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Remote sensing of evapotranspiration over cotton using the TSEB and METRIC energy balance models☆

Andrew N. French *, Douglas J. Hunsaker, Kelly R. Thorp

U.S. ALARC, 21881 North Cardon Lane, Maricopa, AZ 85138, USA

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ABSTRACT

Remote sensing of evapotranspiration (ET) can help detect, map and provide guidance for crop water needs in irrigated lands. Two remote sensing ET models based on thermal infrared (TIR), the Two-Source Energy Balance (TSEB) and the Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC), were tested for accuracy, and bias at fine (1 m) and moderate (30–120 m) spatial scales. Airborne and Landsat data were collected over Maricopa, Arizona in 2009 and 2011 as part of a cotton irrigation scheduling study. Based on soil moisture observations at 112 locations across 4.9 ha and image data spanning two growing seasons, TSEB and METRIC were found similarly accurate at both fine and moderate scales with average discrepancies no more than 1.9 mm/day. Tests at 1-m scales showed that TSEB and METRIC model sensitivities were seasonally correlated, with greater sensitivity modeled by METRIC in early growth and slightly greater sensitivity by TSEB at maturity. Time integration of flux estimates was done by assuming constant evaporative fraction and was also tested for 2011 data using ground-based TIR radiometers; this latter approach improved daily ET estimates by 0.8 mm/day or better in two cases. Time-series assessment of the utility of using evaporative fraction as a water-stress indicator was tested using Landsat data and both TSEB and METRIC. Two early season water depletion events were detected and none in mid-season. The impact of overpass frequency upon ET estimates was tested for the field as a whole and found that cumulative ET estimates were significantly affected, up to 200 mm out of ~1000 mm consumed. Results from this study showed that for ET accuracy, TSEB and METRIC perform similarly. METRIC is preferred when model ancillary data are sparse, while TSEB is preferred when support data are plentiful. Future ET modeling should consider implementing both to take advantage of their seasonally dependent sensitivities.

1. Introduction

Accurate maps of evapotranspiration (ET) over crops are a way to improve detection of crop water stress, refine irrigation scheduling, and help manage scarce water supplies. Recently ET maps have begun to be incorporated within drought forecasting systems (Anderson et al., 2013), and thus are beginning to have major local and global impacts. ET mapping is also becoming important for management at watershed scales (Gibson, Münch, Engelbrecht, & Petersen, 2009; Kongo & Jewitt, 2006) and for water allocations (Consult, 2011). In recent times much has been written about ways to create maps using remote sensing data. These ways include use of vegetation indices derived from visible and near infrared bands (VNIR), predominately red (~670 nm) and near infrared (~790 nm), and the inclusion of thermal infrared (TIR) bands, predominated by bands over 10–13.5 μm. Using the normalized difference vegetation index (NDVI) in combination with crop coefficients has been shown by Glenn, Neale, Hunsaker, and Nagler (2011), Hunsaker, Fitzgerald, French, Clarke, and Pinter (2007), and others, to be an effective way to map ET over crops. When coupled with ancillary data and estimates of crop coefficients, ET can be reasonably estimated under standard, non-water-stressed conditions (Gonzalez-Dugo et al., 2009). The choice of modeling ET with VNIR data comes with a substantial advantage: satellite data at these wavelengths are readily available at <100 m resolution, often at no-cost (e.g. Landsat through landsat.usgs.gov). However, use of VNIR data alone also has a distinct disadvantage: short term onset of water stress signals from plants cannot be readily detected (Pinter et al., 2003) except at very fine resolution. Eventually over several days there will be changes in canopy architecture with consequent changes in reflectance, but for applications requiring near real-time information, VNIR-based ET maps will not be sufficient.

Using land surface temperatures (LST) derived from TIR data, in contrast, can provide the needed short-time information. Dehydrated plants are unable to transpire and lack of evaporative cooling results in elevated canopy temperatures. Water shortage in plant root zones is quickly represented by anomalous high plant canopy temperatures. The temperature changes exceed 1 K and are measurable from space. When combined with a surface energy balance model, LST data can be

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* Corresponding author.
E-mail address: andrew.french@ars.usda.gov (A.N. French).

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used to produce instantaneous ET estimates and plant stomatal conductance (Blonquist, Norman, & Bugbee, 2009), a direct indicator of plant stress. Preeminent energy balance models include one-source, contextual models such as SEBAL (Bastiaanssen, Menenti, Feddes, & Holtslag, 1998), its open-source variant, METRIC, (Allen, Tasumi, & Trezza, 2007) a time-integrated variant (Sun et al., 2009), VI/LST/resistance triangle approaches (Carlson, Capehart, & Gillies, 1995; Jiang & Islam, 1999), and the two-source biophysical approach, TSEB (Norman, Kustas, & Humes, 1995).

Questions about which model is best, or which to use, arise frequently. Model inter-comparisons (Gonzalez-Dugo et al., 2009; Timmermans, Kustas, Anderson, & French, 2007) help to highlight model benefits and shortcomings and guide future model development. Results from studies are equivocal, demonstrating good results in some seasons and poor results otherwise. For example, Chirouze et al. (2014) compared instantaneous ET results over crops in Northern Mexico and sometimes found good results with both contextual and dual source approaches and sometimes not.

For studies focused on ET from remote sensing over irrigated crops, the pathway ahead remains unresolved because high spatial resolution data (<100 m) in reflected and emission bands are required. They are not routinely available. Thus model performance at irrigation treatment scales is difficult to evaluate at time steps ranging from days to months. If remote sensing models cannot be shown to be robust and consistently more accurate than standardized weather-based ET models such as Penman-Monteith (Allen et al., 2005) then there is not good justification to implement them. Furthermore, existing model demonstrations typically utilize surface energy flux station measurements for validation (e.g., Byun, Liaqat, & Choi, 2014; Choi et al., 2009), an important but spatially blunt tool for measuring ET over discontinuous or patchy irrigated crops. For irrigation scheduling research at Maricopa, however, ET is obtained from intensive soil moisture monitoring and thus could provide more meaningful validation data for model assessment than would otherwise be possible. To that end a comparison study was conducted to evaluate two accessible but distinctly different models: TSEB and METRIC.

TSEB offers a physics-based approach: energy fluxes between the soil surface, plant canopy, and the overlying air are modeled and supported by physically meaningful parameterizations leading to distinct estimates of transpiration and evaporation from non-plant surfaces. This separation, part of crop ET models such as FAO56 Pereira, Allen, Smith, and Raes (2015), quantifies how much irrigation water is beneficial to plant growth compared with non-beneficial water loss at the soil surface. Implementation of TSEB, however, is complex, sensitive to LST observation errors and algorithmically incomplete without a constrained potential ET parameterization.

METRIC (and its parent model SEBAL) on the other hand, relies upon contextual LST data to model energy fluxes and makes no attempt to differentiate soil and canopy. 'Contextual' is used in the sense that LST values over target sites are modeled with respect to LST values observed at the same time and spatially nearby. This means that METRIC reference pixels can be applied to single or nearly simultaneous adjacent remote sensing scenes. Though criticized for physical simplifications, METRIC offers a major advantage over TSEB: its self-calibrating approach avoids difficult-to-resolve errors and uncertainties in LST data. METRIC enforces meaningful constraints on temperature endmembers wherein the coldest pixels represent conditions close to potential ET and the hottest pixels represent conditions with minimal latent heat flux. Results from studies using METRIC/SEBAL worldwide are certainly encouraging but questions remain about how much local calibration is required and how to make the approach more objective and repeatable.

Although both TSEB and METRIC have been implemented to produce ET estimates, their underlying objectives are not the same and it makes little sense to compare the models in their entirety. Specifically, the salient features that need comparison are the turbulent flux components. While formulations for net radiation soil heat flux components are certainly different, their distinctiveness has little to do with LST data. For TSEB the emphasis lies with canopy geometry and separation of fluxes between plant and soil. The METRIC emphasis lies with atmospheric correction of satellite VNIR to obtain albedo estimates regardless of canopy structure. Thus the approach taken here is to conduct a TSEB/METRIC inter-comparison by providing both with the same net radiation and soil heat flux inputs and then evaluating ET outcomes. The inter-comparison is based on extensive observations over a cotton experiment in Maricopa, Arizona conducted 2009 and repeated in 2011. Remotely sensed data included airborne and Landsat observations. Companion papers describe geospatial modeling, crop simulations (Thorp et al., in review) and irrigation scheduling approaches (Hunsaker et al., in review). Considering that the TSEB algorithms incorporate biophysical soil and canopy properties not provided by METRIC, the TSEB net radiation and soil heat flux estimates were used as standard inputs for both. While this choice does mean that parameterization errors will propagate to both model outputs, differences in turbulent flux estimates will not be confounded.

Hence the presentation of the paper describes the methodology in Section 2, containing some mathematical modeling details in Section 2.1, followed by an overview of the experimental plan in Section 2.4. Results from model implementations are reported in Section 3, which are interpreted in Section 4 and summarized in Section 5.

2. Methods

2.1. Remote sensing of ET

Estimation of ET with the TSEB and METRIC approaches begins with energy balance:

$$LE = R_n - G - H \tag{1}$$

where LE is latent heat flux, R_n is net radiation, G is soil heat flux, and H is sensible heat flux (all computed in W/m^2). Photosynthetic and heat storage are neglected as minor components, being <5% of R_n, although in some instances the latter component may be important for full canopy during morning hours (Meyers & Hollinger, 2004). LE, the target term, cannot be measured with remote sensing and is computed as the residual from solving the other three terms in Eq. (1). To recover ET as a liquid water depth, LE values are divided by latent heat of vaporization and density of liquid water. Since remotely sensed LE values are an instantaneous observation not representative for the entire day, an extrapolation approach is needed. Here two approaches were investigated. In one, a constant evaporative fraction (EF) assumption (Lhomme & Elguero, 1999) is used, i.e., $EF = LE/[R_n - G] =$ constant. During mid-day hours EF is nearly constant, meaning that a single time of day observation could be sufficient for daily ET estimation. Constancy of EF, however, is not assured since it depends upon multiple factors, some of the more important being cloudiness, advected heat or moisture (Crago, 1996) and phase difference between net radiation and soil heat flux (Gentine, Entekhabi, Chehbouni, Boulet, & Duchemin, 2007). Daily ET (mm) is computed:

$$ET_{Daily} = 1000 \times \frac{EF}{\rho\lambda} \times (R_n - G) \times \sum_{t=0}^{t=n} \frac{R_{s,t}}{R_{s,\circ}} \Delta t \tag{2}$$

where $R_{s,o}$ is incoming solar radiation (W/m^2) at remote sensing time, $R_{s,t}$ is estimated incoming radiation (W/m^2) over the whole day, ρ is water density (kg/m^3), λ is heat of vaporization (J/kg), and Δt is the time sample interval (s). For this study at Maricopa, time step t was one hour, $n = 24$, and both R_s, o and $R_{s,t}$ were obtained from AZMET (Brown, 1989) observations (Table 1). The second approach used