Engineers Australia
29th Hydrology and Water Resources Symposium
21–23 February 2005, Canberra

Remote sensing estimates of actual evapotranspiration in an irrigation district

Cressida L. Savige
Department of Civil and Environmental Engineering, University of Melbourne, Australia
Email: c.savige@civenv.unimelb.edu.au

Andrew N. French
US Water Conservation Laboratory, USDA/ARS, Phoenix AZ, USA
Email: afrench@uswcl.ars.ag.gov

Andrew W. Western
Department of Civil and Environmental Engineering, University of Melbourne, Australia
Email: a.western@civenv.unimelb.edu.au

Jeffrey P. Walker
Department of Civil and Environmental Engineering, University of Melbourne, Australia
Email: j.walker@unimelb.edu.au

Mohammad Abuzar
Department of Primary Industries, Tatura, Australia
Email: mohammad.abuzar@dpi.vic.gov.au

Jorg M. Hacker
Flinders University, Airborne Research Australia, Adelaide, Australia
Email: jorg.hacker@flinders.edu.au

Jetse D. Kalma
Environmental Engineering Group, School of Engineering, University of Newcastle, Australia
Email: cejk@alinga.newcastle.edu.au

ABSTRACT: Accurate estimates of the spatial distribution of actual evapotranspiration (AET) are useful in hydrology but can be difficult to obtain. Remote sensing provides a potential capability for routinely monitoring AET by combining remotely sensed surface temperature and vegetation cover observations with near surface meteorological data in a surface energy balance model. Results from two different energy balance models are compared to airborne and ground measurements of surface energy fluxes over an irrigation district in northern Victoria during January 2003. Ground data collected include eddy correlation measurements of latent and sensible heat fluxes and associated meteorological measurements. The airborne data include eddy correlation measurements of latent and sensible heat fluxes (35 m above ground level), surface temperature transects and normalised difference vegetation index (NDVI) imagery (1 m resolution). Surface temperature and NDVI maps were derived from Landsat ETM+ data and combined with the ground meteorological observations in both a one- and two-source energy balance model. The two models produced similar results over irrigated sites, but large discrepancies were present over sparsely vegetated and bare soil areas. Although both models overestimated the latent and sensible heat fluxes in comparison to the ground and airborne measured fluxes, it was found that the modelled and observed Bowen ratios compared well.

INTRODUCTION

Remote sensing estimates of actual evapotranspiration (AET) have been made in hydrology, agronomy and meteorology at a range of spatial scales. Remote sensing data are used to derive surface temperature, surface reflectance and vegetation indices, which are combined with local meteorological observations in models to estimate AET. Recent work has focused on improving the accuracy of AET estimates using remote sensing data at high spatial resolutions.

The surface energy balance method has been commonly used to estimate the latent heat flux density (rate of AET) over land surfaces. Many papers have reported on the accuracy of surface heat flux estimates from energy balance models by comparing the remote sensing estimates to point measurements of latent and sensible heat fluxes (French et al. 2003, Kustas et al. 1999). While these models have been found to estimate fluxes well at the points where field data are available (within 50 Wm^{-2}), little is known about how the models perform across an entire image.

The results from two different one-dimensional energy balance models are used to investigate the spatial variability of surface flux estimates across a remote sensing image. First, the two models are briefly described and key differences are highlighted. The remote sensing data used to derive surface flux estimates are presented, along with the ground and airborne data collected at the time of the satellite overpass. Comparisons are made between the energy balance models and the field data and the models are then inter-compared. Some reasons for the differences between modelled and observed surface heat fluxes are discussed.

DESCRIPTION OF MODELS

Two different energy balance models were used to derive spatial estimates of sensible and latent heat fluxes across an irrigation district. The general approach of surface energy balance models is to evaluate the instantaneous energy balance at each pixel using a combination of remote sensing and meteorological data. The energy balance is given by

$$LE = R_n - G - H \, , \qquad (1)$$

where LE is the latent heat flux, R_n is the net radiation, G is the soil heat flux and H is the sensible heat flux.

The two main types of energy balance models that have been reported in the literature are one- and two-source energy balance models. The key factor differentiating these two approaches is the way in which the land surface is described. One-source models consider the combined soil-vegetation flux at each pixel, while two-source models consider the contribution of the soil and vegetation components to the vertical surface fluxes separately.

The models used in this analysis are the one-source Surface Energy Balance Algorithm for Land (SEBAL) developed by Bastiaanssen et al. (1998) and the two-source energy balance model of Norman et al. (1995).

One-source energy balance model

The SEBAL approach calculates net radiation, soil heat flux and sensible heat flux, while latent heat flux is evaluated as the remaining term in the energy balance equation. Remote sensing data in the visible, near-infrared and thermal infrared bands are used to derive the energy balance components. Air temperature, relative humidity and wind speed at a point in the image are also required.

A wet and a dry pixel are identified in the image and the sensible heat flux is scaled between these two extremes. At the dry pixel the latent heat flux is assumed to be zero and the sensible heat flux is equivalent to the available energy (R_n – G). A pixel with full cover and unstressed vegetation is generally selected as the wet pixel, where it is assumed that sensible heat flux is zero and that all available energy is directed to the latent heat flux. An alternative is to calculate the latent heat flux from the Penman-Monteith method for reference evapotranspiration and the minimum sensible heat flux is found as the residual in the energy balance (Allen et al. 1998). The latter method was followed in this study.

Two-source energy balance model

In the two-source approach, 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. An estimate of vegetation height for each pixel in the image is used to estimate the aerodynamic roughness. Measurements of air temperature, relative humidity and wind speed at a point in the image are required at the time of the overpass.

Fractional vegetation cover estimated from NDVI is used to partition surface temperature between soil and vegetation components in each pixel. For the soil component the net radiation, soil heat flux and sensible heat flux are calculated and the latent heat flux is solved as the residual in the energy balance equation. Over vegetation, the latent heat flux is calculated for unstressed vegetation using a modified Priestley-Taylor formulation and then sensible heat flux is calculated as the residual (Norman et al. 1995).

There are a number of differences between the one- and two-source approaches, aside from the way in which the land surface is described. Accuracy of the surface temperature estimates is very important in the two-source model where sensible heat flux is calculated from the absolute surface temperature for the bare soil component of a pixel. In contrast, SEBAL uses the difference between air and surface temperature to calculate the sensible heat flux and is not as sensitive to errors in the absolute surface temperature. The two-source model estimates aerodynamic roughness at each pixel from vegetation height, whereas in SEBAL the aerodynamic roughness is calculated.

DATA COLLECTION

The data used in this study were collected at a dairy farm near Nathalia in north-central Victoria (Figure 1). Field data were collected on 31 January 2003 to coincide with a Landsat 7 overpass. The land surface is a combination of irrigated pasture (clover and rye grass) and dry paddocks with either sparse or no vegetation cover.

Satellite data

The Landsat 7 ETM+ image used for this analysis was collected at 10:00 (AEST) on 31 January 2003. The ETM+ data have a spatial resolution of 30 m in the visible and near-infrared bands and 60 m in the thermal band. The thermal infrared remotely sensed data were corrected for atmospheric effects using atmospheric profile data from locally released radiosondes. The atmospherically corrected thermal data were used to estimate surface temperature across the Landsat scene. The NDVI was derived from the red and near-infrared bands.

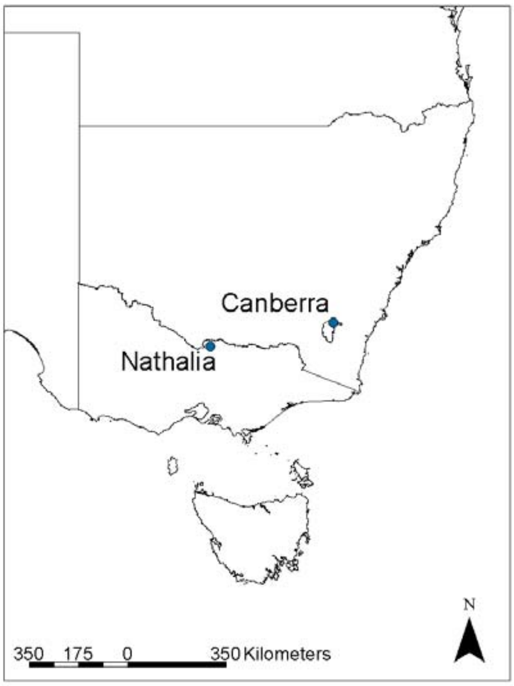

Figure 1. Map showing location of study site (Nathalia)

Ground measurements

A mast mounted eddy correlation system was used to measure the sensible and latent heat fluxes over an irrigated pasture. The sensors were mounted 1.8 m above ground level and the maximum fetch was approximately 400 m. Net radiation, soil heat flux, soil temperature, air temperature and humidity were measured at the same point. The soil heat flux was measured 8 cm below the surface and adjusted for heat storage in the layer above to provide an estimate of the soil heat flux at the surface.

Airborne measurements

A 7 km transect was flown in the along wind direction over the Nathalia field site (Figure 3a). The irrigated pasture site is the green semi-circle between the dashed lines (centre pivot irrigator). Ten consecutive flights were made along this transect at approximately 35 m above ground level. The flights were made between 11:30 and 12:30 (AEST) on 31 January 2003. Winds were predominately south-westerly during the flight time with an average speed of 6 ms^{-1}. Air temperature, air humidity, wind speed and wind direction were sampled at 50 Hz. The instantaneous fluctuations from the transect mean were used to calculate latent and sensible heat fluxes. Non-overlapping block averages were taken at 800 m intervals along each transect and each block was averaged over the ten overpasses to estimate the latent and sensible heat fluxes along the transect. Wind direction was used to help estimate an approximate source area for the measured fluxes.

RESULTS

Ground measurements

The energy balance components measured at the mast are shown in Figure 2 for 31 January 2003. At the time of the Landsat 7 overpass, the sensible heat flux was 130 Wm^{-2} and the latent heat flux was 185 Wm^{-2}. Energy balance closure for the ground measured fluxes was approximately 85% during the daytime period.

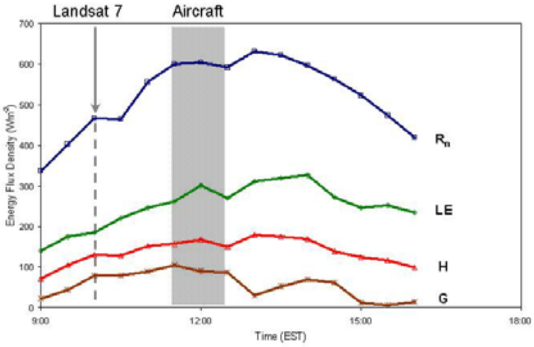

Figure 2. Energy balance components measured at the irrigated pasture site, 31 January 2003

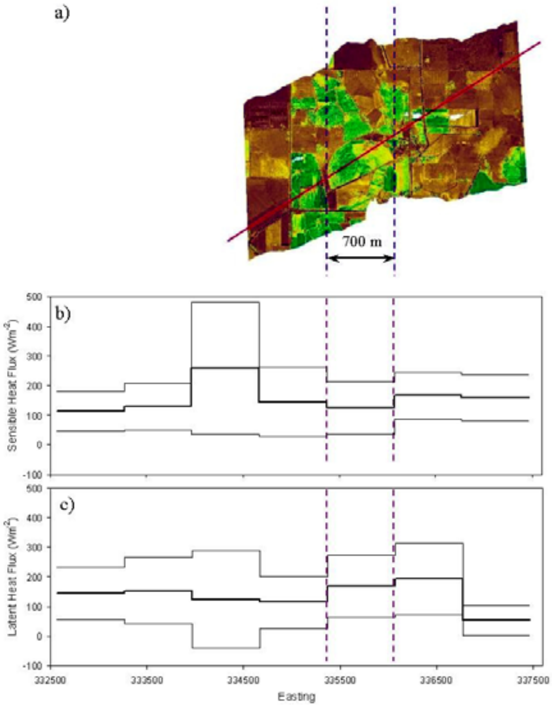

Figure 3. a) NDVI scan of Nathalia site with aircraft track marked in red. Aircraft measured b) sensible and c) latent heat flux (bold line) with plus/minus one standard deviation. Vertical dashed lines indicate the study site.

Airborne measurements

The latent and sensible heat fluxes were averaged over 800 m to correspond to the width of the field site. The between pass standard deviation for the airborne fluxes was calculated to provide an indication of the high variability in fluxes for each overpass of the aircraft (Mahrt 1998). The between pass standard deviation is shown above and below the block average sensible and latent heat flux in Figures 3(a) and 3(b). There is reasonable agreement between the ground and airborne flux measurements. The airborne heat fluxes were lower than the fluxes measured by the mast mounted eddy correlation system by approximately 10 Wm^{-2} for the sensible heat flux and approximately 20 Wm^{-2} for the latent heat flux.

Performance of the models

Figure 4 shows the flux estimates from the aircraft and the two remote sensing models for the same averaging length of 800 m. These plots clearly show that the modelled surface fluxes are higher than the mast and aircraft measured fluxes. Despite the large discrepancy between the modelled and observed (ground and airborne) heat fluxes, the transect average Bowen ratios (*H/LE*) are all very close to 1.2.

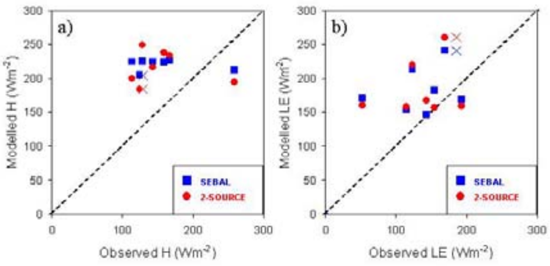

Figure 4. Comparison of modelled and observed a) sensible and b) latent heat fluxes. The ground measurements corresponding to the remote sensing methods are shown as a cross.

The spatial variation in the latent and sensible heat fluxes is shown in Figure 5. The study site corresponds to the section of the flight track between the vertical dashed lines and the mast measured flux appears as a horizontal dashed line. The models compare well to one another along the length of the flight track while the airborne fluxes (green) are considerably lower in magnitude. The modelled (blue and red) and airborne (green) fluxes follow a similar pattern along some sections of the flight track.

Inter-comparison of the models

A pixel by pixel comparison of the two energy balance models was performed to investigate how the flux estimates of each model vary in space (Figure 6). At each pixel, the surface heat flux estimated by the one-source SEBAL model was subtracted from the two-source model estimate. The red areas in Figure 6 indicate that the two-source model estimates were higher than the SEBAL estimates. Over bare soil the two-source model estimates of sensible heat flux were much greater than the SEBAL estimates (100 Wm^{-2}). White areas indicate good agreement between the two models (20 Wm^{-2}) and these areas generally correspond to irrigated surfaces. The pale colours represent a difference of 60 to 80 Wm^{-2}.

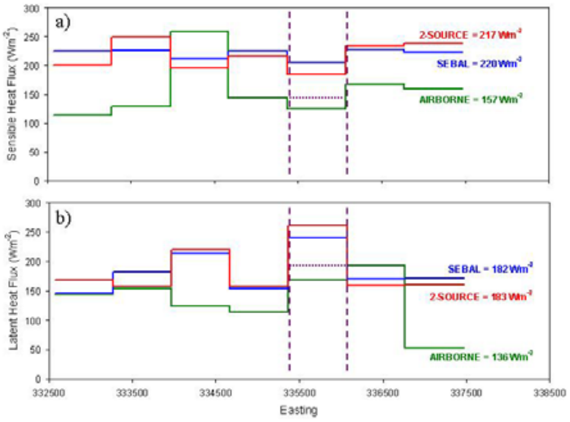

Figure 5. Intercomparison of airborne, mast and remotely sensed a) sensible and b) latent heat flux using the SEBAL (one-source) and two-source models. The study site corresponds to the section of the flight track between the vertical dashed lines and the ground measured flux appears as a horizontal dashed line.

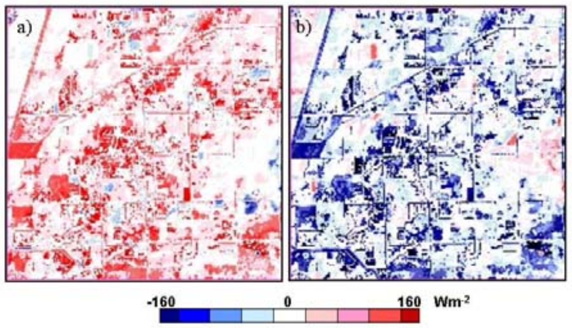

Figure 6. Difference between two-source and SEBAL estimates of a) sensible and b) latent heat fluxes

DISCUSSION

As shown in Figure 5, the airborne fluxes (green) measured at 35 m above ground level were lower than the fluxes measured at the mast. Some separation of the aircraft measured fluxes from the surface heat fluxes is expected in irrigation districts where the contrast between wet and dry land surfaces is very high and horizontal mixing is likely to occur (Mahrt et al. 2001).

The sensible and latent heat flux estimates from both the one- and two-source models are considerably higher than the measured fluxes. This difference is partly because the measured sensible and latent heat fluxes are approximately 15% below the measured available energy, while the models assume that the energy balance is closed. Twine et al. (2000) point to a number of cases where the eddy correlation method underestimates the sensible and latent heat fluxes, and they suggest that the measured fluxes should be corrected to close the surface energy budget. Such an approach would reduce the difference between the modelled and observed fluxes in this study. Despite the difference in magnitude of fluxes, the modelled and observed Bowen ratios for the transect average fluxes are very similar. This indicates that the models are partitioning the surface fluxes appropriately at spatial scales of a few kilometres.

The one- and two-source energy balance models produce similar heat flux estimates over irrigated areas but the difference is large over bare soil areas and pixels with sparse cover. Comparisons to measured fluxes over dry land surfaces will help to improve our understanding of the models. There is some difference between the spatial pattern of the modelled and observed fluxes that may be due to inaccurate source area estimation for the airborne fluxes and the choice of averaging length along the flight track.

CONCLUSIONS

Estimates of the latent and sensible heat flux were derived using one- and two-source energy balance models and the results were compared to ground and airborne flux measurements. The remote sensing estimates of the sensible and latent heat flux obtained with both models were higher than measured values.

Remote sensing provides estimates of surface heat fluxes that vary in space. Differences between the spatial flux estimates were assessed by mapping the difference between two models at each pixel in the image. Model agreement was best over irrigated pasture areas (20 Wm^{-2}) but poor over bare soil areas (80–100 Wm^{-2}).

Both the one- and two-source energy balance models provided reasonable estimates of the surface heat fluxes from high spatial resolution remote sensing data where soil moisture availability is high (irrigated patches). However, large discrepancies between models under certain land surface conditions (dry, bare soil) exist and further investigation is being undertaken to understand the cause of these differences and to assess which of the two models is most reliable.

ACKNOWLEDGMENTS

This research was funded by the Australian Research Council Linkage Program Grant LP0211929 and the Shepparton Irrigation Region Implementation Committee. We wish to thank the landholders in the Nanneella and Nathalia districts where the field measurements were conducted.

REFERENCES

Allen, RG, Pereira, LS, Raes, D & Smith, M 1998, *Crop evapotranspiration: Guidelines for computing crop water requirements*, FAO Irrigation and Drainage Paper 56, FAO, Rome.

Bastiaanssen, WGM, Menenti, M, Feddes, RA & Holtslag, AAM 1998, 'A remote sensing surface energy balance algorithm for land (SEBAL) 1. Formulation', *Journal of Hydrology*, 212–213, 198–212.

French, AN, Schmugge, TJ, Kustas, WP, Brubaker, KL & Prueger, J 2003, 'Surface energy fluxes over El Reno, Oklahoma, using high-resolution remotely sensed data', *Water Resources Research*, 39(6), 1164.

Kustas, WP & Norman, JM 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(1), 13–29.

Mahrt, L 1998, 'Flux sampling errors for aircraft and towers', *Journal of Atmospheric and Oceanic Technology*, 15(2), 416–429.

Mahrt, L, Vickers, D & Sun, JL 2001, 'Spatial variations of surface moisture flux from aircraft data', *Advances in Water Resources*, 24(9–10), 1133–1142.

Norman, JM, Kustas, WP & Humes, KS 1995, 'A two-source approach for estimating soil and vegetation energy fluxes from observations of directional radiometric surface temperature', *Agricultural and Forest Meteorology*, 77(3–4), 263–293.

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', *Agricultural and Forest Meteorology* 103(3), 279–300.