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

A. ERSHADI[1], M. F. McCABE[1], J. P. EVANS[2] & J. P. WALKER[3]

1 *School of Civil and Environmental Engineering, University of New South Wales, Sydney, Australia*
2 *Climate Change Research Centre, University of New South Wales, Sydney, Australia*
3 *School of Civil and Environmental Engineering, Monash University, Clayton, Australia*
a.ershadi@unsw.edu.au

Abstract A comparison between three basic techniques for estimation of actual evapotranspiration, namely: the Energy Balance, the Combination, and the Complementary approaches, is undertaken. We utilize Monin-Obukhov Similarity Theory (MOST) as a framework for the energy balance method, the single-layer Penman-Monteith method for the combination approach, and the Advection-Aridity method as the complementary approach. Data from three flux tower stations are used to evaluate model estimated heat fluxes at short time steps. The 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 method

INTRODUCTION

Accurate estimation of evapotranspiration is important for many agricultural and hydrological applications. Better understanding of its spatial variability and temporal development are required for improved representation of the process across a variety of modelling and resource management applications (McCabe *et al.*, 2005). Moreover, it is one of the key mechanisms in atmospheric, hydrological and agricultural models as it identifies the link between the water and energy balances and describes aspects of the land surface coupling with the atmosphere (Evans & McCabe, 2010). In this study, the relative merits of the energy balance, combination and complementary approaches for estimation of actual evaporation are investigated. We utilise 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 & Katul, 1992) as the complementary approach. Eddy correlation measurements of latent and sensible heat fluxes (λE and H) and measurements of net radiation Rn, 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) is 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 vapour transfer. The Advection-Aridity method is known as a "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 comparisons of these methods have been previously examined in the literature (e.g. Stannard, 1993; Inclán & Forkel, 1995; Shaomin *et al.*, 2004), the novelty in this research is that the comparison of all of these methods is undertaken within 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 the MOST equations simultaneously in an iterative way. This method is used in the SEBS approach (Su, 2002; Su *et al.,* 2007) 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 (see Brutsaert, 2005; Eq. 4.39):

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

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 later by Parlange & 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 can be described as:

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

where α_e is the Priestley-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 solely on meteorological parameters (Brutsaert, 2005).

Estimation of roughness terms

For estimation of the zero-plane displacement height (d_0) and roughness length parameters for momentum and heat transfer (z_{0m} and z_{0h}), the methodology introduced by Massman (1997) and further developed by Su *et al*. (2001) was employed. 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, Iowa, USA (centred 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 approximately east–west and the row spacing was 0.25 m. During the field campaign, soybeans were in a stage of rapid growth, with vegetation height varying between 0.2 and 0.3 m, Leaf Area Index varying between 0.4 and 3.7 m^2 m^{-2}, and fractional vegetation cover of 0.3–0.6. For corn, row direction was nearly east–west and the row spacing was 0.76 m. During the field campaign, corn was also in a growing phase, with vegetation height varying from 1.1 to 2.2 m, leaf area index varying between 2.1 and 5.6 m^2 m^{-2}, and fractional vegetation cover of 0.7 to 1.0.

During SMEX02, precipitation occurred a few days prior to 15 June (DOY 166), with a minor rainfall event (<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 rain. 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 detail of the instrumentation and site conditions 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 located at the Barrax agricultural test site in Spain (39.06°N, 02.10°W), where various crops were grown with some under irrigation. Row spacing was 3.35 m, the within-row spacing was approximately 1.5 m, LAI was 0.52 m^2 m^{-2}, the fractional vegetation cover was 0.33 and vegetation height was 2 m. Data were collected between 15 and 20 July 2004 (DOY 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 as 10-min averages, but half-hourly averages were used here.

Table 1 Instrumentation and measurement height of study sites.

Crops	H, λE	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 data sets to obtain λE. For soybean and corn, the simulation time was limited to 9 am to 4 pm and records filtered for rainy hours. For vineyards, time was limited from 9 am to 5 pm. Note that flux time integration was 10 minutes for soybean and corn and 30 minutes for vineyard measurements.

Scatter plots of observed *versus* simulated λE for each crop using three methods are presented in Fig. 1, and a summary of the regression coefficients is given in Table 2. As can be observed in the scatter plots, PM and EB best match the observations for soybean and corn, while AA overestimates λE. However, the EB approach 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 identifies a potential limitation of the EB approach in sparse canopies. However, even without applying so called "two-source" schemes for accounting of sparse canopies, PM gave good estimation of the latent heat. Again, AA overestimated λE and is more variable compared to the PM approach.

Table 2 Summary of regression coefficient for daily scatter plots shown in Fig 1.

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

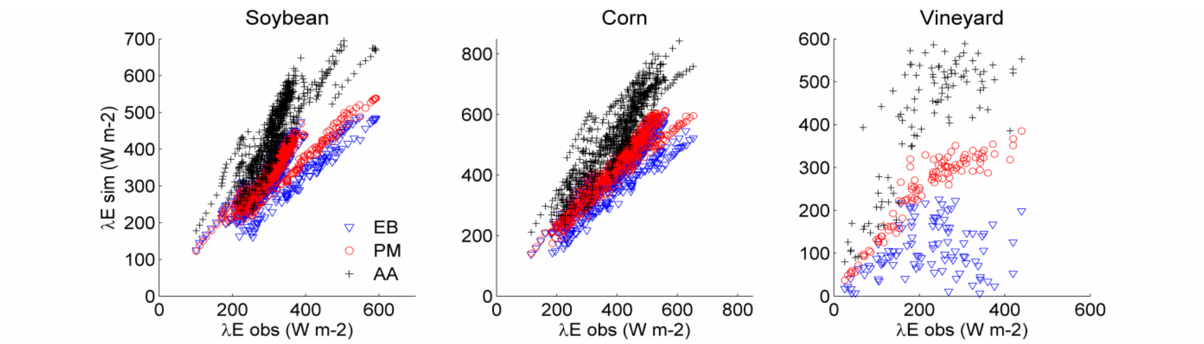

Fig. 1 Scatter plots of observed *versus* estimated latent heat flux using the EB, PM and AA methods.

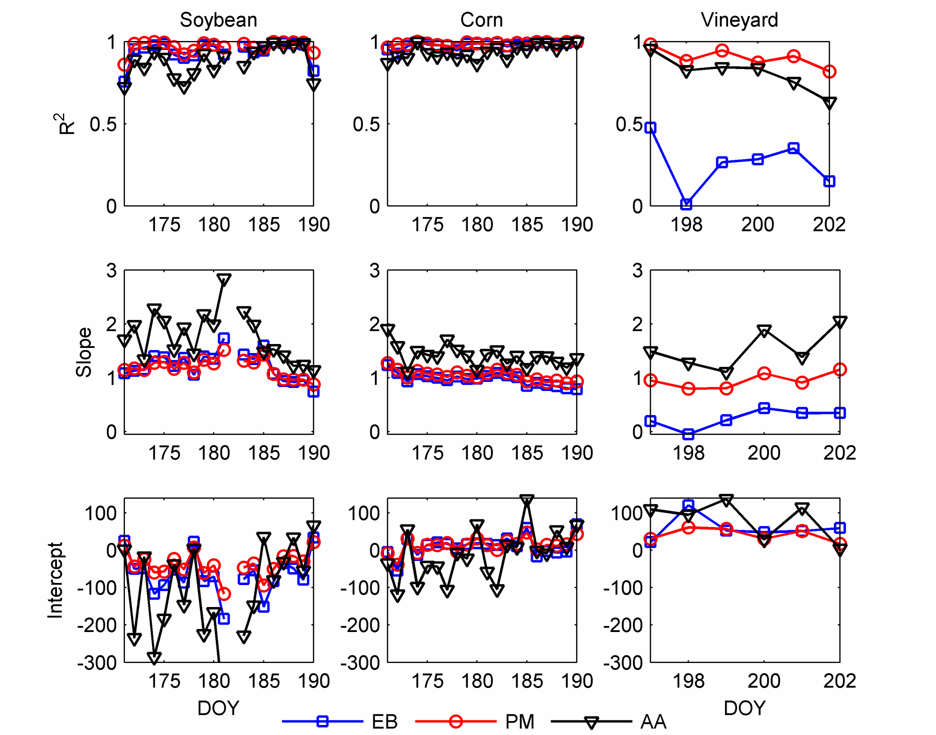

Fig. 2 Variations in regression coefficients for soybean, corn and vineyard calculated at the daily scale.

Figure 2 shows the temporal variations of R^2, the slope and the intercept of linear regressions between observed and simulated λE on a daily basis for the simulation period. R^2 is relatively high for all methods and crops, apart from the energy balance approach over the vineyard. Slope and intercept are variable across techniques and deviate from expected values of 1 and 0 respectively, especially for the Advection Aridity technique. Relatively high slope values for AA show that λE is overestimated using this method. Overall, it seems that the most consistent results are determined when using the Penman-Monteith approach. The increase in slope during the first part of the simulation period for soybean using PM may be related to the moisture depletion during the rain-free condition (up to DOY 185), since this not replicated for the corn site.

CONCLUSION

The variability of the λE derived using three standard methods (EB, PM and AA) highlights the importance of process model evaluation over a range of vegetation types and climate zones (Su *et al.*, 2007). Understanding model sensitivity is particularly important in the estimation of regional scale (Evans & McCabe, 2010) and global scale (Jimenez *et al.,* 2011) fluxes of sensible and latent heat fluxes – especially in identifying the appropriateness of using a either a single technique or an ensemble of approaches. Further work on the sensitivity of these different algorithms using a variety of forcing data from hydro-climatological databases, remote sensing products, or model outputs is required to better understand the capacity for robust retrieval of land surface fluxes.

Acknowledgements Funding for this research was provided by an Australian Research Council Linkage Project LP0989441 with industry support from the Department of Primary Industry.

REFERENCES

Beljaars, A. C. M. & Holtslag, A. A. M. (1991) Flux parameterization over land surfaces for atmospheric models. *J Appl. Met.* **30**(3), 327–341.

Bouchet, R. J. (1963) Evapotranspiration réelle, evapotranspiration potentielle, et production agricole. *Ann. Agron.* **14**, 743–824.

Brutsaert, W. (1982) *Evaporation Into the Atmosphere: Theory, History, and Applications*. Reidel Publishing, Dordrecht, The Netherlands.

Brutsaert, W. (2005) *Hydrology: An Introduction*. Cambridge University Press, Cambridge, UK.

Ershadi, A. (2010) Land–atmosphere interactions from canopy to troposphere, a study of similarity, roughness characteristics and scaling using data from SMEX02 and EAGLE 2006 campaigns. Department of Geo-Information Science and Earth Observation, Enschede, The Netherlands, University of Twente. MSc no. 74.

Inclán, M. G. & Forkel, R. (1995) Comparison of energy fluxes calculated with the Penman-Monteith equation and the vegetation models SiB and Cupid. *J. Hydrol.* **166**(3-4), 193–211.

Kustas, W. P., Hatfield, J. L. & Prueger, J. H. (2005) The Soil Moisture–Atmosphere Coupling Experiment (SMACEX): Background, hydrometeorological conditions, and preliminary findings. *J. Hydromet.* **6**(6), 791–804.

Massman, W. J. (1997) An analytical one-dimensional model of momentum transfer by vegetation of arbitrary structure. *Boundary-Layer Met.* **83**(3), 407–421.

Monin, A. S. & Obukhov, A. M. (1945) Basic laws of turbulent mixing in the surface layer of the atmosphere. *Tr. Akad. Nauk SSSR Geophiz. Inst.* **24**(151), 163–187.

Monteith, J. L. (1965) Evaporation and environment. *Symp. Soc. Exp. Biol.* 19, 205–234.

Parlange, M. B. & Katul, G. G. (1992) An advection-aridity evaporation model. *Water Resour. Res.* **28**(1), 127–132.

Penman, H. L. (1948) Natural evaporation from open water, bare soil and grass. *Proc. Royal Soc. London. Series A.* **193**, 120–145.

Shaomin, L., Zhongping, S., *et al.* (2004) Comparison of different complementary relationship models for estimating regional evapotranspiration. Geoscience and Remote Sensing Symposium, 2004. IGARSS '04. Proceedings. 2004 IEEE International.

Stannard, D. I. (1993) Comparison of Penman-Monteith, Shuttleworth-Wallace, and Modified Priestley-Taylor evapotranspiration models for wildland vegetation in semiarid rangeland. *Water Resour. Res.* **29**(5), 1379–1392.

Su, Z. (2002) The Surface Energy Balance System (SEBS) for estimation of turbulent heat fluxes. *Hydrol. Earth Syst. Sci.* **6**(1), 85–100.

Su, H., McCabe, M. F., Wood, E. F., Su, Z. & Prueger, J. H. (2005) Modeling evapotranspiration during SMACEX: comparing two approaches for local- and regional-scale prediction. *J. Hydromet.* **6**(6), 910–922.

Su, Z., T. Schmugge, T., Kustas, W. P. & Massman, W. J. (2001) An evaluation of two models for estimation of the roughness height for heat transfer between the land surface and the atmosphere. *J. Appl. Met.* **40**(11), 1933–1951.

Su, Z., Timmermans, W., Gieske, A., Jia, L., Elbers, J. A., Olioso, A., Timmermans, J., Van Der Velde, R., Jin, X., Van Der Kwast, H., Nerry, F., Sabol, D., Sobrino, J. A., Moreno, J. & Bianchi, R. (2008) Quantification of land–atmosphere exchanges of water, energy and carbon dioxide in space and time over the heterogeneous Barrax site. *Int. J. Remote Sens.* **29**(17), 5215–5235.

Timmermans, W. J., Su, Z., *et al.* (2009) Footprint issues in scintillometry over heterogeneous landscapes. *Hydrol. Earth Syst. Sci. Discuss* **6**(2), 2099–2127.

Twine, T. E., Kustas, W. P., Norman, J. M., Cook, D. R., Houser, P. R., Meyers, T. P., Prueger, J. H., Starks, P. J. & Wesely, M. L. (2000) Correcting eddy-covariance flux underestimates over a grassland. *Agric. For. Met.* **103**(3), 279–300.

van den Hurk, B. J. J. M. & Holtslag, A. A. M. (1997) On the bulk parameterization of surface fluxes for various conditions and parameter ranges. *Boundary-Layer Met.* **82**(1), 119–133.

van der Tol, C., van der Tol, S., Verhoef, A., Su, B., Timmermans, J., Houldcroft, C. & Gieske, A. (2009) A Bayesian approach to estimate sensible and latent heat over vegetated land surface. *Hydrol. Earth Syst. Sci*. **13**(6), 749–758.