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On the sensitivity of soil–vegetation–atmosphere transfer (SVAT) schemes: equifinality and the problem of robust calibration

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Abstract

Current 'physically based' soil–vegetation–atmosphere transfer (SVAT) schemes use increasingly complex descriptions of the physical mechanisms governing evapotranspiration fluxes, thereby requiring the specification of a large number of parameters controlling the vertical fluxes over a single homogeneous area. Recent attention towards the incorporation of sub-grid scale spatial variability in SVAT parameterisations promises to increase the number of parameters for these models. In this paper, it is demonstrated that a simple patch scale SVAT model still permits too many degrees of freedom in terms of fitting the model predictions to calibration or validation data; it is shown that good model fits may be achieved in many areas of the parameter space. Using a Monte Carlo framework, a sensitivity analysis is performed for simulations of data sets from FIFE and Amazonian sites. This is employed to evaluate the role of each parameter for each forcing dataset, and to identify the controlling and redundant parameters and processes. The results suggest that equifinality of parameter sets in calibration to field data must be expected, that there will be a consequent uncertainty in predictive capability and that more emphasis will be required on identifying the critical controls on evapotranspiration in extending predictions from patch to landscape scale in different environments. © 1997 Elsevier Science B.V.

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1. Introduction

Recent research on improving the representation of land surface–atmosphere interactions within general circulation models (GCMs) has led to the investigation of a wide variety of different soil–vegetation–atmosphere transfer (SVAT) schemes (Henderson-Sellers et al., 1993). These SVAT schemes range in complexity from a simple bucket model as used by Manabe (1969), to vertically complex models, such as BATS (Dickinson et al., 1986), and SiB (Sellers et al., 1986). Current active areas of research include developing more realistic SVAT models by the incorporation of sub-grid scale heterogeneity (Famiglietti and Wood, 1994; Liang et al., 1994),

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and by improving the representation of plant physiological processes (e.g. Wang and Jarvis, 1990). The incorporation of these additional processes further increases the complexity and number of parameters of SVAT models.

This would not be such a problem if the model parameters could be measured independently at some reasonable 'patch' or greater scale, but this is generally not the case. Measured parameter values often require the assumption of some simplified theory or model structure for their determination. Thus, an important question should be raised at this point; how much complexity in a SVAT model can be supported by the available data? There is no complete answer to such a question but what follows is intended as contribution to the discussion.

SVAT models have the primary aim of providing estimates of latent and sensible heat fluxes between the land surface and atmosphere. Accurate measurements of these quantities have improved in recent years but remain local, often of limited duration in short field campaigns, and subject to errors. Where parameter values of a SVAT scheme (such as a surface resistance) are back-calculated from such measurements, the 'measured' values and model predictions will be subject to significant uncertainty. In more complex schemes there is the possibility of over-parameterisation and consequent equifinality of parameter sets in the predictions (see Beven, 1989, 1993). Equifinality is used here in the sense that the same end (i.e. simulating the evaporative flux record) may be achieved equally well by a number of models or parameter sets, all of which may be physically reasonable. There may be no clear single optimum parameter set, and consequently it may be difficult to achieve a robust calibration (see also Duan et al., 1992; Gupta and Sorooshian, 1994; Spear et al., 1994).

The problems associated with SVAT models are particularly interesting in this respect. SVAT model parameters are calibrated on the basis of small 'patch' scale experiments. The application of SVAT models as the land surface component of atmospheric circulation models, however, requires that the SVAT parameterisations be applied at much larger grid scales, those characteristic of the grid elements of global and mesoscale models. Because of continuing computational constraints the grid elements are, generally, still treated as homogeneous patches but without any theory of how the parameter values at the local scale relate to 'effective' parameter values required at the macroscale. In this paper it will be shown that there is likely to be significant uncertainty associated with effective parameter values even at the local patch scale. Heterogeneity at the grid scale will only increase the uncertainty in predicted land surface–atmosphere fluxes. The problems of identifiability of parameters will generally increase with increasing complexity of the model. Complexity is needed to reflect the changing response of the surface to different meteorological conditions, stage of vegetation development and moisture availability. Simplicity is required for robust calibration.

The purpose of this paper is to demonstrate the utility of simpler, rather than more complex, SVAT constructs by investigating the range of output predictions resulting from different parameter sets. Monte Carlo analysis is used to illustrate the equifinality arising in calibrating a simple SVAT scheme, and a sensitivity analysis is performed to identify the relative importance of parameters and the processes they represent.

2. Model description

This section describes a simple patch scale SVAT model, TOPUP, first used by Beven and Quinn (1994). The purpose of this model is to simulate evaporative fluxes between the land surface and atmosphere. The form of this model is similar to a simple bucket type SVAT model, commonly used within GCMs, except that the lateral (downslope) redistribution of water is incorporated within the model structure. The aim has been to provide sufficient functionality in the model to reproduce the main controls on evapotranspiration, while minimising the number of parameters to be identified. The calculation of evapotranspiration is based upon the Penman–Monteith equation (Monteith, 1981), whereby the evapotranspiration flux is governed by resistance terms:

$$\lambda E = \frac{\Delta R_n + (\rho C_p \delta q)/r_a}{\Delta + \gamma[1 + (r_s/r_a)]} \tag{1}$$

where λE is latent heat flux ($W m^{-2}$), R_n is net radiation ($W m^{-2}$), C_p is specific heat of air ($J kg^{-1} K^{-1}$), r_a is aerodynamic resistance ($s m^{-1}$), r_s is surface resistance ($s m^{-1}$), γ is pyschrometric constant ($kg kg^{-1} K^{-1}$), ρ is density of dry air ($kg m^{-3}$), δq is specific humidity deficit ($kg kg^{-1}$) and Δ is rate of change of saturated specific humidity with temperature ($kg kg^{-1} K^{-1}$).

Although this model has been widely used, clearly the accuracy of its predictions will be constrained by the simplifying assumptions that underlie it (such as the big leaf approximation and the elimination of the surface temperature). However, in operation, given meteorological forcing data at a site and physical constants, the solution of this equation relies on the correct specification of 'effective' values of the resistance terms, r_a and r_s.

3. Calculation of aerodynamic resistance

To calculate the aerodynamic resistance, r_a, an empirical relationship that permits the effects of near-surface instability, and the different source and sink heights of water vapour and momentum, was employed in the model (Verma, 1989; Wright et al., 1992:

$$r_a = \frac{u_z}{u_*^2} + \frac{1}{\kappa u_*}\left[\ln\left(\frac{z_0}{z_h}\right) + \psi_m - \psi_h\right] \quad (2)$$

where

$$u_* = \frac{u_z \kappa}{\ln[(z-d)/z_0] - \psi_m} \quad (3)$$

z is measurement height of windspeed (m), d is zero plane displacement (m), z_0 is roughness length for momentum flux (m), z_h is roughness length for heat flux (m), κ is von Kármán's constant (taken as 0.41), u_z is windspeed at height z ($m s^{-1}$) and u_* is an index of the rate of rotation of the frictionally driven eddies in the airflow above the surface (Thom, 1975). The calculation of the stability correction factors, ψ_m and ψ_h (Paulson, 1970), is achieved after the calculation of the Monin–Obukov stability length, a dimensionless stability variable (Monin and Obukov, 1954). However, this requires the specification of u_*, and as the calculation of u_* requires a stability corrected profile, a simple iterative solution is employed.

As the aerodynamic resistance may be calculated from the meteorological conditions, the solution of the Penman–Monteith equation relies upon the correct conceptualisation and parameterisation of the surface resistance term, r_s. As the surface resistance is very much dependent upon the moisture available to the plant (Monteith, 1995), accurate estimation of evapotranspiration rates will depend on the representation of the subsurface hydrological processes which, even in the most complex multi-layered SVAT parameterisations, is generally greatly simplified.

4. Representation of subsurface hydrological processes

The model developed here represents the dominant hydrological processes that affect evapotranspiration as simply as deemed possible, while retaining a physically reasonable conceptual basis. The use of multiple layer solutions for flow and heat transport, as used for example in SiB (Sellers et al., 1986), has been avoided because of the additional number of parameters required and the expected heterogeneity of those parameters in space. Thus water availability is controlled primarily by a single conceptual root zone storage element. The difference between this and other 'bucket' models is the addition of a component to represent lateral (downslope) fluxes of water in a simple way. This is included because within many landscapes lateral redistribution of water may be an important means of maintaining the water supply to roots, leading to significant spatial heterogeneity of evapotranspiration rates.

The TOPUP model (Beven and Quinn, 1994) consists of three sources from which moisture is available for evapotranspiration (see Fig. 1): (1) a canopy–topsoil interception store (with capacity MAXINT), which as well as representing the canopy interception store, can also serve to mimic the recovery of evapotranspiration in a dry soil following rainfall; (2) a root zone store (with capacity SRMAX); (3) a variable water table. Given a rainfall event, the rainfall will first be routed to the interception store. When this store is full, moisture will overflow to fill the root zone. When the capacity of the root zone (SRMAX) is exceeded, the excess moisture is then routed to the water table with a time

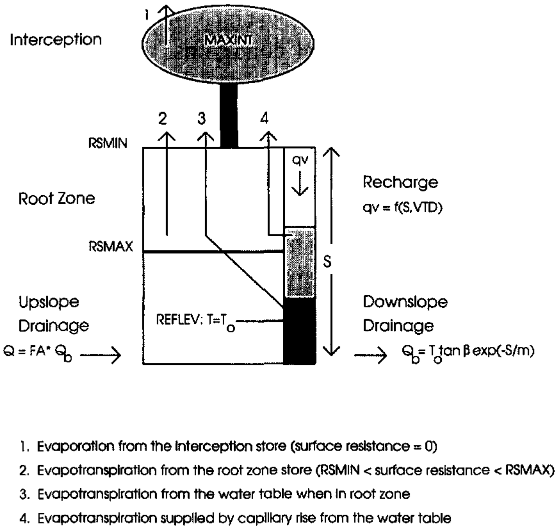

Fig. 1. Schematic diagram of TOPUP model.

delay parameter, VTD. Conversion of root zone storage to a depth depends on the root zone effective storage parameter, DTH2.

The lateral subsurface flow component of the model is based on a similar set of assumptions to those used by TOPMODEL (Beven and Kirkby, 1979; Quinn and Beven, 1993; Beven et al., 1995) in which downslope fluxes are assumed to be in equilibrium with a recharge rate calculated from total hillslope discharge averaged over some area, lateral transmissivity is assumed to be an exponential function of subsurface storage, and the downslope hydraulic gradient is assumed equal to the surface slope. With these assumptions, the outflow per unit contour length is given by

$$Q_\mathrm{b} = T_0 \tan\beta \mathrm{e}^{-S/m} \tag{4}$$

where $\tan\beta$ is the hydraulic gradient (assumed a constant for the given patch area), T_0 is the transmissivity of the soil when the water table is at a level given by the parameter REFLEV, S is a storage deficit owing to drainage of the water table below that level, and m is a scaling parameter for transmissivity. Within this model structure, T_0 and $\tan\beta$ occur as a product so they may be considered as a single parameter, thereby further reducing the number of parameters to be considered. The TOPMODEL theory, where the exponential transmissivity function is often accepted as an adequate approximation, allows the m parameter to be related to the discharge recession characteristics of a catchment area. The introduction of the reference level parameter REFLEV, the depth at which $T = T_0$, allows the treatment of deeper water tables than with the normal version of TOPMODEL where the reference level is taken to be the soil surface (see Quinn et al., 1991). Conversion of storage deficit to water table depth depends on the effective gravity drainage storage parameter DTH1.

Keeping the same assumption that subsurface flow upslope of the patch is always in a quasi-steady equilibrium with the current drainage, lateral discharge can be calculated as

$$Q_\mathrm{in} = Q_\mathrm{b} F_\mathrm{A} \tag{5}$$

where F_A is the ratio of the area per unit contour length draining into the patch to that draining out of the patch. It should be noted that the use of a constant for F_A means that the model does not account for any temporal variability of the effective upslope contributing area or any spatial variability in recharge rates, but does allow a simple representation of the effect of upslope flow in maintaining a water supply to the patch.

5. Calculation of surface resistance

The surface resistance is calculated for each time step according to the moisture content of the stores; the model conceptualisation accounts for evaporation from the interception store, and evapotranspiration from the vegetation and soil surface. As relatively short periods of data are being simulated here, no explicit account has been taken of plant phenology and physiology at this stage, so as to simplify the parameterisation.

When the interception–topsoil store is full to its capacity, the surface resistance is set at $0\,\mathrm{s\,m^{-1}}$. As this storage is decreased, the surface resistance is linearly increased up to a value RSMIN (which is the model parameter for surface resistance of a dry canopy not limited by water supply) to take some account of the gradual drying of the canopy.

When no moisture is present in the interception store, the surface resistance is calculated from the moisture available to the vegetation for evapotranspiration following a linear relationship. The available moisture is calculated from the moisture in the root zone, from capillary rise through the unsaturated zone (using the formula of Eagleson (1978), after conversion of storage deficit to a water depth using a constant effective storage coefficient DTH1), and from a possible intersection of the root zone by the water table. The calculated capillary rise depends on the current depth of the water table within the patch and a soil type for the matrix properties. Four soil types have been considered here, spanning the range from clay to sand, with the parameters taken directly from Eagleson (1978). The surface resistance is increased linearly as the available moisture decreases to a value of RSMAX (the maximum surface resistance) which will depend on the vegetation type.

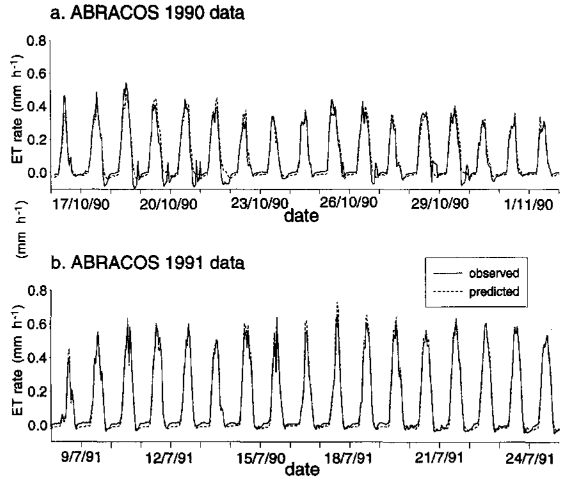

Fig. 3. Measured evapotranspiration data and sample TOPUP prediction run for (a) 1990 and (b) 1991 Amazonian data.

6. Meteorological data

Data sets from two sites were used in this study. Two periods for each of the sites were available. IFC-3 (6–21 August 1987) and IFC-4 (5–16 October 1987) from the First International Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) were employed. The FIFE campaign was conducted over an area of 225 km^2 in Kansas, USA. The data used in this analysis are taken from five meteorological stations in the region of the King's Creek catchment (Famiglietti and Wood, 1994). Meteorological forcing data consist of wet and dry bulb temperatures, net radiation, windspeed and rainfall. Evapotranspiration fluxes were measured by a combination of eddy correlation and Bowen ratio techniques at the five sites (see Fig. 2). We have followed Famiglietti and Wood (1994) in spatially averaging the data sets. IFC-3 contains a storm event, whereas IFC-4 was a particularly dry period when the tall grass vegetation canopy was reaching senescence. The flux behaviour of the site is therefore markedly different for the two periods. Early work with the IFC-4 data set suggested that predictions following the small rainstorm in the last part of the data set were always poor (see also Famiglietti and Wood (1994)); calibration of the model was therefore only carried out for the first 440 half-hourly time steps.

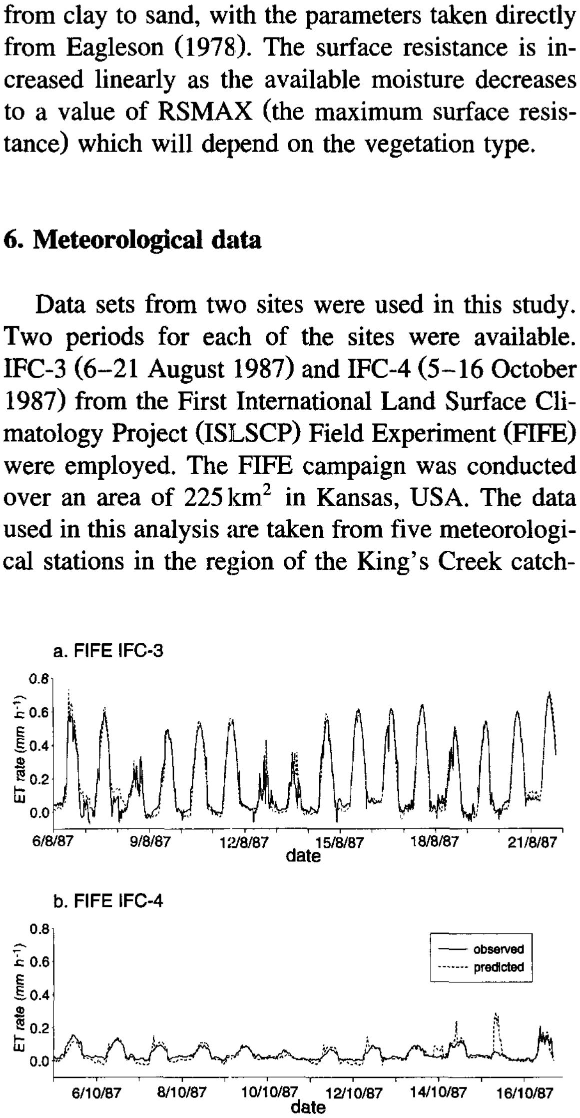

Fig. 2. Measured evapotranspiration data and sample TOPUP prediction run for (a) FIFE IFC-3 and (b) FIFE IFC-4.

Meteorological forcing data and evapotranspiration measurements were also employed for an Amazonian, post-deforestation pasture site at Fazenda Dimona, central Amazonia, collected as part of the ABRACOS UK–Brazilian collaboration (Shuttleworth et al., 1991). Two data sets were available, for 16 October–2 November 1990 and 29 June–10 September 1991. Details of the instrumentation employed at the site have been given by Wright et al. (1992). As the 1991 study period was significantly wetter than that in 1990, again, it is hoped that a representative sample of the variable behaviour of the study site is incorporated. Evapotranspiration fluxes were measured using eddy correlation and Bowen ratio techniques for the two periods. The measured fluxes are illustrated in Fig. 3 along with sample modelled runs.

7. Model parameters

By representing the basic processes that govern evapotranspiration as simply as deemed possible, the resultant model requires significantly fewer parameters than most contemporary SVATS, and it includes the novel feature of the contribution of water to the patch from upslope. The parameters are summarised in Table 1. It should be noted that the SOIL parameter, in permitting the soil parameters to be varied to represent four distinct soil types, fixes three hidden parameters. It will be shown that the TOPUP model structure has more than enough degrees of freedom to fit an observed time series of evapotranspiration data, and, although simple, should be considered as overparameterised in a systems simulation sense. Clearly, other more complex models will be worse in this respect.

8. Initialisation of model stores

The model requires initialisation of the interception storage, the root zone storage and the depth to the water table at the start of each simulation period. The interception store has been always set to be empty at the start of a period, the initial root zone storage (SRO) becomes a parameter of the model, and the initial water table depth depends upon the values of the TTANB and REFLEV parameters together with an initial subsurface discharge which has been fixed for each simulation.

9. Monte Carlo sensitivity analysis procedure

To investigate the sensitivity of the TOPUP model parameters, a Monte Carlo framework is used. To represent the uncertainty of parameter estimates or measurements, a range of physically realistic values was assigned to each parameter (see Table 1). The specification of each range is subjective but might be achieved with some justification through physical

Table 1
Parameters of the TOPUP model

		Parameter range
Varied parameters		
F_A	fractional upslope area	0.1–1.0
TTANB	product of saturated transmissivity and hydraulic gradient (m^2 h)	0.0005–0.0400
m	transmissivity profile and recession curve parameter (m)	0.005–0.050
RSMIN	minimum surface resistance (s m^{-1})	50–150
RSMAX	maximum surface resistance (s m^{-1})	300–1000
SRMAX	root zone storage (m)	0.020–0.200
SR0	initial fractional root zone store	0.01–1.00
MAXINT	interception store (m)	0.0005–0.0050
VTD	vertical time delay through unsaturated zone (h m^{-1})	0.05–50.0
z_0	roughness length for momentum flux (m)	0.02–0.12
d	zero displacement height (m)	0.15–0.35
DTH1	gravity drainage effective storage coefficient	0.05–0.15
DTH2	root zone effective storage coefficient	0.05–0.40
$\ln(z_0/z_h)$	log of the ratio of roughness lengths for momentum and heat flux	1.0–3.0
REFLEV	reference level for soil transmissivity (m)	0.01–1.00 (FIFE data) 8.0–15.0 (Amazon data)
SOIL	soil type for capillary rise (matrix properties taken from Eagleson (1978))	
Hidden parameters for each SOIL type		
$\Psi(1)$	saturated soil matrix potential (m)	
KZERO	saturated effective hydraulic conductivity (m s^{-1})	
mc	index of pore size distribution and disconnectiveness (Eagleson, 1978)	

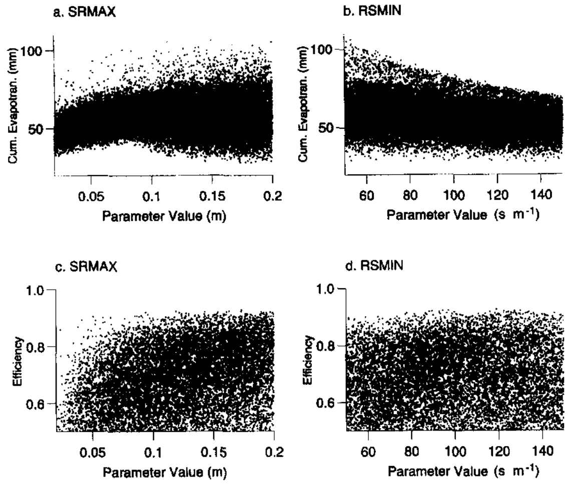

Fig. 4. (a,b) Scatter plots showing the range of cumulative evapotranspiration totals produced across two model parameter ranges, the root zone storage (SRMAX) and the minimum surface resistance (RSMIN), respectively, when forced with the FIFE IFC-3 data set. (c,d) Same as for (a,b) but with respect to the model efficiency.

argument or experience. All possible parameterisations of the area are used to set these ranges. In addition to varying all model parameters simultaneously, the initial fractional moisture content of the root zone, SR0, was varied between unity and zero. For each period of the meteorological forcing data, 20000 random sets of the parameters were generated from uniform distributions across the specified ranges and the model was run for each parameter set. No account was taken of possible covariation between the parameter values in these prior choices of parameter sets. This could be done but prior knowledge of such covariation will generally be lacking.

Fig. 4(a) and Fig. 4(b) show the range of cumulative evapotranspiration totals across the parameter ranges for two of the model parameters, for the IFC-3 dataset. Fig. 4(c) and Fig. 4(d) demonstrate the range of modelling efficiencies produced for the same data set. The efficiency measure employed here is the proportion of variance explained, as by used Nash and Sutcliffe (1970) and defined as

$$\text{Efficiency} = \frac{\sum_{i=1}^{N}(x_i - \bar{x})^2 - \sum_{i=1}^{N}(\hat{x}_i - x_i)^2}{\sum_{i=1}^{N}(x_i - \bar{x})^2} \quad (6)$$

where N is the total number of time steps, $\bar{x}$ is the mean of the measured evapotranspiration, and, x_i and $\hat{x}_i$ are the measured and predicted evapotranspiration at time step, i, respectively.

From Fig. 4, it can be seen that reasonably large ranges of cumulative evapotranspiration and efficiencies are achieved. What is perhaps more important to note is that high efficiencies are produced in all areas of the parameter ranges. The same behaviour is found for those parameters that have not been plotted here. Also, predictions of cumulative evapotranspiration can be seen to range over at least a factor of two across the parameter ranges. This indicates that the individual parameter values are less important in the specification of model behaviour than the parameter set taken as a whole.

The sensitivity of the TOPUP SVAT model may be illustrated by comparing cumulative distributions for discrete performance classes defined in terms of cumulative evapotranspiration, or efficiency. The method employed here is a variant of the Generalised Sensitivity Analysis of Spear and Hornberger (1980). The 20000 realisations were ranked according to the cumulative flux totals or the efficiency measure. Ten performance classes where then created by dividing the realisations into groups of 2000. Cumulative distributions of parameter values of each performance class were then plotted for each parameter. A straight line would represent a uniform distribution of the parameter, reflecting insensitivity for the performance range, whereas a marked departure from the straight line would represent a non-uniform distribution, indicating sensitivity of the parameter.

10. The sensitivity of the parameters with respect to evapotranspiration totals

The sensitivity of two of the model parameters with respect to the cumulative evapotranspiration totals forced with the Amazon 1991 data set is shown in Fig. 5(a) and Fig. 5(b), and for the IFC-3 data set in Fig. 5(c) and Fig. 5(d). Set 1 corresponds to the subset of the lowest cumulative evapotranspiration totals, and Set 10 to the highest. The sensitivities to the parameters are consistent between the data sets in the sense that any bias towards one end of the parameter range for the performance ranges is also shown in the sensitivity plots of the other data set. The parameter sensitivities do vary slightly between each data set in terms of the degree of the sensitivity; however, their relative sensitivities remain consistent. This was found to be the case for all parameters, except SR0 and MAXINT (see discussion below), indicating that the relative importance of each parameter is insensitive to the climatic forcing, at least under the conditions considered here.

Fig. 5(e) and Fig. 5(f) show the sensitivity of the REFLEV parameter when forced with the IFC-3 and IFC-4 data sets. From these plots, it can be seen that the inclusion of a dynamic water table can contribute significantly to the total evapotranspiration of an area; the highest evapotranspiration subsets contain a bias towards lower values of the parameter indicating a shallow water table control. Under certain circumstances, the water table can significantly affect the moisture content available to the vegetation for transpiration, either through an intersection with the root zone, or through significant capillary rise owing to the close proximity of a water table. The inclusion of a mechanism permitting lateral redistribution of moisture should therefore be deemed a necessity in some environments for SVAT schemes aiming to reproduce the heterogeneity of surface fluxes at the landscape scale.

Following this sensitivity analysis, the parameters may be 'ranked' in terms of importance. The less important parameters may be essentially redundant at least for these meteorological forcing data sets. If the quality of the forcing data is good, i.e. if the available data incorporate much of the behaviour produced by the patch, then the insensitive parameters would not significantly affect the model predictions. One of the parameters showing little sensitivity is the vertical routing time delay VTD (Fig. 5(g) and Fig.

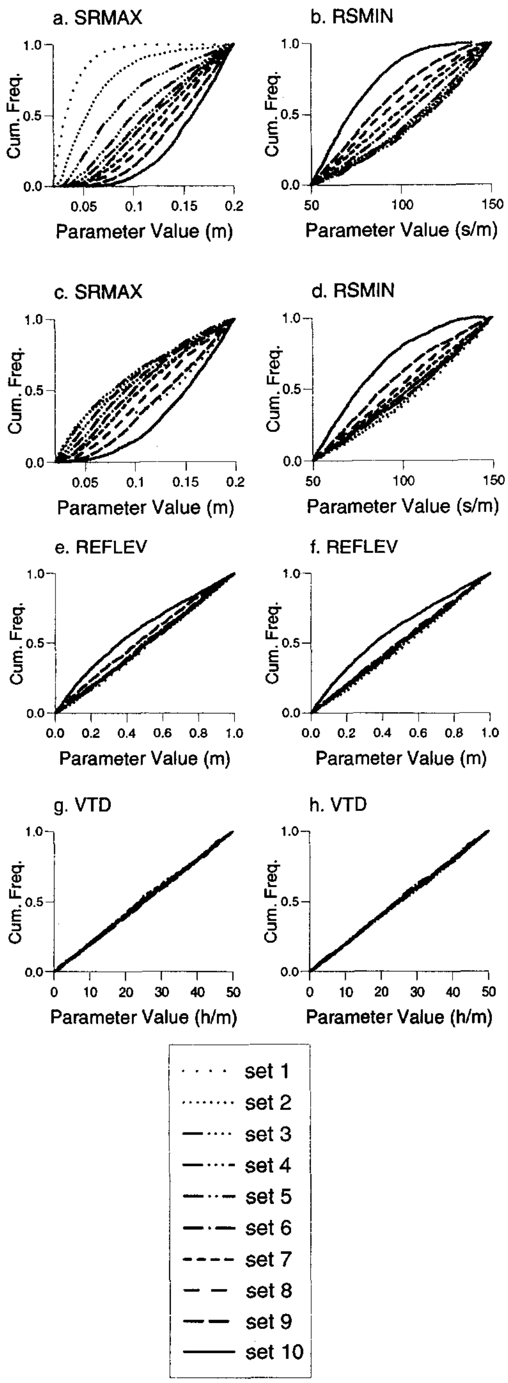

Fig. 5. Plots of sensitivity of performance class to model parameters—Set 1 is the lowest performance class, Set 10 is the highest. (a,b) The root zone storage (SRMAX) and the minimum surface resistance (RSMIN) in terms of the cumulative evapotranspiration when driven with the Amazon 1991 data set. (c,d) The root zone storage (SRMAX) and the minimum surface resistance (RSMIN) in terms of the cumulative evapotranspiration when driven with the FIFE IFC-3 data set. (e,f) The reference level for soil transmissivity (REFLEV) with respect to the cumulative evapotranspiration when forced with the FIFE IFC-3 data set, and FIFE IFC-4 data set, respectively. (g,h) The vertical time delay through the unsaturated zone (VTD) for the FIFE IFC-3 data set in terms of cumulative evapotranspiration and efficiency, respectively.

5(h)). This has very little effect on either cumulative evapotranspiration or model efficiency for these conditions. It can be inferred that these parameters could be eliminated from the model or simply be given a 'typical' value from within their prescribed range, and the ensuing model fits will not be compromised.

The sensitivity analysis outlined above may therefore give insights into the behaviour of SVAT models; the sensitivity of the parameters with respect to the cumulative evapotranspiration totals indicates the relative importance of each of the parameters. The relative sensitivities of the parameters are ordered below, the most sensitive first:

SR0—the initial root zone storage. This was found to be the most sensitive parameter for the shorter FIFE data sets and had a significant effect for the relatively dry Amazon 1990 data set. However, for the longer, wetter Amazon 1991 data set, the initial root zone storage becomes rather insensitive as a result of the more frequent rewetting of the root zone by rainfall.

SRMAX—this parameter was found to be highly dominant in defining the behaviour of the model in terms of the cumulative totals. This represents the capacity of the moisture store in the root zone. As would be expected, low values of SRMAX are associated with low evapotranspiration totals and vice versa (as in Fig. 5(a) and Fig. 5(c)).

RSMIN—the minimum surface resistance. This displays some sensitivity for all subsets. As one would expect, lower values are associated with higher flux totals, and vice versa.

RSMAX—the maximum surface resistance. This shows less sensitivity than RSMIN, but for the lower evapotranspiration subsets, there is bias towards the higher values of the parameter range.

MAXINT—the maximum interception store. The sensitivity to this parameter, like the initial root zone store, was found to be a function of the meteorological records of the forcing data sets. Specifically, the sensitivity was found to vary as a function of the rainfall record. For the IFC-4 and Amazonian 1990 data sets, which were both relatively dry, output is largely insensitive to MAXINT, as the operation of the interception store is not forced during these periods. For the IFC-3 and Amazonian 1991 data sets where significant rainfall events were recorded, there is a noticeable bias in the lower evapotranspiration subsets to the lower end of the parameter range, though the higher subsets show no significant sensitivity.

REFLEV—the control depth of the water table. Cumulative evapotranspiration was fairly insensitive to REFLEV for most of the evapotranspiration range. However, as the higher totals are approached the parameter distributions become biased towards the lower end of the parameter range, which will tend to increase the supply of water for evapotranspiration from the water table by capillary rise.

F_A—the fractional contributing area recharging the patch. Model output was insensitive to this parameter, except for the top subset, which proved to be biased towards the higher parameter values—this will help to maintain the water table during dry periods and consequently increase the cumulative evapotranspiration flux.

TTANB—the transmissivity–slope parameter. This parameter, like F_A, controls the drainage from the patch. Output was insensitive to TTANB, except for the highest subsets being slightly sensitive to the lower values.

m—the transmissivity profile and recession curve parameter. This showed a slight bias toward the lower values for the highest cumulative totals for the FIFE data sets, but model output for the Amazonian data sets was insensitive to this parameter.

DTH1 and DTH2—the effective storage coefficient parameters. These, like the m parameter, produced slight sensitivity when the model was run with the FIFE data sets, and insensitivity for the Amazonian data sets.

z_0, $\ln(z_0/z_h)$, d and VTD—model output proved to be insensitive to these parameters, indicating redundancy of the parameters with respect to influencing the cumulative total evapotranspiration.

11. The sensitivity of the parameters with respect to the efficiency of simulated records

Fig. 6(a) and Fig. 6(b) show the sensitivity of the parameter RSMAX with respect to the efficiency measure, when using the Amazon 1990 and 1991 meteorological forcing data sets. From the plots, it can be seen that the pattern of sensitivity of this parameter is similar for both data sets. This was found to be the case for all of the parameters when forced with the Amazonian data sets, even though the longer 1991 data set is for a much wetter period (and yields a higher number of good model fits) than the 1990 data set.

Fig. 6(c) and Fig. 6(d) show the sensitivity of the parameter RSMAX when driven using the FIFE IFC-3 and IFC-4 data sets, respectively. Although these plots demonstrate a near-equivalent degree of sensitivity of the parameter between data sets, it can be seen that the sensitivity of RSMAX differs for IFC-3 and IFC-4. When using the IFC-3 meteorological forcing data, it can be seen that greater efficiencies are biased toward the lower end of the parameter range for the parameter RSMAX. The opposite is observed when using the IFC-4 data. A similar contrast was observed for the parameter SRMAX. This indicates that, for IFC-4, higher values of RSMAX, and hence higher surface resistances, are required to achieve the better efficiencies. This indicates that a single parameterisation of this area would not yield consistently good fits to the short data periods of the intensive field campaigns.

There are several possible reasons for this. The IFC-4 data set corresponds to a very dry period. Evapotranspiration was therefore very much soil–plant controlled. Soil moisture became so limited that senescence of the vegetation was observed in the field (Famiglietti and Wood, 1994). The TOPUP model as used here does not contain any dynamic description of plant phenology (which would necessarily add further parameters), nor does it explicitly partition evapotranspiration from plants or the soil surface. It is clear that in the case where plants die, evaporation from the soil surface will become more important in terms of total flux, although the mulching effect of the senescent vegetation may exert a significant control on evaporation from the soil surface, intercepting radiation and sheltering the surface from the drying wind. As this model describes evapotranspiration using a lumped surface resistance, this change in the relative importance of flux sources is not described by the model, but is revealed by the change in sensitivities.

The sensitivity of the parameters when compared with the observed records of evapotranspiration through the efficiency measure, gives insight into the acceptability of the model structure. For both Amazonian data sets it was found that the best efficiencies were produced with similar distributions within each of the parameter ranges, indicating a degree of 'stationarity' in the processes affecting evapotranspi-

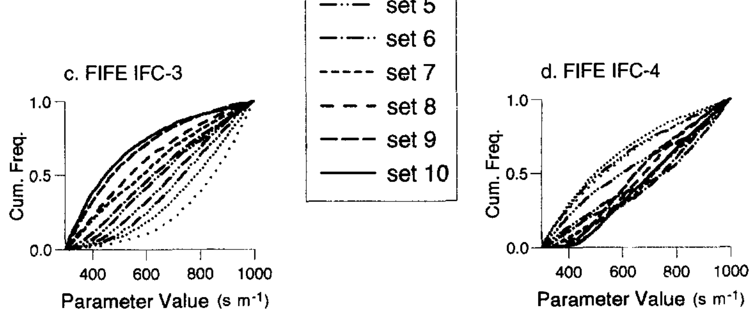

Fig. 6. Sensitivity plots of the maximum surface resistance (RSMAX) with respect to the efficiency measure, driven with various data sets: (a) Amazon 1990; (b) Amazon 1991; (c) FIFE IFC-3; (d) FIFE IFC-4. Set 1 represents the lowest performance class, Set 10 is the highest.

ration. This was not found to be the case for the FIFE data sets, when a variation in the values of parameters giving good fits to the two periods suggests that there may be significant time variability in the controlling processes. In particular, senescence of the vegetation leads to observed evapotranspiration fluxes being much less than those predicted after the small 9 mm rainstorm at the end of the IFC-4 period.

12. Discussion

Current SVAT schemes, by attempting to represent a multitude of physical (and in some cases physiological and chemical) processes, are grossly over-parameterised in a systems identification sense, with the result that a robust calibration is unlikely to be achieved based upon the available observations of latent and sensible heat fluxes alone, even at the local scale. This results in the equifinality of different parameter sets revealed by the Monte Carlo sensitivity analysis of the relatively simple TOPUP model. Good model efficiencies (proportion of explained variance greater than 0.90) were achieved across the ranges of parameters considered for both sites when modelling the wetter periods (IFC-3 and the Amazonian 1991 data). Explained variances of greater than 0.85 and 0.75 were also produced across each of the parameter ranges for the 1990 Amazonian data and IFC-4, respectively. The potential importance of water supplied by a water table, which may be fed by lateral downslope inputs, has also been revealed by the analysis, although the initial water table level was shown to be more important at these sites (and short measurement periods) than the F_A and TTANB parameters.

The implication of this work is that the robustness of SVAT schemes in calibration would be improved by reducing the dimensionality of the parameterisation, either by fixing relatively insensitive parameters or by removing some of the complexity of SVAT constructs. This goes against the current trend towards making SVAT schemes more complex by inclusion of more processes and controlling variables (although see Monteith (1995) for a valuable counter-example in this respect). The argument for increased complexity is usually made on the basis that the inclusion of improved understanding of controlling mechanisms should both improve predictive capability and make the parameter values more easily estimated on the basis of physiological characteristics or measurement. The evidence presented here undermines the notion that parameter values may be physically meaningful if they are in any way calibrated against observations, as parameters giving good fits to the observations will be conditional on the values of the other parameters, whatever the model structure. It also raises doubts that calibrated parameter values can be considered to be meaningful outside of the model structure in which they have been calibrated.

For the TOPUP model, the analysis revealed that SRMAX (the available water capacity of the root zone), RSMIN (the dry canopy surface resistance without water limitation), RSMAX (the maximum surface resistance), and REFLEV (which controls depths to the water table), are the dominant parameters controlling the model behaviour in this simple SVAT scheme at the two sites considered. The limitations of the model in not properly representing the temporal change in the nature of the vegetation at the FIFE site were also revealed by changes in the parameter distributions conditioned on the model efficiency. It should, perhaps, be expected that different minimal model structures might be appropriate for different vegetation types or different environments.

However, it would appear that the problem of equifinality may be endemic to SVAT type models for land surface fluxes. This implies that there may be significant uncertainty apparent in the predictions of the many different parameter sets that are compatible with the observed data. This suggests that ways should be sought of constraining that uncertainty by making additional measurements. To some extent, this may be achieved by having longer periods of data available for calibration that include a wider range of conditions for testing any SVAT model. This is unlikely, however, to provide a sufficient constraint to preclude the type of behaviour revealed in this study. Another way of proceeding in this respect may be to look for ways to exclude parameter sets, currently considered acceptable, by the collection of additional data of different types (such as water table levels, or refining the range of SRMAX by seasonal soil moisture measurements).

Measurements of this type will be easiest to implement at the scale of the individual patch. This study has not addressed the additional problem of the representation of the heterogeneity of fluxes of latent and sensible heat at the landscape scale. This problem is of increasing interest (see studies by Avissar and Pielke (1989), Dolman (1992) and Quinn et al. (1995), amongst others). If one considers only two areas within a landscape—one that is supplied continuously with water by lateral flow and one that is subject to limitations on evapotranspiration rates owing to lack of available water—then this would suggest that estimating the average landscape flux over time with a single set of effective parameters will lead to a poor prediction, no matter how complex the SVAT formulation used (see, e.g. Becker, 1995). Thus, if the ultimate aim is the prediction of landscape (or grid element) scale fluxes, it may be more useful to have simpler models that reflect any strong heterogeneity than complex models that treat the surface as homogeneous. Much remains to be learned about what constitutes an appropriate and robust SVAT parameterisation in different circumstances, but it is clear that their predictions must be expected to be subject to significant uncertainty.

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