DERIVING HOURLY SURFACE ENERGY FLUXES AND ET FROM LANDSAT THEMATIC MAPPER DATA USING METRIC™

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ABSTRACT

Surface energy fluxes, especially the latent heat flux from evapotranspiration (ET), determine exchanges of energy and mass between the hydrosphere, atmosphere, and biosphere. In this study, we applied the METRIC™ (Mapping ET at high Resolutions with Internal Calibration) algorithm on a Landsat Thematic Mapper (TM) image acquired on July 10, 2007 to derive hourly surface energy fluxes and ET for the highly advective Texas High Plains. Performance of the METRIC™ algorithm was evaluated by comparing estimated surface temperature, net radiation, soil heat flux, and hourly ET measured on four large lysimeters in Bushland, Texas [35^0 11' N, 102^0 06' W; 1,170 m elevation MSL]. Agreements between predicted and measured values of both surface temperature and net radiation were excellent. Comparison of METRIC™-estimated instantaneous ET values with lysimetric measurements indicated that METRIC™ may provide good ET estimates for both irrigated and dryland fields. However, relatively large errors in predicting ET for lysimeter fields under dryland management may be due to errors in the selection of the hot pixel.

INTRODUCTION

Remote sensing has been recognized as the most feasible means to provide spatially distributed regional ET information on land surfaces (Park et al., 1968; Jackson, 1984). Since ET requires a large amount of energy to change water from a liquid to a vapor in the environment (Su et al., 2005), remote sensing based energy balance (EB) models can convert satellite sensed radiances into land surface characteristics such as albedo, leaf area index, vegetation indices, surface emissivity, and surface temperature to estimate ET as a "residual" of the land surface energy balance equation:

$$LE = R_n - G - H \qquad (1)$$

where R_n is the net radiation resulting from the energy budget of short and long wave radiation, LE is the latent heat flux from evapotranspiration, G is the soil heat flux, and H is the sensible heat flux (all in Wm^{-2} units). LE is converted to ET (mm h^{-1} or mm d^{-1}) by dividing it by the latent heat of vaporization (λ_v; ~2.45 MJ kg^{-1}), density of water (ρ_w; ~1.0 Mg m^{-3}), and an appropriate time constant (e.g. 3600 s hr^{-1} for hourly ET).

Numerous remote sensing algorithms were available for estimating magnitude and trends in regional evapotranspiration. These models included the Two-Source Model (TSM; Norman et al., 1995; Kustas and Norman, 1996), where the energy balance of soil and vegetation are modeled separately and then combined to estimate total LE, Surface Energy Balance Algorithm for Land (SEBAL; Bastiaanssen et al., 1998a,b) and Mapping Evapotranspiration with Internalized Calibration (METRIC™; Allen et al., 2007a,b) that both use 'hot' and 'cold' pixels to develop an empirical temperature difference equation, and Surface Energy Balance Index (SEBI; Menenti and Choudhury, 1993) based on the contrast between wet and dry areas. Other models include Simplified Surface Energy Balance Index (S-SEBI; Roerink et al., 2000); Surface Energy Balance System (SEBS; Su, 2002); the excess resistance (kB^{-1}; Kustas and Daughtry, 1990); the aerodynamic temperature parameterization models proposed by Crago et al. (2004); Beta (β) approach (Chehbouni et al, 1996); and most recently ET Mapping Algorithm (ETMA; Loheide and Gorelick, 2005).

Mapping Evapotranspiration with Internalized Calibration (METRIC™) is an EB-based spatial ET estimation method. It has been applied with Landsat Thematic Mapper (TM) data throughout the United States. Tasumi et al. (2003) validated METRIC™ for various crops grown in weighing lysimeters located at the USDA-ARS laboratory in Kimberly, ID. Allen et al. (2007b) compared seasonal ET estimated for two agroecosystems in Idaho: an irrigated meadow in the Bear River Basin and a sugar beet field near Kimberly, using METRIC™ with lysimeters measurements resulted in 4% and 1% errors, respectively; with ET overestimation errors as high as 10% to 20%. Errors in predicted monthly ET at Montpelier, ID averaged ± 16% relative to a local lysimeter, although the difference for ET sums over a four-month period was only 4%. However, the METRIC™ algorithm has never been compared with lysimeter data from fields larger than the Landsat Thematic Mapper's thermal pixel size (120 by 120 m). This is important because smaller lysimeter fields cause contamination of thermal pixels from surface temperatures from surrounding fields and limits our ability to evaluate ET algorithms accurately (Kramber et al., 2002). The main objective of this paper was to evaluate METRIC™ (Ver. 2.0.4) using lysimeter data and a Landsat TM image covering a major portion of the Texas High Plains acquired during the 2007 cropping season.

METHODS AND MATERIALS

Study Area

This study was conducted at the USDA-ARS Conservation and Production Research Laboratory (CPRL) located in Bushland, TX (Fig. 1). The geographic coordinates of the CPRL are 35° 11' N, 102° 06' W, and its elevation is 1170 m above mean sea level. For this study, a 30-m resolution Landsat 5 TM scene was used to derive energy fluxes at the land surface. The scene path/row was 31/36 and was acquired at 17:27 GMT on 10 July 2007 (DOY 191). The TM band 6 image was captured at a coarser resolution of 120 m, and was resampled to 30 m by the image supplier. Soils around Bushland are described as slowly permeable Pullman clay loam soils. The major crops in the study area are corn, sorghum, winter wheat, and cotton.

METRIC™ estimated ET values were verified by comparison to soil water mass change-based hourly ET values from four large monolithic precision weighing lysimeters located at the CPRL. Each lysimeter (3 m length × 3 m width × 2.4 m depth) is located in the middle of 4.7-ha fields and all four lysimeters are arranged in a block pattern (see Fig. 1). Dryland cropping systems are managed on two lysimeter fields in the west and irrigated cropping systems are managed on two lysimeter fields in the east with a 10-span lateral move sprinkler system. In 2007, SW and NW were planted to dryland grain sorghum in clumps (SW) and rows (NW) as part of another study. The irrigated SE and NE lysimeter fields were planted to forage corn and sorghum, respectively. A grass reference ET weather station field (0.31 ha), which is a part of the Texas High Plains ET Network (TXHPET, 2006) is located in the eastern side of the irrigated lysimeter fields. Each lysimeter field was equipped with one net radiometer [Q*7.1, Radiation and Energy Balance Systems (REBS)[1/], Seattle, WA] and two infrared thermometers (IRT) (2G-T-80F/27C, Exergen, Watertown, MA) for measuring net radiation and surface temperature, respectively. More information of lysimeter setup can be found in Howell et al. (1995).

Mapping Evapotranspiration with Internalized Calibration (METRIC™)

METRIC™ is a single-source model that solves the EB for LE as a residual. R_n absorbed by the surface is the sum of the net shortwave and long wave radiations. It is estimated as:

$$R_n = (R_S\downarrow - R_S\uparrow) + (R_L\downarrow - R_L\uparrow) \qquad (2)$$

where $R_S\downarrow$ and $R_S\uparrow$ are the incoming and reflected shortwave radiation, respectively. $R_L\downarrow$ and $R_L\uparrow$ are the incident long wave radiation and outgoing radiation, respectively. The main differences between SEBAL and METRIC™ is that the latter (1) applies correction to at-surface-reflectance following the procedure developed by Tasumi et al. (2008); (2) does not assumes H=0 or LE = R_n–G at the wet pixel, instead a soil water budget is applied for the hot

1/ Mention of trade or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

pixel to verify that ET is indeed zero and for the wet pixel, LE is set to 1.05 ET_r λ_v, where ET_r is the hourly (or shorter time interval) tall reference (like alfalfa) ET calculated using the standardized ASCE Penman-Monteith equation; (3) it selects extreme pixels purely in an agricultural setting whereby the cold pixel should have biophysical characteristics (e.g., h_c, LAI) similar to the reference crop (alfalfa), and (4) uses the alfalfa reference evapotranspiration fraction (ET_rF) mechanism to extrapolate instantaneous LE flux to daily ET rates instead of using the evaporative fraction. The ET_rF is the ratio of ET_i (remotely sensed instantaneous ET) to the reference ET_r that is computed from weather station data at overpass time.

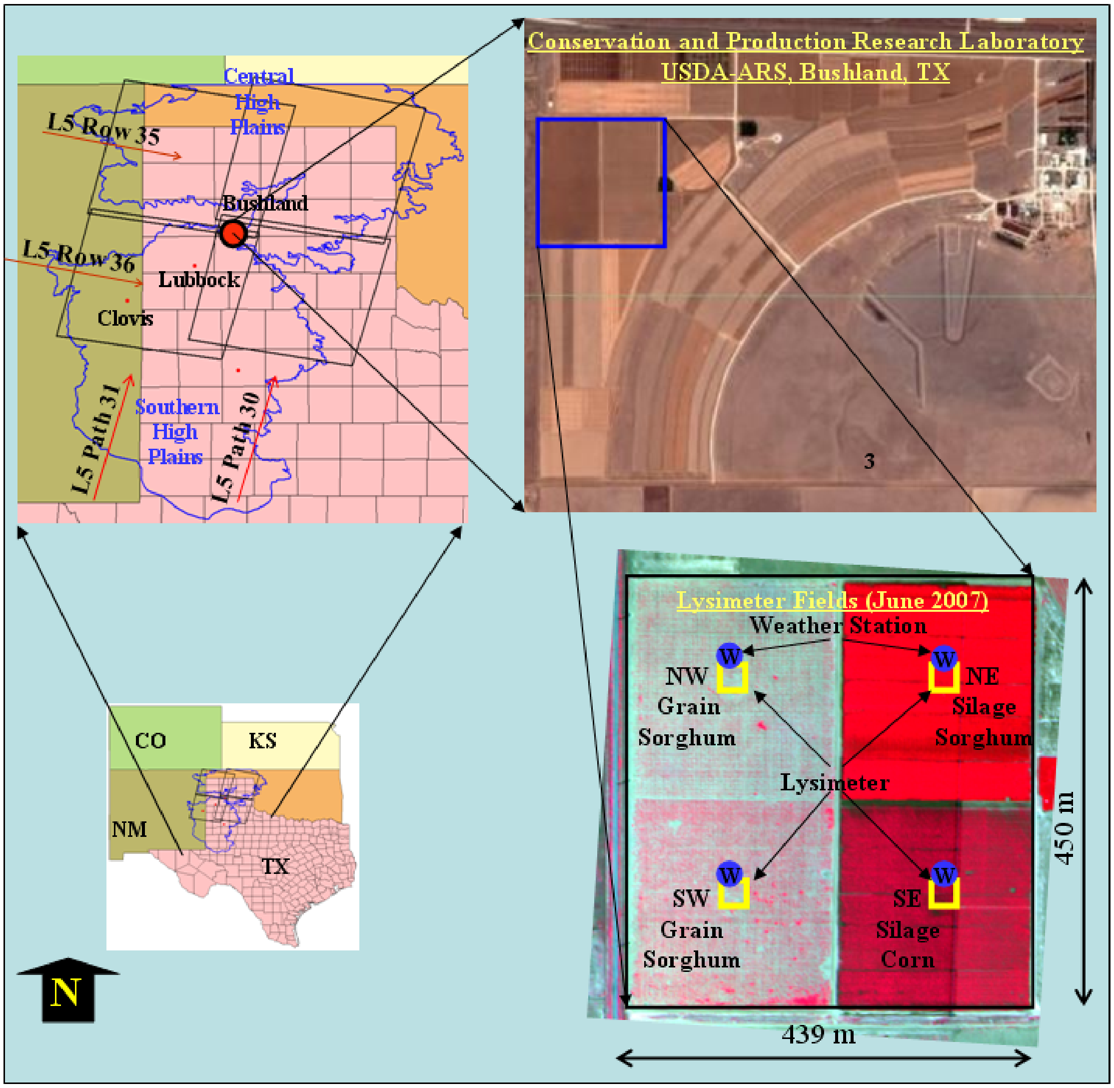

Figure 1. Location of Texas High Plains and four large weighing lysimeters in the USDA-ARS Conservation and Production and Research Laboratory, Bushland, TX, USA.

Soil heat flux (G) is the rate of heat storage into the soil and vegetation due to conduction. METRIC™ computes the ratio of G/R_n using an empirical equation developed by Bastiaanssen (1995) representing near-midday values as:

$$G/R_n = T_s\,(0.0038 + 0.0074\,\alpha)\,(1 - 0.98\,NDVI^4) \qquad (3)$$

Sensible heat flux (H) was estimated using the bulk aerodynamic resistance model and a procedure that assumed a linear relationship between the aerodynamic surface temperature-air temperature difference (dT) and radiometric surface temperature (T_s) calculated from extreme pixels as:

$$H = \rho_a \, C_p \, dT / r_{ah} \qquad (4)$$

where ρ_a is air density (kg/m^3), C_p is specific heat of air (1004 J kg^{-1} K^{-1}), and r_{ah} is the aerodynamic resistance to heat transport (s m^{-1}). After calculating dT at both cold and hot pixels, a linear relationship between dT and T_s is developed to estimate H iteratively correcting r_{ah} for atmospheric stability. This was done by applying the Monin-Obhukov Similarity (MOS) theory (Foken, 2006). This step required horizontal wind speed (u, m s^{-1}) that were measured at a nearby weather station, and a mechanism that extrapolates wind speed to a blending height of 100-200 m. In this study, a height of 200 m was used in the calculation of distributed friction velocity, a term utilized in the estimation of H. The dT artifice is expected to compensate for errors due to lack of proper atmospheric effects correction in the calibration of "at-sensor" brightness surface temperature in the process of obtaining radiometric surface temperature estimates. A full description of the METRIC™ and a detailed step by step procedure can be found in Allen et al. (2007a, b; 2008). Finally, METRIC™ was evaluated by comparing predicted R_n, G, H and instantaneous (hourly rates at satellite overpass time) ET (ET_{Inst}) with observed data. Root Mean Square Error (RMSE) and Mean Bias Error (MBE) statistics were used in the comparison of predicted against measured data.

RESULTS AND DISCUSSION

METRIC™ (Ver. 2.0.4) algorithms were used to derive α (albedo), T_s, R_n, G, H and ET_{Inst} maps. Figure 2 compares predicted radiometric surface temperatures on four lysimeters NE (31.0°C), SE (27.9°C), NW (39.2°C), and SW (39.6°C) with measured data. Excellent agreement was found between and observed and predicted T_s values. However, the model slightly under predicted T_s in the NW (3.2%) and over predicted for the SW (1.5%) lysimeter fields managed under dryland conditions. The MBE for all four lysimeters was 0.2°C with RMSE of only 2% of the observed mean T_s. These results were slightly better than that reported in Gowda et al. (2008) with SEBAL algorithm where the MBE and RMSE were 1.1°C and 3.8%, respectively.

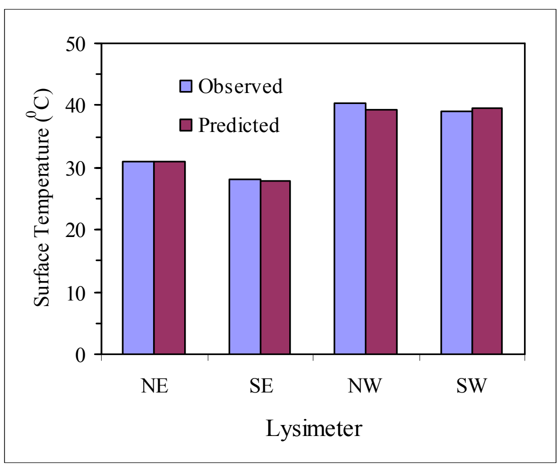

Figure 2. Comparison of predicted surface temperatures with measured data on four large lysimeters in Bushland, TX.

The anchor cold and hot pixels were selected in an agricultural setting where the cold pixel was planted to corn under center pivot irrigation system. The hot pixel was found on a bare soil site. The surface temperatures for cold and hot pixels were about 26.4 and 41.2°C, respectively. After determining the hot and cold pixels, initial estimation of dT and H was made for them under neutral atmospheric conditions and were subsequently adjusted for the unstable atmospheric conditions encountered on day of year (DOY) 191 using the MOS length scale iterative method. After six iterations, changes in r_{ah}, for the hot/cold pixels satisfied the convergence criteria of 5% difference in r_{ah} for each iteration cycle.

Figure 3(a-d) illustrates the comparison of predicted R_n, G, H, and ET_{Inst} with measured data on four lysimeters. R_n estimates compared well with the observed data. The MBE was about 29.7 W m^{-2} with the RMSE being only about 7.2% of the observed mean R_n on all four lysimeters. However, predicted R_n on NE lysimeter was 12.8% higher than the measured value. Comparison of G estimates with observed data indicated that the G sub-model used in the METRIC™ over predicted for all four lysimeters. The MBE±RMSE for predicted G was 26.3±26.4 Wm^{-2}.

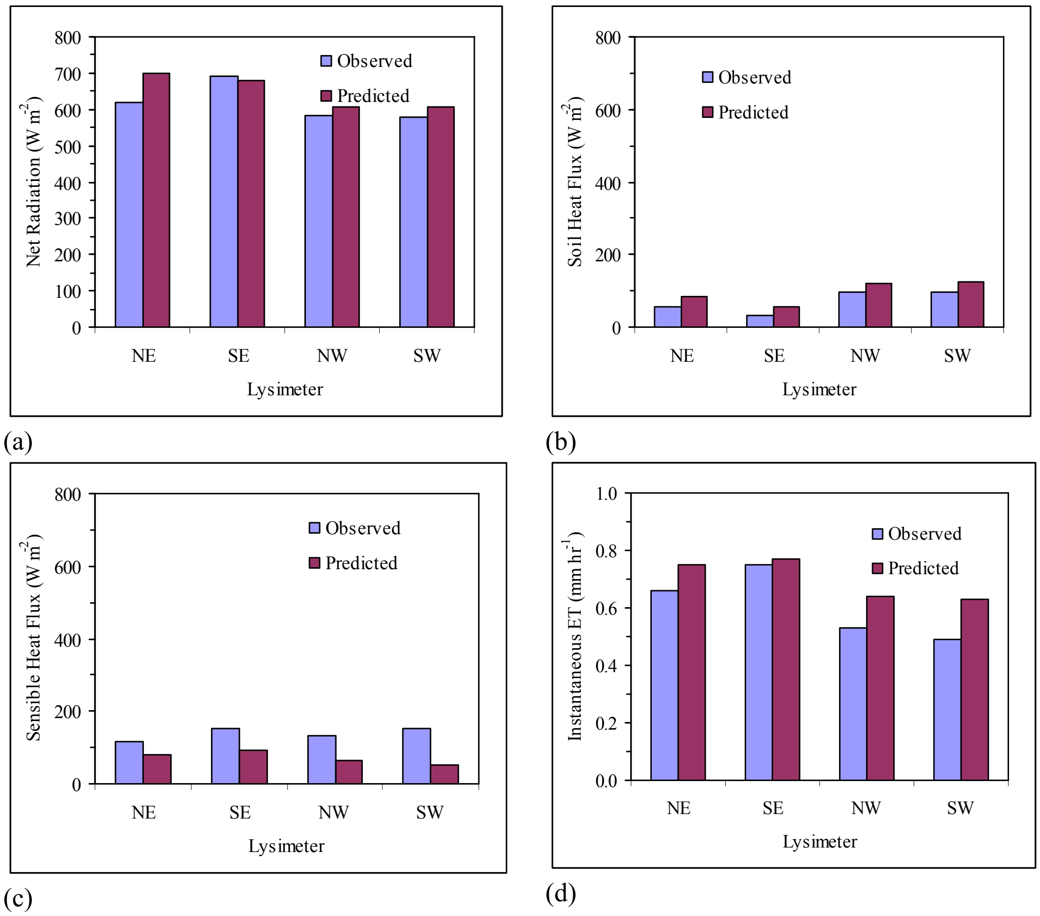

Figure 3. Predicted versus observed energy fluxes on four large lysimeters in Bushland, TX at 11:30 AM CST on July 10, 2007.

METRIC™ under predicted H for all four lysimeter fields. The MBE for predicted H was 65 W m^{-2} and the RMSE was about 50% of the observed mean H (138.1 W m^{-2}) for all four lysimeters. Consequently, the ET_{Inst} for all lysimeters fields were slightly over predicted with errors exceeding 7% and 20% for lysimeter fields under irrigation (SE and NE) and dryland management (SW and NW), respectively. This is consistent with the results reported in Timmermans et al. (2007) for SEBAL. However, ET predictions for dryland fields significantly improved over SEBAL estimates (Gowda et al., 2008). Errors in the ET predictions may be mainly due to errors in the prediction of G and in the selection of the hot pixel. This error associated with H pixel selection propagates into the T_s scaling-regression model used to derive dT in eq. 4 and corrupted sensible flux estimates in areas with moisture and surface roughness characteristics very different from those in the hot pixel. The NW and SW lysimeter fields were managed under dryland conditions and grain sorghum was planted in clumps (SW) and rows (NW) as part of another study that hypothesized to achieve higher water use efficiency. Relatively dry conditions at the time of satellite data acquisition combined with sparse but clumped vegetation on SW lysimeter and limited vegetation cover on the NW lysimeter field presented relatively hot pixels with very different moisture and roughness characteristics compared with other agricultural land in the surrounding region. The MBE±RMSE for estimated ET for all four lysimeters was 0.1±0.1 mm/hr.

CONCLUSIONS

METRIC™ is a single-source model requiring minimal amount of ancillary data. It was applied on a Landsat 5 TM image acquired on July 10, 2007 at 11:27 CST hours. Predicted T_s values agreed well with observed data on all four lysimeter fields. Predicted R_n compared well with the measured data. However, METRIC™ over predicted H for dryland conditions apparently due to errors in the selection of the hot pixel and surface roughness differences between the hot pixel and the dryland sorghum fields. Predicted ET_{Inst} for irrigated lysimeter fields compared better with measured data. Considering the minimal amount of ancillary data required for applying METRIC™ and good performance in predicting instantaneous ET on both dryland and irrigated fields, it is a promising tool for mapping ET in extensively irrigated Texas High Plains. However, a thorough evaluation of METRIC is needed for all major crops in the Texas High Plains under different agroclimatological conditions. At present, efforts are being made to thoroughly evaluate METRIC™ with 19 Landsat TM images acquired during 2006-2008 cropping seasons with short and tall crops.

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