An Evapotranspiration Algorithm in a Dryland Irrigation System: A Case Study in Coleambally, NSW, Australia

Chemin, Y.
International Water Management Institute, 127 Sunil Mw, Pelawatta, Sri Lanka

Abstract
This research expands on the continuous collection of ground truth data to feed in various empirical relationships enabling the calibration of a simple two source energy balance in order to provide with instantaneous remote sensing based ET in an irrigated area of Murray Darling Basin under Australian conditions. Standard satellite remote sensing Terra MODIS products such as NDVI, LST or Albedo correlations to ground truth through scales differences are explored for Coleambally Irrigation Area where extensive field campaigns have been carried out over two years. The sensible heat flux (the energy used for air convection) and evaporative fraction results estimated from a two source energy balance approach has been calibrated with Eddy Covariance Flux Tower installed at the experimental farm where maize crop was grown. Additionally, an input parameters sensitivity analysis has been carried out by replacing flux tower data with semi-empirical data derived from crop calendar and Terra MODIS products.

1. Introduction

Satellite remote sensing methods are a powerful means to provide an actual evapotranspiration (ET) measurement for a wide range of spatial scales ranging from individual pixels to an entire raster images that may cover a whole river basin. Remote sensing methods use surface reflectance and radiometric surface temperature from satellite spectral data in combination with ground based meteorological data to solve the energy balance equation and estimate ET from local to regional scales. These satellite radiance responses are related to ET in two steps. First, the surface parameters such as surface albedo, surface emissivity, surface temperature and normalized difference vegetation index (NDVI), are derived. Second, these surface parameters together with measured field data are used to solve the energy balance and actual ET is taken as a residual term. Different methods have been developed to estimate evapotranspiration from remote sensing data, from empirical approaches such as the simplified relationship method to complex methods based on remote sensing data assimilation along with SVAT models (Courault et al., 2005). The complexity of these methods depends on the balance between the empirical and physically based modules to solve the energy budget. As a summary, there are two broad categories i.e., analytical versus (semi) empirical approaches for the estimation of actual evapotranspiration through remote sensing. Seven operational algorithms that have produced ET and soil moisture maps on local, regional, or national scales are: the North American Land Data Assimilation Systems (NLDAS, (Cosgrove et al., 2003); the Land Information Systems (LIS, (Kumar et al., 2006)); the Atmosphere Land Exchange Inverse (ALEXI, Anderson et al., 1997); the disaggregated ALEXI model (DisALEXI, Norman et al., 2003); the Surface Energy Balance Algorithm for Land (SEBAL, Bastiaanssen et al., 1998a,b); Mapping ET at high spatial Resolution with Internalized Calibration (METRIC, Allen et al., 2007) and SEBS4BEAM (Wang et al., 2008). Analytical approaches include detailed biophysical process and require various parameters, mainly surface biophysical attributes, which can be retrieved either through satellite based remote sensor or through campaign in the field (Jackson et al., 1981, 1988). The foundation for the application of analytical approaches was laid by (Menenti, 1984) who proposed a two layer combination equation for a drying soil to be able to reduce to the Penman Monteith combination equation. Later on, Menenti and Choudhury, (1993) extended the Crop Water Stress Index (CWSI) concept to the so called Surface Energy Balance Index (SEBI) approach which was based on the use of Planetary Boundary Layer (PBL) scaling. However, SEBI results for the Aral Sea region revealed that the parameterization was not universally applicable (Menenti and Choudhury, 2001). Another model is the two source model developed by Norman et al., (1995) where the surface fluxes are calculated separately for the soil and vegetation components from remote sensing and ground based observations and then summed to satisfy the total energy balance at each pixel. The remote sensing inputs are radiometric temperature and NDVI. However, this model can overestimate the actual evapotranspiration over certain land surface conditions i.e., dry and bare soil (Savige et al., 2005). Cleugh et al., (2004) used convective boundary layer (CBL) budget methods for estimating regionally averaged sensible and latent heat fluxes in the OASIS experiment in Australia. The regional evaporation fluxes were predicted either from a coupled Penman–Monteith – CBL slab model or inferred as a residual term from estimates of the regionally averaged available energy and sensible heat flux. However, this method requires detailed information about atmospheric boundary layer (ABL) profiles, meteorological and physiological parameters, vegetation descriptions and antecedent data (rainfall, soil moisture) which is difficult to obtain at a catchment level, even in Australian context. Compared to all previous remote sensing algorithms for heat fluxes estimation, the Surface Energy Balance System (SEBS) developed by Su (2002) has the most important advantage through its inclusion of a physical model for the estimation of the roughness height for heat transfer which is the most critical parameter in the parameterization of the heat fluxes of a land surface. Based on the SEBS algorithm, some validations have been completed successfully in different geographical locations with differing scales (Su and Jacobs, 2001, Su et al., 2003 and 2005). On the empirical side, the work of Nieuwenhuis et al., (1985) was among the earliest attempts but was valid only for a single crop. Later, Surface Energy Balance Algorithm for Land (SEBAL), an intermediate approach using both empirical relationships and physical parameterizations, was developed in Spain (Bastiaanssen et al., 1998a, 1998b). SEBAL is a thermodynamically based model, which partitions sensible heat flux and latent heat of vaporization flux and this method has been widely used in many countries. Semi empirical relationships are used to estimate emissivity, and roughness length from NDVI. However, due to the difficulties associated with clearly defining exactly the right pixels of dry and wet conditions in certain images; its application is limited to a certain degree (Su, 2005). Su and Pelgrum (1999) remedied a theoretical problem of SEBAL model and added a scheme to apply NWP fields with an upscaling and downscaling approach to improve its applicability. In another effort, Roerink and Su (2000) developed a new method to derive the surface energy fluxes from remote sensing measurements, called the Simplified Surface Energy Balance Index (S-SEBI), which fits dry and wet cases present in the spatial radiometric data and showed reasonable success for application of the approach to semiarid areas. Allen et al., (2007) modified SEBAL and developed METRIC (Mapping Evapotranspiration with high Resolution and Internalized Calibration), an energy balance based ET mapping approach which is tied down and partly calibrated using ground based reference ET (from weather data) to work well in advective conditions of the western United States of America. In Australia, Cleugh et al., (2007) reported that the Penman–Monteith (P–M) equation performed better than aerodynamic resistance–surface energy balance model in estimating land surface evaporation at 16-day intervals over 3 years using MODIS remote sensing data and meteorological measurements from two contrasting ecosystems, a cool temperate, evergreen Eucalyptus forest and a wet/dry, tropical savanna. In Australia, there is a need of remote sensing application for measurement, monitoring and management of agricultural water use in irrigated region of Murray Darling Basin. This research aims at addressing this need by expanding on the continuous collection of ground truth data already taking place in an Australian irrigation system. Various empirical relationships are derived to enable the calibration of a simple two source energy balance methodology. Some of the relationships are derived from standard satellite remote sensing products (MODIS NDVI, land surface temperature and Albedo) and correlated to ground truth through scales differences. Finally, a sensitivity analysis of the sensible heat flux and evaporative fraction is made by replacing flux tower data with estimated data from those semi-empirical relationships.

2. Location and Crop Data

The Coleambally Irrigation Area (CIA) as shown in Figure 1 is located in the lower part of the Murrumbidgee River Basin (MDB), approximately 650 km south-west of Sydney in the Riverina District of New South Wales.

Figure 1: Corn field location (2009-2010) upper MIA (orange) and below CIA (green)

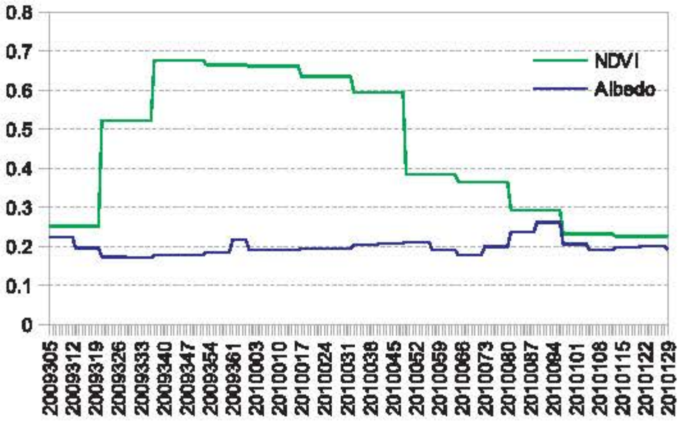

Figure 2: MODIS 1Km Albedo (MCD43B3) and NDVI (MOD13A2)

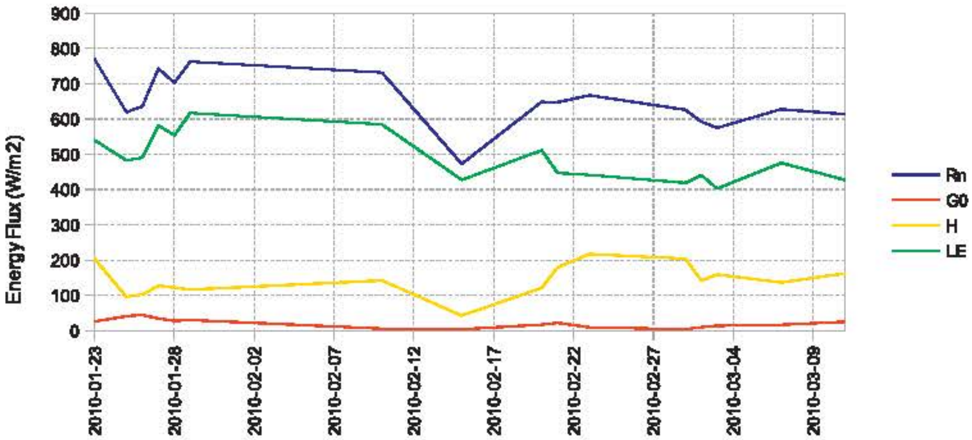

Figure 3: Observed energy-balance in the experimental field at satellite overpass

The Irrigation Area contains approximately 79,000 ha of intensive irrigation, 42,000 ha of irrigation/dryland farms and 297,000 ha of the Outfall District area, supplying water to 478 farms owned by 362 business units (CICL, 2007). Water is diverted to the area from the Murrumbidgee River at Gogeldrie Weir through a 41km long main canal, and is then distributed through 477 km of supply channels. The average farm has 220 hectares and approximately 1,400 megalitres of general security water entitlement. The total average rainfall in the CIA lies between 400–450 mm/year. The shallow water tables fluctuate every year due to changes in climatic conditions and land management practices within the CIA. There are also a number of piezometers wells, climate and stream flow recording stations installed in CIA. The corn crop establishment is followed in Figure 2 below by the Normalized Difference Vegetation Index (NDVI) and the Albedo reflectance. Sources of data are Terra satellite platform, featuring the MODIS sensor. We extracted energy balance terms from the Flux tower located in the middle of the large experimental field. They appear in the figure below at the closest 30 minutes average to the satellite overpass. This dataset is used to assess the accuracy of the application of the theoretical model and its configuration equations derived earlier.

3. Theoretical Formulation

The proposed formulation follows a two-source energy balance approach, inspired especially from TSEB (Kustas and Norman, 1999) and SEBS (Su, 2002). It stems from the concept of the radiation and energy balances to have separate formulations for either bare soil or canopy. The energy balance at any instantaneous moment is expressed by:

$$Rn = G + H + \lambda E$$

Equation 1

Where R_n is Net Radiation, G is soil heat flux, H is sensible heat flux and λE is latent heat of vaporization. Later, it is separated into two sources, bare soil and canopy energy balances express themselves as:

$$Baresoil : R_{ns} = G + H_s + \lambda E_s$$

Equation 2

Where R_{ns} is the net radiation of bare soil surface, H_s is the sensible heat flux from bare soil, Les is the latent heat of vaporization from soil surface:

$$Canopy : R_{nc} = H_c + \lambda E_c$$

Equation 3

Where R_{nc} is the net radiation from canopy of crop, H_c is the sensible heat flux from canopy, λE_c is the latent heat of vaporization of crop. Once the elements of those two equations are found, the fraction of vegetation cover (fc) is used to combine them into the area of a satellite remote sensing pixel, which is inherently a mixel of bare soil and canopy. The Net Radiation is partitioned according to the formulation commonly used in two-sources model, where the soil partition of Rn is an LAI-based extinction coefficient (Choudhury, 1999) with a coefficient C ranging from 0.3 to 0.7 (Friedl, 1996), depending on the arrangement of the canopy elements. Friedl (1996) mentions that a canopy with spherical (random) leaf angle distribution would lead to a C value of 0.5.

$$R_{ns} = R_n \, e^{\left(\frac{-C\, LAI}{\cos(sunza)}\right)}$$

Equation 4

$$R_{nc} = R_n - R_{ns}$$

Equation 5

Where LAI is the leaf area index, sunza is the sun zenith angle. Friedl (1996) mentions that he derived his soil heat flux formulation from his previous work (Friedl, 1996). It takes the already available soil fraction of net radiation and the cosine of the sun zenith angle. A coefficient is then multiplied to those whereby soil type and moisture conditions are taken into consideration after Choudhury et al., (1987).

$$G = Kg \; R_{ns} \; \cos(sunza)$$

Equation 6

Where Kg is the soil type and moisture condition coefficient in the soil heat flux. The Fraction of Vegetation cover is necessary to split the two-sources of heat transfer studied in such models. They are the soil surface (bare soil) and the vegetation canopy surface. Initial development of the fraction of vegetation cover is taken from Jia et al., (2003) quoting Barrett et al., (1995).

$$fc = 1 - \left[\frac{\left(NDVI - NDVI_{min} \right)}{\left(NDVI_{min} - NDVI_{max} \right)} \right]^K$$

Equation 7

K being taken as 0.4631 in Jia et al., (2003) and $NDVI_{min}$ at LAI=0 and $NDVI_{max}$ at LAI = +INF. We took the pre-season and max within season at 0.1 floor and 0.9 ceiling approximation. It is interesting to note that in the development of their Monin-Obukhov Similarity Theory (MOST, Monin and Obukhov, 1954) considered the friction velocity to be about 5% of the geostrophic wind velocity having an average speed of 10m/s results in the friction velocity being around 0.5 m/s, and with the Coriolis parameter $l=10^{-4}$ s-1 and a tolerance of 20%, an estimate of the height of the surface layer is found at H=50m, that is also the DisALEXI blending height for air temperature (Norman and Anderson, 2003). The dynamic velocity within this layer can be considered near to constant and the effect of Coriolis Force neglected (Monin and Obukhov, 1954). Under those conditions of neutral stratification the processes of turbulent mixing in the surface layer can be described by the logarithmic model of the boundary layer.

$$if\left(h != 0.0\right):$$
$$most_L = \frac{-1004\ air_{density}\ wind_{speed}^3\ temperature}{vonK\ g\ h}$$
$$else:$$
$$most_L = -1000.0$$

$$if\left(most_L < 0.0\right):$$
$$most_x = \left(1 - 16\left(\frac{wind_{height}}{most_L}\right)\right)^{1/4}$$
$$\psi_h = 2\log\left(\frac{1 + most_x^2}{2}\right)$$
$$\psi_m = 2\log\left(\frac{1 + most_x}{2}\right) + \log\left(\frac{1 + most_x^2}{2}\right) - 2\ atan\left(most_x\right) + \frac{\pi}{2}$$
$$else:$$
$$\psi_h = -5\frac{2}{most_L}$$
$$\psi_m = -5\frac{2}{most_L}$$

Equation 8

With $\psi_{(m,h)}$ the diabatic correction of momentum and heat through their changes of states, $most_x$ a MOST internal parameter, $most_L$ the Monin-Obukhov Length, vonK is the von Karman constant, g the gravity acceleration and other parameters explicitly named within. To calculate the aerodynamic resistance to heat momentum (soil), the Monin-Obukhov Length (Monin and Obukhov, 1954) is needed with RS-based T_{soil} input to ψ_m. ψ_m is used to compute within canopy wind velocity (U_c) that can be attenuated with canopy architecture information until reaching soil surface wind velocity (U_s). Soil resistance (r_s) is then derived (Kustas and Norman, 1999). The Leaf architecture is found in (Kustas and Norman, 1999) quoting (Goudriaan, 1977). The ratio leaf_area/leaf_perimeter was taken as 3.2184 and was created from knowledge scattered in (Maddonni et al. 2001, Jordan-Meille and Pellerin, 2004, Garcia, 2010). The displacement height (disp) is addressed further below:

$$Uc = wind_{speed} \frac{\log\left(\frac{canopy_{height} - disp}{z_{0m}}\right)}{\log\left(\frac{wind_{height} - disp}{z_{0m}}\right) - \psi_m}$$
$$s = 4\frac{leaf_{area}}{leaf_{perimeter}}$$
$$a = 0.28\ LAI^{2/3}\ canopy_{height}^{1/3}\ s^{-1/3}$$
$$U_s = U_c \exp\left(-a\left(1 - \frac{0.05}{canopy_{height}}\right)\right)$$
$$r_s = \frac{1}{\left(0.004 + 0.012 U_s\right)}$$

Equation 9

The aerodynamic resistance to heat momentum (r_{ah}) is using MOST through its expression in ψ_m and ψ_h, including T_{air} as temperature parameter to $most_L$ since this part is dealing with the canopy level.

$$r_{ah} = \frac{\left(\log\left(\frac{wind_{height} - disp}{z_{0m}}\right) - \psi_m\right) \times \left(\log\left(\frac{\left(temperature_{height} - disp\right)}{z_{0m}}\right) - \psi_h\right)}{vonK^2 wind_{speed}}$$

Equation 10

Monin and Obukhov (1954) mention that for observations made at height superior to 1 meter, the displacement height can be nullified. This is particularly interesting for dry C_3 and most of C_4 crops after the 60 first days of their growth, since crop height is not an input requirement anymore in this case. Exceptions will be valid for (semi-)dwarf wheat varieties cropped in Australia which never reach a full 1 meter height. Vegetation canopy Sensible heat flux of evaporation (H_c) is straight-forward since LST over canopy is T_{canopy} and T_{air} is the potential temperature over vegetation cover at an arbitrary height (Monin and Obukhov, 1954).

$$H_c = \rho_{air} C_p \frac{\left(T_{canopy} - T_{air}\right)}{r_{ah}}$$

Equation 11

Where ρ_{air} is the air density, C_p is the specific heat capacity at constant pressure. The soil sensible heat flux of evaporation (H_s) is derived from prior knowledge of fc, T_{air}, ρ_{air}, r_{ah} and H_c.

$$Hs = \frac{\left(\rho_{air} C_p \left(\frac{\left(\left(\left(LST^4\right) - fc\left(T_{air} + \frac{H_c r_{ah}}{\rho_{air} Cp}\right)^4\right)\right)}{\left(1 - fc\right)^{1/4}}\right) - T_{air}\right)}{\left(r_{ah} + r_s\right)}$$

Equation 12

4. Methodology

The satellite remote sensing data set is a group of standard Terra platform's MODIS sensor products, namely MOD11A1 (LST), MOD13A2 (NDVI) and MCD43A3/B3 (Albedo). The latest product being a mixed Terra/Aqua platforms for MODIS data, to increase reliability of BRDF corrections of Albedo. Quality Assessment (QA) flags were appropriately checked and pixels were removed on a conservative mode when compared with the QA flags. The Eddy Covariance Flux Tower (FT) was set up in the middle of the corn field with a minimum radius of 800m of homogeneous corn crop around. The flux tower provides a large amount of high-frequency and low-frequency data from a large array of sensors. Only a few amount of sensors have been directly used for this work (Albedo from net short wave radiation sensor, T_{air} from low frequency temperature probe, and T_{soil} and soil heat flux from plates). For simplicity reasons and lack of more consistent trends (Figure 4), we considered a multiplicative factor to relate Albedo from MODIS 1Km to Flux Tower data. Standard deviation of the multiplication factor is 0.0836.

$$Albedo_{FT} = 0.654 Albedo_{MODIS}$$

Equation 13

The Flux Tower temperature data set is compared with the MODIS LST product at 1 Km (Figure 5). We extracted relationships from them for soil temperature (Figure 6) and air temperature (Figure 7). T_{air_hmp} is low-frequency air temperature (as opposed to CSAT-based T_{air} not shown here).

$$T_{air_{hmp}} = 0.68 LST_C + 2.43$$

Equation 15

The LAI measurement have been taken extensively, however 2009-2010 campaign has been plagued by a LAI-sensor malfunction rendering data collected unreliable eventually. We therefore used the best results of Corn crop for the previous season (2008-2009) for CIA. Figure 8 shows LAI and NDVI values at different growth stages for corn crop. The relationship derived here in Figure 9 is the best approximation with missing actual LAI data from the Corn field in summer season 2009-2010. The equation has a R2 = 0.5231 which is limited, but understandable from the change of scale of observation and the change of index descriptor.

$$LAI = 3.2658 \ln\left(NDVI\right) + 6.9212$$

Equation 16

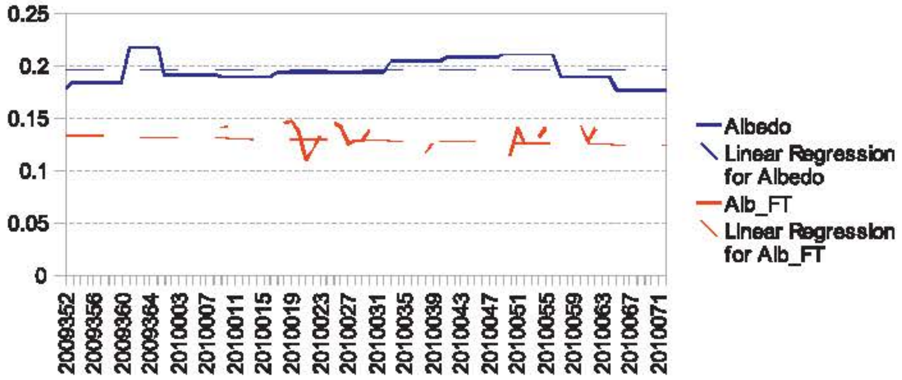

Figure 4: Albedo from MODIS 1 Km vs FT at satellite overpass time

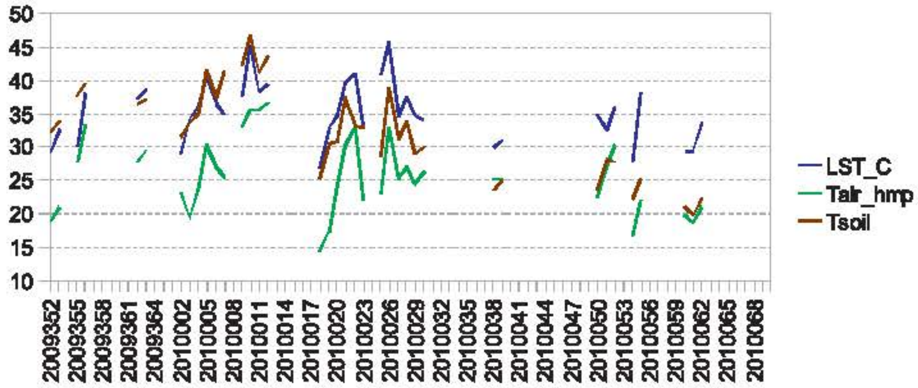

Figure 5: LST (Celsius) from MODIS 1Km vs FT recorded Temperature (Tair_hmp, Tsoil) at satellite overpass

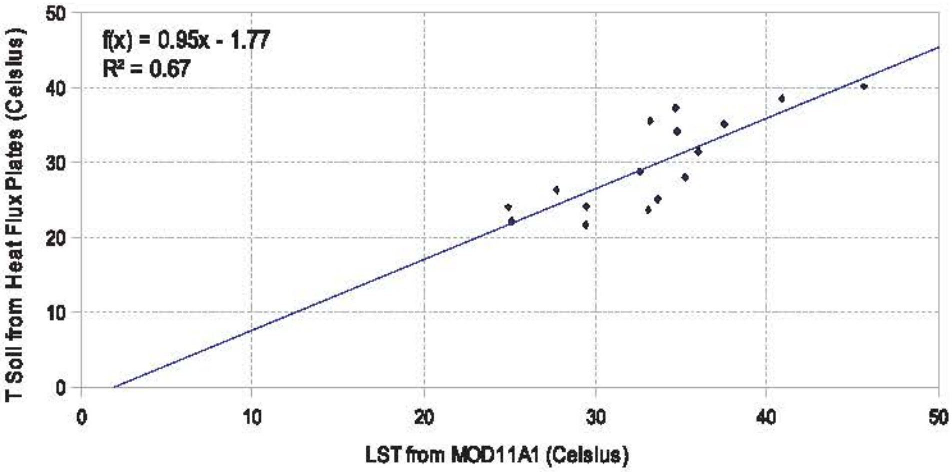

Figure 6: Relationship between MODIS LST (Celsius) vs Tsoil (FT)

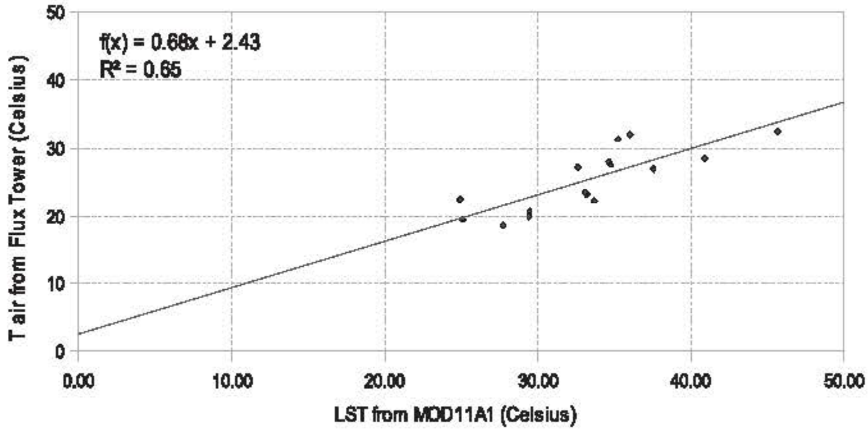

Figure 7: Relationship between MODIS LST (Celsius) vs Tair_hmp (FT)

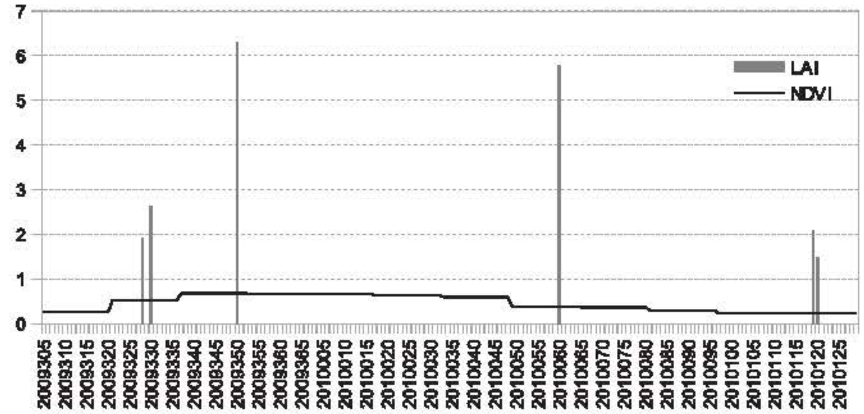

Figure 8: LAI (2008-2009) vs NDVI (2009-2010)

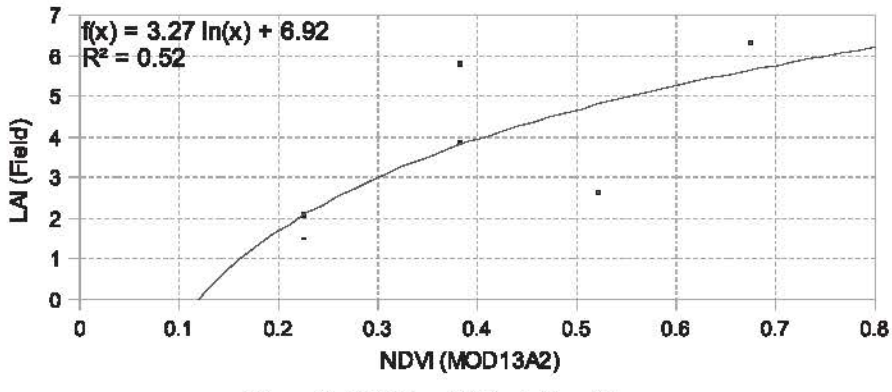

Figure 9: NDVI vs LAI relationship

As seen previously, the fraction of vegetation cover after Barrett et al. (1995) is depending on NDVI minimum and maximum ($NDVI_{min}$ at LAI=0 and $NDVI_{max}$ at LAI = +INF), and a K factor being initially taken as 0.4631 in Jia et al. (2003).

We apply it with known boundaries for NDVI of [0.1; 0.9].

$$fc = 1 - \left[\frac{(NDVI - 0.9)}{0.8}\right]^{K}$$

Equation 17

The roughness length formulation from SEBS (Su et al., 2002) as found in (Wang et al., 2008) is:

$$z_{0m} = 0.136h$$

Equation 18

The relationship found spans 6 months of the Corn cropping season with a 24 days delay for LAI appearance from the start of the cropping season (Figure 10).

$$z_{0m} = 0.1\left[\ln\left(CornAge - 24\right) - \frac{CornAge^2}{181^2}\right]$$

Equation 19

With the following formulation for algorithm encoding:

$$CornAge = Cumulative_{DOY} - SowingDate_{DOY}$$

Equation 20

It is necessary to add to all of these different empirical regressions some information about stabilization of internal diabatic heat transfer parameters (psim, psih) to the roughness momentum of heat (rah). psim and psih are parameters that require prior knowledge of sensible heat flux (H) to be estimated through the Monin-Obukhov Length. Since all the effort is about generating knowledge about H, an iterative process is setup to incrementally estimate a more accurate set of values for psim and psih through each new estimation of H. This is found in most of the energy balance models involving estimation of r_{ah} (i.e., TSEB, SEBS, SEBAL, METRIC, etc). Within this very specific process, we used SEBS method (Su et al., 2002) of estimation of virtual temperature at planetary boundary layer (PBL) to reassess T_{air}, for convergence of r_{ah} values. Within the irrigation system studied, two automatic weather stations, two flux towers and one large aperture scintillometer are recording net radiation (R_n). They are well spread and the irrigation area is small enough to use this information confidently. We used the formulation of Friedl (2002) to extract R_{ns} from Rn with a RS-based LAI attenuation equation holding a C value estimated on a satellite overpass basis by an exhaustive search algorithm designed in parallel of this research. Friedl (2002) mentioned a range of 0.3 to 0.7 for canopy architecture variations. We had to loosen the range to account for MODIS large pixel scale averaging of NDVI-based LAI values. We found a range of 0.16 to 0.30 for C. This was used as a basis for configuring the sensitivity analysis in the "Results" section. The LAI was derived from the RS-based NDVI values into the empirical equation we derived earlier. Figure 11 is explaining the relationship between Soil heat flux from flux plate and a modified soil heat flux equation from Friedl (2002) with MODIS data input.

$$G = 0.30G_{MODIS} + 8.64$$

Equation 21

The Kg coefficient for soil heat flux equation of Friedl (2002) was best set at a value of Kg = 1.

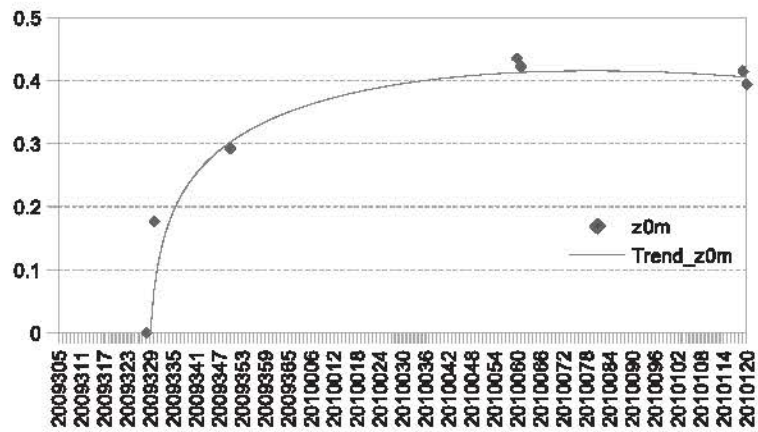

Figure 10: Proposed equation (curve) for z0m from day of planting vs height derived values

5. Results

The satellite images of MODIS were downloaded from Internet, 16 images matching the instruments observation period were selected and prepared for this research. Quality Assessment information was used, but less needed as the study zone has a continental dry climate. Those images were used in combination with the instrumentation records at the time of satellite overpass to solve the instantaneous energy balance. The Figure 12 is going through the level of deviation of difference of H observed minus H simulated. "Full" here means "Observed", which is in fact modeled through all available Flux Tower data (Figure 12). There is a need to estimate the parametrization of the soil heat flux better (Figure 11), and the estimations of Kg (Equation 6) and C (Equation 4) contributing it seems to the two differences between observed and modeled sensible heat flux values in Figure 12.

Every parameter subtracted to "Full" is estimated from one way or another, as per available in the methodology section. RhoAir is the air density, UStar is the friction velocity, Tsoil and Tair are the soil and air temperatures. In Figure 13, it is clear that U_{star} and T_{soil} are critical parameters where most accuracy is required if not recorded from instruments. It is also interesting to note that certain combinations of estimated parameters are having similar levels of deviations (estimated ρ_{air} , T_{air} and T_{soil} bring similar accuracy than estimated ρ_{air} and T_{soil}, or only estimated Tsoil). If the soil heat flux is taken from soil heat flux plates measurement, using any range of estimated parameters has little impact on the evaporative fraction difference to the one modeled from the full flux tower data (Table 1).

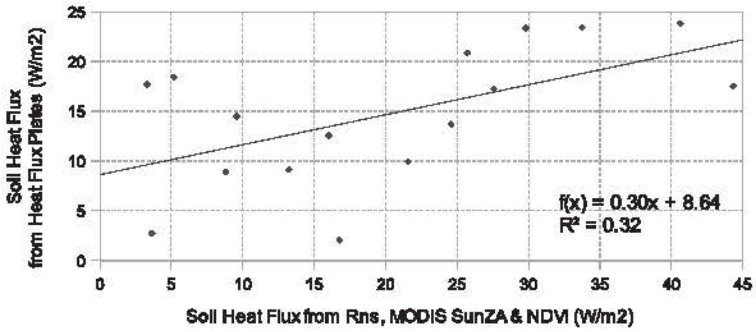

Figure 11: Relationship from RS-based (Friedl, 2002) to soil heat flux plates

Table 1: Average deviation of evaporative fraction difference from reference difference (-)

Parameterization	Diff2Evapfr (-)
Full-Tair	0
Full-RhoAir-Tair	0
Full-RhoAir	0
Full-RhoAir-Tair-Tsoil	0.002
Full-RhoAir-Tsoil	0.002
Full-Tsoil	0.002
Full-UStar-Tair-Tsoil	0.006
Full-Tsoil-Tair	0.006
Full-UStar-Tsoil	0.006
Full-RhoAir-UStar-Tair-Tsoil	0.006
Full-RhoAir-UStar-Tsoil	0.006
Full-UStar-Tair	0.007
Full-UStar	0.007
Full-RhoAir-UStar-Tair	0.007
Full-RhoAir-UStar	0.007

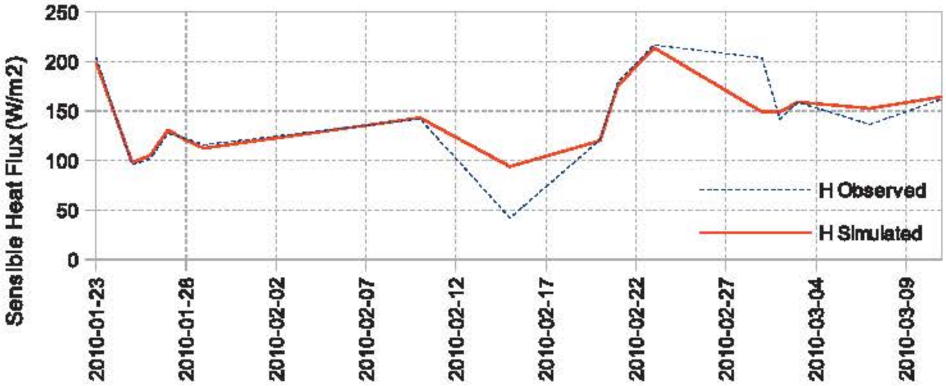

Figure 12: Comparison of sensible heat flux observed and simulated

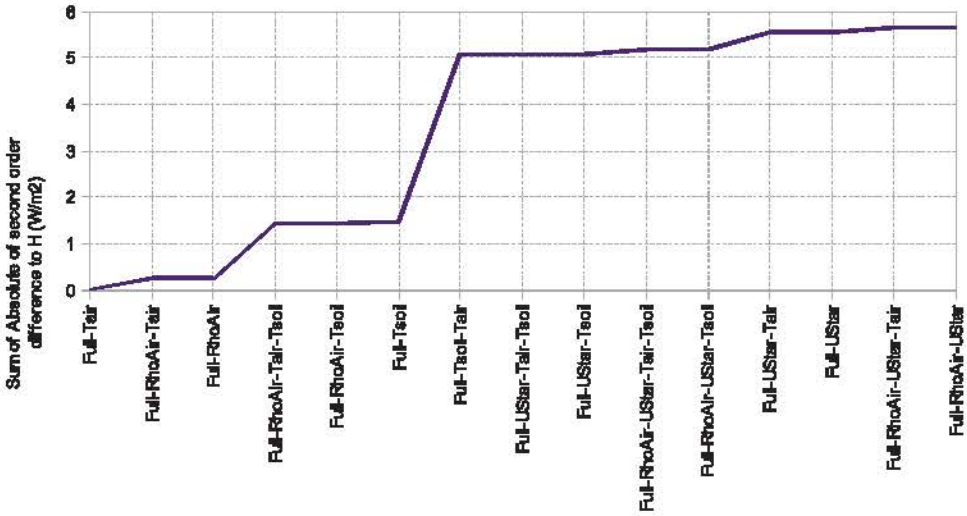

Figure 13: Averaged deviation of differences to the difference from the Flux Tower data calculation of H

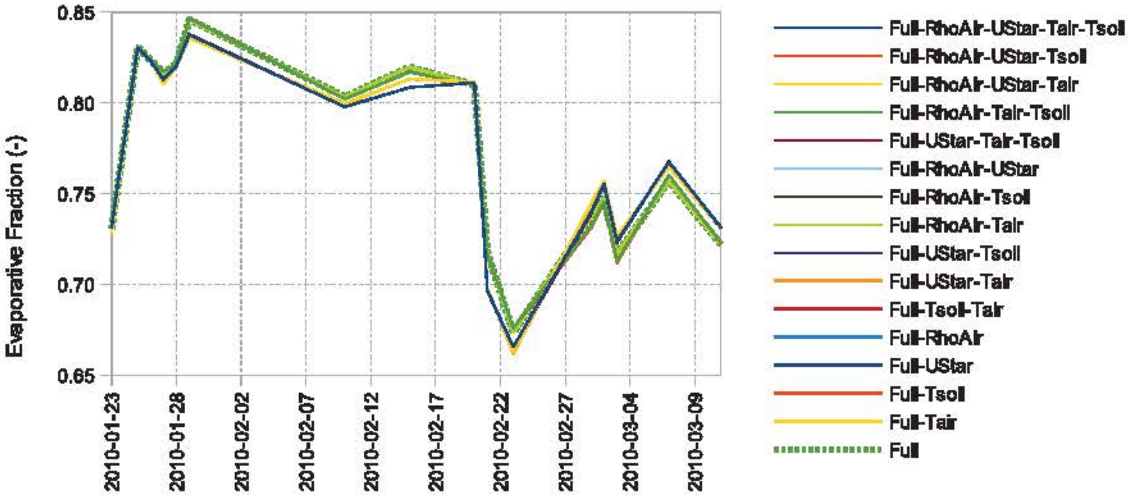

Figure 14: Sensitivity analysis of various parameters for estimation of evaporative fraction

6. Discussion

This experiment has taken 16 satellite overpass from a set of Terra MODIS imagery at 1 km pixel size. The authors are aware of the small number of samples. On the other hand, the irrigated corn field studied under this pixel is very large (40 ha) and quite homogenous. Those circumstances bring forth the fact that the methodology generates proper semi-empirical relationship for an irrigated crop to fit in a customized energy balance methodology. The particular element of interest is that semi-empirical relationships are fitting very well within this two source formulation. The sensitivity analysis of the energy balance formulation has shown that semi-empirical relationship can replace favorably flux tower data input for sensible heat flux modeling with an average deviation of maximum 5.7 W/m2 at satellite overpass. However, this has to be taken with some amount of scrutiny as two of the samples studied have shown some higher level of difference than all others. The sensitivity analysis of evaporative fraction has given very interesting information and difference found with running the model with flux tower data with all substitution of all data with semi-empirical relationship did not practically yield any absolute difference more than 0.03 which is 3% of a theoretical 100% evaporative fraction for the entire satellite overpasses studied. The LAI attenuation factor, C, is responsible for changing the portioning of net radiation to soil fraction of net radiation. While, Friedl (1996) gave a range of 0.3-0.7 due to the architecture of the plants, we found that C varied from satellite overpass time to time by data assimilation modeling. Bearing the fact that 1 km pixel size, scale factor, sensor response, soil types, vegetation patterns, our range was 0.16-0.3 for this two source energy balance formulation. It is a subject of research from instruments experimentation to multi-scale remote sensing.

7. Conclusions

This initial step of developing a methodology for input into two source energy balance algorithm has provided a firm ground for developing an irrigated based semi-empirical library, as LAI and z0m do rely on corn age and corn height respectively. Those two elements are easily recorded by the farmers and irrigation companies within available technology and time. The irrigation company of Coleambally is already monitoring some of these elements through various research projects which are being collated as a ground for further development of semi-empirical relationships.

Further in-situ experimentation is aiming at increasing accuracy of semi-empirical relationship derived in the methodological section (g_0, [T_{soil} - T_{air}], [T_{canopy} - T_{air}], fc, and C factor). This is expanding on the continuous collection of ground truth data to feed in various empirical relationships enabling the calibration of a simple two source energy balance in order to set ground for the calculation of instantaneous remote sensing based ET within irrigated areas of the Murray Darling Basin in Australian conditions. The methodology in this paper has been calibrated in a single large irrigated corn field with 16 satellite overpasses. This needs to be extended for various other irrigated crops including wheat and rice over the cropping season in Murray Darling Basin, Australia. There is a need to further develop the model for high spatial resolution optical-thermal satellites like Terra-ASTER and Landsat 5/7/8 and also high resolution optical-thermal data from drones. This research work is a stepping stone in the development of an operational ET monitoring system which aims at being validated with on ground flux tower and large aperture scintillometer in all of major irrigated crops of Australia. Including soil water vertical balance is under study (Rabbani, 2014), to expand the energy balance above ground in space and time with SMOS soil moisture states that will permit a closer binding of the above ground surface fluxes with the below ground heat and water fluxes. Interpolation and extrapolation modes are also under study to assess future root zone conditions and improve crop irrigated water management practices. Expanding this model application to other parts of this World and their different crops is possible, the crop library has to be updated with new semi-empirical relationships, scale rules for temperature parameters have to be redefined. The tight binding of the parametrization is the strength of such model for applied water management science at the field/farm/irrigation level. The same can be said as a weakness, since it requires instrumentation and measurements for tight coupling of parameters, such instrumentation is not always available in irrigation systems.

Acknowledgements

This research was initiated out when the author was at Charles Sturt University, Wagga-Wagga Campus and funded by the National Water Commission of Australia. The author would like to thank the Coleambally Irrigation Company Limited for their trust, funding and support along those years of research. Sincere thanks also go to Ralf Faux for the instrumentation/logistics and Josh Sixsmith for the cartographic work. Usual disclaimers apply.

References

Allen, R. G., Tasumi, M. and Trezza, R., 2007, Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC) Model. *J. Irrig. Drain. Engrg*, 133(4), 380-394.

Anderson, M. C., Norman, J. M., Diak, G. R., Kustas, W. P. and Mecikalski, J. R. 1997, A Two-Source Time-Integrated Model for Estimating Surface Fluxes using Thermal Infrared Remote Sensing. *Remote Sensing of Environment*. 60(2), 195-216.

Barrett, F., Clevers, J. P. W. and Stevens, M. D., 1995, The Robustness of Canopy Gap Fraction Estimates from the Red and Near Infrared Reflectance. A Comparison between Approaches for Sugar Beet Canopies. *Remote Sensing of Environment*, 54, 141-151.

Bastiaanssen, W. G. M., Menenti, M., Feddes, R. A. and Holtslag, A. A. M., 1998a, A Remote Sensing Surface Energy Balance Algorithm for Land (SEBAL): 1. *Formulation. J. Hydrol*. 212-213, 198-212.

Bastiaanssen, W. G. M., Pelgrum, H., Wang, J., Ma, Y., Moreno, J. F., Roerink, G. J. and van der Wal, T., 1998b, Surface Energy Balance Algorithm for Land (SEBAL): 2. *Validation. J. Hydrol*. 212-213, 213-229.

Choudhury, B., Idso, S., and Reginato, R., 1987, Analysis of an Empirical Model for Soil Heat Flux under a Growing Wheat Crop for Estimating Evaporation by an Infrared-Temperature Based Energy Balance Equation. *Agricultural and Forest Meteorology*, 39, 283-297.

Choudhury, B., 1999, Estimating Evaporation and Carbon Assimilation using Infrared Temperature Data: Vistas In Modeling. *In Theory and Applications of Remote Sensing*, G. Asrar, Eds.; Publisher: New York Wiley, USA, 628-690.

CICL, 2007, Annual Report for the year ended June 30.

Cleugh, H. A., Raupach, M. R., Briggs, P. R. and Coppin, P. A., 2004, Regional-Scale Heat and Water Vapour Fluxes in an Agricultural Landscape: Evaluation of CBL Budget Methods at OASIS. *Boundary-Layer Meteorology*. 110(1), 99-137.

Cleugh, H. A., Leuning, R., Mu, Q. and Running, S. W., 2007, Regional Evaporation Estimates from Flux Tower and MODIS Satellite Data. *Remote Sensing of Environment*. 106(3), 285-304.

Courault, D., Seguin, B. and Olioso, A., 2005, Review on Estimation of Evapotranspiration from Remote Sensing Data: From Empirical to Numerical Modelling Approaches. *J. Irrig. Drainage Syst*., 19, 223-249.

Cosgrove, B. A., Lohmann, D., Mitchell, K. E., Houser, P. R., Wood, E. F., Schaake, J. C., Robock, A., Marshall, C., Sheffield, J., Duan, Q., Luo, L., Higgins, R. W., Pinker, R.T., Tarpley, J. D. and Meng, J., 2003, Real-Time and Retrospective Forcing in the North American Land Data Assimilation System (NLDAS) Project. *J. Geophys. Res*., 108(D22), 8842.

Friedl, M. A., 1996, Relationships among Remotely Sensed Data, Surface Energy Balance and Area-Averaged Fluxes over Partially Vegetated Land Surfaces. *Journal of Applied Meteorology*. 35(11), 2091-2103.

Friedl, M. A., 2002, Forward and Inverse Modeling of Land Surface Energy Balance using Surface Temperature Measurements. *Remote Sensing of Environment*. 79, 344-354.

Garcia, Y., 2010, Growing Maize for Silage. A Guide for Dairy Farmers. Future Dairy Forages Technical Note. Future Dairy Project, University of Sydney.

Goudriaan, J., 1977, Crop Micrometeorology: A Simulation Study. *Center for Agric*. Publ. and Doc., PUDOC, Wageningen, The Netherlands.

Jackson, R. D., Idso, S. B., Reginato, R. J. and Pinter P. J. Jr., 1981, Canopy Temperature as a Crop Water Stress Indicator. *Water Resources Research*. 17(4), 1133–1138.

Jackson, R. D., Kustas, W. P. and Choudhury, B. J., 1988, A Re-Examination of the Crop Water Stress Index. *Irrigation Science*. 9, 309–317.

Jia, L., Su, Z., van den Hurk, B., Menenti, M., Moene, A., de Bruin, H. A. R., Yrissary, J. J. B., Ibanez, M. and Cuesta, A., 2003, Estimation of Sensible Heat Flux using the Surface Energy Balance System (SEBS) and ATSR Measurements. *Physics and Chemistry of the Earth*. 28, 75-88.

Jordan-Meille, L. and Pellerin, S., 2004, Leaf Establishment of a Maize (Zea Mays L.) Field Crop under Potassium Deficiency. *Plant and Soil*. 265, 75-92.

Kumar, S. V., Peters-Lidard, C. D., Tian, Y., Houser, P. R., Geiger, J., Olden, S., Lighty, L., Eastman, J. L., Doty, B., Dirmeyer, P., Adams, J., Mitchell, K., Wood, E. F. and Sheffield, J., 2006, Land Information System: An Interoperable Framework for High Resolution land Surface Modeling. *Environmental Modelling and Software*. 21(10), 1402-1415.

Kustas, W. P. and Norman, J. M., 1999, Evaluation of Soil and Vegetation Heat Flux Predictions using a Simple Two-Source Model with Radiometric Temperatures for Partial Canopy Cover. *Agricultural and Forest Meteorology*. 94, 13-29.

Maddonni, G. A., Otegui, M. E. and Cirilo, A. G., 2001, Plant Population Density, Row Spacing and Hybrid Effects on Maize Canopy Architecture and Light Attenuation. *Field Crops Research*. 71, 183-193.

Menenti, M. and Choudhury, B. J., 1993, Parameterization of Land Surface Evapotranspiration using a Location Dependent Potential Evapotranspiration and Surface Temperature Range. In Exchange Processes at the Land Surface for a Range of Space and Time Scales, Bolle H.J.; Feddes R.A.; Kalma J.D., Eds.; Publisher: IAHS, 1993, 212, 561–568.

Menenti, M., 1984, Physical Aspects of and Determination of Evaporation in Deserts Applying Remote Sensing Techniques. *Institute for Land and Water Management Research* (ICW). 10.

Menenti, M. and Choudhury, B. J., 2001, Di Girolamo, N. Monitoring of Actual Evaporation in the Aral Basin using AVHRR observations and 4DDA results. In Advanced Earth Observation – Land Surface Climate, Su Z.; Jacobs C.; Eds.; Publisher: National Remote Sensing Board (BCRS): 2001, USP-2(01–02), 79–83.

Monin, A. S. and Obukhov, A. M., 1954, Basic Laws of Turbulent Mixing in the Surface Layer of the Atmosphere. Tr. *Akad. Nauk SSSR Geophiz. Inst.* 24(151), 163-187.

Nieuwenhuis, G. J. A., Schmidt, E. A. and Tunnissen, H. A. M., 1958, Estimation of Regional Evapotranspiration of Arable Crops from Thermal Infrared Images. *International Journal of Remote Sensing Environment,* 6, 1319–1334.

Norman, J. M., Kustas, W. P. and Humes, K. S., 1995, A Two-Source Approach for Estimating Soil and Vegetation Energy Fluxes from Observations of Directional Radiometric Surface Temperature. *Agricultural and Forest Meteorology*. 77, 263–293.

Norman, J. M., Anderson, M. C., Kustas, W. P., French, A. N., Mecikalski, J., Torn, R., Diak, G. R., Schmugge, T. J. and Tanner, B. C. W., 2003, Remote Sensing of Surface Energy Fluxes at 101-m Pixel Resolution. *Water Resour. Res.* 39(8), 1221.

Rabbani, U., 2014, Model-Data Fusion for Land-Atmosphere Coupling: Interfacing RS Energy Balance Model with Microwave Soil Moisture. PhD Thesis, Charles Sturt University, NSW, Australia, 120.

Roerink, G. J. and Su, Z., 2000, S-SEBI: A Simple Remote Sensing Algorithm to Estimate the Surface Energy Balance. *Physics and Chemistry of the Earth*. 25, 147-157.

Savige, C., Western, A. W., Walker, J. P., Kalma, J. D., French, A. N. and Abuzar, M., 2005, Obtaining Surface Energy Fluxes from Remotely Sensed Data. *In Proceedings, 16th Congress of the Modelling and Simulation Society of Australia and New Zealand,* 12-15 December 2005, Melbourne, 2946-2952.

Su, Z. and Pelgrum, H., 1999, Aggregation Effects of Surface Heterogeneity in Land Surface Processes. *Hydrology and Earth System Sciences*. 1999, 3(4), 549-563.

Su, Z., 2002, The Surface Energy Balance System (SEBS) for Estimation of Turbulent Heat Fluxes. *Hydrol. Earth Syst. Sci*. 6(1), 85-99.

Su, Z. and Jacobs, C., 2001, Advanced Earth Observation – Land Surface Climate. *National Remote Sensing Board* (BCRS), USP-2(01–02).

Su, Z., Li, X., Zhou, Y., Wan, L., Wen, J. and Sintonen, K., 2003, Estimating Areal Evaporation from remote sensing. In Proceedings of the International Geoscience and Remote Sensing Symposium, 21–25 July 2003, Toulouse.

Su, Z., 2005, Estimation of the Surface Energy Balance. In Encyclopaedia of Hydrological Sciences: 5 Volumes. Anderson M.G.; McDonnell, J.J.; Chichester etc; Eds.; Publisher: Wiley & Sons, 3145. ISBN: 0-471-49103-93. Vol., 2., 731-752

Wang, L., Parodi, G. and Su, Z., 2008, SEBS Module BEAM: A Practical Tool for Surface Energy Balance Estimates from Remote Sensing Data. *In Proceedings of the 2nd MERIS – (A) ATSR User group*, ESRIN, 22-26 September.