ENERGY BUDGET OVER SEMI-ARID AGRO-ECOSYSTEM USING SATELLITE DATA

*K.K. Dakhore, B.K. Bhattacharya[b], K. Mallick[c], R. Nigam[b], N.K. Patel[b], V. Pandey [a], B.I. Karande[a] and A.M. Shekh[a]

[a]Deptt. of Agril. Meteorology, Anand Agricultural University, Anand-388 110, India
[b]Agriculture-Forestry and Environment Group, Space Applications Centre (ISRO), Ahmedabad-380 015, India
[c]Deptt. of Environmental Science, Lancaster Environment Centre Lancaster University, LA1 4YQ
*Deptt. of Natural Resources, International Institute for Geo-Information Science and Earth Observation,
P.O. Box 6, 7500 AA Enschede, The Netherlands

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ABSTRACT:

Energy-water-carbon cycle is the central theme of biosphere-atmosphere interaction to understand the response and feedback processes in a climate system. The crop response in a semi-arid climate is frequently encountered by water scarcity due to maldistribution of rainfall or lack of irrigation water leading to low agricultural productivity. The characterization of water stress over large agriculture using thermal regime over crop surface in periodic manner throughout crop growth cycle is thus extremely important. Though, conventional measurements with Lysimeter keep record of field and soil specific water balances in root zone but cannot be extrapolated to larger area. The combination of optical band data in terms of albedo, NDVI threshold based emissivity and thermal band data in terms of Land Surface Temperature can represent evapotranspiration (ET) through energy balance approach over a spatial domain. Energy balance estimates derived from MODIS AQUA were validated with in situ attented and unattended observations for two wheat seasons, 2005 - 06 and 2006 - 07, within a 5km x 5km wheat growing region of Kheda district in Gujarat. Daily AQUA evapotranspiration estimates in terms of daytime latent heat fluxes were found to have root mean square error (RMSE) 29 Wm-2 (r = 0.72) and 26 Wm-2 (r = 0.8), respectively as compared to attended measurements during both the seasons. Correlation was substantially more and RMSE were less when estimates were compared with in situ measurements using Large Aperture Scintillometer (LAS) sensible heat fluxes.

1. INTRODUCTION

The crop response in semi-arid agro-ecosystem is frequently encountered by water scarcity due to maldistribution of rainfall or lack of irrigation water or its timely availability. It gives low productivity to overall growth in agriculture. The characterization of water stress over large area agriculture using thermal and radiation regime over crop surface in periodic manner throughout crop growth cycle is extremely important. Though, conventional measurements with lysimeter keep record of field and soil specific water balances in root zone but cannot be extrapolated to larger area. The ground based micrometeorological or Bowen ratio towers having net radiometer at one height and temperature, humidity, wind speed sensors at multiple heights are also used to compute energy budget components to derive stress behavior over relatively larger area depending on the fetch (Shekh et al., 2001). Most of the times, the ground based equipments lose the proper calibration and become non-functional in the long run. These are rather more useful to derive crop and soil specific parameters and coefficients required to calibrate soil-atmosphere-vegetation-transfer (SVAT) models to simulate energy balance components. The concomitant use of satellite optical and thermal data directly or their assimilation through SVATs is useful to represent water stress on pixel-by-pixel basis using energy balance approach for regular monitoring on a regional scale (state level).

Land surface temperature (LST) is a good indicator of the evaporation from the Earth's surface and the so-called greenhouse effect because it is one of the key parameters in the physics of land-surface processes on a regional as well as global scale. It acts as a link for surface-atmosphere interactions and energy fluxes between the atmosphere and the ground (Mannstein, 1987; Sellers et al., 1988). Therefore, it is required for a wide variety of climatic, hydrological, ecological and biogeochemical studies (Camillo, 1991; Schmugge and Becker, 1991; Running, 1991; Running et al., 1994; Zhang et al., 1995). Another important surface parameter is expressed in terms of the Normalized Difference Vegetation Index (NDVI), derived from the red and near infrared (NIR) channels in electromagnetic spectrum (Tucker et al., 1984). The NDVI represents amount of greenness and fractional vegetation cover (Tucker et al., 1984; Tucker et al., 1986) and is an indicator of leaf area index and energy partitioning between canopy and soil below. Thus, the combination of optical bands data in terms of albedo, NDVI threshold based emissivity and thermal signatures in terms of LST from satellite platform can generate evapotranspiration on spatial scale through energy balance approach. Regional evapotranspiration is, therefore, important to understand energy, water and carbon cycles and their relevance to climate change studies. As a subset of that, the present study was undertaken with the following objectives :

- To implement a simplified single-source energy balance scheme with MODIS TERRA (11.00hrs) and AQUA (13.30 hrs) optical and thermal data.

*dakhorekk@yahoo.com

- To assess the accuracy of energy balance estimates with respect to measurements over semi-arid wheat

2. MATERIALS AND METHODS

Intensive diurnal measurements on energy balance components were made *in situ* portable Bowen ratio observations in replicates as well as area averaged unattended observations from Large Aperture Scintillometer (LAS) within a 5km x 5km wheat growing region of Kheda district in Gujarat. This validation experiment was carried out for two consecutive wheat seasons, 2005-06 and 2006-07.

2.1 Approach for Estimating Surface Energy Balance Components and Evapotranspiration

Actual evapotranspiration (AET) or ET can be estimated from latent heat fluxes (λE) and latent heat (L) of evaporation. Latent heat flux (λE) is generally computed as a residual of surface energy balance. A single (soil-vegetation complex as single unit) source surface energy balance can be written as

$$\lambda E = Rn - G - H - M \quad (1)$$

The energy component for metabolic activities (M) is very small and hence can be neglected. The equation 1 can be rewritten as

$$\lambda E = Rn - G - H \quad (2)$$

Rn = net radiation, H = sensible heat flux, G = ground heat flux, Q = net available energy Q.

Assuming energy balance closure at any instance during a day, equation 2 can also be written as

$$\lambda E_{ins} = Q_{ins}.\Lambda_{ins} = (Rn - G)_{ins}.\Lambda_{ins} \quad (3)$$

Where Λ_{ins} = instantaneous evaporative fraction

2.2 Estimation of Λ_{ins}

In the present study, Λ_{ins} was estimated from LST- albedo two dimensional scatterogram using techqnique given by Roerink et al. (2000) and further used by Verstraeten et al. (2005) over European forest with NOAA AVHRR data and by Mallick et al. (2009) over Indian agroecosystems using MODIS AQUA data. LST and albedo from MODIS TERRA and AQUA observations corresponding to overpass timings, 11: 00-11:30hrs and 13:00-13:30hrs Local Mean Time (LMT) respectively was used to derive Λ_{ins}.

2.3 Estimation of Q_{ins}

Instantaneous net available energy

$$Q_{ins} = Rn_{ins} - G_{ins} \quad (4)$$

G_{ins} = instantaneous ground heat flux

Clear sky instantaneous net radiation (Rn_{ins}) was computed from surface radiation budget.

$$Rn_{ins} = Rns_{ins} - Rnl_{ins} \quad (5)$$

Rns_{ins} = instantaneous net shortwave radiation (Wm^{-2})

$$= Rns_{ins} = Rs_{ins}(1-\alpha) \quad (6)$$

α = surface albedo which was computed by converting seven narrow-band optical reflectances using coefficients given by Liang (2002)

Rs_{ins} = instantaneous insolation (Wm^{-2}) computed using WMO clear sky model

$$Rs_{ins} = a.I_0.\varepsilon.(SIN\gamma)^b \quad (7)$$

The coefficients, 'a' and 'b' were worked out to be 0.75 and 1.28 over Indian sub-continent by Mallick et al (2009)

Where I_0 = solar constant = 1367 Wm^{-2}

= sun-earth distance correction factor

γ = sun elevation angle

Rnl_{ins} = instantaneous net longwave radiation (Wm^{-2})

= downwelling longwave – outgoing longwave

$$= \varepsilon_s \varepsilon_a \sigma T_a^4 - \varepsilon_s \sigma T_s^4$$

T_s = land surface temperature (K). Here, MODIS land surface temperature (LST) products from TERRA and AQUA were used.

σ = Stephan-Boltzmann constant (5.67 X 10^{-8} $Wm^{-2}S^{-1}K^{-4}$)

ε_s = surface emissivity was estimated from NDVI based method given by Van de Griend and Owe (1993)

ε_a air emissivity estimated from air temperature using empirical model given by Campbell and Norman (1998).

Air temperature (T_a) at satellite overpass was estimated from NDVI-LST 2D triangular scatter by extracting LST at maximum NDVI within a spatial domain of 20 x 20 pixels.

Instantaneous ground heat flux (G_{ins}) was estimated as:

$$Rn_{ins}\left[\frac{(Ts-273.15)}{\alpha}\right]\left[(0.0032\alpha + 0.0062\alpha^2)(1+0.978NDVI^4)\right]$$

Bastiaanssen et al. (1998) (8)

The conversion of instantaneous net radiation and net available energy to daytime estimates was made using a sinusoidal integral function. The daytime average latent heat fluxes were computed from day time net available energy and constant evaporative fraction hypothesis.

3. RESULTS AND DISCUSSION

3.1 Net Radiation

The estimates of instantaneous and day time Rn using MODIS TERRA and AQUA LST, NDVI, albedo were compared with in situ measurements. Error statistics comprising of bias, MAE, RMSE are presented in Table 1 (a) for instantaneous and Table 1 (b) for daytime estimates.

These varied between 12 -14 Wm^{-2}, 31- 35 Wm^{-2}, 38-48 Wm^{-2}, respectively at TERRA overpass.

MODIS Overpasses	Error Statistics (Wm^{-2})			Correlation Coefficient (r)
	Bias	MAE	RMSE	
At TERRA				
2005-06	22	71	76	0.67
2006-07	16	41	50	0.47
Pooled	20	59	67	0.44
At AQUA				
2005-06	10	31	35	0.85
2006-07	15	44	49	0.92
Pooled	12	36	40	0.88

Table 1a: Error Statistics of Instantaneous Net Radiation Estimates

MODIS Overpasses	Error Statistics (Wm^{-2})			Correlation Coefficient (r)
	Bias	MAE	RMSE	
At TERRA				
2005-06	12	31	38	0.86
2006-07	14	35	48	0.86
Pooled	13	33	42	0.86
At AQUA				
2005-06	8	49	45	0.87
2006-07	19	86	92	0.92
Pooled	14	62	71	0.88
TERRA +AQUA	14	47	58	0.93

Table 1b: Error Statistics of MODIS Based Daytime Average Net Radiation Estimates

The overall correlation coefficient (r) was found to be 0.86 with datasets pooled over both the seasons for TERRA overpasses producing RMSE of the order of 42 Wm^{-2}. At AQUA overpasses, the bias, MAE, RMSE varied from 8-19 Wm^{-2}, 49-86 Wm^{-2} and 45-92 Wm^{-2}, respectively with overall r = 0.88. The RMSE over pooled datasets was 71 Wm^{-2}. The RMSE over pooled estimates of Rn_{ins} at TERRA and AQUA overpasses were found to be 58 Wm^{-2} with r = 0.93 Figure 1a. The daytime Rn estimates from TERRA showed 16-22 Wm^{-2} bias, 41-71 Wm^{-2} MAE and 50-76 Wm^{-2} RMSE with 'r' varying between 0.47 – 0.67. The RMSE for pooled estimates with two year TERRA datasets was 67 Wm^{-2}. The bias, MAE and RMSE for daytime Rn estimates from AQUA were found to be 10-15 Wm^{-2}, 31-44 Wm^{-2} and 35-49 Wm^{-2}, respectively with 'r' varying between 0.85 - 0.92. The RMSE over AQUA pooled estimates was 40 Wm^{-2} (12% of mean). Though the error of instantaneous net radiation at TERRA overpasses were less than those at AQUA overpasses, but the errors from daytime estimates were less in AQUA than those from TERRA. The 1:1 validation plot of AQUA estimated daytime Rn and measured Rn is shown in Figure 1b.

The daytime estimates were generated from single clear sky instantaneous estimates from either TERRA and AQUA using sinusoidal integration. It was found by earlier workers that daytime net radiation estimates from single morning (10.30 to 11.00 AM) and afternoon (14.00 to 15.00 hrs) estimates showed overestimation (Bisht et al., 2005) and underestimation (Nishida et al., 2003).

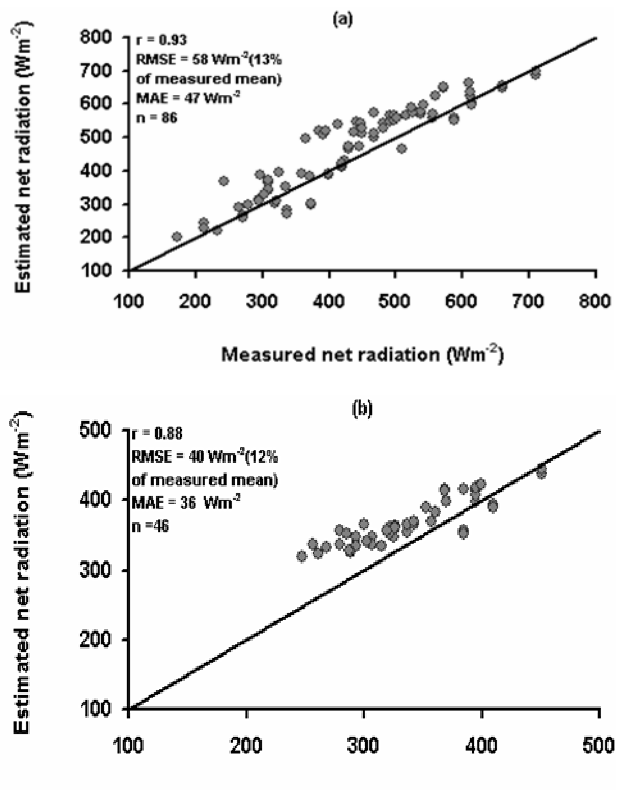


Figure 1. Validation Plot of Estimated and Measured (a) Instantaneous (TERRA+AQUA) and (b) Daytime Net Radiation (AQUA only)

Only, noon time estimates (at 12.00 to 13.00 hrs) can lead to better representation of daytime net radiation when atmospheric boundary layer becomes fully developed. The resulting error from AQUA daytime estimates is little higher than obtained over homogenous agro-ecosystems (Mallick et al., 2009) in India. Though it is higher than the errors over sparse and heterogeneous agro-ecosystems in LASPEX region with NOAA AVHRR data, the overall RMSE is lower than globally reported error in daytime net radiation estimates (Gupta et al., 2001) obtained by several workers with NOAA AVHRR (Hurtado and Sobrino, 2001) and MODIS TERRA (Bisht et al., 2005) optical and thermal data.

3.2 Using Area Integrated Sensible Heat Fluxes from LAS

Sensible heat flux is very critical in properly representing Bowen ratio to compare λE estimates at moderate spatial scale (~1km). Moreover, frequent change in sensible heat fluxes over 1 sq. km area due to frequently changing stability, instability conditions specially in semi-arid climate (Chehbouni et al., 2000) may not be sufficiently represented through one or two Bowen ratio samples within the study area at each hour. Rather area averaged sensible heat flux measurements over MODIS 1 sq. km pixel along with measurements on Rn and G can represent better in situ λE while validating its satellite based estimates.

As a follow up to that, instantaneous and daytime λE estimates were compared with limited λE generated through area averaged 'H' from large aperture scintillometer (LAS). The percent error was drastically reduced to 9% of mean having absolute RMSE 29 Wm^{-2} with increase in r (= 0.97) for TERRA and AQUA Figure 2.

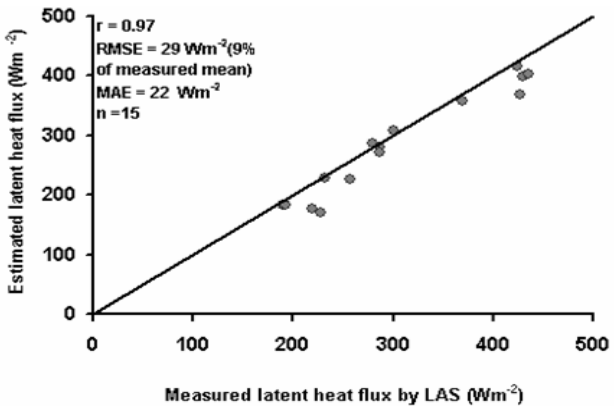
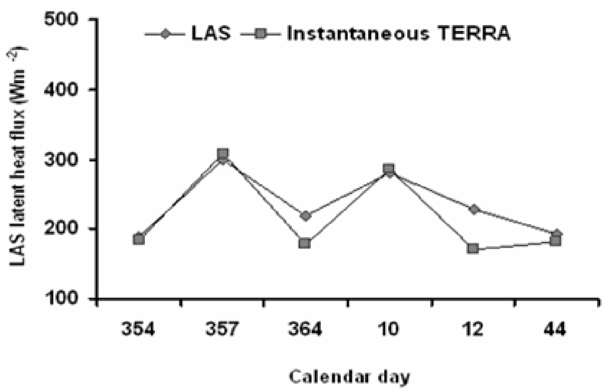


Figure 2. Validation of TERRA and AQUA 'λE' Estimation with *in situ* Measurements when area Averaged LAS 'H' was used

The seasonal variation of instantaneous estimates from TERRA-AQUA and LAS measurements showed close resemblance in Figure 3. The daytime estimates also showed increment in accuracy (RMSE = 27 Wm^{-2}) even with limited LAS datasets (n=8) and correlation coefficient was also increased to 0.85.



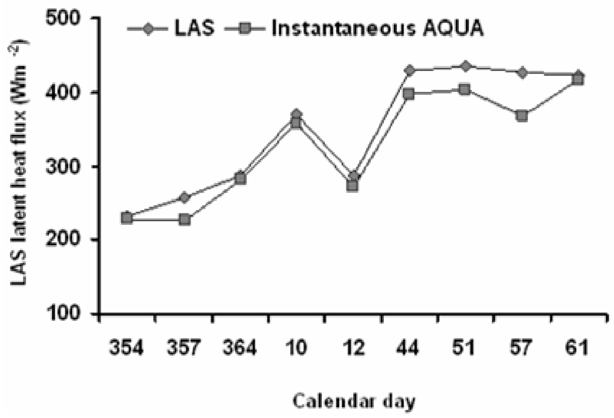


Figure 3. Temporal Comparison of Instantaneous λE estimates from TERRA and AQUA and LAS Measurements

The comparison of daytime AQUA λE estimates and area averaged λE using LAS 'H' showed a good match in Figure 4.

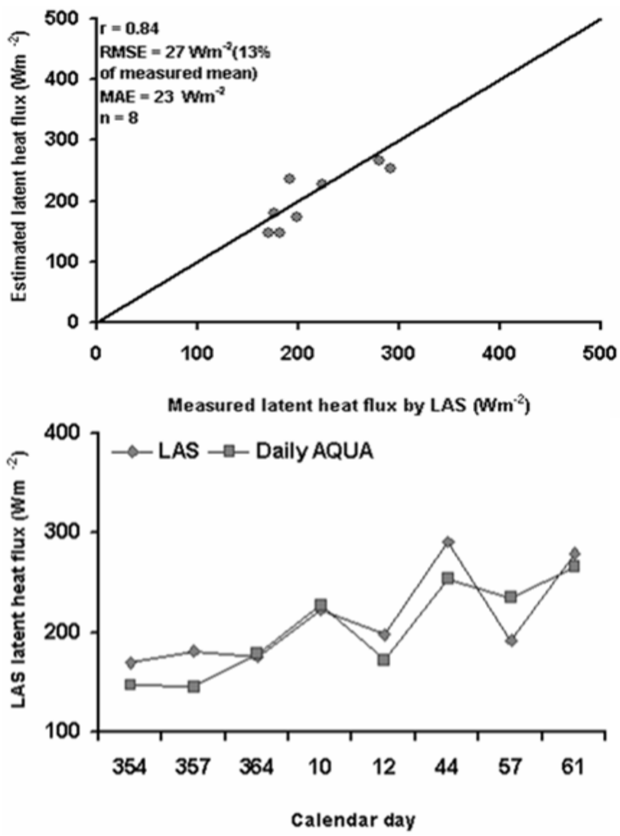


Figure 4. Comparison of Estimated and Measured Daytime Latent Heat Flux with AQUA and LAS

CONCLUSION

The accuracy of MODIS AQUA based energy balance estimates was better than TERRA for daytime averages. Accuracy of λE estimates was improved (9 % of measured mean) when compared with *in situ* measurements with large area averaged sensible heat fluxes from LAS. The correlation coefficient between estimates and measurements was also improved (r = 0.97). Partitioning of system evapotranspiration needs to be attempted in future using two-source energy balance formulation to derive soil evaporation and canopy transpiration.

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