Remote Sensing Techniques for Obtaining Effective Land Surface Parameters in the Estimation of Evapotranspiration with SVAT Models.

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Abstract. Determining the spatial and temporal variability in land surface processes over regional scales is a difficult task and considerable effort has been put into deriving appropriate models to deal with this challenge. Despite improvements in predictions of the surface energy balance through the use of remote sensing, the lack of appropriate measurements and prediction methods for both surface fluxes and soil moisture over a range of space and time scales remains. In this paper we introduce a stochastic approach to improving land surface parameterisation which is based on coupling remotely sensed thermal imagery and simulations within a SVAT modelling framework. This approach acknowledges and is based on the inherent uncertainty of both SVAT model parameterisations and the actual measurement of thermal signatures of the land surface. Issues related to the implementation of a methodology incorporating remote measures of the lands surface, SVAT modelling procedures and constraints are examined. An investigation on whether a time series of remotely sensed thermal data can be usefully employed to improve the land surface parameterisation of SVAT constructs is also presented. Utilising this technique may allow more robust predictions and calibrations of land surface fluxes to be achieved. The aims of this paper are to revisit some of the issues associated with energy flux simulations with SVAT models and remote sensing and also to discuss a possible approach to achieving some tractability in land surface parameterisations.

Introduction.

As part of a risk based groundwater management project undertaken within the Newcastle region of NSW, an estimate of the temporal variation in aquifer recharge over an area of around 300 km^2 is required. The use of groundwater resources in a sustainable manner requires knowledge of the aquifer water balance to ensure that the resource is not over-exploited and that ecosystems connected with the aquifer are not unduly affected. Whilst direct measurement of recharge is extremely difficult, an estimate can be derived using a simple mass balance approach - i.e. recharge will be related to the fraction of rainfall that is not returned to the atmosphere by evapotranspiration. If rainfall can be accounted for, the remaining term in the mass balance approach is the evaporative component (excluding runoff).

Evapotranspiration, or the latent heat flux, can be quantified at the small scale using ground-based measurement, but to obtain a large-scale estimate alternative measuring and estimation techniques must be used. Remote sensing is the only viable alternative to regional and larger scale estimation of many components of the energy balance from which the latent heat flux can be solved. The number of operational satellites available provides a vast choice of both spatial and temporal resolutions as well as a variety of multi-spectral channels to choose from. However, the use of remote sensing is not without its problems. Much study has been undertaken to resolve many of the shortcomings of this approach to regional scale modelling with varied success (Becker and Li, 1995; Stewart *et al.*, 1996). Thermal observations in particular are hindered by factors due to unknown surface emissivities, atmospheric corrections and the presence of numerous variables affecting the relationship between thermal radiance and the partitioning of energy fluxes

This paper examines some of the issues associated with simulations of the energy balance with SVAT and boundary layer models coupled with remote sensing. An approach aimed at achieving some tractability in land surface parameterisations is also introduced.

An Approach to Regional Scale Estimation of Evapotranspiration.

Evapotranspiration, like recharge, is highly variable in both space and time and is strongly affected by spatial variations in land use, vegetation, soils and topography. The estimation of heat fluxes at large scales is hindered by various atmospheric and land surface effects which conspire to limit the accuracy of attempts to characterise these variables. Heterogeneity at the land surface for example, precludes the extrapolation of point source estimates of surface fluxes over larger scales.

Implementing a methodology that accounts for spatial heterogeneity at a range of scales, necessitates the use of remote sensing in some form to adequately account for this variability. However, remote sensing on its own is ineffective in characterising the range of processes operating at the land surface. In order to effectively utilise the information potential of remote platforms to produce reliable estimates of evapotranspiration, and hence recharge, the following approach is being implemented.

The use of a geographic information system (GIS) along with aerial photography and SPOT panchromatic images, aid in the qualification of vegetation type and structure throughout an area of interest. Satellites such as LANDSAT-7 allow high spatial estimates of vegetative state to be resolved using simple vegetation indices. These additional data sources, coupled within a GIS framework, provide the user with a valuable and informative base from which to launch further modeling studies. The aim of modeling within this context, is to provide effective land surface parameters from which estimates of evapotranspiration can be made.

Using remote sensing to monitor temporal changes in the temperature at the land surface is discussed below. Applying this information in conjunction with standard meteorological variables and early morning radio-sonde soundings provides the input necessary to model evapotranspiration within a framework that combines remotely sensed parameters and atmospheric and land surface processes. The complex and non-linear processes involved demand models that can represent the key physical processes controlling surface energy fluxes in both a realistic and parametrically refined manner. The use of SVAT models, the importance of coupling these with the lower boundary layer, and combining both within an uncertain framework such as the GLUE methodology (Beven and Quinn, 1994), is discussed in the following sections along with some of the issues related to employing such a methodology.

SVAT Modelling.

Numerous soil-vegetation-atmosphere transfer (SVAT) schemes are derived from complex descriptions of the physical mechanisms governing land surface processes. A trend towards even more complex SVAT structures requiring large numbers of soil and land surface parameters seems to be prevalent. The rationale behind such an approach is that improved process representation will result in parameters which are easier to measure or estimate. However, this is not necessarily so, mainly because SVAT models require effective values for the various parameters at patch, regional or larger scales which are not easily estimated (Kalma *et al.*, 1999).

Modelling complex environmental systems with models that are unable to be satisfied in regard to the information required for their operation, must lead to significant predictive uncertainty. Uncertainty in land surface parameterisation will inevitably lead to considerable uncertainty in predicted land surface fluxes. Conversely, a simple model structure, while providing more robust parameter calibration may produce a degree of uncertainly due to the simplistic nature of the model representation. Obviously, some balance between exceedingly complex and overly simplistic model descriptions needs to be found. It is generally accepted however, that SVAT models are typically over-parameterised with respect to the available calibration data.

TOPUP-SVAT (Beven and Quinn, 1994; Franks *et al.*, 1997) is a simple SVAT model that, unlike other more complex SVAT constructs such as SiB, BATS and SiB2, requires a minimum of only eight parameters to be specified (Fig. 1). The rationale for developing a simpler model structure is that simplicity is necessary to empirically validate the use of such SVAT models in the field. Limited calibration data is available for such purposes, again highlighting the significant parametric and predictive uncertainty existing in the calibration and evaluation of SVAT models (Franks and Beven, 1997). This problem is compounded for more complex models that are grossly over-parameterised with respect to the available calibration/evaluation data sets.

The model incorporates the effects of near-surface stability for the calculation of aerodynamic resistance, and utilises a series of equations describing aerodynamic evaporation, plant physiological evaporation and sensible heat in the prediction of latent heat fluxes (see Franks, 1999 for more detailed model description). The evaporative pathways include (Figure 1.);

1. Evaporation from the interception store

2. Evapotranspiration from the root zone store
3. Evapotranspiration supplied by capillary rise from the water table.
4. Evapotranspiration from the water table when in the root zone.

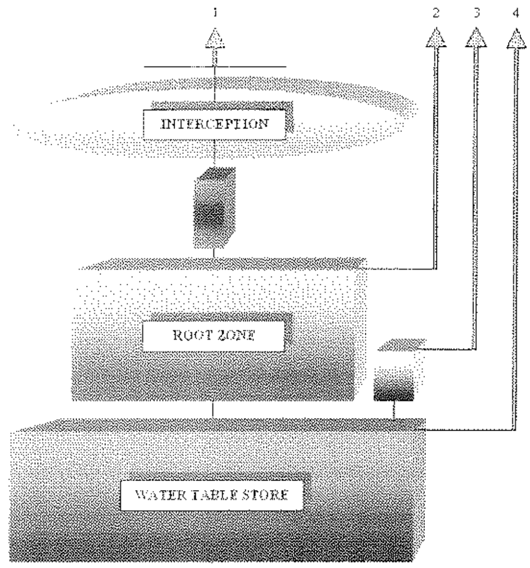

Figure 1 – Schematic representation of the TOPUP-SVAT model illustrating the various evaporative pathways and moisture stores.

GLUE Methodology

The Generalised Likelihood Uncertainty Estimation (GLUE) methodology is an extension of the Generalised Sensitivity Analysis of Spear and Hornberger [1980] and was developed as a method of calibration and uncertainty estimation of models based on generalised likelihood measures. Previous application of this approach has predominantly been directed to rainfall-runoff modelling and the prediction of critical loads. It has also been applied to the TOPUP-SVAT model. Beven and Binley [1992] introduced the GLUE methodology in an effort to deal with multiple acceptable parameter sets within a Bayesian Monte-Carlo framework. Implementation of the GLUE methodology involves the following steps;

1. Definition of feasible parameter ranges for the land surface cover type(s).
2. A large number of model runs – usually greater than 5000 – are made with the SVAT model, each parameterised with randomly selected values of the parameters chosen from uniform distributions across the ranges specified in 1.
3. The acceptability of each run is assessed by some chosen likelihood measure calculated from comparison of observed and simulated responses.
4. Following the rejection of non-behavioural runs, the likelihood weights of the retained runs are re-scaled so that their cumulative total is 1.0.
5. Finally, at each time step the predicted output from the retained runs are likelihood weighted and ranked to form a cumulative distribution of the output variable from which chosen quantiles can be selected to represent the model's uncertainty.

Some of the advantages of this approach include the facility to directly quantify the relative uncertainty of model predictions and also to assess the relative sensitivity of model parameters. Furthermore, the additional information content of long data sets and periods of poor model prediction within the data are able to be discriminated.

Functional Similarity and Non-Uniqueness

Whilst significant uncertainty exists in the specification of land surface parameters the actual functional behaviour, or temporal pattern, of latent heat flux over time is relatively conservative - the flux rarely exceeds the input net radiation and hence daytime fluxes are typically constrained between zero and the net radiation. Additionally, the occurrence of 'non-uniqueness' in parameter sets is common in most modeling structures. This reproduction of model response for different parameter sets is referred to as *equifinality*. Basically, the term refers to the reproduction of the same model output by numerous parameter sets – hence the non-uniqueness of solutions.

Furthermore, the observation of this 'non-uniqueness' of parameter sets may be seen in a converse light. Multiple *unique* parameter sets from very different parts of the parameter space, may produce the same model output response – in this example a temporal series of latent heat fluxes. The importance of this observation lies in the fact that if we wish to simulate a time series of latent heat fluxes, then one need only identify the functional behaviour of the land surface (Beven and Franks, 1999).

In terms of land surface flux behaviour in a drying period, differences in unstressed fluxes might be of secondary importance. Of greater significance is the accurate simulation of how and when a surface reduces and stops evaporative losses, as this is more directly linked to the total available moisture store of the land surface. It is therefore expected that the temporal pattern of energy flux response will provide more appropriate parameter values than any single estimate of the instantaneous flux is capable of doing. By comparing the temporal pattern of thermal responses, one may therefore achieve robust characterisation of the land surface function, as well as a degree of parameter tractability.

A simplified example of non-uniqueness is the prediction of an instantaneous latent heat flux from a single temperature measurement - both of which are TOPUP-SVAT outputs. Figure 2 illustrates the inherent uncertainty associated with derivations of latent heat fluxes from surface temperatures alone. Parameter uncertainty is such that a large range of inferred latent heat fluxes is possible.

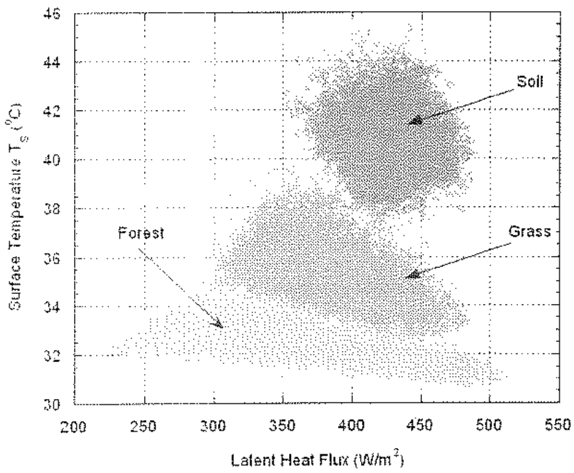

Figure 2 – Ranges of latent heat fluxes for surface temperature measurements produced during an artificial dry-down period with the TOPUP-SVAT model. Each of the three land surface classes was run for 5000 different parameter sets.

Parameter Inference in TOPUP-SVAT

Surface temperatures are significantly sensitive to land surface aerodynamic properties. Furthermore, model predicted aerodynamic surface temperature is not the same as the remotely measured radiometric surface temperature, although the difference between the two is approximately constant over the typical range of temperatures (Huband and Monteith, 1986). If one were to utilise the sensed surface temperatures, significant error may be incorporated and any defined objective function may be inappropriately biased.

To distinguish those modelled responses that most closely represent the actual behaviour of the land surface, some form of comparison is required. Implementing a procedure that fits the model output to an observed record and applying a simple objective function – in this case a least squares error – facilitates the identification of those responses that display similar trends to the observed record. A simple normalising procedure can be employed to fit the model output to the extreme temperatures of the observed record and then scale the remaining temperatures throughout the time series using the a simple linear equation. By comparing the temporal patterns of land surface temperatures with those predicted from the model output, it is expected that some parameter tractability may be resolved.

To examine this hypothesis in the absence of remotely sensed surface temperatures, a pseudo-observed record was used. In this example, a temporal series of surface temperatures was produced with the TOPUP-SVAT using a unique parameter set. The model was then run 5000 times, each run using a unique parameter set extracted from broadly defined parameter ranges for a grassed surface type. The results were compared using the procedure discussed above, with reference to a number of key parameters. Analysis of results using cumulative totals are shown below.

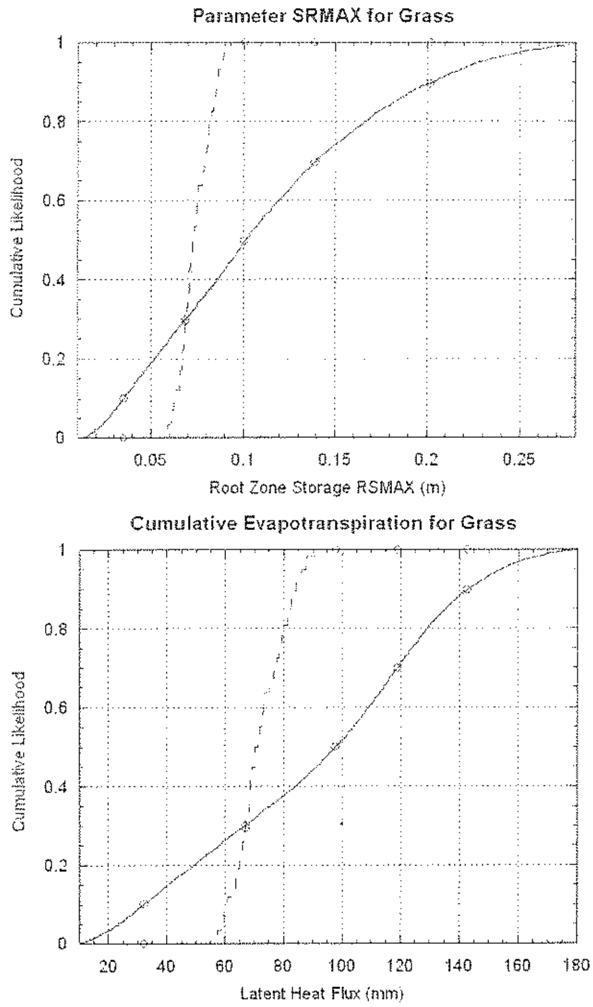

Figure 3 – Cumulative likelihood plot of the conditioning of TOPUP-SVAT runs relative to a time series of surface temperatures.

The solid line in Figure 3 refers to all of the 5000 modelled runs, while the dashed line are those that best match the temporal function of the observed sequence of surface temperatures. The 'best match' was subjective in that out of the 5000 runs, the top 1% were deemed acceptable simulators of the 'observed' thermal time series. The plot of Figure 3 shows the effect of the conditioning with respect to the a key model parameter SRMAX – the available soil moisture store – and the cumulative latent heat flux over the simulation period. As can be seen, employing this approach produces a highly constrained range of evaporative flux predictions, thus reducing the parameter uncertainty and aiding in the identification of effective parameters. This resulted despite the lack of constraint between the individual parameters – other parameters examined showed relatively little constraint. Hence, the correct functional performance was achieved regardless of the different discrete parameter responses exhibited for the surface type.

Linking SVAT and ABL models

Application of modeling techniques that characterise the spatial and temporal heterogeneity within a remote sensing framework facilitates more accurate reproduction of the processes under investigation. Links between the root zone, vegetation and surface layers have been modelled extensively with both single and dual-source models (Kalma and Jupp, 1990; Norman *et al.*, 1995). McNaugton and Jarvis [1991] recognised the significance of convective planetary boundary layer (PBL) processes in the interaction between stomata, the gateways of transpiration, and the atmosphere. The dependence of the surface conductance, or resistance, of vegetation on environmental factors and the resultant effect of this on the PBL is an important positive feedback operation that can be simulated within a modeling context. Linking the relatively stable surface layer described in SVAT models to the mixed layer allows the feedback mechanisms inherent in these systems to be represented.

A simple example of this feedback can be illustrated if an extensive period of fine, dry weather is considered. As areas of vegetation run short of water, the actual transpiration rate decreases, along with latent heat flux – a result of closing stomata. As the need to retain water increases – and latent heat decreases – and the input of sensible heat to the PBL increases making it even more warmer and drier, and the demand for water continues (the plants transpire even less).

The dynamic structure of the CBL is such that the top of the layer, defined by an inversion above which air is warmer and drier, can vary between 1 and 3km. Modeling of the boundary layer can be initialised with early morning radio-sonde soundings. Coupling the atmospheric component of SVAT models with some form of boundary layer model is a continuing area of research (McNaugton and Spriggs, 1986; Anderson *et al.*, 1997). Linking TOPUP-SVAT with a relatively simple ABL model, in an effort to more accurately capture some of the physical dynamics of the evaporative process, is the focus of current study.

Estimation of Land Surface Temperature using Remote Sensing

One of the major advantages of satellites is their ability to obtain information at a regional scale as opposed to the point scale estimation of ground based data collection. Thermal infrared measurement of the land surface has the potential to supply relatively accurate measures of land surface temperature (LST) at a range of spatial and temporal scales. Particular interest is directed at the extraction of a temporal record of thermal measurements of radiative temperature, and the associated application as input into a SVAT model.

Prata and Cechet [1999] showed that LST estimates from the Geostationary Meteorological Satellite Visible and Infrared Spin Scan Radiometer (GMS-VISSR), can be determined to RMS accuracy of 2-3°C with little bias. They contend that accuracies of 3°C would be of marginal use, whereas predictions approaching 1°C would potentially be of much benefit in modelling applications. The problem of inexact measurements of the LST may to some extent be addressed with the functional similarity technique employed by McCabe *et al.* [1999]. Some further approaches to account for the inherent uncertainty of LST estimates include the time rate of change of surface temperature (Diak and Whipple, 1995) and the use of heating rates to aid in partitioning the energy balance at the land surface (Jones *et al.*, 1998).

Actual measurement of LST however, remains the focus of continuing study. There have been a number of attempts to more accurately extract temperature measurements from a variety of remote sensing platforms. Most of these have focused on either the NOAA-AVHRR series of satellites or geostationary platforms such as the GMS-VISSR, GOES or METEOSAT. These types of satellites have an advantage in that they provide large area coverage with a comparatively frequent repeat cycle (1/day in the case of NOAA and up to hourly for the infrared radiometer on the GMS).

Two major problems in the use of remote sensing to estimate LST can be categorised as atmospheric and land surface emissivity effects. The methods currently used to account for these factors also fall into two broad categories – direct and indirect methods. Direct methods combine in-situ measurements of temperature and moisture (often through atmospheric soundings) coupled with atmospheric radiative transfer models. Indirect methods may use atmospheric radiative transfer models with vertical soundings of the atmosphere, or they may be based on so called split-window algorithms (Prata and Cechet, 1999).

Discussion

Determining the spatial and temporal variability in evapotranspiration over large areas and long time periods is a difficult task. This variability underlines the need for proper determination of the SVAT parameters used in land surface parameterisation. Various case studies have shown that remote sensing in combination with SVAT modelling has significant potential in improving the estimation of land surface fluxes and derived variables. Modelling of the mixed layer in combination with SVAT constructs using a simple boundary layer model, will more fully represent the dynamic nature of processes at the land surface. Application of these procedures within an uncertainty framework and the use of a temporal pattern of surface temperatures, will facilitate further insight into land surface behaviour and the determination of effective parameters.

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