An Aerodynamic Temperature-based Regional ET Model Evaluation for Texas High Plains' Agrometeorological Conditions

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ABSTRACT

High groundwater pumping costs and rapidly declining water levels in the Texas High Plains makes it imperative to improve irrigation water management for sustainability and regional economic viability. In this area, agriculture uses approximately 89% of groundwater withdrawals. Accurate regional evapotranspiration (ET) maps would provide valuable information on crop water use, irrigation efficiencies and aid in estimating important regional hydrology (e.g., recharge, groundwater pumping, etc.). In this study, an Aerodynamic Temperature-based Surface Energy Balance Model for estimating spatially distributed ET rates was evaluated. Data from four large monolithic weighing lysimeters (two with irrigated crops and two with dryland crops) and one smaller lysimeter (in a grass field) at the Conservation and Production Research Laboratory, USDA-ARS at Bushland, TX [35º 11' N, 102º 06' W; 1,170 m elevation MSL] were used to evaluate the model. For this purpose, a Landsat 5 Thematic Mapper image was acquired on 23 July 2006, for the overpass at 17:19 GMT. The satellite image covered a major portion of the Southern High Plains (parts of the Texas Panhandle and northeastern New Mexico). Lysimeter-measured ET rates varied from 2.4 to 7.8 mm d^{-1}. An excellent agreement was found between remote sensing ET estimates and lysimeter derived ET values for four lysimeter fields (ET estimation error ranging from -5.5 to 4.5%) while less agreement was found for the south-west lysimeter field (-14.0%) which appears to have been affected by advection. These results indicate that the remote sensing aerodynamic temperature based ET model may be suitable for application in the Texas High Plains. However, further research will include the evaluation of the aerodynamic model over the entire crop growing season under different agroclimatological conditions.

KEYWORDS: Ogallala Aquifer Region, remote sensing, crop water use, irrigation

INTRODUCTION

Irrigation and rainfall water are beneficially used by agricultural crops through the process known as evapotranspiration (ET). Improvements in agricultural water use efficiency must be based on accurate and reliable estimates of ET, which includes water evaporation from land and water surfaces and transpiration by vegetation. ET varies spatially and seasonally according to vegetation and soil types, and weather conditions. Reliable regional ET estimates based on remote sensing (RS) inputs could be useful to improve spatial crop water management. RS-based ET models use images in the visible, infrared, and thermal infrared bands (acquired by sensors on airborne and satellite platforms) as input mainly in energy balance (EB) of land surfaces algorithms. One of those EB algorithms is based on the RS estimation of aerodynamic temperature, which is used in the estimation of sensible heat flux.

OBJECTIVE

To evaluate an "Aerodynamic Temperature"-based Surface Energy Balance Model for its ability to derive daily ET from Landsat 5 Thematic Mapper (TM) data using measured ET from four large monolithic weighing lysimeters and one smaller lysimeter, at the Conservation and Production Research Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Bushland, TX.

METHODS AND MATERIALS

EB algorithms convert RS radiances into land surface characteristics such as albedo, leaf area index, vegetation indices, surface emissivity and surface temperature to estimate ET as:

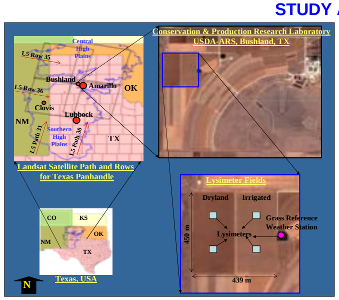
$$LE = R_n - G - H \quad (1)$$

Where, R_n is the net radiation resulting from the budget of short and long wave incoming and outgoing radiation respectively, 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}). LE is converted into ET (mm h^{-1} or mm d^{-1}) by multiplying LE by an appropriate time unit (e.g., 3600 s for hourly ET) and dividing it by the latent heat of vaporization (λ_v; ~2.45 MJ kg^{-1}) and by the water density (ρ_w; 10^3 kg m^{-3}). R_n is estimated by incorporating weather data and spatially-distributed surface reflectance and radiometric temperature (Jackson et al., 1983) as:

$$R_n = (1 - \alpha)R_s + \varepsilon_a \sigma T_a^4 - \varepsilon_s \sigma T_s^4 \quad (2)$$

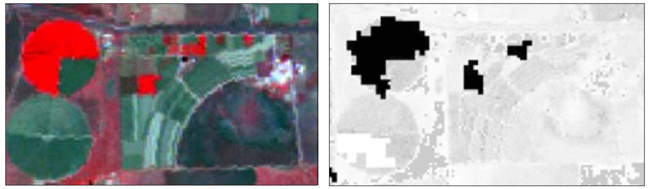
where α is surface albedo, R_s is incoming short wave radiation (W m^{-2}) measured with pyranometers or calculated, σ is the Stefan-Boltzmann constant (5.67E-08 W m^{-2} K^{-4}), ε is emissivity (dimensionless) and T temperature (K) with subscripts "a" and "s" for air and surface respectively. T_s is the remotely sensed radiometric surface temperature which is obtained after correcting the sensor brightness temperature imagery for atmospheric effects and for thermal surface emissivity using the radiative transfer model MODTRAN v4 (Berk et al., 2000).

STUDY AREA



The USDA-ARS Conservation and Production Research Laboratory (CPRL) is located at Bushland, TX. The CPRL is located 1170 m above mean sea level at 35°11' N, 102°06' W. The soil is classified as slowly permeable Pullman clay loam. The weighing lysimeter facility used in this research consists of four large and one small weighing lysimeters (Howell et al., 1995). Each of the four large lysimeters are located in the middle of 4.7-ha fields; and are arranged in a block pattern. The smaller lysimeter is located in a 0.8-ac grass field. Dryland cropping systems are managed on two lysimeter fields in the west and irrigated cropping systems are managed on the two lysimeter fields in the east with a 10-span lateral move sprinkler system. The smaller lysimeter is located within a grass reference field, which is part of the Texas High Plains ET Network.

Landsat 5 TM Imagery



Three-band surface reflectance (left) and radiometric temperature (right) images, from LandSat 5, covering the experiment area and a couple of commercial center pivot fields to the west.

Soil heat flux (G, W m^{-2}) was modeled as a function of R_n, vegetation index NDVI, T_s, and surface albedo (α) for near midday values following the model by Bastiaanssen (2000):

$$G = ((T_s - 273.15)\ (0.0038+0.0074\ \alpha)\ (1\text{-}0.98\ NDVI^4))\ R_n \quad (3)$$

where NDVI is [(R-NIR)/(R+NIR)]. R is reflectance in the red band and NIR is reflectance in the near infrared band.

Sensible heat flux (H, W m^{-2}) is defined by the bulk aerodynamic resistance equation, which uses aerodynamic temperature ($\mathbf{T_{aero}}$) and aerodynamic resistance to heat transfer (r_{ah}). $\mathbf{T_{aero}}$ is average aerodynamic temperature (K), which is defined for a uniform surface as the air temperature at the height of the zero plane displacement (d, m) plus the roughness length (Z_{oh}, m) for sensible heat transfer, and r_{ah} is aerodynamic resistance (s m^{-1}) to heat transfer from Z_{oh} to Z_m [height of wind speed measurement (m)]. $\mathbf{T_{aero}}$ was computed adopting Chávez et al. (2005) model that was developed using H data collected using eddy covariance energy balance systems over corn and soybean fields (rainfed) in central Iowa.

$$H = \rho_a C_{pa} (\mathbf{T_{aero}} - T_a) / r_{ah} \quad (4)$$

where ρ_a is air density (kg m^{-3}), C_{pa} is specific heat of dry air (1005 J kg^{-1} K^{-1}).

$$\mathbf{T_{aero}} = 0.534\ (T_s - 273.15) + 0.39\ (T_a - 273.15) + 0.224\ LAI - 0.192\ U + 1.67 \quad (5)$$

where U is horizontal wind speed (m s^{-1}) and LAI is the leaf area index obtained using remote sensing inputs through a locally calibrated model (Gowda et al., 2007).

$$LAI = 8.768 \times (NDVI)^{3.616} \quad (6)$$

r_{ah} was calculated between two near surface heights, 0.1 and 2.0 m using a wind speed extrapolated from a blending height above the ground surface of 200 m and an iterative stability correction scheme for atmospheric heat transfer based on the Monin-Obhukov stability length scale (L, m) described by Foken (2006).

$$r_{ah} = \{\ln[(Z_m - d) / Z_{oh}] - \Psi_h[(Z_m - d) / L] + \Psi_h[Z_h / L]\} / (u_* k) \quad (7)$$

where k is the von karman constant (0.41), Ψ_h is the stability correction factor for atmospheric heat transfer (m), u_* is the friction velocity (m s^{-1}) and was calculated as:

$$u_* = \{ U k \} / \{\ln[[(Z_m - d) / Z_{om}] - \Psi_m[(Z_m - d) / L] + \Psi_m[Z_{om} / L]\} \quad (8)$$

where Ψ_m is the stability correction factor for momentum transfer (m).

Daily ET estimates were calculated from the instantaneous (at overpass time) remote sensing evaporative fraction $(LE/(R_n - G))_i$ estimates and ground-based measurements of average daily available energy $(R_n - G)_d$ in units of W m^{-2}. To convert energy units into equivalent evapotranspirated water depth, a division by the latent heat of vaporization [λ_{LE} = 2.501 – 0.00236 (T_a – 273.15)], in units of MJ kg^{-1}, is needed :

$$ET_d = (LE/(R_n - G))_i\ (R_n - G)_d\ \{ t / [2.501 - 0.00236\ (T_a - 273.15)]\ (10^6)\ (\rho_w) \} \quad (9)$$

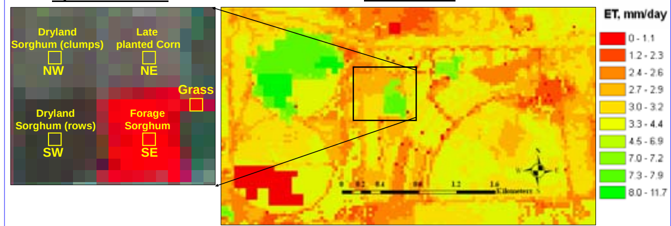
where t is a time factor equal to 86400 s, and ρ_w is density of water (1 Mg m^{-3}).

We evaluated resulting ET_d values by comparing with lysimeter measured ET values by computing absolute differences and percent errors:

$$\text{Difference (\%)} = (ET_{d}\text{\_estimated} - ET_{d}\text{\_measured}) \times 100 / ET_r \quad (10)$$

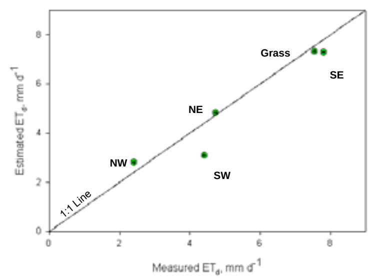
where ET_d_estimated was ET estimated by the RS $\mathbf{T_{aero}}$-based method and ET_measured was ET derived from the lysimeters daily water mass balance (loss/gain) data. ET_r is the alfalfa reference ET value obtained from the Bushland-ARS weather station published on line (TXHPET, 2007).

RESULTS



Comparison of Estimated vs. Measured daily ET (ET_d)

Lysimeter Location	Measured ET_d (mm/d)	Predicted ET_d (mm/d)	Difference (mm/d)	Difference (%)
NE	4.7	4.8	0.1	1.2
SE	7.8	7.3	-0.5	-5.5
NW	2.4	2.8	0.4	4.5
SW	4.4	3.1	-1.3	-14.1
Grass	7.5	7.3	-0.2	-2.2



CONCLUSIONS

The remote sensing based $\mathbf{T_{aero}}$ model was found suitable for estimating ET in the semi-arid Texas High Plains Region in the south-central United States. Daily ET estimation errors ranged from – 0.5 mm d^{-1} (-5.5 %) to 0.4 mm d^{-1} (+4.5 %) on four lysimeter fields while the error reached -1.3 mm d^{-1} (-14.1 %) for the SW lysimeter field, which most likely was more affected by advected heat from dry surfaces south-west (predominant wind direction) of this field. Overall, this is an excellent result of an aerodynamic temperature model that was developed for a different environment. However, more evaluation is needed for different agroclimatological conditions in the Texas High Plains Region.

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