Irrig Sci (2008) 27:67–81
DOI 10.1007/s00271-008-0122-3

ORIGINAL PAPER

Daily evapotranspiration estimates from extrapolating instantaneous airborne remote sensing ET values

José L. Chávez · Christopher M. U. Neale · John H. Prueger · William P. Kustas

Received: 14 December 2007 / Accepted: 29 May 2008 / Published online: 21 June 2008

Abstract In this study, six extrapolation methods have been compared for their ability to estimate daily crop evapotranspiration (ET_d) from instantaneous latent heat flux estimates derived from digital airborne multispectral remote sensing imagery. Data used in this study were collected during an experiment on corn and soybean fields, covering an area of approximately 12 × 22 km, near Ames, Iowa. ET_d estimation errors for all six methods and both crops varied from $-5.7 \pm 4.8\%$ (MBE ± RMSE) to $26.0 \pm 15.8\%$. Extrapolated ET_d values based on the evaporative fraction (EF) method better compared to eddy covariance measured ET values. This method reported an average corn ET_d estimate error of -0.3 mm day^{-1}, with a corresponding error standard deviation of 0.2 mm day^{-1}, i.e., about $5.7 \pm 4.8\%$ average under prediction when compared to average ET_d values derived from eddy covariance energy balance systems. A solar radiation-based ET extrapolation method performed relatively well with ET_d estimation error of $2.2 \pm 10.1\%$ for both crops. An alfalfa reference ET-based extrapolation fraction method (ET_rF) yielded an overall ET_d overestimation of about $4.0 \pm 10.0\%$ for both crops. It is recommended that the average daily soil heat flux not be neglected in the calculation of ET_d when utilizing method EF. These results validate the use of the airborne multispectral RS-based ET methodology for the estimation of instantaneous ET and its extrapolation to ET_d. In addition, all methods need to be further tested under a variety of vegetation surface homogeneity, crop growth stage, environmental and climatological conditions.

Communicated by J. Ayars.

J. L. Chávez (✉)
Conservation and Production Research Laboratory, USDA-ARS, P.O. Drawer 10, Bushland, TX 79012, USA
e-mail: jose.chavez@ars.usda.gov

C. M. U. Neale
Biological and Irrigation Engineering Department, Utah State University, 4105 Old Main Hill, Logan, UT 84322, USA
e-mail: cneale@cc.usu.edu

J. H. Prueger
National Soil Tilth Laboratory, USDA-ARS, 2150 Pammel DR, Ames, IA 50011-3120, USA
e-mail: john.prueger@ars.usda.gov

W. P. Kustas
Hydrology and Remote Sensing Laboratory, USDA-ARS, Bldg. 007, BARC-WEST, Beltsville, MD 20705, USA
e-mail: bill.kustas@ars.usda.gov

Introduction

Remote sensing (RS) of land surface energy balance (EB) terms provides essentially instantaneous estimates of latent heat flux (LE) or evapotranspiration (ET_i); which are used in the prediction and monitoring of spatially distributed daily (24 h) crop water use/evapotranspiration (ET_d), irrigation scheduling, and in general hydrologic modeling. However, ET_i values are relatively unimportant unless they can be used to predict ET_d; therefore, the determination of an accurate method for extrapolating RS-based ET_i estimates to daily values is imperative.

Several ET_i extrapolation methods proposed in the literature were selected and applied to the airborne-based estimated LE. It is worth mentioning that a great deal of the literature regarding the extrapolation issue has been devoted to satellite-derived LE.

In the use of satellite imagery there are other important issues to consider, such as their coarser spatial resolution, overpass frequency, possibility of cloud cover presence at overpass time, imagery delivery time, etc., that sometimes limits the effectiveness of the above methods for mapping ET_d at very high resolution (crop fields) and on a regular basis for near real time irrigation scheduling. Airborne remote sensing (RS), by virtue of its ability to operate on demand, i.e., able to fly on cloud free days and at different elevations, is a valuable tool for mapping ET_d at very high resolution on a near daily basis.

Carlson et al. (1995) proposed a modification of the so-called "Simplified Method" (Jackson et al. 1977; Thunnissen and Nieuwenhuis 1990; Seguin et al. 1994) to obtain the integrated ET_d from surface radiant temperature over variable vegetation cover. Mathematically, the simplified equation takes the form "$R_{n24} - LE_{24} = B\,(T_{s13} - T_{a13})^{n}$", where R_{n24} and LE_{24} are integrated net radiation and ET over a 24-h period (in units of centimeter per day). T_{s13} and T_{a13} are surface radiant (radiometric) and air temperatures at 50-m height acquired at 13:00 local time. B and n are pseudo constants, B representing an average bulk conductance for the daily integrated sensible heat flux and a non-unity value of n as a correction for non-neutral atmospheric stability. B and n are given as functions of the normalized difference vegetation index (NDVI) and expressed as a scaled index (N^*) from 0 to 1. NDVI is the ratio (NIR − R)/(NIR + R), where R and NIR are reflectance values in the red and near-infrared bands or portions of the electromagnetic spectrum (Rouse et al. 1973; Tucker 1979). Both N^* and T_{s13} are determined using remotely sensed measurements which are viewed on scatter plots of T_{s13} versus NDVI. The significance of this equation is that it accounts for considerable variation in the constants B and n due to variable vegetation fraction, wind speed, and surface roughness (Seguin et al. 1994).

Narasimhan and Srinivasan (2002) used a similar method that Carlson et al. (1995) applied to NOAA-AVHRR satellite imagery, to estimate ET_d (LE_{24}) using an EB method along with air temperature (T_a) estimated from surface radiant temperature (T_s) at the time of the satellite overpass; which was close to solar noon. For EB computation, they used 24-h shortwave radiation estimates in the calculation of net radiation and assumed that the daily soil heat flux integration result was negligible. Daily LE, in W m^{-2} units, was computed as "$LE_{24} = R_{n24} - \rho_a Cp_a U (T_s - T_a)/r_{ah}$"; where ρ_a is air density (kg m^{-3}), Cp_a is the specific heat capacity of air (MJ kg^{-1}°C^{-1}), r_{ah} is the aerodynamic resistance (s m^{-1}), and U is horizontal wind speed at 2-m height (m s^{-1}). However, they did not get good agreements when compared with weather station (WS) data based ET estimates (using the Penman-Monteith equation). This was attributed to two factors: (1) use of different approaches in ET estimation and (2) assumption of using a constant 2 m s^{-1} for U in the remote sensing method (while WS method used measured wind speed values). Moreover, they compared point ET estimates with ET estimates derived from 1 × 1 km AVHRR data, and neglected daily soil heat flux; which according to Simmers (1977) may not be insignificant.

Limitations of applying Carlson et al. (1995) method for airborne remotely sensed imagery, used in this paper, are mainly due to the air temperature measurement height and time of surface radiometric temperature acquisition. In this study, air temperature was measured up to a height of 4.0 m above the ground level, and time of overpass imagery acquisition was not restricted to 13:00 CST. The method by Narasimhan and Srinivasan (2002) introduced U in the sensible heat flux computation to compensate for using T_s instead of aerodynamic temperature (T_{aero}). T_{aero} may not correlate very well with horizontal wind speed if used alone (Chávez et al. 2005). Therefore, the methods discussed to this point do not seem adequate to be used with the digital airborne multispectral RS imagery; although they raise the question whether ignoring daily soil heat flux may adversely affects daily ET estimates.

Brutsaert and Sugita (1992) assumed that the partitioning of available energy ($AE = R_n - G$) into sensible heat flux (H) and LE was constant (self-preservation of AE partitioning) or that the evaporative fraction ($EF = LE/AE$) remains almost constant during daytime and G is soil heat flux. Zhang and Lemeur (1995) added that EF indicates how much of the AE is used for ET and that the assumption that instantaneous EF was representative of the daily energy partitioning was an acceptable approximation for extrapolating ET under clear-sky conditions. Crago (2000) concluded that EF has a tendency to be nearly constant during daytime thus permitting estimation of daytime evaporation from only one or two estimates of EF from satellite imagery obtained during the middle of the day.

Kustas et al. (1994) used NOAA-11 AVHRR satellite imagery collected over the USDA-ARS Walnut Gulch Experimental Watershed in southeastern Arizona, during the MONSOON 90 field campaigns. During that study, they used an EB model that relies primarily on remotely sensed inputs to extrapolate ET estimates from one location containing near-surface meteorological data to other areas in the watershed. They extrapolated one time of day ET estimates to daytime averages using the EF concept. Model derived daytime average ET compared reasonably with local ground-based measurements.

Chemin and Alexandridis (2001) used a surface energy balance for land algorithm called SEBAL (developed by Bastiaanssen et al. 1998) to derive daily ET estimates on irrigated rice fields from NOAA-AVHRR and Landsat 7

ETM + imagery. They used the EF concept to extrapolate ET_i estimates to ET_d. The authors did not verify their estimates with actual measured data. In a very similar study, Haffeez et al. (2002) used SEBAL and EF with different satellite sensors over rice fields (rain-fed and flood irrigated) and vegetable fields. Satellite based estimated ET_d differed from calculated values in 9.0, 3.0, and 13.5% for ASTER, Landsat 7 ETM+, and MODIS sensors respectively. Calculated ET_d values were obtained using meteorological WS data and the Penman-Monteith ET model. In the Haffeez et al. (2002) study, calculated ET_d values were used as reference (or measured) values.

Suleiman and Crago (2004) used daytime conservation of EF as ET/R_n to extrapolate from hourly to daytime ET. They reported an RMSE (root mean square error) between hourly predicted and measured LE [by eddy covariance (EC) and Bowen ratio (BR) systems, Kustas et al. (2005)] of 30–50 W m^{-2}. The slope and R^2 for the zero-intercept linear regression between daytime estimated and measured LE ranged from 0.89 to 1.07 and 0.69 to 0.9, respectively. These results demonstrated that, for grassland, the model might give good estimates of ET when T_a and T_s are available. More EF applications can be found elsewhere (Vogt et al. 2001 and Courault et al. 2003, 2005). Since the EF method has been applied widely with relatively good results (for satellite data-based ET_d estimates) and the terms involved in ET_d estimation using EF were available in our study, this was one of the methods selected for evaluation.

Trezza (2002) proposed an alternative to EF by suggesting the use of the ratio instantaneous LE over (hourly or shorter-period) alfalfa reference ET (ET_r) instead of the ratio LE/AE considering that ET_r would perform better (as an indicator of total AE) under advective conditions. He called this new ratio the alfalfa reference evapotranspiration fraction (ET_rF). This method is based on the assumption that the value of instantaneous ET_rF $(ET_rF)_i$ is similar to the daily average ET_rF $(ET_rF)_d$. ET_rF is similar to the crop coefficient (K_c), widely used in estimating crop ET for irrigation scheduling (Allen et al. 1998).Both K_c and ET_rF represent the ratio of a given crop ET to a reference crop ET (like grass or alfalfa), with the difference that ET_rF is an actual spatial K_c value representing actual crop management and environmental conditions; while the traditional K_c value is a tabulated parameter function of the crop phenological stage; which assumes no water, nutrients, and/or pests stress (Allen et al. 1998). Trezza (2002) extrapolated Landsat-based estimates of ET_i to daily values using ET_rF for irrigated crops. He reported prediction errors ranging from −2.7 to −35.0% (average error of −18.2%), when compared to lysimeters-based ET measurements. Romero (2004) studied the ET_rF method, where she found that ET_rF remained constant during the day. This was not a surprising result in an irrigated area where soil moisture deficits are usually kept to a minimum. Therefore, in our study we also use ET_rF considering it could work better than EF and considering that WS-based meteorological data were available to compute ET_r. Further applications of ET_rF can be found in Allen et al. (2007a, b).

Yet another ET_i extrapolation approach, introduced by Jackson et al. (1983), indicated that daily estimations of ET could be derived from instantaneous measurements on the basis of similarity between diurnal course of LE and solar irradiance (R_s). The method is based, for cloudless days, on the ratio of daily R_s $[(R_s)_d]$ to instantaneous irradiance values (R_s). This ratio is a sinusoidal function of the time period "N" between sunrise and sunset in time units, and maximum irradiance at solar noon, where "N" can be calculated knowing the day of year and location latitude as described in Allen et al. (1998). Daily ET results for wheat, from emergence to senescence, were compared to lysimetric determined ET values in Phoenix, Arizona, USA. In their comparison, Jackson et al. (1983) found a difference of 10%, an under estimation of measured values, that they attributed to errors incurred by not considering nighttime ET in their $(R_s)/(R_s)_d$ method to extrapolate instantaneous RS based ET values. Their results indicated that reliable ET_d estimates could be made for cloud free days and for instantaneous ET estimates made within 2 h of solar noon. Yet, in another study, Jackson et al. (1987) found that daily RS ET estimates using the R_s method for cotton, wheat and alfalfa fields resulted in a difference of less than 8% in predicted ET; with the greatest difference being 25%. Their comparison of estimated daily RS ET was done using Bowen ratio energy balance systems-based ET data.

Ibáñez and Castellví (2000) adopted Jackson et al. (1983) model and extrapolated ET_i to ET_d for short unstressed crops with a leaf area index (LAI) > 3. Their method was based on the radiative Bowen ratio energy balance method, similarities between the diurnal course of LE and solar irradiance. This regression-based approach uses continuous measurements of air vapor pressure, air temperature, surface radiative temperature, and solar irradiance during day light hours. Their method was tested in the Mediterranean region on grass, wheat, and alfalfa crops. Daily ET was estimated with an error < 15% when compared to LE estimates made using Bowen ratio energy balance equipment.

Since Jackson's et al. (1983) method seems to be a viable method and since measured R_s data were acquired at the study experiment site, then this method was also tested for its ability to extrapolate ET_i to ET_d.

The main objective of this paper was to assess how well different methods, found in the literature, extrapolate airborne multispectral remote sensing based instantaneous estimates of evapotranspiration to daily values for corn and soybean crops grown under rainfed conditions in the north-central United States.

Materials and methods

The experiment site is located within Walnut Creek watershed near Ames, Iowa over an area of approximately 12 × 22 km. The data acquisition was part of the 2002 soil moisture and water cycle field experiments [SMACEX (Soil Moisture Atmosphere Coupling Experiment) and SMEX02 (Soil Moisture Experiment 2002)] conducted in support to Aqua Advanced Microwave Scanning Radiometer (AMSR), NASA's Global Water and Energy Cycle Program, and future satellite missions for Terrestrial Hydrology. Main elements of the experiment were validation of AMSR brightness temperature and soil moisture retrievals, extension of instrument observations and algorithms to more challenging vegetation conditions (heterogeneous and somewhat water limited land cover conditions), integration of land surface and boundary layer measurements, and evaluation of new instrument technologies for soil moisture remote sensing. The intensive field portion of the experiment was conducted over a one-month period between mid-June and mid-July, 2002. Kustas et al. (2005) present an overview article of SMACEX which provides background, rationale for study, site description, experimental design, hydro-meteorological conditions, and summary of results.

Data

Airborne RS estimates of instantaneous LE were obtained using imagery from the Utah State University (USU) airborne[1] multispectral digital system over corn and soybean fields near Ames, Iowa. This system acquires imagery in the shortwave and longwave (thermal infrared) portions of the electromagnetic spectrum (Neale and Crowther 1994; Cai and Neale 1999).

The method used to obtain instantaneous LE from airborne imagery is described in detail in Chávez et al. (2005). They also show the comparison of the remotely sensed LE estimates to EC measured LE fluxes. Their results showed small LE estimation errors of -9.2 ± 39.4 W m^{-2} [mean bias error (MBE) ± root mean square error (RMSE)]; which were within measurement errors of EC systems.

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

Forty-seven datasets were used in the evaluation of ET_i extrapolation methods. Twenty-seven datasets were acquired from aerial overpasses on corn fields (Table 2 in Appendix), and 20 were from overpasses on soybean fields (Table 3 in Appendix). In this study, we used measured fluxes from 5 EC stations on corn fields and from 5 EC stations on soybean fields. The 47 datasets were obtained from multiple overpasses, ranging from 9:00 a.m. to 15:30 p.m. CST, on EC station fields for DOY 167, 182, 184, and 189.

Thirty-minute and daily EC stations EB terms are shown in Tables 2 and 3 in Appendix. These terms are R_n, G, and LE_m. Subscript "m" on LE indicates eddy covariance "measured" LE values. Data time stamp corresponds to the USU airborne system overpass time over those corn and soybean fields with EC stations. In addition, the WS SCAN 2031 provided local weather data. SCAN site characteristics and data information can be found in Jackson (2002) and USDA (2006).

ET extrapolation methods

Six ET_i to ET_d extrapolation methods were tested in this research. Different methods were selected from the literature; some of them were modified to test variations. The selection was carried out considering their applicability to the RS system used and the ancillary data available for this study.

The EF method by Shuttleworth et al. (1989) and Brutsaert and Sugita (1992), described below, was used:

$$EF = LE_i/(R_n - G)_i \quad (1)$$

$$LE_i = (R_n - G - H)_i \quad (2)$$

where EF is the Evaporative Fraction (dimensionless), and $(R_n - G)_i$ is instantaneous available energy (AE in W m^{-2}), which was estimated from RS (Chávez et al. 2005), LE_i = instantaneous RS latent heat flux rate in W m^{-2}, $(R_n - G - H)_i$ = instantaneous remotely sensed (spatially-distributed) net radiation, soil heat flux, and sensible heat flux, respectively, in (W m^{-2}). These terms were estimated with remotely sensed surface albedo and surface radiometric temperature, and ground inputs like wind speed and air temperature measured and averaged over periods of 30 min (Chávez et al. 2005).

This method became the first selected ET_d model and was denominated ET_{d1}.

$$ET_{d1} = \left[EF(R_n - G)_d\right] \times [cf/\lambda_v \rho_w] \quad (3)$$

where ET_{d1} = method "1" daily or 24 h evapotranspiration rate, mm day^{-1} , $(R_n - G)_d$ = mean measured 24 h AE, W m^{-2}, cf = time (unit) conversion factor equal to

86,400 s d^{-1} for daily ET and 3,600 s h^{-1} for hourly ET, λ_v = latent heat of vaporization, MJ kg^{-1} or 10^6 W s kg^{-1} and ρ_w = water density, 10^3 kg m^{-3}.

Mean measured 24 h AE, $(R_n - G)_d$, values were obtained by averaging 30-min readings over a 24-h period. Measured R_n and G at the EC sites were made using net radiometers and soil heat flux plates respectively; thus representing point measurements rather than areal as in the RS instantaneous energy balance components estimation case.

The latent heat of vaporization was calculated following Harrison (1963).

$$\lambda_v = 2.501 - (0.00236\, T_a) \quad (4)$$

where T_a = air temperature (°C).

A variance to the method was called ET_{d2}, when daily measured G was neglected in Eq. 3. This was done to assess the importance of including or excluding average daily G in estimating ET_d, and because different researchers claim that the average daily G tends to zero (Chemin and Alexandridis 2001; Brutsaert 2005; Allen et al. 1998).

$$ET_{d2} = \left[EF(R_n)_d\right] \times [cf/\lambda_v \rho_w] \quad (5)$$

The third method is a further variation of the first two methods presented above. In this new model, besides ignoring average daily G value, instantaneous G values were not used either. Ignoring the instantaneous or 30-min average G value may result in an augmentation of AE.

$$ET_{d3} = \left[LE_i/(R_n)_i\right] \times (R_n)_d \times [cf/\lambda_v \rho_w] \quad (6)$$

The Jackson et al. (1983) procedure was adopted as the fourth method to be tested. This model is based on the assumption that ET ~ R_s, i.e., that ET is well correlated and proportional to R_s.

$$ET_i/ET_d = R_s/(R_s)_d \quad (7)$$

$$ET_i = (LE_i) \times [cf/\lambda_v \rho_w] \quad (8)$$

$$ET_{d4} = \left[(R_s)_d/R_s\right] \times ET_i \quad (9)$$

where R_s is average measured solar radiation for the 30-min period considered, W m^{-2} and $(R_s)_d$ is measured mean daily (24 h) solar radiation, W m^{-2}.

In this study, R_s was measured with pyranometers (Kustas et al. 2005), deployed on most of EC stations, and not calculated as in Jackson et al. (1983).

Another method tested (ET_{d5}) was the ET_rF procedure proposed by Trezza (2002), Romero (2004), and Allen et al. (2007a, b). In Eq. 10, ET_rF is the ratio of actual crop ET (LE_i, which is spatially estimated) to alfalfa reference ET or ET_r (which represents a WS point measurement) ratio that essentially is synonymous with the crop coefficient K_c (Allen et al. 1998). Equations 10 and 11 show how ET_rF is used to obtain model ET_{d5}.

$$ET_rF = \left[ET_i/(ET_r)_i\right] = \left[ET_d/(ET_r)_d\right] \quad (10)$$

$$ET_{d5} = \left[ET_i/(ET_r)_i\right] \times (ET_r)_d \quad (11)$$

where ET_i = instantaneous actual ET, from RS LE_i, mm $(30\ \text{min})^{-1}$, $(ET_r)_i$ = alfalfa reference ET, mm $(30\ \text{min})^{-1}$ and $(ET_r)_d$ = daily alfalfa reference ET, mm day^{-1}.

Rather than calculating ET_r from daily maximum and minimum weather data (e.g., maximum and minimum T_a and relative humidity, average wind speed and solar radiation) ET_r was calculated hourly and results were summed up over a period of 24 h, yielding $(ET_r)_d$. This procedure was adopted following findings by Irmak et al. (2005).

$(ETr)_i$ was calculated using ET calculator REF-ET version 2.01.17, developed by Allen (2002). REF-ET provided hourly grass reference ET (ET_o) and ET_r values using the 1999/2000 standardized ASCE Penman-Monteith method (Walter et al. 2000). Hourly ET_r and ET_o values were divided by 2 in order to obtain 30-min values to match the period of remotely sensed ET_i integration.

ET_{d6} was calculated similarly to ET_{d5} with the difference that ET_6 uses ET_o instead of ET_r for scaling ET_i, i.e., ET_oF instead of ET_rF as the extrapolation mechanism. For this new method, $(ET_o)_i$ represented instantaneous or 30-min grass reference ET in millimeter.

$$ET_{d6} = \left(ET_i/(ET_o)_i\right) \times (ET_o)_d \quad (12)$$

Eddy covariance systems energy balance closure

Typical errors for EC EB terms were reported by Weaver (1990), Field et al. (1994), and Hipps (2003) to fall between 15 and 20% for H, 15–20% for LE, 5–10% for R_n, and 20–30% for G. Wilson et al. (2002) found an average 80% closure, or a 20% imbalance, on a study using 22 EC sites and 50 site-years in contrasting ecosystems and climates (Mediterranean, temperate, and arctic). EB closure, in percent, is calculated according to the following expression: $\{[(LE + H)/(R_n - G)] \times 100\}$.

Chávez et al. (2005) found that the EC systems EB closure ranged from 57 to 109%. The lack of EB closure for EC measured EB components called for adjustments since the airborne RS method solves the EB equation by forcing closure to obtain LE_i as a residual. Therefore, the Bowen ratio method recommended by Twine et al. (2000) was used to adjust the 30-min EC based LE_m values for lack of EB closure. This procedure was fully described in Chávez et al. (2005).

Furthermore, EC LE_m values were adjusted for EB closure using two different BR averaging periods: (a) using 30-min BR values to adjust each corresponding 30-min average LE_m value, and (b) using an around noon average BR values to adjust each 30-min average LE_m value. The EC-based ET_d values were computed by averaging measured (non EB closure adjusted LE_m values) and by averaging adjusted instantaneous "30 min" LE values over a 24-h period. A 24-h period was considered since nighttime ET contribution may not be negligible. According to Tolk et al. (2006a) the nighttime ET was 3% of ET_d for a dryland cotton crop and 7.2% for an irrigated alfalfa crop, over a season; and as much as 12% on a given night in the semi-arid Northern Texas High Plains. Along the same lines, Kustas et al. (1994) found that nighttime ET was 13% of ET_d over rangeland, shrub and grass covers, thus not negligible. In this study, nighttime ET_r (calculated using the ASCE-EWRI (2005) procedure) was 2.2, 4.6, 6.0, 1.0, and 2.6% of daily ET_r for DOYs 167, 174, 182, 184, and 189 respectively.

Approach (a) was denoted EC_{30} while approach (b) was denoted EC_n, with subscript "n" to indicate that around "noon" BR values were used in the closure adjustment procedure to obtain EC-based ET_d. This last described procedure was adopted in order to obtain reference EC-based ET_d values for the purpose of evaluating the capabilities of different RS-based methods in extrapolating ET_i to ET_d. Approach (b) was selected as reference because BR and EF are inversely related (EF = 1/(1 + BR)), implying that inferences on the EF are valid for BR as well. It has been suggested that around noon EF averages are good representations of daily EF averages; therefore, around noon BR average values would be appropriate to represent daily BR averages for adjusting LE_m for lack of EB closure (Kustas et al. 1994; Shuttleworth et al. 1989; Crago, 2000). Kustas et al. (1994) compared average EF near noon (10:30–14:30 MST) to daytime averages (07:00–18:00 MST) and found a slight bias in midday EF and an underestimation of 8% for daytime average EF. In other studies, Shuttleworth et al. (1989) and Crago (2000) concluded that an estimate of EF around midday would be representative of the daytime average. Therefore, a BR average value between 10:00 and 14:00 CST was used in Twine et al. (2000) procedure to adjust each 30-min EC-based LE_m value for lack of EB closure.

Statistical analysis

Comparison between RS daily ET estimates and measured values was done assessing mean bias error (MBE), the root mean square error (RMSE) in mm day^{-1} and in percent (%), and through a linear regression analysis based on least squares method for comparison of fitted equation slope, intercept and goodness of fit values.

Results and discussion

Applying the EC_n procedure produced an EF that was constant during the day. For instance, Fig. 1 illustrates this

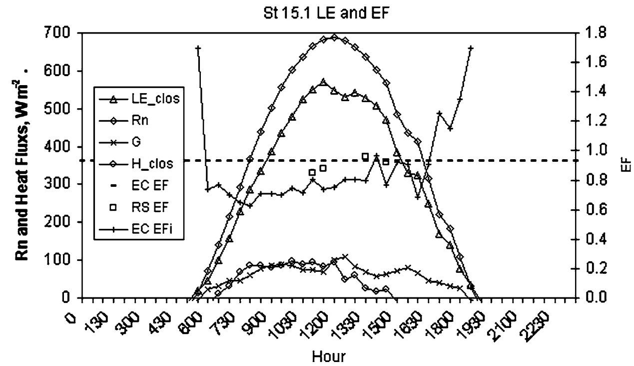

Fig. 1 St 15.1 Evaporative Fraction (EF) and Energy Balance (EB) for DOY 182

case through the dashed line (EC EF) for EC tower station (St.) 15.1 in a corn field (DOY 182) where EF was constant at 0.93. In the same figure, RS estimates of EF (RS EF) for four overpasses around noon (square symbols) resulted in an average value of 0.90 (from EF values of 0.85 (10:43 CST), 0.88 (11:15 CST), 0.96 (13:21 CST) and 0.92 (14:15CST)), i.e., −3.1% below the EC daily EF average value. Eddy covariance St. 16.1 (DOY 182), on a soybean field, showed an EF value that remained practically constant at 0.45, 0.45, and 0.43, during three different overpasses (graph not shown).

An EF of 0.93 for corn and 0.45 for soybean, on DOY 182, showed different stages of development/soil moisture condition for these two crops; with corn (St. 15.1) already at full cover (LAI > 3.0) using most of the AE for LE; while contrastingly the soybean field (St. 16.1) was consuming more than 50% of AE in H; thus in heating air rather than in the ET process.

Using the entire corn and soybean RS-based datasets together, ET_d estimation error was assessed for all six ET_i extrapolation models when compared to EC-based ET_d values obtained through procedure EC_n. Models ET_{d1} and ET_{d2} results, which rely on the EF method, agreed better to measured values, i.e. -0.37 ± 0.31 (MBE ± RMSE) and 0.17 ± 0.35 mm day^{-1} or -7.41 ± 6.97 and 4.03 ± 8.56% error respectively. These values translate into a small ET_{d1} underestimation and ET_{d2} overestimation. Particularly, model ET_{d1} correlated better to EC_n ET_d values with a linear regression slope (a) of 1.05 and an intercept (b) value of 0.09 mm day^{-1}, and with a coefficient of determination, R^2, of 0.95 (Fig. 2 below and Table 4 in the Appendix).

In contrast, models ET_{d5} and ET_{d6} based on the reference crop ET fraction did not perform very well; errors in estimating ET_d were greater than 10.0 ± 16.0% (Table 4 in Appendix). In Fig. 3, model ET_{d6} showed a large error variation or spread (RMSE) for larger ET_d values located on corn fields. Performance displayed by ET_{d5} and ET_{d6} methods may be an indication that these methods have

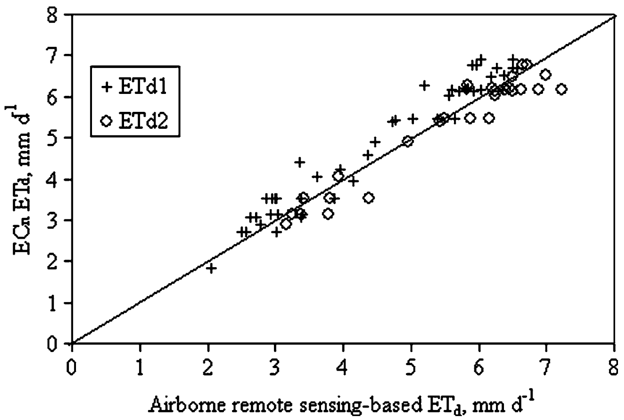

Fig. 2 ET_{d1} and ET_{d2} estimates comparison to measured EC_n–ET_d values

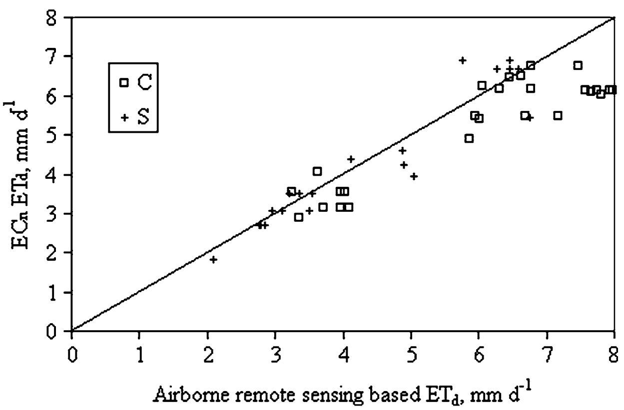

Fig. 3 ET_{d6} estimates comparison to measured EC_n–ET_d values, where label *C* stands for corn and *S* for soybean

some limitations under plant soil-water stress and surface heterogeneity conditions. The ET_oF (or ET_rF) extrapolation mechanism relies on the weather station data; which can be thought as a point measurement rather than as a spatial representation of AE. Further discussion on this subject is presented towards the end of this section.

To further refine our analysis, ET_d estimates were split separating corn and a soybean ET into two groups. These groups were compared with measured EC based ET_d (EC_m), EC-based ET_d closure adjusted using every 30-min BR value (EC_{30}), and with EC-based ET_d closure adjusted with an around noon average BR value (EC_n). Table 5 in Appendix lists the different RS-based ET_i to ET_d extrapolation methods errors (mm day^{-1}) for corn alone; while Table 6 presents ET_d estimation errors in percent (%). In addition, the linear regression slope, intercept and R^2 values were included in Table 6 in Appendix for EC-based ET_d closure adjusted procedure EC_n.

When analyzed separately, RS-based models ET_{d1} to ET_{d4} for corn fields better matched EC_m-based ET_d values. These models showed ET_d estimation errors ranging from -0.31 ± 0.64 to 0.58 ± 0.51 mm day^{-1} (-5.64 ± 13.39–12.98 ± 12.20%) (Tables 5, 6 in Appendix). After adjusting EC measured ET values, for EB closure using the EC_{30} method, ET estimation errors on average increased to -15 ± 17% for ET_d models ET_{d1} through ET_{d4}; while the average bias error decreased from 23.5 to −5.5% for models ET_{d5} and ET_{d6}, although in average the variability of the bias (RMSE) remained unchanged (~14.5%).

For the case of corn, RS ET_d comparison to EC_n ET (Table 6, Appendix), ET estimation errors decreased to -5.36 ± 6.29% for method ET_{d1} and to 5.20 ± 7.29% for ET_{d2}. In a linear regression ET_d comparison (estimated vs. measured), a closer agreement with the 1:1 line resulted from method ET_{d1}, with a slope of 1.06 and an intercept of −0.01 mm day^{-1} ($R^2 = 0.94$).

For soybean fields, Tables 7 and 8 in Appendix list different RS ET_d estimation errors in millimeter day^{-1} and in percent respectively. Model ET_{d1} resulted with the smaller ET estimation error for soybean, with -0.30 ± 0.38 mm day^{-1} or -6.16 ± 10.09% error when compared to EC_n ET_d values. This error is somewhat larger than the error for corn ET. This result was expected since Chávez et al. (2005) reported some bias in estimating RS LE_i for soybean fields with low biomass (LAI < 2.0 m^2 m^{-2}) and exposed bare soil. Soybean LE_i bias was mainly caused by biases in surface radiometric temperature that affected *H* estimates. Uncertainty in surface thermal emissivity values for the bare soils of the study (Chávez et al. 2005) may have caused bias in the calibration of surface radiometric temperature, using the radiative transfer model MODTRAN, for the mixture bare soil/soybean canopy. Further, the atmospheric interference correction, on (at-sensor) surface brightness temperature was larger (~5–9°C) for higher surface temperatures (38–41°C) than for lower temperatures (30.5–31.5°C); where it was 1–2°C. This correction was a function of surface thermal emissivity, relative humidity, air temperature, optical thickness, aerosols, etc. Thus, errors in surface temperature atmosphere interference effect correction could be larger for higher surface temperatures (soybean fields' case).

Closer to solar noon, i.e. from 10:00 a.m. to 2:00 p.m. CST, R_s hence ET changes at a slower rate compared to early morning and late afternoon hours. According to Colaizzi et al. (2006) and Jackson et al. (1983), scaling ET_d from one time of the day measurements resulted in better agreement when ET_i measurements were made within 1 or 2 h of solar noon. Therefore, another analysis was performed in which only ET_d estimates for corn and soybean separately were compared to measured values considering only around noon airborne RS overpasses.

Results for this new around noon analysis were reported in Appendix, Table 9 for corn and Table 10 for soybean. Best agreement with EC_n-based ET_d values for corn and soybean still occurred for RS-based models ET_{d1} and ET_{d2}. Estimation errors for corn were -0.36 ± 0.31 mm day^{-1} or $-6.59 \pm 5.18\%$ and 0.22 ± 0.34 mm day^{-1} or $4.19 \pm 5.87\%$ respectively; with less error for model ET_{d1} which regression coefficients were: slope of 1.03, intercept of 0.23 mm day^{-1} and R^2 of 0.95. For soybean, also ET_{d1} and ET_{d2} resulted in smaller ET_d estimation errors, -0.38 ± 0.35 mm day^{-1} or $-8.59 \pm 9.01\%$ and 0.09 ± 0.37 mm day^{-1} or $3.80 \pm 11.63\%$ respectively. Although models ET_{d4} and ET_{d6} showed relatively smaller errors as well: -0.19 ± 0.53 mm day^{-1} ($-4.80 \pm 11.12\%$), and 0.14 ± 0.50 mm day^{-1} ($4.05 \pm 11.12\%$), respectively.

Eliminating ET_d values estimated for flight overpasses outside the period 10:00 a.m.–2:00 p.m. decreased the average estimation error by about 1% for both corn and soybean fields. The new analysis marginally decreased the errors of ET_rF methods ET_{d5} or ET_{d6}.

On DOY 189, the atmospheric stability condition was unstable during morning hours, i.e. the Monin-Obukohv stability length scale was negative ($L_{M\text{–}O} < 0$), and became stable in the afternoon ($L_{M\text{–}O} > 0$). This fact may have had implications on extrapolating those RS-based ET_i estimates to daily values. For this reason, another comparison to measured/adjusted EC-based ET_d values was made; this time excluding those data for DOY 189 and those outside the 10:00 a.m.–2:00 p.m. (around noon) period. As a result, estimation errors for model ET_{d1} further decreased to $-5.71 \pm 4.77\%$ and those for model ET_{d2} decreased to $5.18 \pm 5.72\%$ for corn (Table 11 in Appendix). In the case of soybean fields, Table 12 (Appendix) shows smaller errors for models ET_{d4} and ET_{d6}; which decreased to $-5.96 \pm 9.5\%$ and $4.31 \pm 10.68\%$ respectively while the bias for model ET_{d1} increased to $-8.70 \pm 10.17\%$ with respect to previous analysis that included only around noon data.

In general, from the three levels of analysis, i.e. (1) using RS-based ET_d estimates from ET_i values obtained at different times of the day, (2) estimated from around noon only ET_i values, and (3) from around noon excluding DOY 189 ET_i values, it can be inferred that model ET_{d1} better compared to EC_n-based ET_d values. This method uses EF and the average 24 h ($R_n - G$) value; which seems to better characterize the spatially distributed AE for the environmental and heterogeneous vegetation cover conditions encountered during this study. It also indicates that average daily G should not be neglected in extrapolating ET_i to ET_d. The good agreement of ET_{d1} with EC_n-based ET_d for corn and soybean is depicted in Fig. 4 below.

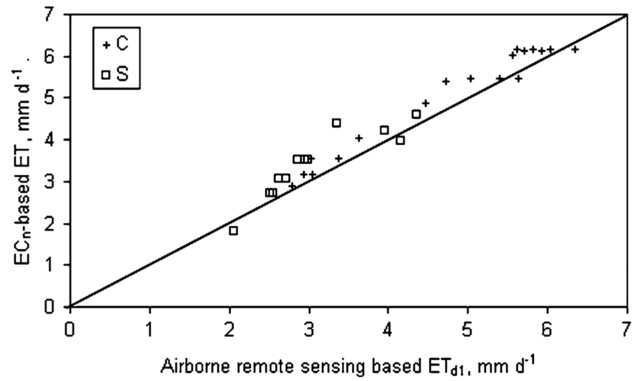

Fig. 4 ET_{d1} comparison to EC_n–ET_d values for corn (*C*) and soybean (*S*) fields, using ET_i extrapolated values around noon and excluding ET from flights on DOY 189

Method ET_{d3} was not consistent for corn and soybean, showing larger MBE values for soybean than for corn; varying from -21.95 to -11.20%, and RMSE values ranging from 8.87 to 11.02%; thus its application is not recommended.

Method ET_{d4}, based on R_s, in general overestimated corn ET by $6.39 \pm 13.18\%$ (Table 11 in Appendix) while underestimated soybean ET by $5.96 \pm 9.53\%$ (Table 12 in Appendix). Daily ET estimates based on the solar radiation method had rather a relatively good agreement with measured values. This method may need to be adjusted to consider nighttime ET loss (Jackson et al. 1983), for accurate daily ET estimations, maybe including daily AE, i.e. daily net radiation and soil heat flux. This method may be applied in situations where average daily net radiation and soil heat flux are not possible to be obtained.

In general, methods ET_{d5} and ET_{d6} (ET_rF and ET_oF, respectively) did not perform as well as method ET_{d1}. ET_oF performed slightly better than ET_rF (Appendix Tables 11, 12), with an ET_d overestimation of over $4.0 \pm 10.0\%$ for both crops. This result is in agreement with the magnitude of the errors reported by Colaizzi et al. (2006), who tested five different methods to scale ET_i to ET_d, for fully irrigated alfalfa, partially irrigated cotton, dryland grain sorghum, and bare soil (tilled fallow sorghum). They scaled daily ET from, around solar noon time, one-time-of-day 0.5 h ET and compared results with lysimeter data [lysimeter details can be found in Howell et al. (1995)].

In the Colaizzi et al. (2006) study, no remote sensing data were involved. The authors used the ASCE-EWRI (2005) standardized ASCE-PM procedure to calculate 30-min grass and alfalfa reference ET (ET_o and ET_r, respectively), and integrated these values over the day to obtain daily ET. The authors found ET_d underestimation errors within 10% for $ET_d > 6$ mm day^{-1}, RMSE of 0.33 to 0.46 mm day^{-1} and errors within 20% for ET_d values between 3.9 and

5.8 mm day^{-1}, and >20% for ET_d values between 0.4 and 3.2 mm day^{-1}.They concluded that the ET_oF extrapolation method worked better for transpiring crops while the EF method did it for bare soil. In their study, ET prediction errors increased as ET rates decreased when using the ET_oF extrapolation method.

At first hand, our results may seem contradictory to Colaizzi et al. (2006) findings, i.e. that the EF (which uses average daily R_n and G) resulted being a better extrapolation mechanism; in contrast to the Colaizzi et al. results that indicate ET_oF performed better. To this effect, these two "apparently" contradictory results in fact are complementary. In our case, the EF never was greater than 1 for both crops, wind speed was low to moderate, and relative humidity levels were in general high (Table 1). This means LE (or ET) was always smaller than the available energy ($R_n - G$); thus no advected energy existed to be incorporated (to enhance) in the ET process. In contrast, in the Colaizzi et al. (2006) study, advection was part of the ET process. Tolk et al. (2006b) reported an average ET rate of 11.3 mm day^{-1}, measured with a large weighing lysimeter, for irrigated alfalfa in Bushland, Texas, with ET for some days exceeding 15 mm day^{-1} due to regional advection. Tolk et al. (2006b) found that an average of 61% of the total ET could be attributed to advective sensible heat in Bushland, TX, for average wind speeds of 4.4 m s^{-1}.

For instance, Colaizzi et al. (2006) indicated that for a situation of strong regional advection with wind speeds of over 11 m s^{-1}, irrigated alfalfa ET was 18.1 mm day^{-1}. Under those conditions the ET_oF extrapolation method worked very well. Similarly, Chávez et al. (2007) found that the ET_rF mechanism applied to a Landsat 5 TM scene acquired over lysimeter fields in Bushland, Texas, under advective conditions (ET for a well irrigated crop was 11.2% larger that the AE), yielded ET_d values that matched reference values measured with large precision monolithic weighing lysimeters very well. In this study, ET_d values were from fully irrigated forage sorghum (LAI = 4.2 m^2 m^{-2}) and irrigated grass (LAI = 3.0 m^2 m^{-2}) fields. For these crops, ET estimation errors were −1.3 and 0.8% respectively. However, the daily ET prediction error was 23.7% for a forage corn field depicting very low biomass (LAI = 0.4 m^2 m^{-2}). Interestingly, for this same forage corn field using the EF scaling method resulted in a small under prediction of ET, only 6.9%; while showing a large under prediction for the irrigated forage sorghum and grass fields of 23.8 and 18.0% respectively.

Table 1 Evaporative Fraction (EF) range, wind speed (U) and relative humidity (RH)

DOY	EF range		U m s^{-1}	RH (%)
	Corn	Soybean		
167	0.52–0.60	0.42–0.51	1.7–2.7	27.6–30.0
182	0.96–0.81	0.45–0.63	4.5–6.5	46.7–58.2
184	0.78–0.79	0.66–0.70	2.2–3.3	54.7–67.5
189	0.91–0.96	0.91–0.96	3.3–5.0	76.2–81.9

In summary, it seems that the extrapolation method ET_{d1} (EF) works better for heterogeneous vegetation cover conditions showing moderate to considerable soil water stress, and for non-advectice climate conditions; while the ET_oF (or ET_rF) method, on the contrary, seems to perform better under more homogeneous surface conditions, for transpiring crops, i.e., little to no plant soil water stress, and under advective conditions.

The EF method incorporates spatial variability of surface conditions because the instantaneous RS derived LE, R_n and G are spatially distributed values (raster image or grid); while the ET_oF (or ET_rF) method only uses LE from RS and ET_o (or ET_r) calculated from "point" data measured at a weather station location. Hence, both extrapolation methods may complement each other, i.e., using one or the other (or combination) depending on the crop growth (developing) stage, surface cover and environmental conditions.

Furthermore, some errors in the application of methods ET_{d5} and ET_{d6} may be partly explained by errors in the computation of reference ET, etc. According to Chávez et al. (2005), on DOY 182 corn fields were at full cover while the soybean fields were at early stages of growth showing a mix of bare soil and growing canopy. This may suggest that for large biomass (LAI > 3), full cover crops experiencing little to no soil water limitations, ET_rF (or ET_oF) method underestimates the 30-min (or hourly) $(ET_r)_i$ values calculated from reference WS data. Since $(ET_r)_i$ is the denominator in ET_rF, the greater the $(ET_r)_i$ underestimation the greater the overestimation for ET_rF, consequently ET_d is in turn overestimated. Lascano and Van Bavel (2007) found that the standardized ASCE-PM and/or FAO–56, in that regard, [since they are similar because both use the ET Penman-Monteith method (PM)] underestimated true reference ET or potential ET (ET_p). They used the direct combination method (DCM)**,** of ASCE-EWRI (2005) and Allen et al. (1998)**,** to calculate ET_p which uses standard climatological data and is based on assumptions regarding temperature and humidity at the evaporating surface not made using a recursive combination method (RCM). They compared calculated values of ET_p or reference ET (ET_r), by means of the DCM method to results obtained using the RCM method, for 10 days using weather data collected in Lubbock, Texas. In addition, they compared ET_r values with values calculated using the standardized ASCE-PM method (ET_o). Their results show that on hot summer days the DCM method underestimated ET_p by as much as 21% and ET_r by 16% compared to the RCM method**;** while differences were minimal on cool days. To verify these results Lascano and Evett (2007) compared values of alfalfa ET measured with large precision weighing lysimeters at Bushland, TX, for a range of environmental conditions, to those calculated with the RCM method. Results indicated that the RCM method correctly calculated alfalfa ET rates.

In summary, the ET_o calculation used in this study is based on the DCM method and thus apparently subject to errors according to Lascano and Van Bavel (2007) and Lascano and Evett (2007).

On the other hand, errors on the calculation of hourly reference ET can be attributed to the incapability of some data loggers to record true maximum and minimum air temperatures during short periods since they average temperature values over 1 h or ½ h period. Bullock et al. (2005) discussed daily reference ET underestimation due to weather data not representative of true daily maximum and minimum air temperatures.

Conclusions

In this ET extrapolation study, estimations of instantaneous airborne remote sensing EF better matched average daily EC-based EF values for flight overpasses from local noon to close to 2:00 p.m. CST. Better EF agreement was found for soybean fields than for corn fields.

When comparing ET_d estimates for corn and soybean fields together to EC-closure adjusted ET_d values, model ET_{d1} (EF) yielded the smaller overall error, i.e. $-7.41 \pm 6.97\%$ (MBE ± RMSE). This result might indicate that daily average soil heat flux should be included in the computation of the daily AE for the EF extrapolation method and that EF may be a suitable coefficient to scale ET_i to ET_d.

When analyzed individually for corn, the ET_{d1} method estimation error decreased to $-5.71 \pm 4.77\%$ (-0.28 ± 0.25 mm day^{-1}) after excluding those data outside of the 10:00 a.m.–2:00 p.m. CST period and DOY 189 which changed from unstable to stable atmospheric conditions after local noon time. For soybean alone, ET_{d1} estimation error was $-8.70 \pm 10.17\%$ (-0.33 ± 0.35 mm day^{-1}).

Method ET_{d3} was not consistent for corn and soybean ET estimation, showing larger MBE values for soybean than for corn; in general varying from −21.95 to −11.20%, and RMSE values ranging from 8.87 to 11.02%, thus the application of this method is not recommended.

Methods ET_{d5} and ET_{d6} (ET_rF and ET_oF respectively) had an overall ET_d overestimation error of over $4.0 \pm 10.0\%$ for both crops.

In general, it appears that the extrapolation method ET_{d1} works better for crops having some to considerable soil water stress, for non-advective and heterogeneous vegetation cover conditions; while the ET_oF (or ET_rF) method, on the contrary, seems to perform better for transpiring crops, i.e., little to no plant soil water stress, for advective and homogeneous surface conditions. Hence, both extrapolation methods may complement each other under a range of crop phenological, surface and environmental conditions.

An alternative methods appears to be method ET_{d4}, based on R_s, which worked relatively well for both crops with an average estimation errors around $2.2 \pm 10.1\%$. This model may be applied under situations where measured daily net radiation and soil heat flux data are not available.

In addition, these results validate the use of the airborne multispectral RS-based ET methodology for the estimation of instantaneous ET and its extrapolation to daily ET with margin of errors similar to those reported in other studies and to typical errors of weather and land surface energy balance systems.

Acknowledgments The authors are thankful to NASA's Global Water and Energy Cycle Program, Utah Agricultural Experiment Station, to the Remote Sensing Services Laboratory-BIE-Utah State University and to the USDA-ARS, Conservation and Production Research Laboratory for their support. We also wish to thank Drs. Prasanna H. Gowda, Harikishan Jayanthi, and Jairo E. Hernandez for their constructive suggestions to improve the quality of this article.

Appendix

Table 2 EC measured daily and 30-min R_n and heat fluxes over corn fields

DOY	CST	Site	Daily averages			30-min averages[a]			
			R_n W m^{-2}	G W m^{-2}	LE_m W m^{-2}	R_n W m^{-2}	G W m^{-2}	LE_m W m^{-2}	H W m^{-2}
182	11:30	15.1	212	26	177	664	66	481	81
182	11:30	15.2	201	17	154	655	50	357	93
182	13:30	15.1	212	26	177	363	60	458	44
182	14:30	15.1	212	26	177	603	45	540	44
182	14:30	15.2	201	17	154	642	62	363	97
182	11:00	15.1	212	26	177	637	66	410	69
182	11:00	15.2	201	17	154	617	40	381	104

Table 2 continued

DOY	CST	Site	Daily averages			30-min averages[a]			
			R_n W m^{-2}	G W m^{-2}	LE_m W m^{-2}	R_n W m^{-2}	G W m^{-2}	LE_m W m^{-2}	H W m^{-2}
182	12:30	24	192	17	173	684	65	483	52
182	11:30	6	203	22	173	665	68	490	79
182	14:30	24	192	17	173	615	50	437	17
189	9:00	15.1	208	10	178	405	74	254	29
189	9:00	15.2	200	13	167	387	80	227	26
167	11:30	15.1	183	21	88	636	184	246	160
167	11:30	15.2	174	17	80	648	143	199	174
167	15:30	15.1	183	21	88	548	139	223	103
167	15:30	15.2	174	17	80	578	107	173	110
167	12:00	15.1	183	21	88	634	205	195	159
167	12:00	15.2	174	17	80	645	161	195	154
167	12:00	6	190	15	98	672	248	250	152
167	11:00	33	178	22	70	609	194	174	158
184	11:00	15.1	192	25	137	568	72	418	115
184	11:00	15.2	180	18	125	530	27	323	106
189	11:00	15.1	214	19	178	620	97	419	38
189	11:00	15.2	200	19	171	600	48	417	52
189	11:30	24	196	22	192	651	64	461	24
189	11:00	6	173	19	189	547	80	439	28
189	10:00	24	196	22	192	519	58	410	28

[a] Coinciding with USU airborne RS system overpass time

Table 3 EC measured daily and 30-min R_n and heat fluxes over soybean fields

DOY	CST	Site	Daily averages			30-min averages[a]			
			R_n W m^{-2}	G W m^{-2}	LE_m W m^{-2}	R_n W m^{-2}	G W m^{-2}	LE_m W m^{-2}	H W m^{-2}
182	11:30	16.1	210	25	102	648	87	257	213
182	13:30	16.1	210	25	102	610	103	208	219
182	11:00	16.1	210	25	102	625	108	242	196
182	12:00	14	207	20	117	657	114	266	194
182	12:00	3	207	20	100	672	104	288	167
167	15:15	16.1	194	33	71	505	125	162	119
167	15:15	16.2	169	22	72	517	164	155	101
167	11:30	13	166	28	50	600	292	116	203
167	11:15	16.1	194	33	71	657	240	191	186
167	11:15	16.2	169	22	72	623	258	215	198
167	11:45	16.1	194	33	71	656	212	174	187
167	11:45	16.2	169	22	72	625	228	177	163
184	11:00	16.1	205	20	103	563	85	282	147
184	11:00	16.2	179	21	111	534	79	300	131
189	11:00	16.1	156	13	170	611	85	417	31
189	11:00	16.2	200	16	170	600	91	476	42
189	11:00	14	203	19	175	593	104	441	20
189	9:00	16.1	206	18	170	406	66	258	13
189	9:00	16.2	200	16	170	369	61	291	10
189	10:00	14	203	19	175	500	76	408	4

[a] Coinciding with USU airborne RS system overpass time

Table 4 RS-ET_d estimation errors including corn and soybean fields together

Model	MBE mm day^{-1}	RMSE mm day^{-1}	MBE %	RMSE %	*a*	*b* mm day^{-1}	R^2
ET_{d1}	−0.37	0.32	−7.41	6.97	1.05	0.09	0.95
ET_{d2}	0.17	0.35	4.03	8.56	0.97	−0.07	0.94
ET_{d3}	−0.64	0.4	−15.12	10.26	0.95	0.83	0.94
ET_{d4}	0.11	0.69	1.27	12.65	0.79	0.80	0.80
ET_{d5}	0.81	0.97	15.79	16.59	0.71	0.93	0.79
ET_{d6}	0.53	0.85	10.28	14.87	0.69	1.16	0.72

Table 5 Daily ET estimation errors in "mm day^{-1}" for corn fields

Model	EC_m		EC_{30}		EC_n	
	MBE mm day^{-1}	RMSE mm day^{-1}	MBE mm day^{-1}	RMSE mm day^{-1}	MBE mm day^{-1}	RMSE mm day^{-1}
ET_{d1}	−0.09	0.66	−1.55	0.83	−0.31	0.34
ET_{d2}	0.46	0.61	−1.00	0.78	0.24	0.35
ET_{d3}	−0.31	0.64	−1.77	0.70	−0.52	0.40
ET_{d4}	0.58	0.51	−0.88	0.80	0.36	0.69
ET_{d5}	1.27	0.81	−0.19	0.89	1.05	1.02
ET_{d6}	0.95	0.72	−0.52	0.86	0.73	0.89

Table 6 Daily ET estimation errors in percent (%) for corn fields

Model	EC_m		EC_{30}		EC_n				
	MBE %	RMSE %	MBE %	RMSE %	MBE %	RMSE %	*a*	*b* mm day^{-1}	R^2
ET_{d1}	0.60	13.90	−22.27	7.94	−5.36	6.29	1.06	−0.01	0.94
ET_{d2}	11.76	14.90	−13.55	9.45	5.20	7.29	0.97	−0.08	0.94
ET_{d3}	−5.64	13.39	−27.07	7.62	−10.92	9.42	0.91	0.99	0.92
ET_{d4}	12.98	12.20	−12.34	10.32	7.09	12.50	0.79	0.81	0.81
ET_{d5}	26.28	15.21	−2.08	11.76	19.88	17.09	0.62	1.35	0.71
ET_{d6}	20.30	14.37	−6.74	10.99	14.08	15.30	0.69	1.16	0.72

Table 7 Daily ET estimation errors in "mm day^{-1}" for soybean fields

Model	EC_m		EC_{30}		EC_n	
	MBE mm day^{-1}	RMSE mm day^{-1}	MBE mm day^{-1}	RMSE mm day^{-1}	MBE mm day^{-1}	RMSE mm day^{-1}
ET_{d1}	0.01	0.52	−0.89	0.93	−0.30	0.38
ET_{d2}	0.51	0.59	−0.40	0.96	0.20	0.42
ET_{d3}	−0.44	0.47	−1.35	0.91	−0.75	0.36
ET_{d4}	0.13	0.46	−0.77	0.89	−0.18	0.53
ET_{d5}	0.59	0.45	−0.32	0.88	0.28	0.55
ET_{d6}	0.38	0.44	−0.53	0.91	0.06	0.54

Table 8 Daily ET estimation errors in percent (%) for soybean fields

Model	EC_m		EC_{30}		EC_n				
	MBE %	RMSE %	MBE %	RMSE %	MBE %	RMSE %	*a*	*b* mm day^{-1}	R^2
ET_{d1}	1.70	14.22	−15.67	15.24	−6.16	10.09	1.04	0.14	0.95
ET_{d2}	15.62	18.44	−4.02	19.49	6.60	13.32	0.99	−0.15	0.94
ET_{d3}	−11.61	12.95	−26.91	12.37	−18.46	8.86	1.07	0.51	0.95
ET_{d4}	4.25	13.33	−13.66	13.89	−3.58	11.25	0.99	0.21	0.89
ET_{d5}	16.33	13.06	−3.65	14.30	7.73	12.05	0.94	−0.02	0.90
ET_{d6}	11.23	12.92	−7.85	14.08	2.97	11.38	1.00	0.10	0.89

Table 9 RS-based ET_d estimation errors for corn resulting from extrapolating around noon ET_i values only and when compared to EC_n-based ET_d values

Model	EC_n						
	MBE mm day^{-1}	RMSE mm day^{-1}	MBE %	RMSE %	*a*	*b* mm day^{-1}	R^2
ET_{d1}	−0.36	0.31	−6.59	5.18	1.03	0.23	0.95
ET_{d2}	0.22	0.34	4.19	5.87	0.92	0.21	0.94
ET_{d3}	−0.54	0.42	−11.48	10.00	0.86	1.25	0.93
ET_{d4}	0.31	0.73	5.49	12.12	0.75	1.13	0.79
ET_{d5}	1.13	1.08	20.56	17.85	0.58	1.61	0.68
ET_{d6}	0.79	0.95	14.61	15.80	0.65	1.42	0.71

Table 10 RS-based ET_d estimation errors for soybean resulting from extrapolating around noon ET_i values only and when compared to EC_n-based ET_d values

Model	EC_n						
	MBE mm day^{-1}	RMSE mm day^{-1}	MBE %	RMSE %	*a*	*b* mm day^{-1}	R^2
ET_{d1}	−0.38	0.35	−8.59	9.01	1.04	0.23	0.95
ET_{d2}	0.09	0.37	3.80	11.63	0.94	−0.03	0.94
ET_{d3}	−0.79	0.33	−20.35	8.38	1.04	0.66	0.96
ET_{d4}	−0.19	0.53	−4.8	11.12	0.93	0.49	0.89
ET_{d5}	0.36	0.54	8.93	12.04	0.87	0.22	0.90
ET_{d6}	0.14	0.50	4.05	11.12	0.93	0.16	0.90

Table 11 RS-based ET_d estimation errors for corn resulting from extrapolating around noon ET_i values only, excluding DOY 189 and when compared to EC_n-based ET_d values

Model	EC_n						
	MBE mm day^{-1}	RMSE mm day^{-1}	MBE %	RMSE %	*a*	*b* mm day^{-1}	R^2
ET_{d1}	−0.28	0.25	−5.71	4.77	0.97	0.39	0.93
ET_{d2}	0.27	0.32	5.18	5.72	0.86	0.44	0.96
ET_{d3}	−0.47	0.41	−11.20	11.02	0.79	1.40	0.96
ET_{d4}	0.36	0.79	6.39	13.18	0.71	1.08	0.94
ET_{d5}	1.27	1.17	23.76	18.83	0.56	1.39	0.91
ET_{d6}	0.94	1.01	17.61	16.45	0.62	1.24	0.92

Table 12 RS-based ET_d estimation errors for soybean resulting from extrapolating around noon ET_i values only, excluding DOY 189 and when compared to EC_n-based ET_d values

Model	EC_n						
	MBE mm day^{-1}	RMSE mm day^{-1}	MBE %	RMSE %	*a*	*b* mm day^{-1}	R^2
ET_{d1}	−0.33	0.35	−8.70	10.17	1.01	0.31	0.81
ET_{d2}	0.11	0.38	4.86	12.98	0.97	0.00	0.78
ET_{d3}	−0.72	0.32	−21.95	8.87	0.89	1.00	0.85
ET_{d4}	−0.20	0.37	−5.96	9.53	0.83	0.73	0.82
ET_{d5}	0.31	0.46	9.00	11.74	0.71	0.77	0.82
ET_{d6}	0.15	0.41	4.31	10.68	0.76	0.69	0.82

References

Allen R (2002) REF-ET: reference evapotranspiration calculator. Software for FAO and ASCE standardized equations. University of Idaho. Available at http://www.kimberly.uidaho.edu/ref-et/. Accessed 15 October 2005

Allen R, Pereira L, Raes D, Smith M (1998) Crop evapotranspiration (guidelines for computing crop water requirements). FAO Irrigation and Drainage Paper No. 56. Food and Agriculture Organization of the UN, Italy

Allen RG, Tasumi M, Trezza R (2007a) Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC)-model. ASCE J Irrig Drain Eng 133(4):380–394. doi:10.1061/(ASCE)0733-9437(2007)133:4(380)

Allen RG, Tasumi M, Morse A, Trezza A, Wright JL, Bastiaanssen W, Kramber W, Lorite-Torres I, Robison CW (2007b) Satellite-based energy balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)-Applications. ASCE J Irrig Drain Eng 133(4):395–406

ASCE-EWRI (2005) The ASCE standardized reference evapotranspiration equation. Report by the American Soc. Of Civil Engineers (ASCE) Task Committee on Standardization of Reference Evapotranspiration. In: Allen RG, Walter IA, Elliott RL, Howell TA, Itenfisu D, Jensen ME Snyder RL ASCE, 0-7844-0805-X, Reston, VA, 204 pp

Bastiaanssen WGM, Menenti M, Feddes RA, Holtslang AA (1998) A remote sensing surface energy balance algorithm for land (SEBAL): 1. Formulation. J Hydrol 212–213:198–212

Brutsaert W (2005) Hydrology: an introduction. Cambridge University Press, London, pp 618

Brutsaert W, Sugita M (1992) Application of self-preservation in the diurnal evolution of the surface energy budget to determine daily evaporation. J Geophys Res 97:18377–18382

Bullock P, Renwick R, Angadi S, Shaykewich C (2005) Correcting daily maximum and minimum air temperature to improve estimation of reference evapotranspiration. In: Proceedings of the ASA/CSSA/SSSA 97th international annual meeting. November 6–10, Salt Lake City, UT. ASA/CSSA/SSSA

Cai B, Neale CMU (1999) A method for constructing three dimensional models from airborne imagery. In: 17th biennial workshop on color photography and videography in resource assessment. May 5–7, 1999. Reno, NV

Carlson TN, Capehart WJ, Gillies RR (1995) A new look at the simplified method for remote sensing of daily evapotranspiration. Remote Sens Environ 54:161–167

Chávez JL, Neale CMU, Hipps LE, Prueger JH, Kustas WP (2005) Comparing aircraft-based remotely sensed energy balance fluxes with eddy covariance tower data using heat flux source area functions. J Hydrom AMS 6(6):923–940. doi:10.1175/JHM467.1

Chávez JL, Gowda PH, Howell TA, Copeland KS (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, Irrigation Association CD-ROM, San Diego, pp 268–283

Chemin Y, Alexandridis T (2001) Improving spatial resolution of ET seasonal for irrigated rice in Zhanghe, China. Paper presented at the 22nd Asian Conference on remote sensing, 5–9 November, 2001, Singapore

Colaizzi PD, Evett SR, Howell TA, Tolk JA (2006) Comparison of five models to scale daily evapotranspiration from one-time-of-day measurements. Trans ASABE 49(5):1409–1417

Courault D, Seguin B, Olioso A (2003) Review of estimate ET from remote sensing data: some examples from the simplified relationship to the use of mesoscale atmospheric models. ICID workshop on remote sensing of ET for large regions, 17 September 2003, Montpellier, France

Courault D, Seguin B, Olioso A (2005) Review on estimation of evapotranspiration from remote sensing data: from empirical to numerical modeling approach. Irrig Drain Syst 19:223–249

Crago RD (2000) Conservation and variability of the evaporative fraction during the daytime. J Hydrol 180(1–4):173–194

Field RT, Heiser M, Strebel DE (1994) Measurements of surface fluxes. The FIFE Information System. April 9, 1994. Available at http://www.esm.versar.com/FIFE/FIFEhome.htm http://www.esm.versar.com/FIFE/Summary/Sur_flux.htm. Accessed 10 September 2004

Haffeez MM, Chemin Y, Van De Giesen N, Bouman BAM (2002) Field ET estimation in central Luzon, Philippines, using different sensors: Landsat 7 ETM +, Terra Modis and Aster. Symposium on Geospatial Theory, Processing and Applications, Ottawa 2002, Canada

Harrison LP (1963) Fundamentals concepts and definitions relating to humidity. In: Wexler A (ed) Humidity and moisture, vol 3. N.Y. Reinhold Publishing Co, New York

Hipps L (2003) Land–atmosphere interactions. Class notes and personal communication. Utah State University, PSB Department, Logan, Utah

Howell TA, Schneider AD, Dusek DA, Marek TH, Steiner JL (1995) Calibration and scale performance of Bushland weighing lysimeters. Trans ASAE 38:1019–1024

Ibáñez M, Castellví F (2000) Simplifying daily ET estimates over short full-canopy crops. Agron J 92:628–632

Irmak S, Howell TA, Allen RA, Payero JO, Martin DL (2005) Standardized ASCE Penman-Monteith: impact of sum-of-hourly vs. 24-hour timestep computations at reference weather station sites. Trans ASAE 48(3):1063–1077

Jackson TJ (2002) SMEX02 Soil Climate Analysis Network (SCAN) Station 2031, Ames, Iowa. Boulder, CO: National Snow and Ice Data Center. Digital Media

Jackson RD, Reginato RH, Idso SB (1977) Wheat canopy temperature: a practical tool for evaluating water requirements. Water Resour Res 13:651–656
Jackson RD, Hatfield JL, Reginato RJ, Idso SB, Pinter PJ (1983) Estimation of daily ET from one-time day measurements. Agric Water Manag 7:351–362
Jackson RD, Moran MS, Gay LW, Raymond LH (1987) Evaluating evaporation from field crops using airborne radiometry and ground-based meteorological data. Irrig Sci 8:81–90
Kustas WP, Hatfield JL, Prueger JH (2005) The soil moisture-atmosphere coupling experiment (SMACEX): background, hydrometeorological conditions and preliminary findings. J Hydromet AMS 6:791–804
Kustas WP, Perry EM, Doraiswamy PC, Moran MS (1994) Using satellite remote sensing to extrapolate evapotranspiration estimates in time and space over a semiarid Rangeland basin. Remote Sens Environ 49(3):275–286
Lascano RJ, Van Bavel CHM (2007) Explicit and recursive calculation of potential and actual evapotranspiration. Agron J 99:585–590
Lascano RJ, Evett SR (2007) Experimental verification of a recursive method to calculate evapotranspiration. In: Proceedings of the 28th annual international irrigation show, December 9–11, 2007, San Diego, Irrigation Association CD-ROM, 687–705
Narasimhan B, Srinivasan R (2002) Determination of regional scale evapotranspiration of Texas from NOAA-AVHRR satellite. Final report to the Texas Water Resources Institute March 5, 2002
Neale CMU, Crowther B (1994) An airborne multispectral video/radiometer remote sensing system: development and calibration. Remote Sens Environ 49(3):187–194
Romero MG (2004) Daily Evapotranspiration estimation by means of evaporative fraction and reference evapotranspiration fraction. PhD Dissertation, Biological and Irrigation Engineering Department. Utah State University. Logan–UT, 190 pp
Rouse, JW, Hass RH, Schell JA, Deering DW (1973) Monitoring vegetation systems in the Great Plains with ERTS. Third ERTS Symposium, NASA SP–351 I, pp 309–317
Seguin B, Courault D, Guerif M (1994) Surface temperature and evapotranspiration: Application of local scale methods to regional scales using satellite data. Remote Sens Environ 49:287–295
Shuttleworth WJ, Gurney RJ, Hsu AY, Ormsby JP (1989) FIFE: the variation in energy partition at surface flux sites. Int Assoc Hydrol Sci (IAHS) Publication 186: 67–74
Simmers I (1977) Effects of soil heat flux on the water balance of a small catchment. Hydrol Sci 22(3):433–445
Suleiman A, Crago R (2004) Hourly and daytime ET from grassland using radiometric surface temperatures. Agron J 96:384–390
Thunnissen HAM, Nieuwenhuis GJA (1990) A simplified method to estimate regional 24-hr evapotranspiration from thermal infrared data. Remote Sens Environ 31:211–225
Tolk JA, Howell TA, Evett SR (2006a) Nighttime evapotranspiration from alfalfa and cotton in a semiarid climate. Agron J 98:730–736
Tolk JA, Evett SR, Howell TA (2006b) Advection influences on evapotranspiration of alfalfa in a semiarid climate. Agron J 98:1646–1654
Tucker CJ (1979) Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens Environ 8(2):127–150
Trezza R (2002) Evapotranspiration using a satellite-based surface energy balance with standardized ground control. Ph.D. dissertation, USU, Logan, UT, 339 pp
Twine TE, Kustas WP, Norman JM, Cook DR, Houser PR, Meyers TP, Prueger JH, Starks PJ, Wesely ML (2000) Correcting eddy-covariance flux underestimates over a grassland. Agric For Meteorol J 103(3):229–317
USDA (2006) USDA, NRCS. National Water and Climatic Center. Available at http://www.wcc.nrcs.usda.gov/scan/. Accessed 20 July 2006
Vogt VJ, Niemege S, Viau AA (2001) Monitoring water stress at regional scales. In: Proceedings of the 23rd Canadian symposium on remote sensing, 21–24 August 2001, Laval University, Sainte Foy, pp 315–321
Walter IA, Allen RG, Elliot R, Jensen ME, Itenfisu D, Mecham B, Howell TA, Snyder R, Brown P, Echings S, Spofford T, Hattendorf M, Cuenca RH, Wright JL, Martin D (2000) ASCE's standardized reference evapotranspiration equation. In: Evans RG, Benham BL, Trooien TP (eds). Proceedings of the 4th decennial symposium, National Irrigation Symposium, Phoenix, AZ, November, 2000. ASAE, St Joseph, pp 209–215
Weaver HL (1990) Temperature and humidity flux-variance relations determined by one-dimensional eddy correlation. Bound Layer Meteorol 53:77–91
Wilson K, Goldstein A, Falge E, Aubinet M, Baldocchi D, Berbigier P, Bernhofer C, Ceulemans R, Dolman H, Field C, Grelle A, Ibrom A, Law BE, Kowalski A, Meyers T, Moncrieff J, Monson R, Oechel W, Tenhunen J, Valentini R, Verma S (2002) Energy balance closure at FLUXNET sites. Agric For Meteorol 113(2002):223–243
Zhang L, Lemeur R (1995) Evaluation of daily ET estimates from instantaneous measurements. Agric For Meteorol 74:139–154