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Comparison of three remote sensing based models to estimate evapotranspiration in an oasis-desert region

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ABSTRACT

Regional evapotranspiration (ET) estimation is crucial for regional water resources management and allocation. This paper evaluated the performance of three contextual remote sensing based models for ET estimation (METRIC—Mapping Evapotranspiration at High Resolution with Internalized Calibration; the T_s-VI triangle model; and SSEB-Simplified Surface Energy Balance) in an oasis-desert region during a growing season under advective environmental conditions. The performance of the three models was first assessed using surface fluxes observed at five eddy covariance (EC) flux towers installed in different land-cover types. Comparisons among model outputs were then conducted on a pixel-by-pixel basis for three main land-cover types (farmland, transition zone and desert). For METRIC and SSEB, good correlations were obtained between the modeled versus measured instantaneous latent heat flux (λET), with both R^2 values above 0.90. Outliers occurred when available energy was overestimated for the T_s-VI triangle model. Pixel-wise comparisons showed the greatest consistency between the T_s-VI triangle model and METRIC outputs in farmland with an R^2 of 0.98 and an RMSE of 13.69 W m^{-2}. Overall, METRIC outperformed both the T_s-VI triangle and SSEB models; the T_s-VI triangle model tended to overestimate and the SSEB to underestimate at higher values of λET. ET estimations by SSEB and the T_s-VI triangle model are more sensitive to the estimated surface temperature and available energy than those from METRIC. Two daily ET extrapolation methods were evaluated with the EC measured daily ET . The results indicated that the constant reference ET fraction (ET_rF) method could be used over well-watered areas due to the regional advection effect; the constant evaporative fraction (EF) method tended to give better outputs for other areas. Reasonable estimates of ET can be achieved by carefully selecting extreme pixels or edges, and validation is required when applying remote sensing based models, especially the contextual methods.

1. Introduction

Evapotranspiration (ET) is an important part of both the water and energy cycle. The spatio-temporal variation of ET has been widely used to inform regional water resources management and allocation, including irrigation scheduling, drought monitoring and forecasting. Remote sensing techniques, characterized by high temporal, spatial, and spectral resolution, have been a viable and economical way to map ET in heterogeneous regions. Many models with different degrees of complexity have been developed in recent decades to obtain trends in spatial and temporal variability of ET (Bastiaanssen et al., 1998; Jiang and Islam, 1999; Norman et al., 1995; Su, 2001), which differ with respect to landscape type and spatial extent of model application, type of remote sensing data, and required ancillary meteorological and land-cover data (Kalma et al., 2008).

Chirouze et al. (2014) divided remote sensing based ET estimation models into two groups: single-pixel and contextual methods. Single-pixel methods calculate sensitive heat flux (*H*) and latent heat flux (λET) by solving the surface energy budget for each pixel independently from others; this requires ground-based measurements of vegetation height, surface wind speed, and air temperature (Kustas and Norman, 1999). Representative models that use this method are the SEBS (Surface Energy Balance System) and TSEB (Two-Source Energy Balance) models. Due to the

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limited availability of ground-based characteristics for heterogeneous regions, this type of model is rarely used for ET estimation over large areas for operational applications (Jiang and Islam, 2003). In the contextual method, the pixel-wise H and λET are constrained and scaled by the so-called hot and cold extreme pixels selected within a study area, without the explicit and robust parameterization of aerodynamic resistance (Tang et al., 2011). Wang et al. (2007) pointed out that ET was highly related to surface net radiation, temperature, and vegetation index. Surface parameters, including the surface temperature (T_s), the normalized difference vegetation index (NDVI) or fractional vegetation cover (f_c), and the surface albedo (α), are commonly used to form the two-dimensional scatterplot envelope to scale the H or λET. The SEBAL (Surface Energy Balance Algorithm for Land) model and a modified version thereof, METRIC (Mapping Evapotranspiration at High Resolution with Internalized Calibration), employ the contextual method. The slope of the T_s versus α relationship is related to the area-effective momentum flux calculation (Bastiaanssen et al., 1998), and the near-surface temperature gradient (dT) of the hot and cold extreme pixels is used to anchor the linear relationship between dT and T_s. The T_s-VI triangle model estimates λET based on an extension of the Priestley–Taylor equation using the T_s versus NDVI/f_c triangle spatial variation (Jiang and Islam, 2001). The evaporative fraction (the ratio of λET to surface available energy, EF) can be obtained for each pixel by interpolating the φ parameter (introduced in Section 2.1.2) of the hot and cold edge, and λET can be derived by multiplying the available energy and EF. The SSEB (Simplified Surface Energy Balance) model estimates ET values using only T_s and the maximum ET for the region (Senay et al., 2007). T_s is used as a scalar to indicate the water availability of the pixel by assuming that the hot extreme pixel is located in a dry, bare area with no ET and the cold extreme pixel is located in a well-watered area with the maximum ET.

Although these models were developed based on different theories and have different degrees of complexity, reasonable ET values can be generated by all models under certain conditions (Allen et al., 2007a; Khan et al., 2010; Kimura et al., 2007; Li and Zhao, 2010; Liu et al., 2010b; Tang et al., 2010; Tasumi and Kimura, 2013). The T_s-VI triangle and SSEB models are comparatively simpler than the METRIC model due to fewer input items. Senay et al. (2011) compared the derived ET fractions of SSEB and METRIC using seven Landsat images acquired for south central Idaho during a growing season. The results exhibited good performance in less topographically complex areas. Several studies have compared outputs from the T_s-VI triangle model with those from the SEBAL, METRIC, SEBS, and TSEB models (Choi et al., 2009; Long and Singh, 2013; Tang et al., 2011). However, all of these studies were conducted in irrigated agricultural areas in sub-humid climates. The comparison of contextual models in an oasis-desert region with multiple land-cover types has never been performed, and few studies account for the temporal representativeness of these models (Chirouze et al., 2014).

The objective of this paper was to test the performance of three contextual remote sensing based models (METRIC, the T_s-VI triangle model, and SSEB) for ET estimation during the growing season in an oasis-desert region with advective environmental conditions. The performance of these three models was first assessed using ET values observed at five eddy covariance (EC) flux towers installed in different land-cover types. Comparisons among the model outputs were then conducted on a pixel-by-pixel basis for three main land-cover types (farmland, desert, and the transition zone in between). As the daily and monthly ET values are more frequently applied in practical water resources management, two extrapolation methods to derive daily ET were evaluated using the daily EC measurements at the five flux towers on satellite overpass dates.

2. Materials and methods

2.1. Model description

2.1.1. METRIC model

The METRIC model (Allen et al., 2007b) computes λET as the residual of the surface energy balance:

$$R_n = G + \lambda\text{ET} + H \quad (1)$$

where R_n is the net radiation flux (W m^{-2}); G is the soil heat flux (W m^{-2}); H is the sensible heat flux (W m^{-2}); and λET is the latent heat flux (W m^{-2}). The R_n is given by

$$R_n = (1-\alpha)R_{S,\text{in}} + \varepsilon_0 R_{L,\text{in}} - \varepsilon_0 \sigma T_s^4 \quad (2)$$

where α is the surface albedo (dimensionless); ε_0 is the surface emissivity (dimensionless); $R_{S,\text{in}}$ and $R_{L,\text{in}}$ are incoming short wave and long wave radiation (W m^{-2}), respectively; σ is the Stefan–Boltzmann constant (5.67 × 10^{-8} W m^{-2} K^{-4}); and T_s is the surface temperature (K). The G value is estimated as a fraction of the net radiance using T_s, α, and the Normalized Difference Vegetation Index (NDVI):

$$G = \frac{T_s - 273.16}{\alpha}\left(0.0038\alpha + 0.0074\alpha^2\right)\left(1 - 0.98\text{NDVI}^4\right) R_n \quad (3)$$

The H value is estimated using the bulk aerodynamic resistance equation:

$$H = \frac{\rho_a C_p \mathrm{d}T}{r_{\text{ah}}} \quad (4)$$

where ρ_a is the air density (kg m^{-3}); C_p is the specific heat of dry air (1004 J kg^{-1} K^{-1}); dT (K) is the temperature gradient between two heights z_1 (~0.1 m) and z_2 (~2 m) above the canopy layer; and r_{ah} is the aerodynamic resistance (s m^{-1}) to heat transport between z_1 and z_2.

METRIC computes dT for each pixel by assuming that dT scales linearly with surface temperature:

$$\mathrm{d}T = b + aT_s \quad (5)$$

where a and b are image-specific empirical parameters estimated using two end-pixels (hot and cold extreme pixels) where H values can be reliably assigned. As r_{ah} and H are both unknown, METRIC applies the Monin–Obukhov theory in an iteration procedure with an initial r_{ah} value for neutral atmospheric conditions. The iteration procedure ends when dT and r_{ah} at the hot extreme pixel converge, then H for each pixel can be computed and the instantaneous λET calculated using Eq. (1).

2.1.2. T_s-VI triangle model

The T_s-VI triangle model introduced by Jiang and Islam (1999) is a simple model to estimate surface ET over large heterogeneous areas using only remote sensing data. λET is calculated based on:

$$\lambda\text{ET} = \varphi\left[(R_n - G)\frac{\Delta}{\Delta + \gamma}\right] \quad (6)$$

where Δ is the slope of saturated vapor pressure versus air temperature (kPa °C^{-1}) and γ is the psychrometric constant (kPa °C^{-1}). φ is a complex-effect parameter that accounts for the effects of aerodynamic and canopy resistances (dimensionless). Although φ looks similar to the α parameter (~1.26) in the Priestley–Taylor equation, it encompasses a wide range of evaporative conditions with values ranging from 0 to $(\Delta + \gamma)/\Delta$.

The pixel-by-pixel φ value can be detected from contextual information of an image with a T_s/f_c feature space presented by Jiang and Islam (2001) and Tang et al. (2011) using the two-step