Estimation of Actual Evapotranspiration in Jordan from Satellite Data

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Abstract

Estimation of evapotranspiration (ET) is needed for many applications in diverse disciplines such as agriculture, hydrology and meteorology. Several models have been developed to use satellite radiometric surface temperature (Tr), leaf area index (LAI), albedo and net radiation available from visible and infrared bands to estimate ET. The Analytical Land Atmosphere Radiometer Model (ALARM) has been developed to convert Tr to the aerodynamic surface temperature (Ti) at any view by correcting for vegetation temperature profile and considering LAI, canopy height, fractional cover, leaf angle distribution, and sensor zenith view angle.

The objective of this study was to validate the daily actual ET estimated from satellite (MODIS) data using ALARM and the dimensionless procedure in Jordan Valley by comparing these estimates with ET calculated from ASCE alfalfa reference ET (ETr) and ET obtained from the change of measurements of soil moisture. The study was conducted on an alfalfa field in Jordan Valley in 2006. Since this alfalfa field was irrigated and due to warm air advection, ET rates based on measurements of soil moisture change ranged from about 6 to 10 mm d-1. For this range the Root Mean Square Error (RMSE) for ALARM was 0.87 mm day-1, and coefficient of determination (r2) was 0.36 while the RMSE for ASCE was 1.25 mm d-1 and r2=0.06. The implementation of ALARM to convert satellite radiometric to aerodynamic surface temperature at a well defined scalar roughness length and the use of ALARM along proved to be valuable in providing actual ET estimates. The approach provides the actual ET without the need for soil moisture measurements, and was able to detect ET characteristics. Such estimates, in addition to remotely sensed indices, would provide a real time monitoring system that could detect dry cycles and vegetation response to rainfall. Therefore, future efforts will focus on the validation, calibration and application of ALARM to estimate actual ET in Jordan. Following that, a hydrologic tool will be developed to broadcast efficient accurate daily actual ET maps. Also, the

integration of satellite data with near-real time monitoring may be used to estimate actual crop ET to contribute to irrigation water management in the country. As part of the extension services, the climatic data needed for this purpose are becoming more available on daily, weekly and monthly bases on the web (http://www.merimis.org/).

Keywords: ALARM, Evapotranspiration, Jordan, MODIS, Remote Sensing.

Introduction

Estimates of evapotranspiration, ET, are needed for many applications in diverse disciplines such as agriculture and hydrology. Many studies of long-term averages have shown that more than half of the net solar energy, and subsequently two thirds of precipitation, goes to ET (Brutsaert, 1982). ET is linked to the land surface energy budget as follows (e.g., Brutsaert, 1982):

$$R_n - G = H + E \qquad (1)$$

where R_n (W m^{-2}) is the net incoming radiation, G is the heat flux into the ground (W m^{-2}), and H (W m^{-2}) and E (W m^{-2}) are the sensible and latent (evaporative) heat fluxes into the atmosphere. For the energy balance to close, any part of (R_n - G) that does not contribute to E must be converted into H. In order for that to happen, the surface has to have the temperature (T_s) that forces the energy balance to close. Estimation of H (or ET as a residual) over vegetated terrain is based on an aerodynamic temperature (T_i), which is the temperature that gives the correct value of H at a specified value (denoted $z_{0h,i}$) of the scalar roughness length, z_{oh}, based on Monin-Obukhov Similarity (MOS) theory in the surface sub-layer (Brutsaert, 1982; Stull, 1988). Specification of the value of z_{0h} to give the correct value of H for use with a radiometric surface temperature T_r is a difficult problem (e.g., Mahrt and Vickers, 2004); Crago and Suleiman (2005) outlined a method (discussed here in section 2.a) to specify $z_{0h,i}$ and to convert T_r to T_i. In the MOS theory, the flux is proportional to the difference between T_i and air temperature (T_a), with the ratio H / (T_i-T_a) depending on variables characterizing the atmospheric turbulence and the land surface. This relationship can be expressed as (e.g., Brutsaert, 1982):

$$H = \frac{(T_s - T_a) k u_* \rho c_p}{\left[\ln\left(\frac{z_a - d_0}{z_{0h}} \right) - \psi\left(\frac{z_a - d_0}{L} \right) \right]} \qquad (2)$$

where T_s (C°) is the surface temperature, T_a (C°) is the air temperature at a height z_a (m) in the surface sublayer, k (where k=0.4) is von-Karman's constant, u_* (ms^{-1})

is the friction velocity, ρ (kg m^{-3}) is the density of the air, c_p (J kg^{-1} K^{-1}) is the specific heat at constant pressure, z_{0h} (m) is the scalar roughness length for sensible heat, and d_0 (m) is the displacement height. Atmospheric stability, which affects the efficiency of turbulent transport, is included by means of ψ, which is a function of the stability or buoyancy parameter $(z_a-d_0)/L$, where L (m) is the Obukhov length.

Once T_i is known it can be applied to calculate H (equation 2) and then actual ET can be obtained as a residual (equation 1). In one example, the accuracy of regional scale actual ET (obtained as a residual from (1) after finding H using (2), with T_a measured at a single point within the region) is approximately 70-80% (Wang et al., 2005). Models have been developed to improve accuracy through the use of radiometric surface temperature (Hatfield et al., 1983; Ben-Asher et al., 1992; Kustas et al., 2007; Anderson et al., 2007), leaf area index (LAI) (Consoli et al., 2005) and net radiation (Bandara, 2003) available from visible and infrared bands of satellite data. Suleiman and Crago (2004) developed a dimensionless temperature (Δ_T), may be defined as the $(T_i - T_a)/(T_{max} - T_a)$, for each pixel. The maximum surface temperature (T_{max}) is determined by assuming that ET for the pixel is zero. This approach is advantageous in practice when a dry pixel is not available (Qiu et al., 2006). The dimensionless temperature procedure was used for mapping ET at a local scale with hydrological applications at riparian meadow restoration sites in California, USA (Loheide and Gorelick, 2005).

The Analytical Land Atmosphere Radiometer Model (ALARM) has been developed to convert the radiometric surface temperature T_r to the aerodynamic surface temperature T_i at any view angle (Crago, 1998; Suleiman and Crago, 2002a). ALARM converts radiometric surface temperature measured at any view angle to a well-defined aerodynamic surface temperature (T_i) by correcting for vegetation temperature profile and considering LAI, canopy height, fractional cover, leaf angle distribution, and sensor zenith view angle. ALARM worked well for varied canopy density when the zenith view angle was less than 20^o and satisfactorily for view angles greater than 20^o (Suleiman and Crago, 2002b; Zibognon et al., 2002). Other models such as Lhomme *et al*. (2000) and Massman (1999) also worked best at near-nadir view angles (Suleiman and Crago, 2002a).

The objective of this study was to validate the daily actual ET estimated from MODIS data using ALARM and the dimensionless procedure in Jordan Valley by comparing these estimates with ET calculated from ASSCE reference ET (ET_r) and ET obtained from the change of measurements of soil moisture. Although MODIS data has been used for ET estimation (Allen et al., 2007; Senay et al., 2007), the study might be considered as the first step in the application of MODIS data and the dimensionless temperature approach in estimating actual ET in Jordan and similar environments. Also, this work is an advance in technique because it is the first application of the ALARM method coupled to ET estimate given in Suleiman and Crago (2004). The most significant contribution of this work is ALARM because it converts general remotely sensed surface temperatures to aerodynamic temperature. This is an important topic since methods to estimate actual ET from satellite data have remained elusive principally due to the problem of how to make use of remotely sensed surface temperatures.

Theoretical background

a. ALARM description

Within ALARM, the foliage is assumed to have an exponential vertical temperature profile (Brutsaert and Sugita, 1996) as follows:

$$T_f = T_{fg} + \left(T_{fh} - T_{fg}\right)e^{-b\zeta}, \qquad (3)$$

where T_f is the temperature of the foliage at a height *z* above the soil surface, T_{fh} is the foliage temperature at the top of the canopy, T_{fg} is the asymptotic limit of the exponential foliage temperature profile, far below the bottom of the canopy, ζ=(h-z)/h is the dimensionless depth into the canopy, *h* is the canopy height, and *b* is a decay constant. Qualls and Yates (2001) observed an exponential vertical temperature profile within a grass canopy.

ALARM converts radiometric surface temperature measured at any view angle to a well-defined aerodynamic surface temperature (T_i) by correcting for vegetation temperature profile and considering LAI, canopy height, fractional cover, leaf angle distribution, and zenith sensor view angle as follows:

$$T_i = T_r + \left(T_{fg} - T_{fh}\right)\left(w - W\right). \qquad (4)$$

where W is defined below in (7) and w can be derived (Crago, 1998) as:

$$w = \left(1 - f_{soil}e^{-b}\right)\left[\frac{\mu_r b}{g'LAI} + 1\right]^{-1} \qquad (5)$$

In (5), f_{soil}=exp [-g' (LAI)/μ_r] is the fraction of soil seen by the IRT (Friedl and Davis, 1994), μ_r is the cosine of the view zenith angle, and *g'* is taken as 0.5 which corresponds to a spherical leaf angle distribution and is representative of a wide range of vegetation types. When T_{fh}=T_{fg}, the canopy is isothermal. Under these conditions, Brutsaert and Sugita (1996) showed that the resulting scalar roughness length, $z_{0h,i}$, is given by:

$$z_{0h,i} = z_0 \exp\left[\frac{h}{\left(h - d_0\right)r_2} + \ln\left(\frac{h - d_0}{z_0}\right)\right]. \qquad (6)$$

where d_0 is zero plane displacement height, z_o is momentum roughness length, and r_2 is defined below equation (7). The "aerodynamic" surface temperature T_i found with (4) is actually the "equivalent isothermal surface temperature" (Brutsaert and Sugita, 1996), or the value of T_s needed in (2) to estimate the correct H using the $z_{0h,i}$ for z_{0h}. Alternatively, T_i is the temperature the surface would require to give the correct sensible heat flux if the canopy was isothermal. The r_2 is given by $r_2= [a- (a^2+4C_2)^{1/2}]/2$ and In (4), W is:

$$W = -(r_2 + b)C_2 / \left[r_2\left(b^2 + ba - C_2\right)\right], \qquad (7)$$

In turn, $C_2 = 2(LAI)(Ct_f)\, h/[k\,(h-d_0)]$ and Ct_f is the transfer coefficient in the bulk transfer equation for the foliage elements, given by $Ct_f = C_L Re_*^{-m} Pr^{-n}$. The variable *a* is an exponential decay parameter of eddy diffusivity, Pr is the Prandtl number, and the Reynold's number appropriate for transport through a leaf boundary layer is $Re_* = u_* L_f/\nu$, where L_f is the characteristic length scale of a leaf and v is the kinematic viscosity.

In (5), w is a weighting coefficient, describing the importance of T_{fh} and T_{fg} in determining the radiometric surface temperature seen by a radiometer:

$$T_r = wT_{fh} + (1-w)T_{fg} \qquad (8)$$

Similarly, W is a weighting coefficient describing the relative importance of T_{fh} and T_{fg} in producing sensible heat flux.

b. ALARM parameterization

The ALARM model has several variables (T_{fh}, *b*, *a*, and d_0/h) that need to be parameterized, all of which have real physical meanings independent of the means of measuring surface temperature. Crago and Suleiman (2005), on a study at different sites with varying LAI, found that the use of a generalized parameterization for these variables at the different sites gave sensible heat flux values comparable to those obtained using localized parameterization. Based on their findings, they recommended the following generalized parameterization for the four variables ((T_{fh}, *b*, *a*, and d_0/h):

$$T_{fh} = T_a \qquad (9)$$

where T_a is the air temperature at the top of the canopy.

The parameter *b* controls the rate at which foliage temperature increases with depth into the canopy and was parameterized as a function of LAI:

$$b = 0.75 \quad for\, LAI \geq 1.87, \qquad (10)$$

and

$$b = 3.7 - 1.58LAI \quad for\ LAI < 1.87. \tag{11}$$

Previous work with ALARM (Zibognon *et al*, 2002; Suleiman and Crago, 2002a and b) suggests that the parameters *a* and d_0/h can influence the estimates of ET. Specifically, larger values of *a* (near 5) effectively confine turbulence and turbulent transport to the top layers of the model canopy, while smaller values (near 0) allow turbulence. They were parameterized as follows:

$$a = 0.5LAI, \tag{12}$$

and

$$d_0 / h = 0.335a \tag{13}$$

c. Dimensionless temperature

Suleiman and Crago (2004) introduced a dimensionless temperature (Δ_T) as follows:

$$\Delta_T = \left(\frac{T_i - T_a}{T_{\max} - T_a} \right) \tag{14}$$

A value of T_{max} can be obtained by solving for T_s in Eq. [2], assuming that H equals (R_n - G). The relationship between H and Δ_T is approximately linear, and goes through the origin [assuming the denominator of (2) varies little as T_s goes from T_i to T_{max}]:

$$H = (R_n - G)\Delta_T \tag{15}$$

The relationship between E and Δ_T is:

$$E = (R_n - G)(1 - \Delta_T) \tag{16}$$

and the evaporative fraction EF is:

$$EF = \frac{E}{(R_n - G)} = 1 - \Delta_T = \frac{T_{\max} - T_i}{T_{\max} - T_a} \tag{17}$$

The dimensionless temperature Δ_T can be found from (14) using ALARM T_i, measured T_a, and T_{max} found as described above. Scaling T_i using the dimensionless procedure reduces the sensitivity of ET estimates to errors in T_a and T_r. The assumption of a constant evaporative fraction, EF = E / R_n, was implemented to extend instantaneous to daily ET because orbiting satellites usually provide coverage only once a day.

In all, there are three major assumptions in the integrated ALARM and dimensionless algorithms. Within ALARM, the foliage is assumed to have an exponential vertical temperature profile. Such an assumption should be generally valid during the satellite pass in the middle of the day because exponential foliage vertical temperature profiles are more evident in the middle of the day. The relationship between H and Δ_T is assumed to be linear, and goes through the origin. This assumption should not result in any serious errors in the estimation of ET especially that the variation of the dominator of (2) is little as T_s goes from T_i to T_{max}. The assumption of a constant evaporative fraction contributes to uncertainty in ET estimates but these uncertainties should be most of the time minimum in semiarid climatic conditions.

d. ASCE reference evapotranspiration

Daily actual ET was obtained from the ASCE reference ET (ET_r) approach in order to compare it with the ALARM actual ET. Allen et al. (2005) emphasized that the ASCE Penman-Monteith (PM) reference ET (ET_r) would provide the best estimate of ET under various climatic conditions. The ASCE ET_r was developed for a hypothetical well-watered and actively growing uniform alfalfa of 0.5 m height with a surface resistance of 45 s m^{-1} and an albedo of 0.23 (Allen et al., 2005). The equation for a alfalfa reference crop according to Allen et al. (2005) is defined as follows:

$$ET_r\left(\mathrm{mm\,d^{-1}}\right)=\frac{0.408\Delta(R_n-G)+\gamma\dfrac{1600}{T+273}u_2\left(e_s-e_a\right)}{\Delta+\gamma\left(1+0.38u_2\right)} \qquad (18)$$

where R_n is the net radiation (MJ m^2 d^{-1}), G the soil heat flux (MJ m^2 d^{-1}), T the mean daily air temp (^oC), u_2 the mean daily wind speed at 2 m height (m s^{-1}), e_s-e_a the saturation vapor pressure deficit (kPa), Δ the slope of the vapor pressure-temperature curve (kPa $^oC^{-1}$), and γ the psychometric constant (kPa $^oC^{-1}$).

Site Description and Data

a. MODIS data

Eight-day 1-km leaf area index (LAI), albedo and instantaneous 4-km radiometric surface temperature (T_r) were obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) Terra instrument for 2008. To compensate any possible positional shift, a first- order geometric correction was made for the MODIS images of Albedo and LAI using a geo-coded image of AVHRR. Albedo, the adjusted reflectance value at the mean solar zenith angle for a 16-day period, was derived from the spectral reflectance data (MOD43B) of the first seven bands using the conversion coefficients described by Strahler et al. (1999). Linear interpolation was used to obtain daily LAI from the 8-day LAI. In an earlier study of bare and sparsely vegetated areas, Wan et al. (2002) found that the MODIS Land Surface Temperatures (LSTs) agreed well with in situ measured LSTs within ±1 ºC in the range -10 to 49 ºC for both daytime and nighttime LST; similar uncertainties likely apply here as well. The use of MODIS data for ET predictions does not require site or species-specific calibration (Nagler et al., 2005).

b. Validation data

A validation study was undertaken using data from the Agricultural Research Station of the University of Jordan (ARSUJ) in the central Jordan Valley at 32° 10’ N latitude and 35° 37’E longitude at an altitude of -230 m (below mean sea level). The station has a warm climate in winter with a minimum temperature of 8.5 ^{o}C in January and a hot summer with a maximum temperature of 40.4 ^{o}C in July. The yearly average maximum and minimum temperatures are 30.9 and 18.5 ^{o}C, respectively, while the yearly mean temperature is 24.7 ^{o}C. The experiment site has been selected in an alfalfa field where an automatic weather station (Campbell Scientific, Logan, UT) has been installed. The crop is irrigated with a sprinkler irrigation system twice to three times a week and planted on a sandy loam soil with good internal drainage. Data collected by the weather station include hourly and daily net solar radiation measured by a NR-LITE-L net radiometer (Kipp & Zonen USA Inc., Bohemia, NY), hourly and daily wind speed at 2 m measured using a R.M. Young wind sentry 03101-5 system (Campbell Scientific, Logan, UT), and air temperature and humidity measured at a height of 2 m using a shielded and aspirated REBS THP. ALARM used MODIS LAI, albedo and T_r along with daily and hourly solar radiation, air temperature, and wind speed. American Society of Civil Engineers (ACSE) (2005) alfalfa equation was used for this site. The ASCE used daily solar radiation, air temperature, wind speed and relative humidity.

The soil water content was monitored with TRIME tube access probe (P3, IMKO Micromodultechnik GmbH, Ettlingen, Germany). The access tubes were 1 m in length and 5 probes were installed in the field. The measurements of the volumetric soil water content with the TRIME probe at depths of 0-20, 2-40, 40-60, and 60-80 cm were conducted manually once a day in the morning from March to October 2006. A water balance equation was used to calculate the measured ET using the soil moisture readings as:

$$ET_m = I - D - \Delta W \qquad (19)$$

where ET_m is measured ET (mm d^{-1}), I is irrigation (mm d^{-1}), D is vertical drainage (mm d^{-1}), and ΔW is the change in soil water (mm d^{-1}). Only ET_m for days of no irrigation (I = 0) and zero D (D= 0) were used in this study to minimize the errors of

ET_m. Because of the limited number of usable satellite overpasses needed for use with ALARM, a total of twelve days of data were available for the validation study.

Results and Discussion

Results from the validation study in the ARSUJ alfalfa field are shown in Figures 1, 2, and 3. Since the field was irrigated, ET rates ranged from about 6 to about 10 mm day^{-1}. For this range the Root Mean Square Error (RMSE) for ALARM (as compared to the TRIME probe reference values-referred to as "measured" values hereafter) was 0.87 mm day^{-1}, and coefficient of determination (r^2) was 0.36 while the RMSE for ASCE (2005) was 1.25 mm d^{-1} and r^2=0.06.

While the RMSE of both methods with the measured values was relatively good, the lack of data from non-irrigated fields makes it difficult to estimate the uncertainty of the two estimates at lower evaporation rates. Errors in the ASCE (2005) method for moisture-stressed sites are likely to be dominated by errors in the water stress coefficient. Such errors are likely to be quite large when taken as a percent error of the daily ET, but relatively small in actual magnitude during very dry conditions. Assuming independent random errors equal to 1.25 mm day^{-1} in successive measurements, two daily ASCE measurements that differ by less than $(1.25^2+1.25^2)^{1/2}$ mm day^{-1} = 1.76 mm day^{-1} are not far enough apart to rule out random variability.

Error magnitudes in the ALARM model are unlikely to vary greatly with the magnitude of the ET rate. Theoretically, EF varies with Δ_T, which is a ratio of two temperature differences (14). Absolute errors in both T_i and T_{max} are likely to be largest under conditions of high available energy, but under these conditions (T_i-T_a) and (T_{max}-T_a) are likely to be large, so the relative errors are likely to be similar for a wide range of conditions. Experimentally, Suleiman and Crago (2004) applied the dimensionless temperature approach (without the ALARM model) to grasslands under stressed and unstressed conditions, and found similar scatter of estimated to measured ET under high (up to about 5.5 mm day^{-1}) and low (down to about 1.5 mm day^{-2}) daily ET rates. Thus, assuming random and independent errors, it seems reasonable to assume that two daily ALARM measurements of ET that differ by less than $(0.87^2+0.87^2)^{1/2}$ mm day^{-1} = 1.2 mm day^{-1} are not far enough apart to rule out random variability. Finally, if ALARM ET and ASCE ET estimates are different by less than $(1.25^2+0.87^2)^{1/2}$ mm day^{-1}= 1.5 mm day^{-1}, they are not far enough apart to rule out random variability.

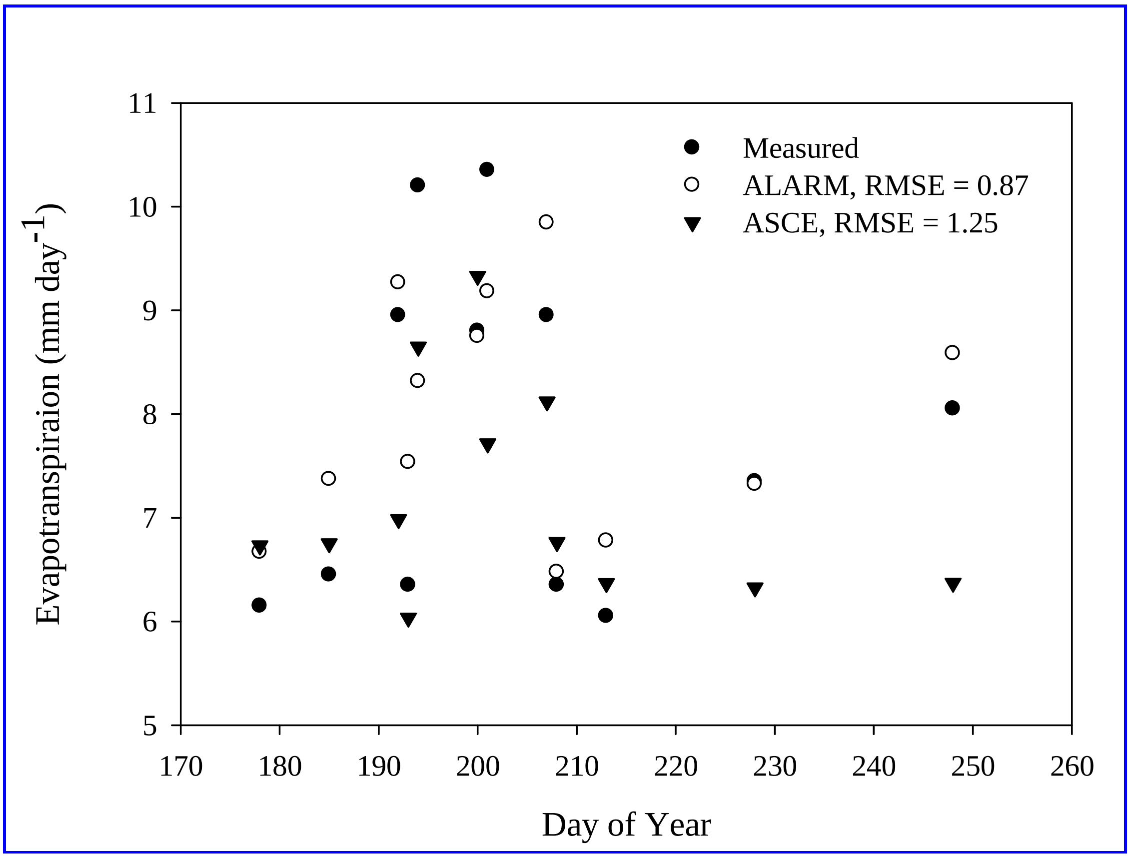

Figure 1. Measured, ALARM and ASCE evapotranspiration at the validation site.

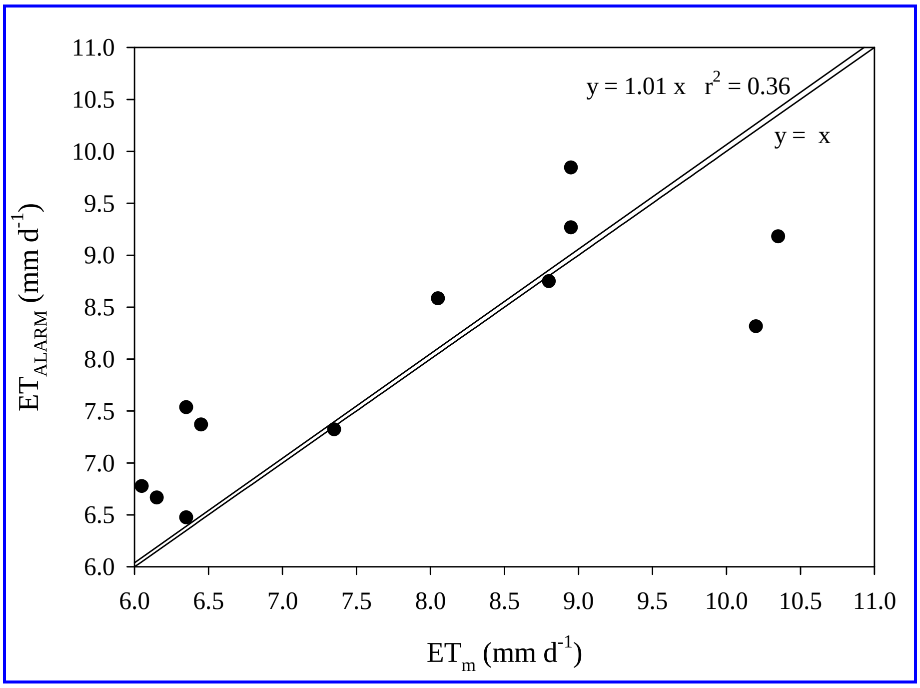

Figure 2. ALARM vs. measured evapotranspiration at the validation site

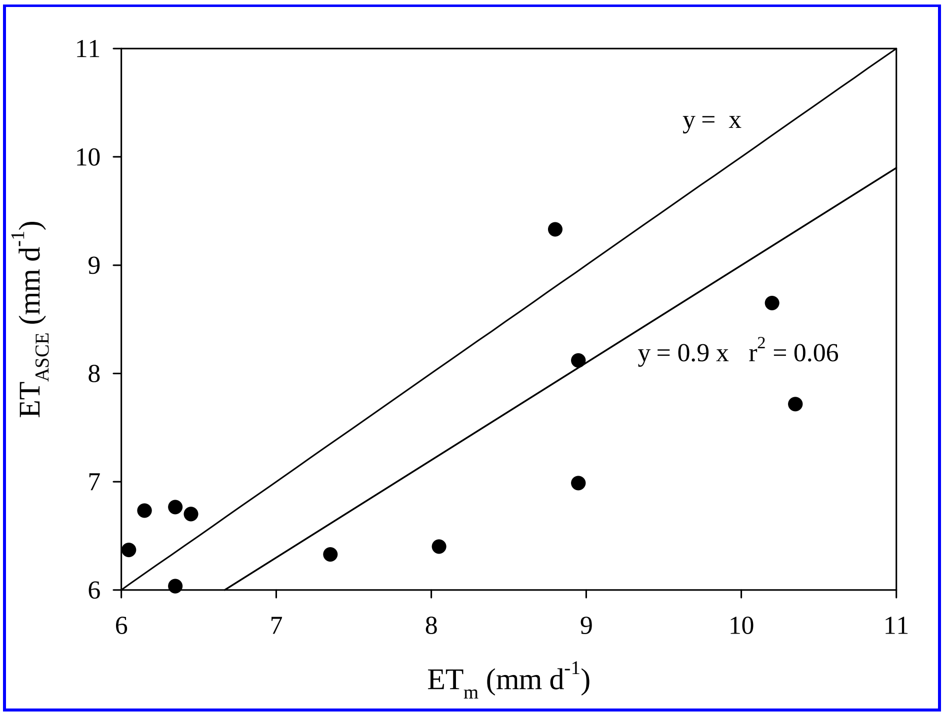

Figure 3. ASCE vs. measured evapotranspiration at the validation site

Summary and Conclusions

Although remote sensing cannot provide a direct measurement of ET (ET) (Venturini et al., 2004), the contribution of remotely sensed data is generally considered to be invaluable, particularly in a country like Jordan where droughts are frequent and meteorological data are scarce. The implementation of ALARM to convert MODIS radiometric to aerodynamic surface temperature at a well defined scalar roughness length and the use of ALARM along with the dimensionless temperature procedure proved to be valuable in providing actual ET estimates. The approach provides the actual ET without the need for soil moisture measurements.Such estimates, in addition to remotely sensed indices, would provide a real time monitoring system that could detect dry cycles and vegetation response to rainfall. Therefore, future efforts will focus on the validation, calibration and application of MODIS data, ALARM and dimensionless temperature to estimate actual ET in Jordan. Following that, a hydrologic tool will be developed to broadcast efficient accurate daily actual ET maps. Also, the integration of MODIS data with near-real time monitoring may be used to estimate actual crop ET to contribute to irrigation water management in the country. As part of the extension services, the climatic data needed for this purpose are becoming more available on daily, weekly and monthly bases on the web (http://www.merimis.org/).

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