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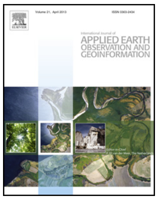

Evaluating five remote sensing based single-source surface energy balance models for estimating daily evapotranspiration in a humid subtropical climate

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ABSTRACT

In the last two decades, a number of single-source surface energy balance (SEB) models have been proposed for mapping evapotranspiration (ET); however, there is no clear guidance on which models are preferable under different conditions. In this paper, we tested five models-Surface Energy Balance Algorithm for Land (SEBAL), Mapping ET at high Resolution with Internalized Calibration (METRIC), Simplified Surface Energy Balance Index (S-SEBI), Surface Energy Balance System (SEBS), and operational Simplified Surface Energy Balance (SSEBop)—to identify the single-source SEB models most appropriate for use in the humid southeastern United States. ET predictions from these models were compared with measured ET at four sites (marsh, grass, and citrus surfaces) for 149 cloud-free Landsat image acquisition days between 2000 and 2010. The overall model evaluation statistics showed that SEBS generally outperformed the other models in terms of estimating daily ET from different land covers (e.g., the root mean squared error (RMSE) was 0.74 mm day^{-1}). SSEBop was consistently the worst performing model and overestimated ET at all sites (RMSE = 1.67 mm day^{-1}), while the other models typically fell in between SSEBop and SEBS. However, for short grass conditions, SEBAL, METRIC, and S-SEBI appear to work much better than SEBS. Overall, our study suggests that SEBS may be the best SEB model in humid regions, although it may require modifications to work better over short vegetation.

1. Introduction

Evapotranspiration (ET) is one of the key variables in many hydrologic, ecosystem, and land surface models. The complex interaction of many environmental and climatic factors (Monteith, 1965) makes quantification of ET a challenging task. Field-based ET measurement methods (e.g., soil water balance, eddy correlation, and Bowen-ratio) are labor- and cost-intensive and yet can only monitor ET for specific areas at most a few square kilometers in size (DeBruin, 2009). In the last two decades, a need to quantify ET at regional/global scale coupled with current advancements in satellite technologies has led to the widespread applications of remote sensing technology in ET modeling, with the surface energy balance (SEB; Eq. (1)) algorithm being one of the most widely used approaches (Liou and Kar, 2014).

$$R_n = G + H + \mathrm{LE} \quad (1)$$

where R_n (W m^{-2}) is the net surface radiation, G (W m^{-2}) is the soil heat flux, H (W m^{-2}) is the sensible heat flux, LE (W m^{-2}) is the latent heat flux and is estimated as the residual term in Eq. (1). SEB models can be categorized into single-source or a two-source (or multi-source) (Kustas and Norman, 1999) model based on how sinks or sources of energy fluxes are parameterized at the land-atmosphere interface. In a single-source SEB model, no distinction is made between vegetation and soil (and hence uses a bulk H formulation), unlike a two-source model, where the components of H are partitioned between the soil and vegetation. In this paper, we specifically focus on five commonly used single-source SEB models that utilize thermal-based remote sensing data to predict ET for

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Nomenclature

List of symbols

a	Surface albedo (-)
C	Correction factor (T_s/T_{max} for full cover: 0.99 in Senay et al. (2013) and 0.98 in this study)
c_p	Specific heat of air at constant pressure (1004 J kg^{-1} K^{-1})
d_0	Zero plane displacement height (m)
dT	Near-surface temperature difference (K)
ET_0	Daily reference ET for short grass (mm day^{-1})
ET_{inst}	Instantaneous ET (mm h^{-1})
ET_r	Reference ET for alfalfa (mm day^{-1})
$ET_{r,d}$	Daily ET_r (mm day^{-1})
$ET_{r,inst}$	Instantaneous ET_r (mm h^{-1})
ET_rF	Reference ET fraction (-)
G	Soil heat flux (W m^{-2})
g	Acceleration due to gravity (9.8 m s^{-2})
H	Sensible heat flux (W m^{-2})
H_{wet}	H at wet limits (W m^{-2})
H_{dry}	H at dry limits (W m^{-2})
k	Scaling factor for scaling ET_0 to maximum ET from a reference crop in SSEBop (-)
K	Von Karman's constant (0.41)
kB^{-1}	Excess resistance to the heat transfer parameter (-)
λ	Latent heat of vaporization (J kg^{-1})
L	Monin–Obukhov length (m)
LE	Latent heat flux (W m^{-2})
LE_{wet}	LE at wet limits (W m^{-2})
r_{ah}	Aerodynamic resistance for heat transfer (s m^{-1})
R_n	Net radiation (W m^{-2})
R_{n24}	Daily net radiation (W m^{-2})
T_a	Near surface air temperature (K)
T_b	At-sensor brightness temperature (K)
T_{cold}	T_s at cold pixel (K)
T_{hot}	T_s at hot pixel (K)
T_{max}	Daily maximum air temperature (K)
T_s	Land surface temperature (K)
u_*	Frictional velocity (m s^{-1})
u_b	Wind speed at z_b (m s^{-1})
z	Reference height (m)
z_b	Blending Height (m)
z_{oh}	Roughness length for heat transfer (m)
z_{om}	Roughness length for momentum transfer (m)
$\Delta\theta$	Potential temperature difference between surface and the air (K)
ε_o	Emissivity (-)
θv	Virtual potential temperature near the surface (K)
Λ	Evaporative fraction (-)
Λ_r	Relative evaporation (-)
ρ_a	Density of air (kg m^{-3})
Ψ_h	Atmospheric stability correction for heat transport (-)
Ψ_m	Atmospheric stability correction for momentum transfer(-)

each pixel and group them into three categories: (1) hot and cold pixel-based full energy balance models (2) excess resistance-based full energy balance model (3) partial energy balance models. The Surface Energy Balance Algorithm for Land (SEBAL; Bastiaanssen, 2000; Bastiaanssen et al., 1998a,b) and its variant Mapping ET at high Resolution with Internalized Calibration (METRIC; Allen et al., 2007, 2011) models fall in the first category. SEBAL introduced the concept of manually selecting two anchor pixels (i.e., hot and cold pixel) within an image and iteratively solving H, while correcting for the buoyancy effects. METRIC incorporates ET_r to inversely and internally calibrate H.

The second SEB model category includes the Surface Energy Balance System (SEBS; Su, 2002) model, which uses a sequence of physically-based equations (Su, 2002; Su et al., 2001) for determining a kB^{-1} parameter to tackle the difference between radiometric and aerodynamic temperature. The Simplified Surface Energy Balance Index (S-SEBI; Roerink et al., 2000) and the operational Simplified Surface Energy Balance model (SSEBop; Senay et al., 2013) do not require calculation of H and hence can be categorized as partial energy balance model. S-SEBI uses a simple Λ (ratio of LE to AE), obtained as the partitioning of H and LE based on linear regression of T_s and α. The SSEBop model uses a predefined dT for each pixel to determine extreme temperatures at hypothetical hot and cold surfaces and compute ET at daily scales.

Studies comparing a number of SEB models are needed to identify model benefits and inadequacies to help guide future model developments (French et al., 2015). There are many studies (listed in Chirouze et al., 2014) that compare the performances of SEB models. However, most studies only compare two to three SEB models (e.g., Choi et al., 2009; Gonzalez-Dugo et al., 2009; Timmermans et al., 2007; Velpuri et al., 2013; Vinukollu et al., 2011). The five single-source SEB models considered in this study have been used in a wide range of applications in different parts of the world (e.g., Bastiaanssen et al., 2005; Olivera-Guerra et al., 2014; Pôças et al., 2013; Tadesse et al., 2015; Wu et al., 2012; Xiong et al., 2010). Other studies have not compared all of these models head-to-head.

As a further motivation for this comparison study, only a limited number of studies have considered remote sensing based ET calculations in the southeastern US (Bhattarai et al., 2012, 2015) even though ET is an important portion of the water budget in the area e.g., 50–110% of annual precipitation in Florida, Sumner and Jacobs (2005). About 60% of the area is covered by marsh, woody wetlands, water, and natural vegetation (Kautz et al., 2007) and field-based ET measurements are labor—and cost-intensive and limited by accessibility and safety concerns. Hence, remote sensing is considered a promising alternative for ET estimation in the area. Because the application of SEB models has not been well explored in the humid southeastern US, there is no clear guidance regarding their applicability in this area. In this context, the major objective of our study was to evaluate the ability of five commonly used remote sensing based single-source SEB models (i.e., SEBAL, METRIC, S-SEBI, SEBS, and SSEBop) to estimate daily ET from four different land cover types (i.e., citrus, grass, marsh, and open water) in the humid southeastern US.

2. Model descriptions

Typically in a SEB model, the available energy ($AE = R_n - G$) is computed first and then partitioned into H and LE (i.e., $LE = R_n - G - H$). R_n and G computations are similar in most SEB models and readers are referred to Allen et al. (2007) for details on R_n and G. Note that these computations are not applicable for SSEBop, where instantaneous (i.e., at image acquisition time) fluxes are not computed.

Differences among the five remote sensing-based SEB models considered in this study arise in two primary ways: determination of instantaneous H (only required in SEBAL, METRIC, and SEBS), and determination of Λ or ET_rF (ratio of actual ET to ET_r), as summarized in Table 1. These differences can be attributed to the differences in utilization of the satellite-derived T_s among the five models. For example, in SEBAL and METRIC models, near-surface temperature difference (dT) is approximated from T_s using a simple linear relationship $dT = a + bT_s$ (where a and b are correlation coefficients)