1994; Petropoulos et al., 2009). The temperature decomposition method was further applied by Long and Singh (2012) and Yang and Shang (2013) to develop their own models. However, several critical issues are related with the application of TIMs: (1) The application of this type of model needs a spatial region large enough to have a wide range of soil wetness and vegetation fractional cover and a spatially homogeneous meteorological forcing (Carlson, 2007; Long & Singh, 2012; Petropoulos et al., 2009; Zhang et al., 2005, 2008). This requirement greatly hampered the application of TIMs to heterogeneous surfaces and a large-scale study (Li et al., 2009). (2) The correct determination of the dry edge and the wet edge is crucial for TIMs (Tang, Li, & Tang, 2010; Zhang et al., 2005, 2008). (3) The assumptions involved in the VFC/LST trapezoid space require more careful study. The assumption that the isoline or the mixed surface temperature in the VFC/LSF trapezoid space is mainly controlled by soil water availability must be satisfied in TIMs. Zhang et al. (2008) realized this issue and tried to eliminate the effects of four controlling factors (air temperature, albedo, water vapor pressure, and aerodynamic resistance) on land surface temperature and made two improvements on the PCACA algorithm. However, these improvements still have limitations, and the assumption is still not fully satisfied. In the method proposed by Zhang et al. (2008), the average values of the air temperature, albedo, water vapor pressure, and aerodynamic resistance in the entire image are assigned to each pixel, and a new surface temperature is calculated. The calculated temperature cannot represent the actual temperature of the underlying surface, and this method needs complex temperature transformations. (4) It is difficult to couple TIMs with other models. Tian et al. (2013) indicated that different dry/wet edges determined in the VFC/LST trapezoid space directly led to the deviation of ET estimates due to the variation of the spatial domain size. This domain-dependent problem led to difficulty with this type of model being coupled with other pixel-based models.

The objective of this study is to develop an enhanced two-source evapotranspiration model for land (EETML) to overcome critical issues related to TIMs by defining a theoretical VFC/LST space for each pixel. Section 2 includes two sub-sections. Section 2.1 presents a description of the conventional trapezoid interpolation model, and Section 2.2 introduces the two-source model scheme, the determination of the theoretical VFC/LST trapezoid space, and the temperature decomposition method applied in EETML. Section 3 introduces the datasets used to assess the model. Section 4 first reports the results of the model applied at the regional scale with input variables retrieved from Landsat imagery. In the remainder of Section 4, EETML is compared to results from two conventional TIMs. Section 5 discusses the advantages and limitations in this work, and the final section provides a conclusion.

2. Model description

2.1. Trapezoid interpolation model (TIM)

In this section, two conventional TIMs are described and were used as control cases in this study. The TIM is based on an interpretation of pixel distribution in the VFC/LST space (Carlson, 2007; Petropoulos et al., 2009). The VFC/LST space, established under the conditions of full ranges of soil moisture content and vegetation, is characteristic of being bounded with a trapezoid envelope or a triangle envelope. A conceptual illustration of the VFC/LST space is shown in Fig. 1(a). There are four extreme points within the trapezoid envelope: Point A represents a dry, bare soil surface; Points B and C represent a fully vegetated area with severe water stress and no water limitations, respectively; and Point D represents a wet, bare surface. As a result, the dry edge of the trapezoid space is determined by Points A and B, and the cold edge is determined by Points C and D. The dry edge represents a boundary with minimal soil water content and ET. Points along the cold edge are assumed to have maximum soil water content and ET equal to the potential rate. Moran et al. (1994) introduced a water deficit index (WDI) based on the VFC/LST trapezoid space and extended the application of CWSI to the partially vegetated surface areas.

$$\text{WDI} = 1 - \frac{\text{LE}}{\text{E}_p} = \frac{a}{a + b} \quad (1)$$

where E_p is the potential evaporation rate (W/m^2), b is the temperature difference between Point M and the dry edge, and a is the temperature difference between Point M and the cold edge (Fig. 1[a]). In this study, the Priestley–Taylor equation is adopted to compute the potential evaporation, and LE (W/m^2) is then estimated using:

$$\text{LE} = 1.26 \frac{\Delta}{\Delta + \gamma} (\text{R}_n - \text{G}) \cdot (1 - \text{WDI}) \quad (2)$$

where Δ is the slope of the saturation vapor pressure curve at air temperature ($\text{kPa } ^\circ\text{C}^{-1}$), and γ is the psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$). R_n is the net radiation (W/m^2), which is calculated from:

$$\text{R}_n = (1 - \alpha) \text{S}_{\text{wd}} + \varepsilon \delta (\varepsilon_a T_{\text{a,k}}^4 - \text{LST}^4) \quad (3)$$

where S_{wd} is the downwelling shortwave radiation (W/m^2) and δ is the Stefan–Boltzman constant. $T_{\text{a,k}}$ is air temperature; LST is the radiative land surface temperature (K); ε is the emissivity of the land surface; ε_a is the emissivity of the atmosphere and α is the surface albedo. In this study, α was estimated from the visible and near-infrared bands of the Landsat image following Tasumi, Allen, and Trezza (2008). The soil heat flux G (W/m^2) was estimated using the equation proposed by Bastiaanssen, Menenti, Feddes, and Holtslag (1998), Bastiaanssen, Pelgrum, et al. (1998):

$$\text{G} = \text{R}_n (\text{LST} - 273.15) (0.0038 + 0.0074\alpha) (1 - 0.98\text{NDVI}^4). \quad (4)$$

The determination of the trapezoid space is crucial for TIMs. Generally speaking, there are two kinds of methodologies to determine the dry edge. For the first one, the dry edge and wet edge are retrieved empirically from the scatter plot defined by vegetation fractional cover and land surface temperature. One good example is Tang et al. (2010), who proposed an automatic method to determine the dry and wet edges of the VFC/LST space. However, this method is not feasible in this study, because the trapezoid space is not very clear in the scatter plot defined by VFC and LST derived from Landsat. Therefore, four extremes are selected manually, as in Choi et al. (2009). This method was called TIM1. For the second one, the dry edge is determined using theoretical boundary conditions by solving for energy balance and radiation budget equations (Long & Singh, 2012; Yang & Shang, 2013; Zhang, 2009; Zhang

Fig. 1. A sketch of the trapezoid in the VFC/LST space: (a) Used in trapezoid interpolation model (Extreme Points A, B, C, and D are determined from the point cloud); (b) involved in ETEML (Extreme Points A, B, C, and D are theoretically determined from the related information from point M).

et al., 2008). This type of method greatly reduces subjectivity and uncertainties related with the specification of the dry edge. This method is called TIM2.

Three important issues related to TIMs remain unresolved: (1) The application of TIMs is restricted to a flat surface with homogeneous meteorological forcing (Moran et al., 1994; Petropoulos et al., 2009). This greatly hampered the application of TIMs over a large-scale study area with heterogeneous surfaces and forcings. (2) Uncertainties and subjectivity are involved in the application of TIMs (Carlson, 2007). In most applications, four extreme points defining the trapezoid space are subjectively selected from a scatter plot. Small changes in these selections can greatly impact the model performance. (3) The crucial assumption is that LST is mainly controlled by soil water availability, and soil water availability can be represented by the configuration of the VFC/LST space (Carlson, 2007; Zhang et al., 2008). But this assumption is rarely satisfied. LST is related to complex surface-atmosphere interaction and is controlled by energy balance and radiation budget equations (see Equation [16] in Long and Singh (2012)). If other controlling factors (such as albedo, aerodynamic resistance, and air temperature, among others) on land surface temperature are not considered, the derivation of evaporation from the VFC/LST trapezoid space would definitely involve uncertainties (Zhang et al., 2008).

2.2. An enhanced two-source evapotranspiration model for land (ETEML)

The enhanced two-source ET modeling (ETEML) approach described here attempts to address some of the shortcomings in current TIM-based modeling. Section 2.2.1 presents a description of the two-source model scheme. Section 2.2.2 introduces the theoretical VFC/LST trapezoid space and its determination, and Section 2.2.3 introduces the temperature decomposition method based on the VFC/LST space.

2.2.1. Two-source model scheme

The energy balance equation can be formulated for the whole canopy-soil system, as well as the canopy and soil components, as follows:

$$R_n = H + LE + G \quad (5)$$

$$R_{nc} = H_c + LE_c \quad (6)$$

$$R_{ns} = H_s + LE_s + G \quad (7)$$

where R_n is the net radiation flux (W/m^2), and H is the sensible heat flux (W/m^2). The subscripts C and S indicate canopy and soil, respectively.

The partitioning of the different fluxes into soil and canopy components was accomplished based on a patch approach (Long & Singh, 2012; Sanchez, Kustas, Caselles, & Anderson, 2008):

$$R_n = f_c R_{nc} + (1 - f_c) R_{ns} \quad (8)$$

$$H = f_c H_c + (1 - f_c) H_s \quad (9)$$

$$LE = f_c LE_c + (1 - f_c) LE_s \quad (10)$$

where f_c is the fractional vegetation cover. R_{nc} and R_{ns} are estimated using the long-wave and the short-wave radiation separately for the canopy and soil component:

$$R_{nc} = (1 - \alpha_c) S + \epsilon_c L_{sky} - \epsilon_c \sigma T_c^4 \quad (11)$$

$$R_{ns} = (1 - \alpha_s) S + \epsilon_s L_{sky} - \epsilon_s \sigma T_s^4 \quad (12)$$

where S is the incident solar radiation on ground (W/m^2), and α_c and α_s are canopy and soil albedos, respectively. σ is the Stefan-Boltzmann constant; L_{sky} is the incident long-wave radiation (W/m^2). T_c and T_s are canopy and soil temperatures, respectively. Surface albedo for every pixel is assumed to be weighted by vegetation and soil components (Zhang et al., 2005, 2008):

$$\alpha = f_c \alpha_c + (1 - f_c) \alpha_s \quad (13)$$

where α is the albedo for a composite pixel. α_c is then estimated using the method given by Campbell and Norman (1998). α_s can be derived from the above equation. G is parameterized as a fraction (0.31) of the net radiation above the soil surface (R_{ns}) following Choudhury, Idso, and Reginato (1987).

A complete and independent energy balance between the atmosphere and each component of the surface is established. The component fluxes to the total sensible heat flux can be written as follows:

$$H_c = \rho C_p \frac{T_c - T_a}{r_a^h} \quad (14)$$

$$H_s = \rho C_p \frac{T_s - T_a}{r_a^a + r_s^a} \quad (15)$$

where ρ is the air density (kg/m^3), and C_p is the specific heat of air at constant pressure ($\text{J/kg} \cdot ^\circ\text{C}$). r_a^h is the aerodynamic resistance to heat transfer between the canopy and reference height (s/m). r_a^a (s/m) was calculated according to Sanchez et al. (2008). r_a^s is the aerodynamic resistance to the heat flow in the boundary layer immediately above the soil surface (s/m). The description to estimate these aerodynamic resistances can be found in the appendix of Sanchez et al. (2008).

Plant foliage temperatures have been shown to be closely correlated with plant transpiration (Jackson, Idso, Reginato, & Pinter, 1981; Jackson, Kustas, & Choudhury, 1988). The crop water stress index (CWSI) for the canopy component can be expressed as follows:

$$\text{CWSI}_c = 1 - \frac{\text{LE}_c}{\text{EP}_c} = \frac{(T_c - T_a) - (T_c - T_a)_{\text{cmin}}}{(T_c - T_a)_{\text{cmax}} - (T_c - T_a)_{\text{cmin}}} \quad (16)$$

where T_a is the air temperature ($^\circ\text{C}$). $(T_c - T_a)$ is the measured canopy temperature minus air temperature. $(T_c - T_a)_{\text{cmax}}$ and $(T_c - T_a)_{\text{cmin}}$ are the theoretical upper and lower limits of $(T_c - T_a)$. The aerodynamic resistance for theoretical limits of the canopy component corresponds to Eq. (14). The CWSI can also be applied to the soil component (Moran et al., 1994), giving rise to the soil water deficit index (SWDI) written as:

$$\text{SWDI}_s = 1 - \frac{\text{LE}_s}{\text{EP}_s} = \frac{(T_s - T_a) - (T_s - T_a)_{\text{smin}}}{(T_s - T_a)_{\text{smax}} - (T_s - T_a)_{\text{smin}}} \quad (17)$$

where $(T_s - T_a)$ is the measured soil surface temperature minus air temperature. $(T_s - T_a)_{\text{smax}}$ and $(T_s - T_a)_{\text{smin}}$ are the theoretical upper and lower limits of $(T_s - T_a)$. The aerodynamic resistance for theoretical limits of soil component corresponds to Eq. (15). The derivation of the $(T_c - T_a)_{\text{cmax}}$, $(T_c - T_a)_{\text{cmin}}$, $(T_s - T_a)_{\text{smax}}$, and $(T_s - T_a)_{\text{smin}}$ can be found in Jackson et al. (1988) and the appendix of Moran et al. (1994).

The component fluxes to the total latent heat flux can be derived as follows:

$$\text{LE}_c = (1 - \text{CWSI}_c) \text{EP}_c \quad (18)$$

$$\text{LE}_s = (1 - \text{SWDI}_s) \text{EP}_s \quad (19)$$

EP_c and EP_s are the potential evaporation rates of the canopy and soil components, respectively. Potential canopy transpiration is computed using:

$$\text{EP}_c = \frac{\Delta}{\Delta + \gamma} R_{nc} + \frac{\gamma}{\Delta + \gamma} E_a \quad (20)$$

For the E_a (W/m^2) term, the equation proposed by Brutsaert (1982) was applied in this study. Potential soil evaporation is estimated as follows:

$$\text{EP}_s = 1.26 \frac{\Delta}{\Delta + \gamma} (R_{ns} - G) \quad (21)$$

After T_s and T_c are derived or estimated, the above equations can be solved, and the component fluxes can be derived.

2.2.2. Theoretical VFC/LST trapezoid space

Soil surface temperature and canopy temperature are two indispensable input variables in the model formulation described in Section 2.2.1. In this study, a theoretical VFC/LST trapezoid space is defined for each pixel and a physical pixel-based surface temperature decomposition method is proposed. A theoretical VFC/LST trapezoid space defined for each pixel is shown in Fig. 1(b). The surface-to-air temperature gradient ($\text{LST} - T_a$) is used to replace LST in the trapezoid space. Following the equations from Moran et al. (1994), the four theoretical extreme points can be derived. That is, for the dry bare soil of Point A, evaporation equals zero and the difference between LST and

T_a can be derived as follows:

$$(T_s - T_a)_{\text{max}} = [r_a (R_n - G) / (\rho_a C_p)] \quad (22)$$

For the saturated bare soil of Point D, where the surface resistance equals zero,

$$(T_s - T_a)_{\text{min}} = [(r_a (R_n - G)) / (\rho_a C_p)] [\gamma / (\Delta + \gamma)] - [\text{VPD} / (\Delta + \gamma)] \quad (23)$$

For the well-watered, full-cover vegetation of Point C,

$$(T_c - T_a)_{\text{min}} = [(r_a (R_n - G)) / (\rho_a C_p)] [\gamma (1 + r_{cp}/r_a) / (\Delta + \gamma (1 + r_{cp}/r_a))] - [\text{VPD} / (\Delta + \gamma (1 + r_{cp}/r_a))] \quad (24)$$

For the water-stressed, full-cover vegetation of Point B,

$$(T_c - T_a)_{\text{max}} = [(r_a (R_n - G)) / (\rho_a C_p)] [\gamma (1 + r_{cx}/r_a) / (\Delta + \gamma (1 + r_{cx}/r_a))] - [\text{VPD} / (\Delta + \gamma (1 + r_{cx}/r_a))] \quad (25)$$

where VPD is the vapor pressure deficit of the air at air temperature T_a (kPa), γ is the psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$), r_a is the aerodynamic resistance (s/m), and the description to estimate r_a can be found in the appendix of Moran et al. (1994). r_{cp} is the canopy resistance at potential evapotranspiration (s/m), and r_{cx} is the maximum canopy resistance (s/m). Values for r_{cx} and r_{cp} are published for many agricultural crops (Allen, Pereira, Raes, & Smith, 1998). If the values are not available, $r_{cp} = 25\text{--}100 \text{ s/m}$ and $r_{cx} = 1000\text{--}1500 \text{ s/m}$ would be reasonable values and will not result in an appreciable error (Moran et al., 1994). In the ETEML algorithm, a theoretical VFC/LST space is constructed for each pixel based on that pixel's values of R_n , G , T_a , and VPD. The point M is located within that space at coordinates f_c , $\text{LST} - T_a$, and the water deficit index is derived for each pixel based on its point M and trapezoid edges.

2.2.3. The temperature decomposition method

The temperature decomposition method proposed by Zhang et al. (2005) is based on the interpretation of the pixel distribution in the VFC/LST space. Two assumptions need to be satisfied in this method. First, it is assumed that the configuration of the VFC/LST space is primarily determined by the variation of soil water availability. Second, the isolines of equal soil water content exist in the VFC/LST space. Previous studies have demonstrated that there are isolines of surface soil wetness/Temperature-Vegetation Dryness Index (TVDI) within the VFC/LST trapezoid space (Carlson, 2007; Gillies, Carlson, Cui, Kustas, & Humes, 1997; Sandholt, Rasmussen, & Andersen, 2002; Wang et al., 2006; Zhang et al., 2005). Zhang et al. (2005) indicated that soil surface temperatures/canopy temperatures for all pixels at an isoline with the same soil surface moisture availability are equivalent, and the mixed radiometric temperature is weighted by soil surface temperature and canopy temperature with the variation of a fractional vegetation cover. The slope of each isoline can be derived by interpolating the slope of the dry edge and that of the cold edge. Then, the soil surface temperature and vegetation canopy temperature can be derived. The determination of the trapezoid space is particularly important for the temperature decomposition method. A more detailed mathematical description of the temperature decomposition method based on the VFC/LST space can be found in the papers by Zhang (2009) and Zhang et al. (2005).

Based on the theoretical VFC/LST trapezoid space described in Section 2.2.2, the composite radiometric surface temperature of each pixel can be decomposed to soil and canopy component temperatures (Long & Singh, 2012; Yang & Shang, 2013; Zhang et al., 2005, 2008):

$$T_s - T_a = (\text{LST} - T_a) - K_s * f_c \quad (26)$$

$$T_c - T_a = K_s * (1 - f_c) + (\text{LST} - T_a) \quad (27)$$

where K_s is the slope of the isoline that passes through point M and can be derived by interpolating the slope of the dry edge and that of the cold edge:

$$K_s = K_{s,dry} + \frac{b}{a+b} [K_{s,wet} - K_{s,dry}] \quad (28)$$

where $K_{s,dry}$ and $K_{s,wet}$ are the slopes of the dry edge and the wet edge, respectively. b is the temperature difference between Point M and the warm edge, and a is the temperature difference between Point M and the cold edge (Fig. 1[b]). The slopes of the dry edge and the wet edge can be derived as follows:

$$K_{s,dry} = (T_c - T_a)_{max} - (T_s - T_a)_{max} \quad (29)$$

$$K_{s,wet} = (T_c - T_a)_{min} - (T_s - T_a)_{min} \quad (30)$$

$$a = (LST - T_a) - (1 - f_c)K_{s,wet} - (T_c - T_a)_{min} \quad (31)$$

$$b = (1 - f_c)(T_s - T_a)_{max} + f_c(T_c - T_a)_{max} - (T_{LST} - T_a). \quad (32)$$

Once T_s and T_c were derived, the equations described in Section 2.2.1 can be solved, and the component fluxes can be derived.

3. Study area and data processing

3.1. Region description

The Soil Moisture–Atmosphere Coupling Experiment (SMACEX) was conducted in conjunction with the Soil Moisture Experiment 2002 (SMEX02) during June and July 2002 near Ames, Iowa. The SMACEX study was designed to provide direct measurement/remote sensing/modeling approaches for understanding the impact of spatial and temporal variability in vegetation cover, soil moisture, and other land surface states on the turbulent flux exchange with the atmosphere. A full description the SMACEX experiment can be found in Kustas, Hatfield, and Prueger (2005). The climate at this site is sub-humid, and the annual average rainfall is approximately 835 mm. The Walnut Creek watershed was the core study area of this experiment. The land cover in the experiment area is primarily composed of corn and soybean. The dataset that consists of extensive measurements of atmospheric, vegetation, and soil properties and fluxes allows for rigorous analysis and the validation of fluxes, which are estimated using remote sensing methods (Choi et al., 2009; Gonzalez-Dugo et al., 2009).

3.2. Remote sensing data and variable derivation

The ETEML model was applied over the SMACEX experiment site using remote sensing data from the Landsat satellite and regional meteorological data. Two Landsat scenes were used: one from the Landsat-5 Thematic Mapper (TM) on June 23, 2002 (DOY 174) and a second scene on July 1, 2002 (DOY 182) from the Enhanced Thematic Mapper plus (ETM+) on Landsat 7. The remote sensing dataset was obtained from the National Snow and Ice Data Center (<http://nsidc.org/index.html>).

The land surface temperature is derived from the thermal infrared band (TIR, band 6). The atmospheric transmittance, spectral radiance, and downwelling sky radiance from the atmosphere were provided by Li et al. (2004). The visible, near-infrared (NIR) bands were re-sampled to be consistent with the thermal infrared band. Details concerning the atmospheric correction and retrieval of land surface temperature are given in Li et al. (2004) and Li, Kustas, Prueger, Neale, and Jackson (2005). Albedo was retrieved from the visible and near-infrared bands (1–5, 7) of the Landsat images following Tasumi et al. (2008) and Allen, Tasumi, Morse, et al. (2007), Allen, Tasumi, and Trezza (2007). The land cover classification for the study area was obtained from the National Snow and Ice Data Center (<http://nsidc.org/index.html>).

Empirical relationships between the Landsat-derived vegetation index and the leaf area index, vegetation cover fraction, and crop height over the watershed were given by Anderson et al. (2004). In this study, these empirical relationships were used to derive the leaf area index and vegetation height for the SMACEX region. For both corn and soybean, the leaf area index was derived using the following equation:

$$LAI = (2.88NDWI + 1.14)(1 + 0.104 \exp(4.1NDWI)). \quad (33)$$

Vegetation heights for corn (h_{corn}) and soybean ($h_{soybean}$) are derived using the following equations:

$$h_{corn} = (1.2NDWI + 0.6)(1 + 0.04 \exp(5.3NDWI)) \quad (34)$$

$$h_{soybean} = (0.5NDWI + 0.26)(1 + 0.005 \exp(4.5NDWI)) \quad (35)$$

where NDWI is the normalized difference water index, which can be computed from the near-infrared (NIR, band 4) and shortwave infrared (SWIR, band5) reflectances:

$$NDWI = (NIR - SWIR) / (NIR + SWIR). \quad (36)$$

The vegetation fractional cover was estimated from the normalized difference vegetation index (NDVI):

$$f_c = 1 - \left(\frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \right)^k \quad (37)$$

where $NDVI_{max}$ and $NDVI_{min}$ are NDVI values for complete vegetation cover and bare soil, respectively. The coefficient k is a function of the leaf orientation distribution within the canopy. k is set as 0.6175 in this study, as suggested by Li et al. (2005).

3.3. Tower measurements

Twelve towers with eddy covariance (EC) were deployed in the central area of the experiment. There were 6 corn sites and 6 soybean sites. The towers were instrumented with sensors to measure turbulent fluxes and soil heat flux. The distribution of the flux towers and land use classifications are provided in Fig. 2. It is well recognized that the field measurements of heat fluxes using the eddy covariance technique often fail to show closure of the surface energy budget (Foken, 2008; Foken, Wimmer, Mauder, Thomas, & Liebethal, 2006; Leuning, van Gorsel, Massman, & Isaac, 2012). During SMACEX, the energy balance closure is 0.71 for the soybean sites and 0.84 for corn sites (Su, McCabe, Wood, Su, & Prueger, 2005). For comparison with model flux partitioning, where energy balance is inherently assumed, the measured LE and H were adjusted for closure errors using the approach suggested by Twine et al. (2000), which conserves the observed Bowen ratio. For a detailed discussion of the flux tower observations and measurement uncertainty during SMACEX, see Kustas et al. (2005) and Prueger et al. (2005).

4. Results

4.1. Comparison with flux observations

The ETEML model was applied to the SMACEX region using satellite data and regional meteorological data. For a comparison with observations from the tower network, the estimated fluxes were averaged over the estimated upwind source-area (1–2 pixels) for each flux tower (Choi et al., 2009; Gonzalez-Dugo et al., 2009; McCabe & Wood, 2006). Comparisons between energy balance components (R_n , G , LE , and H), estimated by ETEML at the time of the Landsat overpass, and those from tower-based measurements, are shown in Fig. 3 and Table 1. In general, the estimated four energy balance components show a good agreement with tower-based measurements. Model biases

Fig. 2. The distribution of flux towers in the Walnut Creek catchment and the land use classifications.

in estimated R_n and G were less than 10 W/m^2 . The averaged H of tower-based measurements is 131 W/m^2 , while the averaged H estimates is 161 W/m^2 . The bias is 30 W/m^2 . The ETEML seems to have slightly overestimated the sensible heat flux. The MAD and RMSD for the estimated H are 44 W/m^2 and 51 W/m^2 , respectively. In ETEML, LE is computed based on the CWSI concept instead of the residual method adopted in many energy balance-based models. The mean LE of tower-

based measurements is 389 W/m^2 , while the mean LE estimate is 383 W/m^2 . The bias is -6 W/m^2 . The MAD and RMSD for the estimated LE are, respectively, 49 W/m^2 and 59 W/m^2 .

In comparison with ETEML, the simpler TIM1 and TIM2 versions of the trapezoid interpolation model perform poorly in application to this dataset. While modeled R_n and G values are reasonable, TIM1 significantly overestimates H and underestimates LE (Table 1 and Fig. 3).

Fig. 3. Comparison between modeled and measured energy fluxes at the Landsat overpass time on DOY 174 and 182 of 2002.

Table 1
Statistics comparing modeled output and flux measurements (W/m^2).

Flux component	Observed average	ETEML				TIM2				TIM1			
		Average	BIAS	MAD	RMSD	Average	BIAS	MAD	RMSD	Average	BIAS	MAD	RMSD
Rn	616	619	3	18	23	623	7	14	19	623	7	14	19
G	97	90	−7	19	23	72	−25	27	34	72	−25	27	34
H	131	161	30	44	51	124	−7	47	62	294	163	161	179
LE	389	383	−6	49	59	425	36	75	92	255	−134	133	150

TIM2 performs better, but is still shown to overestimate LE (Table 1 and Fig. 3).

In summary, ETEML, TIM1, and TIM2 performed similarly in comparison with R_n and G observations. TIM1 produces large errors in estimating H and LE . TIM2 shows improved performance on H and LE estimates compared to TIM1. ETEML shows the best performance among the three models, indicated by the model performance statistics in Table 1.

4.2. Spatial distribution of estimated LE

The spatial and frequency distribution of the LE estimated by ETEML, TIM1, and TIM2 based on the Landsat-derived variables are shown in Figs. 4 and 5. The statistics for LE estimates are listed in Table 2. The spatial patterns produced by the contrast between soybean and corn fields are clear in the ETEML- and TIM2-derived LE map. However, this contrast is less significant in the LE estimate derived by TIM1. In DOY 174, both ETEML- and TIM2-based LE show clear bimodal separation of flux patterns. However, only one peak was observed in the TIM1-based LE estimate. The LE values estimated by TIM1 are obviously less

than those derived by TIM2 and ETEML. In DOY 182, the spatial patterns derived from TIM2 and ETEML are similar. However, the TIM2-based LE estimates of corn field are larger than the ETEML-based LE estimates. The frequency distribution of TIM1- and TIM2-based estimates shows a bimodal feature. However, a multimodal feature is observed in ETEML-based LE in DOY 182. Comparing the mean values listed in Table 2, the ETEML-based LE is larger than that of the TIM1-based and less than that of the TIM2-based LE . The standard deviation values are also listed in Table 2, and the ETEML-based values are larger than TIM1-based and TIM2-based values, which indicate a higher spatial variability of ETEML-based LE estimates.

The spatial distribution of soil evaporation and vegetation transpiration of the study area derived by ETEML is shown in Fig. 6. The transpiration rate in corn fields is larger than that in soybean fields because the corn fields have higher LAI values than the soybean fields; the difference between the two is approximately 120 W/m^2 . The soil evaporation is relatively small compared to the vegetation transpiration, and the value is less than 220 W/m^2 . The derived vegetation transpiration and soil evaporation are comparable to other published studies by Anderson et al. (2005) and Yang and Shang (2013).

Fig. 4. The spatial distribution of LE over SMACEX region based on ETEML, TIM1, and TIM2 from Landsat-based variables on DOY 174 and 182.

Fig. 5. The frequency distribution of LE from ETEML, TIM1, and TIM2 based on Landsat-derived variables on DOY 174 and 182.

4.3. Model inter-comparison and the implications from the VFC/LST trapezoid space

A spatial (pixel-by-pixel) inter-comparison of latent heat flux generated by ETEML, TIM1, and TIM2 was conducted. Fig. 7 shows scatter plots of the latent heat flux derived from TIM1 and TIM2 against that derived from ETEML. The LE derived from TIM1 is mostly lower than that derived from ETEML. For TIM2, the LE estimates are close to ETEML-based estimates. However, LE estimates for soybean fields derived from TIM2 are larger than those derived from ETEML. The discrepancy among the three models may be attributed to the determination of the VFC/LST trapezoid space.

Different strategies for the determination of the VFC/LST trapezoid space are responsible for the large differences among the three modeling approaches. Fig. 8 shows the trapezoid space determined for TIM1 (the blue lines) and TIM2 (the dark lines) on DOY 182. All pixels are being bounded with a single trapezoid space in TIM1 and TIM2. However, this strategy may not be reasonable. The theoretical trapezoid spaces for five random pixels, three from the corn field and two from the soybean field, are determined using ETEML. The theoretical trapezoid space for each pixel and the location of each pixel are plotted in Fig. 8. It is clear that the trapezoid spaces are not coincidental with each other, and the different trapezoid spaces are highly dependent on the vegetation covers. Furthermore, each pixel has its own trapezoid space, and it seems almost impossible to find a universal dry edge and wet edge for all pixels. Therefore, the determined dry edge and wet edge in TIM1 and TIM2 are not reasonable and cannot be used to represent the real boundary conditions for all pixels.

Moreover, the assumptions involved in the VFC/LST trapezoid space are not satisfied in TIM1 and TIM2. The assumption that the isoline or the mixed surface temperature in the VFC/LSF trapezoid space is mainly controlled by soil water availability has to be satisfied. LST is controlled by energy balance and radiation budget equations (Long & Singh, 2012; Yang & Shang, 2013; Zhang, 2009; Zhang et al., 2008). If the impact of

other controlling factors (air temperature, albedo, water vapor pressure, and aerodynamic resistance) on LST is not negligible, the derivation of evaporation from TIM1 and TIM2 would definitely involve uncertainties. To clearly illustrate this problem, two 3D scatter plots are plotted in Fig. 9. In Fig. 9(a), the 3D space comprises the VFC (X axis), LST (Y axis), and albedo (Z axis) from Landsat-based variables on DOY 182. Every point is located in the 3D space with its VFC, LST, and albedo values. The projection of points on the X–Y plane is just the VFC/LST trapezoid space used in TIM1 and TIM2. It is clear that the albedo for pixels has a large variation, ranging from 0.14 to 0.25. This will lead to a difference of about 11% on net radiation, and therefore, it will introduce large uncertainties in the ET estimates. A similar scatter plot for VFC, LST, and crop height is plotted in Fig. 9(b). It is revealed that the crop height has a large variance for the pixels, although they have the same VFC value in the trapezoid space. To summarize, because of the uncertainties involved in TIM1 and TIM2, the TIMs-derived LE estimates are less reliable. However, the assumption involved in the trapezoid space is fully satisfied in ETEML. In the theoretical VFC/LST trapezoid space, the four extreme points are estimated using a simple land surface model, and the variations of $(LST - T_a)$ in the vertical direction in the trapezoid space are only linearly associated with variations in evapotranspiration or water availability. The physical basis of the trapezoid framework-based ET modeling approaches is strengthened.

5. Discussion

5.1. Advantages of ETEML

In realizing the disadvantages of TIMs, an enhanced two-source ET model is proposed. The advantages of ETEML lie in the following three aspects: (1) The ETEML can expand the applications of TIMs to heterogeneous surfaces. Traditionally, traditional TIMs are only applicable to homogeneous surfaces (Carlson, 2007; Petropoulos et al., 2009; Zhang, 2009). Moreover, a recent study from Tian et al. (2013) indicated that the variation of the spatial domain size would directly lead to the deviation of ET estimates. This created difficulty for traditional TIMs to couple with other pixel-based models. In ETEML, the theoretical VFC/LST trapezoid space is determined for each pixel, and the application of the model is not restricted to homogeneous surfaces. (2) In ETEML, a physical pixel-based surface temperature decomposition method is presented based on the theoretical VFC/LST trapezoid space. With the newly defined theoretical VFC/LST trapezoid space, the assumptions involved in the VFC/LST trapezoid space are fully satisfied, and the subjectivity and uncertainties related to the determination of the trapezoid space are greatly reduced. With these improvements, ETEML greatly overcomes the empirical and uncertain nature related to traditional TIMs. (3) ETEML is based on a two-source scheme, and the soil evaporation and vegetation transpiration can be derived separately. ETEML directly uses the component temperatures to calculate the component

Table 2
Statistics for regional-scale latent heat flux (W/m^2).

		DOY 174		DOY 182	
		Mean	Standard deviation	Mean	Standard deviation
ETEML	Regional	360	135	377	139
	Corn	482	144	502	150
	Soybean	271	106	308	108
TIM1	Regional	216	69	264	111
	Corn	258	78	381	114
	Soybean	183	50	188	76
TIM2	Regional	397	83	408	120
	Corn	513	102	576	128
	Soybean	333	60	321	79

Fig. 6. The spatial distribution of vegetation transpiration and soil evaporation of the SMACEX region based on ETEML from Landsat-based variables on DOY 174 and 182.

fluxes, and this deviates from TSEB, which uses an iterative approach to derive a physical solution.

5.2. Comparison with other models

By evaluating the ETEML using the SMACEX data, the performance of ETEML is found to be comparable to other published studies. Kalma et al. (2008) reviewed 30 published articles on remote sensing-based ET

models, and the assessment indicates an average root square error value of about 50 W/m² and relative errors of 15–30%. The SMACEX data have been widely used to validate and evaluate the ET models (Anderson et al., 2005; Cammalleri, Anderson, Gao, Hain, & Kustas, 2013; Chavez, Neale, Hipps, Prueger, & Kustas, 2005; Choi et al., 2009; French et al., 2005; Gonzalez-Dugo et al., 2009; Kustas et al., 2004; Li et al., 2005, 2006; Long & Singh, 2012; Su et al., 2005; Yang & Shang, 2013). Long and Singh (2012) and Yang and Shang (2013) collected

Fig. 7. ETEML predicted latent heat flux (W/m²) versus TIM1 and TIM2 predicted latent heat flux of the SMACEX region from Landsat-based variables on DOY 174 and 182.

Fig. 8. The trapezoid space determined in TIM1, TIM2, and ETEML on DOY 182. The blue lines represent the dry and wet edges used in TIM1. The dark lines represent the trapezoid space applied in TIM2. The red and olive lines represent the theoretical trapezoid space determined for two soybean pixels and three corn pixels randomly selected from the satellite image using ETEML.

the statistics of the discrepancies between surface flux retrievals and flux tower measurements from published studies (Table 4 in Long and Singh (2012); Fig. 10 and Table 3 in Yang and Shang (2013)). In this study, the bias and RMSD of LE estimates based on ETEML are -6 W/m^2 and 59 W/m^2 , respectively. The bias and RMSD of H estimates from ETEML are 30 W/m^2 and 51 W/m^2 , respectively. The statistics of ETEML are within the range of the other published studies, and the performance of ETEML is acceptable.

5.3. Further thoughts on ETEML

Currently, like most other thermal remote-sensing ET models, the ETEML provides instantaneous ET estimates at the time of the satellite overpass, whereas most applications in irrigation and hydrology require ET estimates over daily or longer time periods. This requires extrapolation from instantaneous values to daily or longer time steps. The evaporative fraction method and the referenced ET-based extrapolation fraction method are widely used to derive daily ET (Allen, Tasumi, Morse, et al., 2007; Allen, Tasumi and Trezza, 2007; Brutsaert & Chen, 1996; Brutsaert & Sugita, 1992; Chavez, Neale, Prueger, & Kustas, 2008; Colaizzi, Evett, Howell, & Tolk, 2006; Crago, 1996). Due to the low availability of quality satellite images, developing a reliable method for extrapolating daily values to longer time scales is imperative.

Recently, Van Niel et al. (2011) carefully studied the evaporative fraction method and proposed a generic correction method to reduce bias in daily ET estimates. For monthly scale, Van Niel et al. (2012) evaluated the accuracy of four upscaling approaches with site observations and proposed a simple procedure to minimize the upscaling bias. Furthermore, data fusion will definitely add value to seasonal ET assessment. Cammalleri et al. (2013) proposed a data fusion approach on use of MODIS- and Landsat-derived ET maps to obtain daily and seasonal ET. These works provide an insightful reference. Our ongoing work will focus on expansion of the ETEML to derive daily or longer time scale ET.

Regionally gridded meteorological variables are required for the regional application of ETEML. The representativeness of the in situ data is often limited to the footprint of the site. This could be resolved by incorporating the reanalysis meteorological data from the data assimilation system. NASA Global Modeling and Assimilation Office's (GMAO) Modern Era Retrospective Analysis for Research and Applications (MERRA; Rienecker et al., 2011) uses data from all available global surface weather observations every 3 h, and GEOS-5 was used to interpolate and grid these point data on a short time sequence, thus producing an estimate of climatic conditions for the world, at 10 m above the land surface and at a resolution of 0.5° latitude by 0.6° longitude. Detailed information on the MERRA dataset is available at the Web site (<http://gmao.gsfc.nasa.gov/research/merra/>). This data have been used in developing Global ET products by Mu et al. (2007). The Global Land Data Assimilation System (GLDAS; Rodell et al., 2004) has mapped climatological values for the land surface. One good example is Su, Wood, McCabe, and Su (2007), who evaluated the SEBS model based on MODIS and GLDAS forcing data over the CEOP EOP-1 reference site. These data sources would make it possible to apply ETEML to larger spatial domains in the near future.

6. Conclusion

In this study, a physically based two-source model (ETEMML) is proposed based on the trapezoid framework of the VFC/LST space. In ETEML, a theoretical VFC/LST trapezoid space is defined for each pixel, and a pixel-wise-mixed-surface temperature decomposition method is presented. Using the derived component temperatures, soil evaporation and vegetation transpiration are separately parameterized using the CWSI concept in the newly developed model. With these improvements, ETEML removes the restriction in the application of conventional TIMs. ETEML can be used to separate the soil evaporation and vegetation transpiration in heterogeneous covered area.

To evaluate the performance of ETEML, the model was applied to the SMACEX with a remotely sensed dataset at a regional scale. Compared with tower observations, the MAD and RMSD for the ETEML estimated LE are 49 W/m^2 and 59 W/m^2 , respectively. A further inter-comparison between TIM1, TIM2, and ETEML indicate that ETEML reduces the subjectivity and uncertainties associated with TIM1 and TIM2. In addition, the

Fig. 9. 3D Scatter Plots (a) composed of VFC (X axis), LST (Y axis), and albedo (Z axis); (b) composed of VFC (X axis), LST (Y axis), and crop height (Z axis).

performance of ETEML is comparable to other published studies. Overall, the results suggest that ETEML is promising and can be used to expand the applications of the trapezoid framework-based ET modeling approaches to heterogeneous surfaces.

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