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COMPARING SEBAL ET WITH LYSIMETER DATA IN THE SEMI-ARID TEXAS HIGH PLAINS

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ABSTRACT

SEBAL (Surface Energy Balance Algorithm for Land), a spatial evapotranspiration (ET) estimation method, has been applied with Landsat Thematic Mapper (TM) data throughout the world. However, it has never been tested for semiarid conditions of the Texas High Plains. In this study, SEBAL algorithm was applied to a Landsat TM image acquired on July 10, 2007 covering a major portion of the Texas High Plains. Performance of SEBAL was evaluated by comparing estimated ET with measured ET data on four large monolithic lysimeters at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX. Comparison of SEBAL-estimated instantaneous ET values with lysimetric measurements indicated that SEBAL may provide better ET estimates for irrigated fields. However, it performed poorly in predicting ET for fields under dryland management. This result may indicate that SEBAL might be sensitive to errors in the selection of the hot/dry pixel. Overall, SEBAL is a promising tool for mapping ET in the extensively irrigated Texas High Plains. However, more evaluation is needed for different agroclimatological conditions in the region.

INTRODUCTION

Evapotranspiration (ET) has long been recognized as the most important process that plays an essential role in determining exchanges of energy and mass between the hydrosphere, atmosphere and biosphere (Sellers et al., 1996). In agriculture, ET is a major consumptive use of both irrigation water and precipitation on agricultural land. Any attempt to improve water use efficiency must be based on reliable estimates of ET, which includes water evaporation from land and water

surfaces and transpiration by vegetation. ET varies regionally and seasonally according to weather and wind conditions. Understanding these variations in ET is essential for managers responsible for planning and managing water resources, especially in arid and semi-arid regions of the world where crop water demand generally exceeds precipitation. Irrigation from surface and/or groundwater resources to meet the deficit is required.

Irrigation in the semi-arid Texas High Plains was developed solely from the Ogallala (High Plains) Aquifer, as surface water resources in the region are generally inadequate for this purpose. One impediment to better groundwater management is that the overall water balance of the region is still incompletely understood, particularly in terms of evapotranspiration and recharge as they vary spatially in the region.

Remote sensing has long been recognized as the most feasible means to provide spatially distributed regional ET information on land surfaces (Park et al., 1968; Jackson, 1984). This is based on the rationale that ET is a change of the state of water using available energy in the environment for vaporization (Su et al., 2005). Remote sensing based energy balance (EB) models 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 W m^{-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).

Surface Energy Balance Algorithm for Land (SEBAL; Bastiaanssen et al., 1998a,b) is an EB-based spatial ET estimation method. It has been applied with Landsat Thematic Mapper (TM) data through out the world. However, the SEBAL 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 SEBAL, an EB based ET estimation algorithm 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, Texas, USA (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 classified as slowly permeable Pullman clay loam soils. The major crops in the study area are corn, sorghum, winter wheat, and cotton.

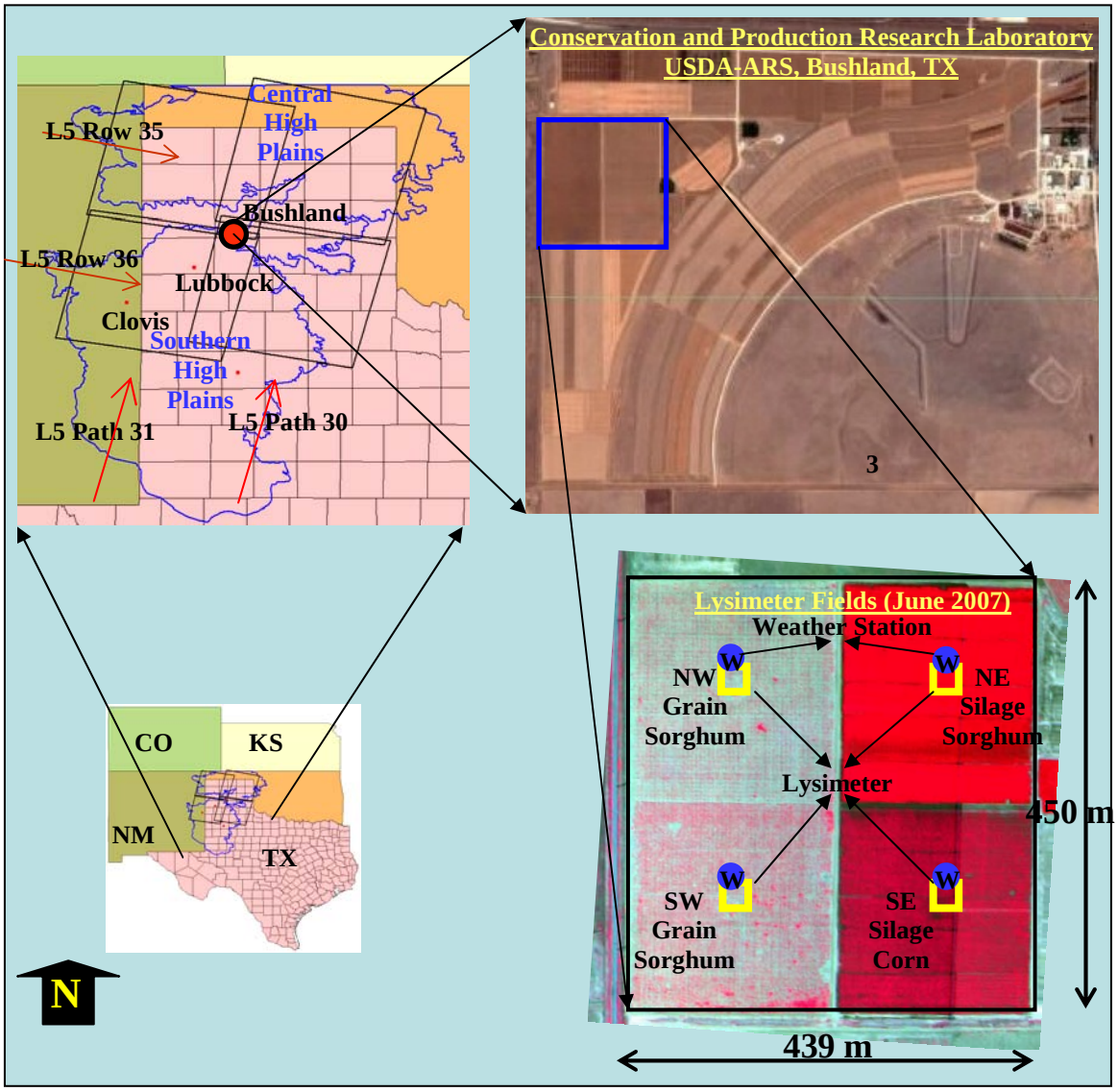

Figure 1. Location of Texas High Plains and four large weighing lysimeters in the USDA-ARS Conservation and Production and Research Laboratory, Bushland, TX, USA.

SEBAL estimated ET values were verified by comparison to soil water mass change-based hourly ET values from 4 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 on 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, Washington] and two infrared thermometers (IRT) (2G-T-80F/27C, Exergen, Watertown, Mass.) for measuring net radiation and surface temperature, respectively. More information of lysimeter setup can be found in Howell et al. (1995).

Surface Energy Balance Algorithm for Land (SEBAL)

SEBAL 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 longwave 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 shortwave radiation, respectively. $R_L\downarrow$ and $R_L\uparrow$ are the longwave incoming and outgoing radiation, respectively. The $R_S\downarrow$ and $R_S\uparrow$ are estimated as:

$$R_S\downarrow = G_{sc} \cos\theta \, d_r \, \tau_{sw} \qquad (3)$$

$$R_S\uparrow = \alpha \, R_S\downarrow \qquad (4)$$

where G_{sc} is the solar constant (1367 W m^{-2}), $\cos\theta$ is the cosine of the solar incidence angle, d_r is the inverse squared relative earth-sun distance, τ_{sw} is the broadband one-way atmospheric transmissivity for shortwave radiation, and α is the broadband albedo of land surfaces. The τ_{sw} is computed as a function of elevation (Allen et al., 1998):

$$\tau_{sw} = 0.75 + 0.0002z \qquad (5)$$

where z is the elevation above the mean sea level in m. The albedo (α) of land surfaces is estimated using albedo of the top of the atmosphere (α_{TOA}), the path radiance albedo ($\alpha_{path\ radiance}$), and τ_{sw} as:

[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.

$$\alpha = (\alpha_{TOA} - \alpha_{path\ radiance}) / \tau^2_{sw} \qquad (6)$$

The $\alpha_{path\ radiance}$ ranges between 0.025 and 0.04, and Bastiaanssen (2000) recommends a value of 0.03.

The $R_L\downarrow$ is the downward thermal radiation flux originating from the atmosphere (W m^{-2}) and is estimated as:

$$R_L\downarrow = \varepsilon_a \sigma T_a^4 \qquad (7)$$

where ε_a (dimensionless) is the atmospheric emissivity, is the Stefan-Boltzmann constant (5.67 x 10^{-8} W m^{-2} K^{-4}), and T_a (K) is the near-surface air temperature. The empirical equation for ε_a is given (Bastiaanssen et al., 1998a) as:

$$\varepsilon_a = 0.85 (-\ln \tau^2_{sw})^{0.09} \qquad (8)$$

The $R_L\uparrow$ is the thermal radiation flux emitted from the earth surface to the atmosphere and is determined by the Stefan-Boltzmann law:

$$R_L\uparrow = \varepsilon_s \sigma T_s^4 \qquad (9)$$

where ε_s is the surface emissivity (the ratio of the energy radiated by a surface to that by the blackbody at the same temperature) and T_s is the surface temperature (K), respectively. In SEBAL, ε_s is estimated using the normalized difference vegetation index (NDVI) when NDVI > 0 as:

$$\varepsilon_s = 1.009 + 0.047 \ln (NDVI) \qquad (10)$$

It is assumed ε_s to be one for NDVI < 0. Surface temperature (T_s) is calculated from the thermal band radiance values for Landsat 5 sensors using the simplified Planck function (Markham and Barker, 1986) and corrected using ε_s as:

$$T_s = k_2 / \ln [(\varepsilon_s k_1/R) + 1] \qquad (11)$$

where R is the Landsat TM/ETM+ band 6 radiance, and k_1 and k_2 are the calibration constants. For Landsat TM, k_1 and k are 607.76 mW cm^{-2} sr-1 μm^{-1} and 1260.56 K, respectively.

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

$$G/R_n = T_s (0.0038 + 0.0074 \alpha) (1 - 0.98 NDVI^4) \qquad (12)$$

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. Basically, extreme pixels showing cold/wet and hot/dry spots were selected to develop a linear relationship between dT and T_s. At the cold pixel in the satellite imagery, H was assumed non-existent i.e. H_{cold}=0 and at the hot pixel, LE was set to zero which in turn allows one to set H_{hot} = $(R_n–G)_{hot}$. Then, dT_{cold}=0 and dT_{hot} can be obtained by solving the bulk aerodynamic resistance equation for the hot pixel as:

$$H = \rho_a C_p dT / r_{ah} \qquad (13)$$

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 T_a and 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. Furthermore, the SEBAL algorithm does not assume that radiometric and aerodynamic temperatures are equivalent. A detailed step-by-step procedure is presented in Morse et al. (2001). Finally, SEBAL 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

SEBAL algorithm was applied to a Landsat 5 TM image acquired on July 10, 2007 to derive α, T_s, R_n, G, H and ET_{Inst} maps. Figure 2 compares predicted radiometric surface temperatures on four lysimeters NE (30.7°C), SE (26.5°C), NW (41.8°C), and SW (44°C) (see Fig. 1) with measured data. Predicted T_s values were slightly lower (0.7% for NE and 5.7% for SE) than measured values in the irrigated NE and SE lysimeter fields. However, the model slightly over predicted T_s in the NW (3.3%) and SW (12.7%) lysimeter fields managed under dryland conditions. The maximum prediction error was associated with SW field where predicted T_s was 12.7% higher than the measured value. The MBE for all four lysimeters was 1.1°C with RMSE of about 3.8% of the observed mean T_s.

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. The surface temperatures for cold and hot pixels were about 24.8 and 52°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 DOY 191 using the MOS length scale iterative method. After five iterations, changes

in r_{ah}, for the hot/cold pixels satisfied the convergence criteria of 5% difference in r_{ah} for each iteration cycle.

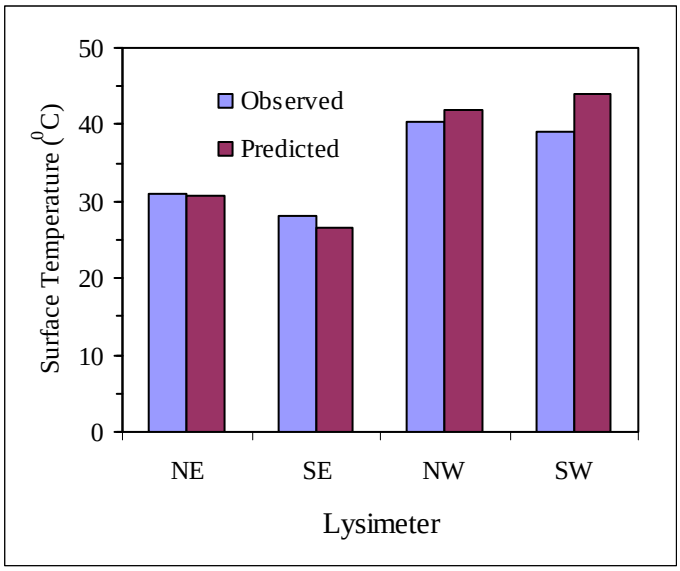

Figure 2. Comparison of predicted surface temperatures with measured data on four large lysimeters in Bushland, TX.

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 22.9 W m^{-2} with the RMSE being only about 3.4% of the observed mean R_n on all four lysimeters. However, predicted R_n on NE lysimeter was 13.4 % higher than the measured value. Comparison of G estimates with observed data indicated that the G sub-model used in the SEBAL over predicted for NE, NW, and SW lysimeters and under predicted for SE lysimeter. The MBE±RMSE for predicted G was 10.8±15.5 W m^{-2}.

SEBAL has grossly over predicted H for NW and SW lysimeters with dryland cropping system. The MBE for predicted H was 127.9 W m^{-2} and the RMSE was about 61% of the observed mean H (125.8 W m^{-2}) for all four lysimeters. Consequently, the ET_{Inst} for NW and SW lysimeters were grossly under predicted indicating that SEBAL had difficulties estimating sensible heat fluxes for relatively dry areas. This is consistent with the results reported in Timmermans et al. (2007). This may be mainly due to error in the selection of the hot pixel. This error propagates into the T_s scaling-regression model used to derive dT in equation (13) and corrupt 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. In addition, lack of atmospheric interference corrections in the calibration of "at-sensor" brightness surface temperature might have cause errors in the derived radiometric surface temperature. Atmospheric effects corrections using a radiative transfer model corrects hotter pixels in greater proportion than cooler pixels. Thus, errors in the true value of T_s coupled with errors in the selection of the Hot pixel may have contributed to the determination of a bias dT vs. T_s relationship. The benefits of properly calibrating the satellite thermal band, considering surface emissivity and atmospheric effects can be found in Chávez et al. (2007). The MBE±RMSE for estimated ET for all four lysimeters was 0.1±0.1 mm/hr, however, the predicted ET_{Inst} compared well with the observed values on the irrigated NE and SE lysimeters with MBE less than 0.01 mm/hr.

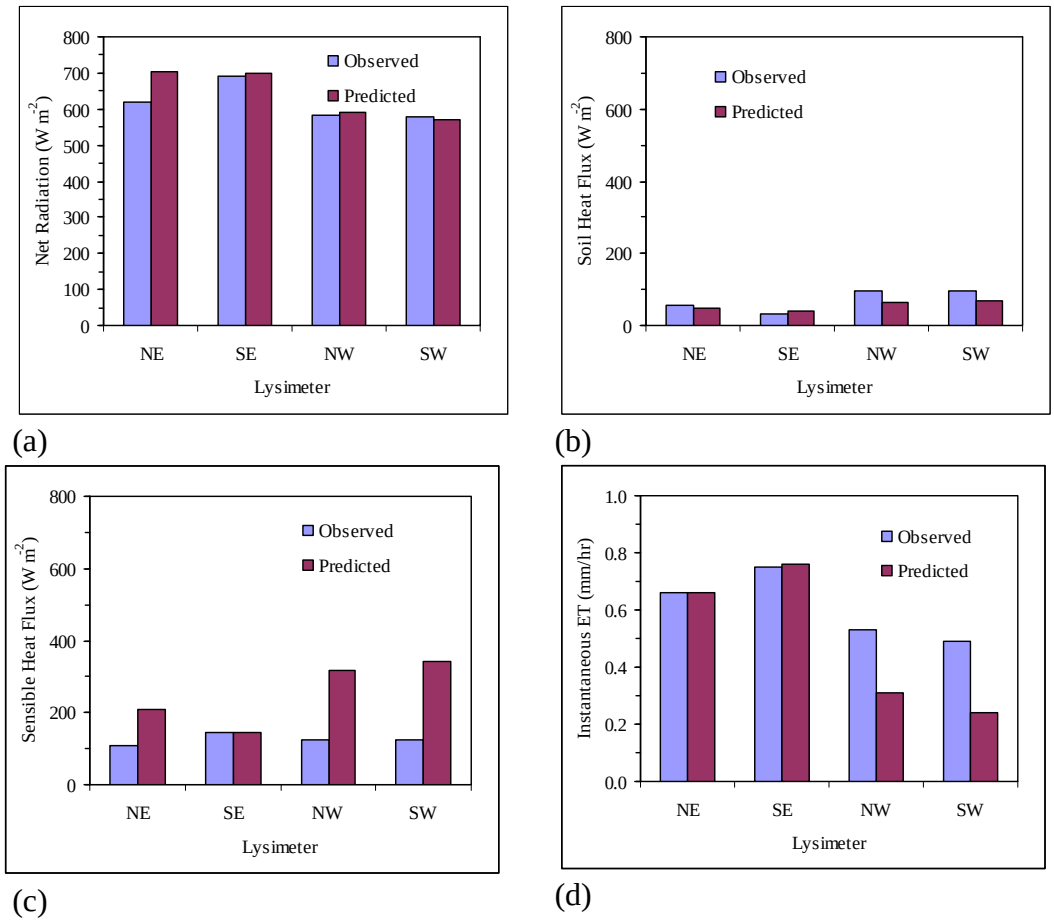

Figure 3. Predicted versus observed energy fluxes on four large lysimeters in Bushland, TX.

CONCLUSIONS

SEBAL 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 compared better with observed values on three lysimeter fields except SW lysimeter field where the model overestimated the measured value

by 12.7%. Predicted R_n compared well with the measured data. However, SEBAL grossly over predicted H for dryland conditions apparently due to lack of atmospheric interference corrections for surface temperature and errors in the selection of the hot pixel. Predicted ET_{Inst} for irrigated lysimeter fields compared better with measured data. Considering the minimal amount of ancillary data required for applying SEBAL and excellent performance in predicting instantaneous ET on irrigated fields, the SEBAL is a promising tool for mapping ET in extensively irrigated Texas High Plains. However, a thorough evaluation of SEBAL is needed for all major crops under different agroclimatological conditions.

ONGOING RESEARCH

At present, efforts are being made to automate the implementation of SEBAL with Landsat TM images. Once it is completed, SEBAL will be applied to 11 Landsat TM images acquired during 2006 and 2007 cropping seasons to thoroughly evaluate its ability and robustness to derive ET maps for the Texas High Plains.

REFERENCES

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. (1998). Crop evapotranspiration: Guidelines for computing crop requirements. *Irrigation and Drainage Paper No. 56*. FAO: Rome, Italy, 300p.

Bastiaanssen, W.G.M. (1995). Regionalization of surface flux densities and moisture indicators in composite terrain: A remote sensing approach under clear skies in Mediterranean climates. *Ph.D. Dissertation*, CIP Data Koninklijke Bibliotheek, Den Haag, The Netherlands, 273p.

Bastiaanssen, W.G.M., M. Menenti, R.A. Feddes, and A.A. Holtslang. (1998a). A remote sensing surface energy balance algorithm for land (SEBAL): 1. Formulation. *Journal of Hydrology*, 212-213, 198-212.

Bastiaanssen, W.G.M, H. Pegrum, J. Wang, Y. Ma, J. Moreno, G.J. Roerink, and T. Van der Wal. (1998b). The surface energy balance algorithm for land (SEBAL): Part 2 validation. *Journal of Hydrology*, 212-213, 213-229.

Bastiaanssen, W.G.M. (2000). SEBAL-based sensible and latent heat fluxes in the irrigated Gediz Basin, Turkey. *Journal of Hydrology*, 229, 87-100.

Chávez, J.L., P.H. Gowda, T.A. Howell, and K.S. Copeland. (2007). Evaluating three evapotranspiration mapping algorithms with lysimetric data in the semi-arid Texas High Plains. *In Proceedings of the 28th Annual International Irrigation Show*, December 9–11, 2007, San Diego, California, USA, p. 268-283. [CDROM].

Foken, T. (2006). 50 Years of the Monin-Obukhov similarity theory. *Boundary-Layer Meteorology*, 119(3), 431 - 447.

Howell, T.A., A.D. Schneider, T.H. Marek, and J.L. Steiner. (1995). Calibration and scale performance of Bushland weighing lysimeters. *Transactions of the ASAE,* 38, 1019 – 1024.

Jackson, R.D. (1984). Remote sensing of vegetation characteristics for farm management. *SPIE,* 475, 81-96.

Kramber, W.J., A. Morse, R.G. Allen, M. Tasumi, R. Trezza, and J.L. Wright. (2002). Developing surrogate pixels for comparing SEBAL ET with lysimeter ET measurements. Geoscience and Remote Sensing Symposium, 2002, IGRASS '02, 2002 IEEE International, 1, 119-121.

Markham, B.L., and J.L. Barker. (1986). Landsat MSS and TM post calibration dynamic ranges, exoatmospheric reflectance, and at-satellite temperatures. *EOSAT Landsat Technical Notes*, 1, 3-8.

Morse, A., R.G. Allen, M. Tasumi, R. Trezza, and J.L. Wright. (2001). Application of the SEBAL methodology for estimating evapotranspiration and consumptive use of water through remote sensing. *A final report to the Ratheon Systems Company Earth Observation System Data and Information System Project.* 142p.

Park, A.B., R.N. Colwell, and V.F. Meyers. (1968). Resource survey by satellite; science fiction coming true. *Yearbook of Agriculture*, 13–19.

Sellers, P.J., D.A. Randall, G.J. Collatz, J.A. Berry, C.B. Field, D.A. Dazlich, C. Zhang, G.D. Collelo, and L. Nounoua. (1996). A revised land surface parameterization (SiB2) for atmospheric GCMS, Part 1: Model formulation. *Journal of Climate*, 9, 676-705.

Su, H., M.F. McCabe, E.F. Wood, Z. Su, and J.H. Prueger. (2005). Modeling evapotranspiration during SMACEX: Comparing Two approaches Local- and Regional-Scale prediction. *Journal of Hydrometerology*, 6(6), 910-922.

Timmermans, W., W.P. Kustas, M.C. Anderson, and A.N. French. (2007). An intercomparison of the surface energy balance algorithm for land (SEBAL) and the two-source energy balance (TSEB) modeling schemes. *Remote Sensing of Environment*, 108, 369-384.