Evaluation of energy balance, combination, and complementary schemes for estimation of evaporation

A. ERSHADI[1], M.F. MCCABE[1], J.P. EVANS[1], J.P. WALKER[2]

1 *The University of NSW, Sydney, Australia*

2 *Monash University, Clayton, Australia*

a.ershadi@unsw.edu.au

Abstract A comparison between three basic approaches for estimation of actual evapotranspiration, namely, the energy balance, the combination, and the complementary approaches is undertaken. We utilized Monin-Obukhov Similarity Theory (MOST) as a framework for the energy balance method, the single-layer Penman-Monteith method as the combination approach, and the Advection-Aridity method as the complementary approach, in a sound analytical framework. Data from 3 flux tower stations are used to evaluate model estimated heat fluxes at short time steps. Results indicate advantages and/or limitations of each method under different conditions, highlighting issues in application of the Advection-Aridity technique in dry conditions and energy balance methods over sparse canopies.

Key words evapotranspiration, evaluation, energy balance, Penman-Monteith, Advection-Aridity

INTRODUCTION

Accurate estimation of evapotranspiration is important for many agricultural and hydrological applications. Moreover, it is a key component of many atmospheric, hydrological, and agricultural models.

In this study, the relative merits of the energy balance, combination, and complementary approaches for estimation of actual evaporation are investigated. We use the theoretical framework of the Surface Energy Balance System (SEBS) described by Su (2002) as the energy balance approach, the Penman-Monteith equations of Monteith (1965) as the combination approach, and the Advection-Aridity method (Bouchet (1963); Parlange and Katul (1992)) as the complementary approach. Eddy correlation measurements of latent and sensible heat fluxes (λE and H) and measurements of net radiation R_n, ground heat flux G_0, standard weather variables, and canopy structure parameters are used to test the accuracy of the three approaches for different crops.

In the energy balance method, only the transfer of heat as sensible heat flux is considered and evapotranspiration (latent heat flux) calculated as the residual term in the general energy balance equation. The Penman-Monteith method is known as the "combination" method as it combines basic equations of heat and water vapor transfer. The Advection-Aridity method is known as the "complementary" method as it is based on complementation and conversion of sensible and latent heat fluxes to maintain a constant turbulent flux quantity. All three of these methods result from the turbulent transfer theory described by the flux-gradient functions of Monin-Obukhov Similarity Theory (MOST) with some form of simplification.

While there are comparisons of these methods in the literature (e.g. Stannard (1993); Inclán and Forkel (1995); Shaomin, Zhongping et al.(2004)), the novelty in this research is in the comparison of all of these methods together in a common conceptual framework.

METHODOLOGY

The Energy Balance Method

In the energy balance method, evapotranspiration, otherwise referred to as the latent heat flux (λE), is calculated as the residual term in the general energy balance equation. In this case, the combination of sensible and latent heat flux is assumed equal to the total available energy flux (Q_n) or $\lambda E+H=Q_n$. By neglecting the effects of advection and CO_2 flux on the energy balance, the equation can be written as $Q_n=R_n-G_0$. It is then possible to quantify H by solving MOST equations simultaneously in an iterative way. This method is used in the SEBS approach (Su, 2002) with thermal remote sensing data of the land surface.

The Penman-Monteith Method

The Penman (Penman, 1948) and Penman-Monteith (Monteith, 1965) equations incorporate energy balance and aerodynamic water vapour mass transfer principles and are therefore known as combination equations. One can write the actual evaporation in its Penman-Monteith form as (Brutsaert, 2005; Eq. 4.39)

$$E = \frac{\Delta Q_{ne} + \gamma r_a^{-1} \rho (q_a^* - \bar{q}_a)}{\Delta + \gamma (1 + r_s / r_a)}, \tag{1}$$

where, $\Delta=(e_s^*-e_a^*)(T_s^*-T_a^*)^{-1}$ is the slope of the saturation water vapour pressure curve, $e^*=e^*(T)$ at the air temperature T_a, γ is the psychrometric constant defined as $\gamma=c_p p/(0.622\lambda)$, q_a^* is the specific humidity of air at saturation, and r_a and r_s are aerodynamic and surface resistances. Q_{ne} is the available energy flux defined as $Q_{ne}=Q_n/\lambda$.

The Advection-Aridity Method

The concept of complementary fluxes with advection-aridity were first developed by Bouchet (1963) and further developed by Parlange and Katul (1992). If evapotranspiration is independent of the available energy flux Q_{ne}, the actual evaporation E decreases below its true potential value, and a certain amount of energy not used by evaporation becomes available as sensible heat. As shown by Brutsaert (2005), the advection-aridity equation for estimation of evaporation is

$$E = (2\alpha_e - 1)\frac{\Delta}{\Delta + \gamma} Q_{ne} - \frac{\gamma}{\Delta + \gamma} \frac{\rho (q_a^* - \bar{q}_a)}{r_a}, \tag{2}$$

Where α_e is the Priestly-Taylor coefficient (=1.26). The main advantage of the Advection-Aridity complementary approach is that it does not require any information related to soil moisture, canopy resistance, or other measures of aridity, because it relies on meteorological parameters alone (Brutsaert, 2005).

Estimation of roughness terms

For estimation of zero-plane displacement height (d_0) and roughness length parameters for momentum and heat transfer ($z_{0m}$and z_{0h}), the methodology originally developed by Massman (1997) and further completed by Su et al. (2001) was used. This model is also implemented in the Surface Energy Balance System (SEBS) to estimate roughness length parameters from remote sensing retrievals of the land (canopy) surface characteristics and locally measured meteorological parameters. Also, The roughness length for water vapour transfer z_{0v} (used in estimation of r_a) is estimated from an expression presented by Brutsaert (1982) for hydrodynamically bluff-rough surfaces.

For corrections of eddy-covariance flux observations for energy closure, the methodology presented by Twine et al. (2000) was used which incorporates i) the 'residual λE closure' (or RE) method by calculating the latent heat flux as a residual of the energy balance, and ii) the 'Bowen-ratio closure' (or BR) method by conserving the measured Bowen ratio.

DATA

Observed flux terms and land-atmosphere forcing data were obtained from METFLUX tower 162 (for soybean) and tower 152 (for corn) at Walnut Creek watershed (centered at 41.96°N, 93.6°W) during the SMEX02 campaigns conducted in June and July 2002 (Kustas et al., 2005). For soybean, row direction was toward East-West direction and row spacing was 0.25 m. During the field campaign, soybeans were in their vegetative stage of growth, with vegetation height varying between 0.2-0.3 m, Leaf Area Index varying between 0.4-3.7 $m^2\ m^{-2}$, and fractional vegetation cover between 0.3-0.6. For corn, row direction was toward East-West direction and row spacing was 0.76 m. During the field campaign, corn was in its vegetative stage of growth, with vegetation height varying between 1.1-2.2 m, Leaf Area Index varying between 2.1-5.6 $m^2\ m^{-2}$, and fractional vegetation cover between 0.7-1

During SMEX02, precipitation occurred a few days prior to 15 June (DOY 166), with a minor rainfall event (0-5 mm) on 20 June (DOY 171). This was followed by a rain-free period until 4 July (DOY 185), resulting in surface moisture (0-5 cm depth) decreasing from near field capacity of 25%-30% in mid-June to 5%-10% before the rains. Near the end of the rain-free period, visual signs of water stress were evident at some field sites (Kustas et al., 2005). Details of instrumentation and measurement heights for different observed parameters are summarized in Table 1. More details about instrumentations and site condition is given by Kustas et al. (2005) and Ershadi (2010). Data used in this study were originally quality controlled using the surface energy budget equation of Su et al. (2005).

Observed flux terms and land-atmosphere forcing data were also obtained over a vineyard (row spacing was 3.35 m, the within-row spacing was approximately 1.5 m, LAI was 0.52 $m^2\ m^{-2}$, fractional vegetation cover 0.33 and vegetation height 2 m) located at the Barrax agricultural test site in Spain (39.06° N, 02.10° W), where various crops were grown with some crops under irrigation. Data were collected between 15 and 20 July 2004 (DOY's 197-202) during an intensive field campaign (SPARC). The experiment has been described in detail by Su et al. (2008) and Timmermans et al. (2009). Here, the processed data were used from van der Tol et al. (2009). Details of instrumentation and measurement heights for different observed parameters are summarized in Table 1. All data were collected at 1 min intervals and stored at 10-min average, but half hourly averages were used here.

Table 1: Instrumentation and measurement height of study sites

Crops	$H, \lambda E$	R_n	G_0	u	T_a, E_a	T_s
Soybean	LI-7500 @2 m	CNR1 @2 m	REBS @-0.06 m	CSAT3 @2 m	HMP45C @1.5 m	Apogee @2.5 m
Corn	LI-7500 @3-4 m	CNR1 @3-4 m	REBS @-0.06 m	CSAT3 @3-4 m	HMP45C @1.5 m	Apogee @5 m
Vineyard	LI-7500 @3.4 m	CNR1 @4.8 m	HFP01 @-0.05 m	Cup ane. @4.88 m	HMP45 @4.78 m	CNR1 @4.8 m

RESULTS AND DISCUSSION

Energy balance (EB), Penman-Monteith (PM), and Advection-Aridity (AA) methods were applied to soybean, corn, and vineyard datasets to obtain λE. For soybean and corn, simulation time limited to 9 AM to 4 PM and records filtered for rainy hours. For vineyards, time limited to 9 AM to 5 PM. Note that time interval for soybean and corn is 10 minute and for vineyard is 30 minute.

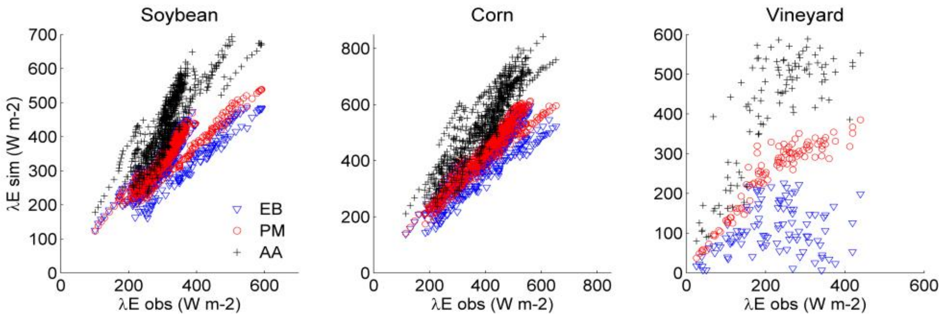

Fig. 1 Scatter plots of observed versus estimated latent heat flux using EB, PM, and AA methods.

Table 2: Summary of regression coefficient for daily scatter plots

Crops	Energy Balance			Penman-Monteith			Advection-Aridity		
	Slope	Intercept	R^2	Slope	Intercept	R^2	Slope	Intercept	R^2
Soybean	0.75	90	0.62	0.86	69	0.82	1.2	53	0.76
Corn	0.92	36	0.83	0.99	36	0.92	1.2	64	0.83
Vineyard	-	-	0.05	0.82	65	0.84	1.1	165	0.61

Scatterplots of observed versus simulated λE for each crop using three methods are presented in Fig. 1 and a summary of regression coefficients are in Table 2. As is obvious in the scatterplots, PM and EB best matched the observations for soybean and corn, while AA overestimated λE. However, EB was unable to correctly estimate λE for the vineyard. This might be due to the advection of hot air from bare ground between the trees, and clearly shows the limitation of using EB in sparse canopies. However, even without applying two-source schemes for accounting of sparse canopies, PM gave good estimation of the latent heat. Again, AA overestimated λE and is more spread than PM.

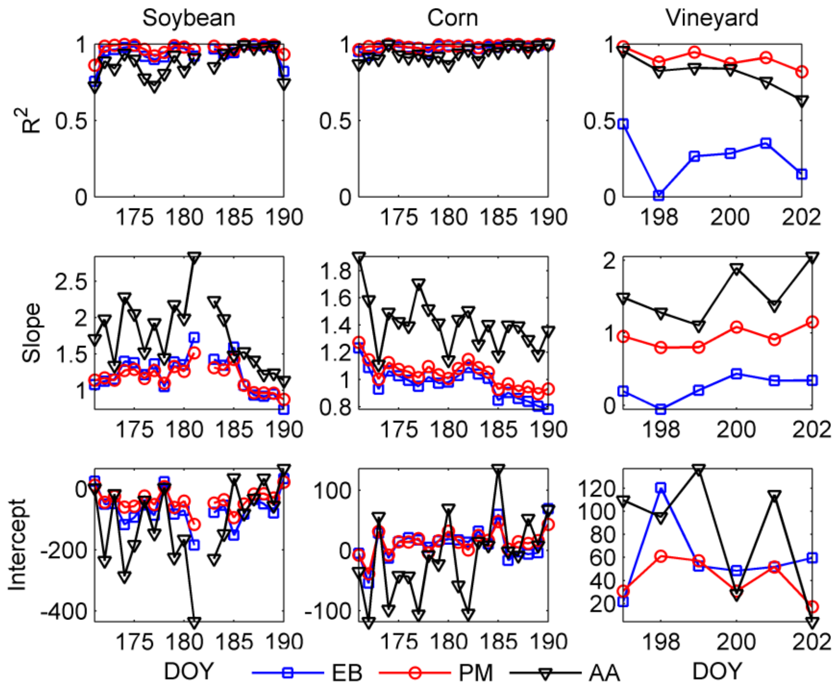

Fig. 2 Daily variations of regression coefficients for soybean, corn, and vineyard.

Fig. 2 shows the temporal variations of R^2, slope, and intercept for the simulation period. Although R^2 is relatively high for all methods and all crops, except for EB for vineyard, slope and intercept are changing and deviate from the expected values of 1 and 0 respectively, especially for AA. Relatively high values of slope for AA show that λE is overestimated by this method. For all methods, best results are from PM. However, the increase of slope in the first part of the simulation period for soybean using PM might be related to the moisture depletion during the rain-free condition (up to DOY 185), but this was scarcely observed for the corn site.

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