Obtaining surface energy fluxes from remotely sensed data

[1]Savige, C., [1]A. W. Western, [1]J. P. Walker, [2]J. D. Kalma, [3]A. N. French and [4]M. Abuzar

[1]University of Melbourne, [2]University of Newcastle, [3]GSFC (now at USDA), [4]DPI Tatura, Email: c.savige@civenv.unimelb.edu.au

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EXTENDED ABSTRACT

Land surface fluxes have been estimated from remotely sensed data at high pixel resolutions (approximately 60 m) with reasonable accuracy when compared to ground measurements (French et al., 2003; Kustas and Norman, 1999). The remote sensing input used to model land surface fluxes may consist of land surface temperature and a vegetation index. Remotely sensed land surface temperature estimates are strongly affected by atmospheric effects and the generally unknown land surface emissivity. These effects mean that land surface temperature estimates can vary by 1–3 degrees. Similarly, the visible and infra-red bands that are used to calculate vegetation indices are affected by the atmosphere and radiance data should be corrected before calculating such indices.

This study investigates the impacts on modelled land surface fluxes of using atmospherically corrected and uncorrected remote sensing input data in two different energy balance models.

Two energy balance models were selected for testing. The first (SEBAL) is a one-source model that calculates the sensible heat flux, net radiation and soil heat flux at each remote sensing pixel and estimates the latent heat flux as the residual term in the energy balance. The second (TSM) is a two-source model that uses a vegetation index to partition the land surface temperature between the vegetation and soil at each pixel and then evaluates the energy balance separately over the two land surface components.

Land surface temperature was estimated from both atmospherically corrected and uncorrected Landsat ETM+ band 6 data. Atmospherically corrected and uncorrected reflectance in the red and near-infrared bands was used to calculate a vegetation index. These remotely sensed data were used as input in the two different models to estimate the energy balance components at the land surface. The resulting latent heat flux (LE) across the study region is shown in Figure 1.

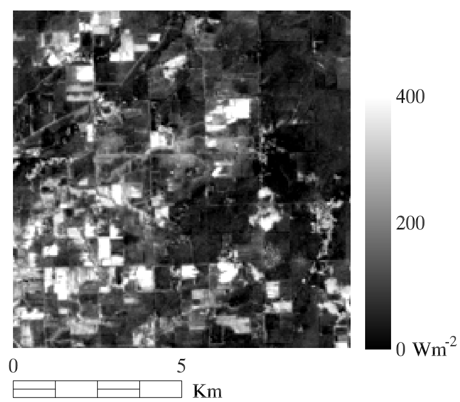

Figure 1. Latent heat flux (LE) in study area from SEBAL model with Landsat 7 ETM+ data as remote sensing input, 31 January 2003.

While atmospheric corrections are important for obtaining accurate estimates of the normalised difference vegetation index (NDVI), the impact on the modelled flux of a 5–15% change in NDVI was less than 10 Wm^{-2} for both models. The atmospheric corrections for the land surface temperature caused the greatest impact on the modelled energy balance components. An increase of 2 degrees in land surface temperature at the pasture sites caused the sensible heat flux estimated by the SEBAL model to be reduced by approximately 10% (or 20 Wm^{-2}) while the TSM sensible heat flux increased by as much as 50–175 Wm^{-2} at the pasture sites. These results indicate the importance of making appropriate atmospheric corrections to thermal remotely sensed data for land surface flux estimation.

1. INTRODUCTION

There is great interest in using remotely sensed data in energy balance models to estimate land surface fluxes; however, there are a number of limitations to implementing these models as part of a routine flux monitoring program. There are three important steps that need to be taken before these models can be used with confidence: (i) validating modelled fluxes against field measured fluxes, (ii) testing the sensitivity of the modelled fluxes to variations in input data, and (iii) testing the sensitivity of the modelled fluxes to the user specified boundary conditions.

Two models that have been widely tested and reported in the literature are the surface energy balance algorithm for land (SEBAL) (Bastiaanssen, 1998) and the two-source model (TSM) of Norman et al. (1995). Despite several papers reporting the validation of these models, very little mention has been made of the sensitivity of the modelled fluxes to the ground based observations and remote sensing inputs or the user specified parameters. The focus of this paper is on the sensitivity of modelled fluxes to variability in remote sensing input, rather than a validation of modelled land surface fluxes.

Remotely sensed input data used to model land surface fluxes are most often a combination of land surface temperature and a vegetation index. Accurate land surface temperature estimates depend on appropriate surface emissivity estimates and, because of the strong absorption in the thermal band by water vapour, atmospheric corrections are very important. Vegetation indices are generally formed by combining the reflectance in a visible and an infra-red bandwidth. Since the atmosphere interacts differently with the signal in these different bandwidths, a vegetation index calculated from atmospherically corrected data can differ significantly from the uncorrected index. The aim of this study is to test the impact of remotely sensed data that have not been corrected for atmospheric effects on modelled land surface fluxes.

The SEBAL and TSM land surface models that were used in this study are outlined in Section 2, followed by a description of the remote sensing and ground based input data in Section 3. The results of four test cases are presented in Section 4 and the implications of using uncorrected data to model land surface fluxes are then discussed.

2. DESCRIPTION OF MODELS

Two energy balance models were selected for this study. These models both rely on evaluating three terms in the energy balance and solving the fourth term as the residual. A simplified surface energy balance is given by:

$$R_n - G = H + LE \tag{1}$$

where R_n is the net radiation, G is the soil heat flux, H is the sensible heat flux and LE is the latent heat flux. The advection and photosynthesis terms are sufficiently small that they are neglected here. Since the energy budget is resolved for a very thin surface layer, the storage term can also be ignored.

Both models require land surface temperature (T_{surf}) and the normalised difference vegetation index (NDVI) as remote sensing input. Land surface fluxes were modelled over a 22500 ha study area in northern Victoria near the township of Rochester. The study area is located in the Nanneella irrigation district where spatial variations in land cover and soil moisture conditions are on the order of hundreds of metres (Figure 1).

2.1. One-source model

The one-source model selected was the surface energy balance algorithm for land (SEBAL) developed by Bastiaanssen (1998). The SEBAL approach calculates net radiation, soil heat flux and sensible heat flux and the latent heat flux is evaluated as the remaining term in the energy balance equation. Remotely sensed data in the visible, near-infrared and thermal infrared bands are used to derive the energy balance components along with ground measured solar radiation if available. The other ground measurements that are required as model input are air temperature, relative humidity and wind speed at a point within the image.

The sensible heat flux calculation in SEBAL is linearly scaled between a wet and a dry pixel that are identified as the two extremes in the image. 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 crop evapotranspiration (ET) and the minimum sensible heat flux is found as the residual in the energy balance (Allen et al. 1998). In this study, the reference ET approach was selected because it provided more realistic flux predictions.

2.2. Two-source model

The second energy balance model that was tested is the two-source model (TSM) of Norman et al. (1995). In the two-source approach, the surface fluxes are calculated separately for the soil and vegetation components using remote sensing and ground based observations and then summed to satisfy the total energy balance at each pixel. The remote sensing inputs are radiometric surface 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, solar radiation 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 the surface temperature between the 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). The Priestley–Taylor method is considered appropriate for ET estimation for an extensive, well-watered grass surface. The TSM model adjusts the Priestley–Taylor ET estimate using a greenness factor to account for vegetation that is below optimal health.

Model fluxes are adjusted if the soil latent heat flux is negative (i.e. if the sensible heat flux from the soil is greater than the net radiation) or if the canopy sensible heat flux is greater than the available energy.

The 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.

3. DATA

Land surface temperature (T_{surf}) and the normalised difference vegetation index (NDVI) are the remotely sensed input data required to run both energy balance models. A single Landsat 7 ETM+ image, collected at 10:00 (EST) on 31 January 2003, was used for this analysis. 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 NDVI was derived from the red and near-infrared bands and the band 6 radiance was used to estimate the land surface temperature.

3.1. Land surface temperature

The data processing steps required to estimate land surface temperature include converting the digital number to radiance and then atmospherically correcting the at-satellite radiance to get an estimate of the surface radiance. The thermal band (Landsat band 6) was adjusted to account for atmospheric effects, mainly absorption due to water vapour, using the radiative transfer model MODTRAN v4.1 (Berk et al., 1999). Atmospheric properties were taken from radiosonde data collected at Wagga Wagga (approximately 200 km from the centre of the scene). The transmissivity and up- and down-welling atmospheric radiance estimated by MODTRAN were used to correct the at-satellite radiance.

The Stefan-Boltzmann law was applied to estimate the surface temperature from the adjusted radiance and the actual land surface temperature was obtained using an estimate of surface emissivity. Surface emissivity was estimated from the NDVI at each pixel using the empirical relationship used by Li et al. (2004). For the uncorrected land surface temperature, the at-satellite radiance was used, along with an estimate of surface emissivity, to calculate the temperature directly.

For the conditions of this study, the atmospheric corrections decreased T_{surf} by 10–25% for temperatures below 300 K (27°C) and decreased T_{surf} by less than 10 % for temperatures above 300 K. The sites with temperatures above 300 K are mainly the bare soil sites in this case. The pasture sites have surface temperatures below 295 K where the effects of the atmospheric corrections on the land surface temperature estimates were the greatest.

3.2. NDVI

The NDVI is an index that is commonly used with remotely sensed data to give an indication of vegetation health. NDVI is calculated from the reflectance in the red and near-infrared:

$$NDVI = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}} \qquad (2)$$

where ρ_{nir} is the reflectance in the near-infrared bandwidth (Landsat band 4) and ρ_{red} is the reflectance in the red bandwidth (Landsat band 3). NDVI was calculated both with and without atmospheric corrections to test the impact of using uncorrected NDVI data on modelled land surface fluxes. To correct for atmospheric effects, the radiance in the red and near-infrared bands was adjusted using the 6S model v4.1 (Vermote, 1997) with a standard atmospheric profile (mid-latitude summer) and a default aerosol model. The corrected radiance was then converted to reflectance in the corresponding bands and used to calculate an atmospherically corrected NDVI. The corrected reflectance is still an apparent surface reflectance because not all atmospheric effects have been accounted for and models were used in the place of measured aerosols. Despite the lack of direct measurements, the corrections provide a useful normalisation of the data in each of the bands.

Table 1. Dominant land cover types and corresponding NDVI ranges (atm. corr. NDVI).

Land Cover	NDVI (atm. corr.)
Water	-0.5–0
Bare soil	0.20–0.28
Dry pasture/stubble	0.38–0.45
Mixed cover	0.45–0.60
Pasture	0.60–0.85
Corn	>0.85

Thirteen sites were selected within the study region to examine the effect on the model output of changing the remotely sensed input data. The sites were selected to include the full range of NDVI and T_{surf} observed in the study area. Land cover at five of the sites is pasture and the remaining eight sites are a mixture of bare soil, dry pasture and stubble. The dominant land cover types and the corresponding NDVI ranges are summarised in Table 1.

Field measurements of NDVI were available at seven of these sites within four days of the Landsat 7 overpass. Between 20 and 50 measurements were taken at each site with a portable radiometer and averaged to give a representative NDVI for each site. The radiometer used for the sampling had similar bandwidths to the Landsat ETM+ sensor and a direct comparison has been made (Figure 2) between remote sensing based estimates and ground based observations. The atmospherically corrected NDVI estimates compared well to the field measured NDVI, particularly at the pasture sites where NDVI is high.

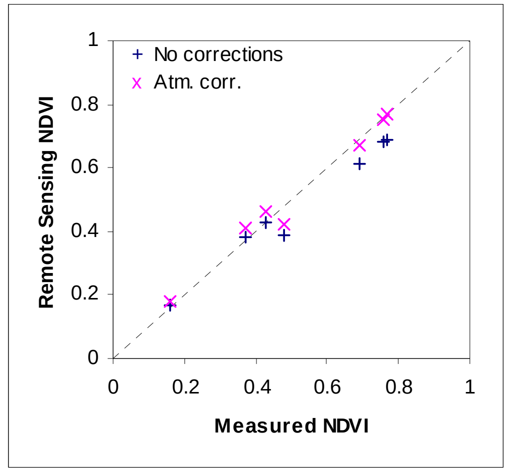

Figure 2. Comparison of uncorrected and atmospherically corrected NDVI values based on remote sensing and ground based NDVI values measured at 7 sites.

Both atmospherically corrected and uncorrected land surface temperature and NDVI at the thirteen study sites is shown in Table 2. These values are an average of a 3 by 3 neighbourhood of pixels (approximately 150 x 150 m) that closely matches the sites where NDVI was sampled.

Table 2. NDVI and T_{surf} at 13 locations in the study region showing the effects of atmospheric corrections.

Site	Corrected		Uncorrected	
	NDVI	T_{surf}	**NDVI**	T_{surf}
1	0.18	301.9	0.17	303.4
2	0.20	306.7	0.17	307.7
3	0.23	304.1	0.21	305.6
4	0.32	299.6	0.3	301.7
5	0.37	299.4	0.35	301.6
6	0.41	300.1	0.38	302.2
7	0.42	300.0	0.39	302.3
8	0.46	298.2	0.43	300.6
9	0.67	293.2	0.61	296.5
10	0.75	291.5	0.68	295.2
11	0.77	290.4	0.69	294.3
12	0.81	290.2	0.74	294.2
13	0.88	287.5	0.82	291.9

The only other spatially distributed data required as model input is a land cover map for the scene. The land cover at each pixel is used to estimate surface roughness based on an approximation of vegetation height. For the purposes of testing the impacts of atmospheric corrections on the modelled surface fluxes a constant land cover layer was assumed.

3.3. Ground based data

The meteorological data used as model input included air temperature, air humidity, solar radiation and wind speed. These measurements were made at a weather station within the 22500 ha study region.

4. RESULTS

Four different cases were used to demonstrate the effects of using either atmospherically corrected or uncorrected input data on the modelled land surface fluxes. The input data for case 1 were atmospherically corrected T_{surf} and NDVI. For case 2, T_{surf} was not atmospherically corrected, while NDVI was not atmospherically corrected for case 3. In case 4, both T_{surf} and NDVI were calculated from at-satellite radiances that were not atmospherically corrected. The cases that were tested in this study are summarised in Table 3.

Table 3. Summary of the 4 cases that were tested.

Case	Description
1	T_{surf} and NDVI corrected (base case)
2	T_{surf} is not corrected; NDVI is corrected
3	NDVI is not corrected; Tsurf is corrected
4	No atmospheric corrections

Vegetation height was kept constant for all test cases. Most other input parameters were also kept constant for all runs with two exceptions. The first is the value of the maximum NDVI in the TSM. Since the uncorrected NDVI was lower than the atmospherically corrected NDVI, particularly at high NDVI, the maximum NDVI value in the TSM was reduced from 0.85 to 0.78 for cases 3 and 4. The second exception was to adjust the maximum and minimum temperatures at the endpoints in SEBAL to match the corrected or uncorrected land surface temperature value at these pixels.

The results presented here are for the sensible heat flux, since in SEBAL the latent heat flux is calculated purely as the residual term in the energy balance. A comparison of the base case sensible heat flux estimated by the two models at the 13 selected sites (Figure 3) shows that SEBAL H is higher at all sites. At the high NDVI pasture sites SEBAL H was 40–100% greater than TSM H and 10–35% greater than TSM at the low NDVI non-pasture sites.

Despite using different methods to calculate the net radiation (R_n), both models predicted R_n to within 5–15% or 25–75 Wm^{-2}. At the pasture sites, TSM R_n was slightly lower than SEBAL R_n and at the non-pasture sites TSM R_n was slightly higher than SEBAL R_n. Modelled G was within 5 Wm^{-2} in most cases, ranging up to 15 Wm^{-2} at the pasture sites for the cases where NDVI was altered.

The SEBAL modelled H fluxes for cases 2–4 were compared to the base case and the results are shown in Figure 4. Uncorrected surface temperature has the greatest impact on the sensible heat fluxes, while the uncorrected NDVI (case 3) has little impact on the modelled sensible heat flux. The combined effects on H, Rn and G meant that in most cases LE changed very little.

The TSM sensible heat flux is highly variable with changing surface temperature as shown in Figure 5. Net radiation and soil heat flux were affected very little and hence the latent heat flux responded strongly to changes in the sensible heat flux.

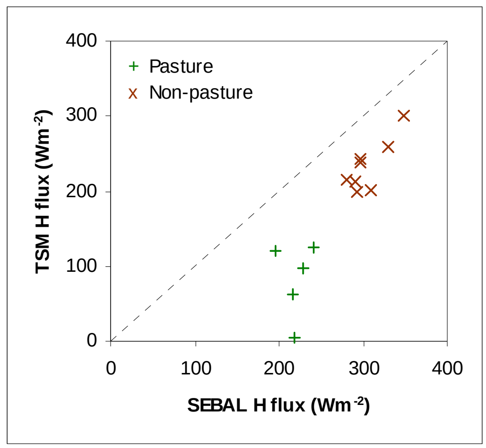

Figure 3. Difference between TSM and SEBAL estimated sensible heat flux at the 13 sites selected for the study.

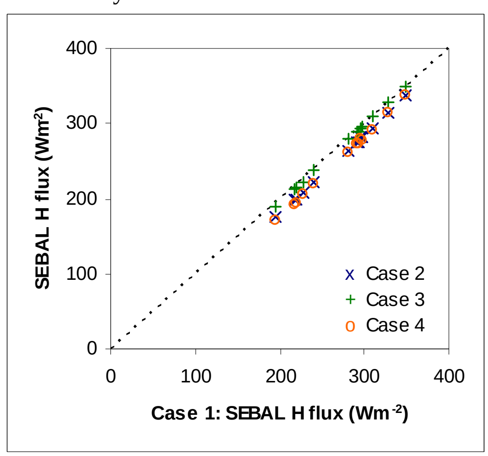

Figure 4. Variation of SEBAL sensible heat flux (H) from the base case for cases 2–4.

5. DISCUSSION AND CONCLUSIONS

SEBAL was less sensitive than the TSM to variations in land surface temperature estimates, although the sensible heat flux did not change as expected with changes in surface temperature. The reliance of the SEBAL flux estimates on the selection of the hot and cold endpoints is clearly demonstrated by the response of the model when the uncorrected land surface temperature was used as input (cases 2 and 4). The uncorrected land surface temperature was higher than the atmospherically corrected surface temperature, which would cause an increase in the surface–air temperature difference. This increase would enhance the transfer of heat from the surface to the atmosphere i.e. the sensible heat flux should increase. However, the relative temperature approach used in SEBAL caused the modelled H to decrease instead.

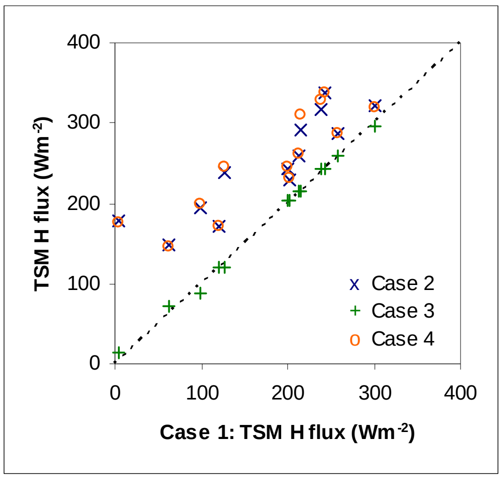

Figure 5. Variation of TSM sensible heat flux (H) from the base case for test cases 2–4.

The TSM was far more sensitive to errors in land surface temperature estimates than SEBAL. Because the model calculates the sensible heat flux from the absolute surface temperature, the modelled flux estimates responded as expected to changes in surface temperature. When the uncorrected surface temperature was used, the modelled sensible heat flux increased due to the increase in the surface–air temperature gradient.

While the atmospherically corrected NDVI provided a better comparison to the field measured NDVI, the impact of decreasing NDVI was minimal on the modelled fluxes. However, adjusting the surface temperature had a significant effect on the modelled fluxes. The impact was more significant in the TSM where the sensible heat flux calculations over the soil component are dependent on the temperature gradient between the surface and the air. The impact of adjusting the land surface temperature on the SEBAL modelled fluxes was not as large as for TSM but was still significant. These results show that great care should be taken in applying atmospheric corrections to thermal remotely sensed data for the estimation of land surface fluxes.

6. ACKNOWLEDGMENTS

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