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The accuracy of simple soil water models in climate forecasting

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Abstract

Several simple soil water models with four layers or less, typical of those used in GCMs, are compared to a complex multilayered model. They are tested by applying a repeating wetting/drying cycle at different frequencies, and run to equilibrium. The ability of the simple soil models to reproduce the results of the multilayer model vary according to the frequency of the forcing cycle, the soil type, the number of layers and the depth of the top layer of the model. The best overall performance was from the four layer model. The two layer model with a thin top layer (0.1 m) modelled sandy soils well while the two layer model with a thick top layer (0.5 m) modelled clay soils well. The model with just one layer overestimated evaporation during long drying periods for all soil types.

Introduction

General Circulation Models (GCMs) are used for weather forecasts and climate predictions. At their bottom boundary, they use a SVAT (Surface Vegetation Atmosphere Transfer) scheme which represents the effect of vegetation and soil processes on the atmosphere. There is mounting evidence that the modelling of soil moisture is important to the weather and climate predictions (e.g. Beljaars *et al.*, 1996). However, the models in present use are not consistent with each other: Shao and Henderson-Sellers (1996) reported on several GCM soil models run to equilibrium with the same forcing data where the simulations predicted cumulative evaporation ranging from 20 to 80 percent of the applied rainfall. Perhaps the cause of this lack of agreement between the soil models is the paucity of data with which to test and calibrate the models over long periods and under different climatic regimes. In the absence of such data, there is a need for another way to check the performance of soil models to be used in GCMs.

In this paper, a method is developed whereby the performance of simple soil models for use in climate prediction can be assessed. To avoid dependence on initial conditions, the models are forced with a repeating cycle of meteorological conditions until they reach equilibrium. Three different climate types are imposed, each with the same total rainfall and evaporative demand but with different wetting/drying frequencies (weekly, monthly, three monthly). The performance of the simple soil models is assessed in terms of their ability to partition correctly the total rainfall into evaporation and drainage as compared to a fine layered model, considered to be the 'truth' in this context.

Many GCM SVATs (BATS (Dickinson *et al.*, 1992), BEST (Pitman *et al.*, 1991), CLASS (Verseghy, 1991), MOSES (Cox *et al.*, 1997), SSiB (Xue *et al.*, 1991)) use the Darcy equations to describe the vertical flow of water in the soil. These equations are the most general representation of the physical process of water flow through a uniform soil. However, they are highly non-linear and it is generally thought that a fine vertical layering is required for an accurate numerical solution. There are several reasons why a finely layered model is impractical for a GCM; knowledge of the soil properties and the root distributions in such detail is not available over the globe and in addition, the great computational expense of making climate predictions results in the soil models in GCMs being, at present, limited to a maximum of about 4 layers (Garratt, 1993), with a top soil layer depth of between 0.01 to 0.1 m. The use of a relatively coarse grid to solve the Darcy equations can introduce numerical errors. It is these errors that are studied in this paper by comparing the predictions of several simple soil models with those from a fine layered model.This paper is not intended to represent a real climate and a real surface. Rather the paper introduces a method for studying general surface models and in particular the soil hydraulic part of surface models for use in general climate models.

Only bare soil evaporation has been simulated, so that the hydraulic performance of the model is tested without the analysis being complicated by the extraction of water by roots. Examples of a sand, a loam and a clay are used as soil types.

The fine layered model used was SWEAT (Daamen and Simmonds, 1996) while the GCM soil model used as a basis for this study was taken from MOSES. However, several different versions of the model were run to test the sensitivity of the results to three aspects of the model. These are, firstly, the top boundary condition, secondly the formulation of the finite difference scheme and thirdly the thickness and number of the layers.

The multi-layered model

The multi-layered model used in this paper is the SWEAT model (Daamen and Simmonds, 1994; Daamen and Simmonds, 1996) which follows the approach of Philip and De Vries (1957) as described by Campbell (1985). A multi-layer, Philip and de Vries (1957) type model has been used with success in many different environments and the SWEAT formulation is representative of the best of the soil water models in use at present. The SWEAT model was used here with 24 layers, ranging in thickness from 1 mm at the top to 400 mm at a depth of 2.0 m. In the model, liquid water flows in response to matric and gravitational potential gradients, and water vapour flows in response to temperature and humidity gradients. The equations for these fluxes are given below. The model also solves for heat transfer within the soil, but the equations and results of this are not included.

$$Q_l = -K\frac{d}{dz}(\psi + gz) \quad (1)$$

$$Q_v = -D_v e^*\frac{dh}{dz} - D_v h\eta\frac{de^*}{dT}\frac{dT}{dz} \quad (2)$$

The Clapp and Hornberger (1978) equations are used to describe the dependence of the hydraulic conductivity and matric potential on the water content of the soil.

$$\psi = \psi_s\left(\frac{\theta}{\theta_s}\right)^{-b} \quad (3)$$

$$K = K_s\left(\frac{\theta}{\theta_s}\right)^{(3+2b)} \quad (4)$$

The top boundary condition is the evaporation from the soil surface, which is determined by the energy balance (Eqns (5) to (7)). The bottom boundary condition is drainage under a gradient in gravitational potential alone.

The equations for the energy balance are as follows

$$H = \rho c_p\frac{(T_0 - T_a)}{r_a} \quad (5)$$

$$\lambda E = \lambda\frac{(h_0 e_0^* - e_a)}{r_a} \quad (6)$$

$$\lambda E + H = R - G \quad (7)$$

Aerodynamic resistance is a function of windspeed with a stability correction as used by Choudhury and Monteith (1988). The mass balance and the heat balance are both solved using the Newton-Raphson iterative method.

Simple soil water models

The simple soil models are based on the soil water model of MOSES (Cox *et al.*, 1997). There is no water vapour transport in MOSES and the flow of liquid water is given by Eqns (1), (3) and (4). The equations are solved in a finite difference scheme, ensuring conservation of mass.

EVAPORATION FORMULATION

The evaporation formulation used in SWEAT is designed for use with a fine top layer. For coarser gridded models, more empirical formulae are required. There are two types of top boundary condition used in simple soil models, often referred to as α and β type formulations (see Mahfouf and Noilhan, 1991 for a review). Both formulations have the same upper limit as the potential, or reference evaporation:

$$p = \frac{\Delta(R - G) + \rho c_p(e_a^* - e_a)/r_a}{\Delta + \rho c_p/\lambda} \quad (8)$$

Below this limit, the α formulation gives an evaporation that is a function of both P, the demand, and the water content of the top layer, the supply. This type of top boundary condition is used in MOSES, SSiB and CLASS. In MOSES, the formulation is given as follows:

$$\lambda E = P\left(\frac{\theta_0 - \theta_w}{\theta_c - \theta_w}\right) \text{ when } \theta_0 < \theta_c \quad (9)$$

Values for θ_w and θ_c are given in Table 1.

Table 1. Parameters for Eqns (9) and (10)

	θ_w (m^3 m^{-3})	θ_c	A 0.1m	0.5m	2.2m
Sand	.033	.096	20	3.5	.8
Loam	.136	.242	170	20	3
Clay	.221	.310	800	80	10

Below the upper bound of potential evaporation, the β type formulation gives an evaporation which is independent of P, and depends only on the supply. This type of formulation is used in BEST. An example of this type of formulation was developed for this study, as described in Appendix A. The equation is as follows:

$$\lambda E = AK_0 g\lambda \qquad (10)$$

where values of A are given in Table 1

To make a direct comparison of the simulation of soil water movement, the hourly potential evaporation, P, is taken from SWEAT (Eqn. (8)). In this way the ground heat flux and sensible heat flux are already accounted for, so the analysis is simplified.

FINITE DIFFERENCING METHOD

To apply Eqn. (1) in a finite difference scheme, it is necessary to choose a definition of hydraulic conductivity to multiply with the gradients in potential. Unlike in a fine layered model such as SWEAT, the results of a coarsely gridded model are sensitive to this. MOSES calculates K at the value of water content at the interface between the two layers as follows:

$$K = \left(\left(\frac{\theta_1 dz_2 + \theta_2 dz_1}{dz_1 + dz_2}\right) / \theta_s\right)^{3+2b} \qquad (11)$$

Other possibilites are to use the mean water content or weight the water content according to the layer thickness, as shown in the two following equations:

$$K = \left(\left(\frac{\theta_1 + \theta_2}{2}\right) / \theta_s\right)^{3+2b} \qquad (12)$$

$$K = \left(\left(\frac{\theta_1 dz_1 + \theta_2 dz_2}{dz_1 + dz_2}\right) / \theta_s\right)^{3+2b} \qquad (13)$$

It has also been suggested (Mahrt and Pan, 1984)) that K should be calculated at the maximum value of water content:

$$K = \left(\frac{\max(\theta_1, \theta_2)}{\theta_s}\right)^{3+2b} \qquad (14)$$

The sensitivity of the results to using Eqns (12), (13) or (14) to calculate K instead of Eqn. (11) is tested.

THICKNESS AND NUMBER OF THE LAYERS

MOSES has four layers of thickness 0.1, 0.25, 0.65 and 2.0 m. These values were originally chosen to minimise errors in the heat flux calculations and, since the heat and water fluxes are coupled, the soil moisture is mapped onto the same layered model. To compare with SWEAT, where the total soil depth modelled is 2.2 m, the final layer thickness was reduced to 1.2 m for this study. This soil model is referred to in this paper as Model 4.

Three other model structures were tested, all with the same total model depth but with different numbers of layers. Two of the models have two layers, one with the same top layer depth as Model 4 (Model 2b) and one with a deeper top layer (Model 2a). One model has just one layer (Model 1) which is the total depth of modelled soil. The depths of the layers of the four models, from the top down, are as follows.

Model '1' : 2.2 m
Model '2a': 0.5 m, 1.7 m
Model '2b': 0.1 m, 2.1 m
Model '4' : 0.1 m, 0.25 m, 0.65 m 1.2 m

Tests

Three soil types were tested, typical of a sand, a loam and a clay. The soil hydraulic parameters for these model soils are given in Table 2. The values are chosen as representative of the many parameters available in the literature and they cover a broad range of soil properties.

Table 2. Parameters for soil hydraulic properties in Eqns (3) and (4)

	ψ_s J kg^{-1}	K_s kg s m^{-3}	b	θ_s m^3 m^{-3}
Sand	1	.002	2	.4
Loam	4	.0001	4	.45
Clay	10	.00002	8	.5

Tests were designed to give a wide range of wetting/drying cycle frequencies. The cycles were run to equilibrium (about 1 year) to avoid dependence of the results on initial conditions, and to allow the internal compensatory errors of the model to develop in a similar way to that which they would in a GCM. The same amount of rain was applied to each soil type and for each frequency with an overall average (including the dry days) of 4.9 mm per day. This relatively large rainfall rate was used to ensure a significant drainage term, thus fully testing the performance of the simple models. A high evaporative demand was also applied using hourly meteorological data from a clear day at the 'Southern Super Site' in the HAPEX-Sahel study in Niger (Wallace *et al.*, 1994). A graph showing the data is shown in Fig. 1. These data were applied every day during the dry periods. During rain, SWEAT sets the evaporation to zero, so, to avoid unrealistic heating of the soil profile, the net radiation was set to zero and the air temperature was held at the 6 am value.

The rain was applied as follows:

a) 10 day cycle: 0.7 mm/hr for 70 hours every 10 days
b) 30 day cycle: 0.7 mm/hr for 210 hours every 30 days
c) 100 day cycle: 0.7 mm/hr for 700 hours every 100 days.

The combined effect of requiring high rainfall amounts (4.9 mm per day) and low rainfall rates (0.7 mm per hour, the maximum infiltration rate for the clay soil and used to avoid runoff) has resulted in the unrealistic case c) where 490 mm falls steadily over 30 days. But the aim of the

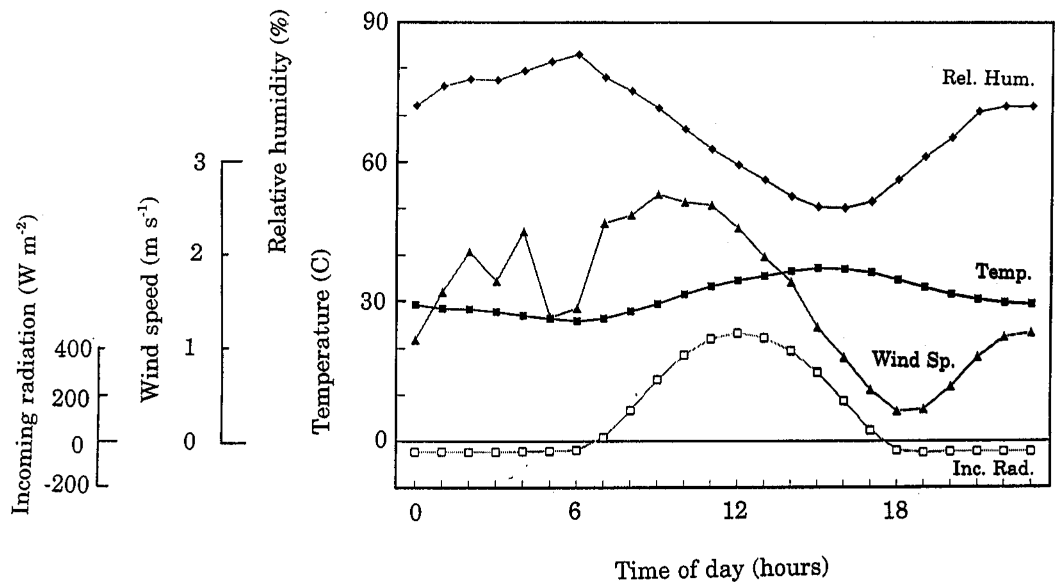

Fig. 1 *Meteorological forcing data for SWEAT (temperature (solid square), relative humidity (diamond), wind speed (triangle) and incoming radiation (open square)*

paper is a model-to-model comparison, so realism is not a high priority. These tests are designed so that any difference in evaporation between the simple models is a result of differences in the soil hydraulic properties, the solutions of the water flow equations or the frequencies of the applied rainfall. The time to equilibrium was minimised by using initial soil moisture profiles with a conductivity of 4.9 mm/day (the average rainfall rate).

Results

SWEAT

Before examining the simple models, it is useful to look at the results of SWEAT. Table 3 gives the cumulative evaporation for the nine test cases: 3 soil types with 3 wetting/drying frequencies. To summarise the results, Fig. 2 is a plot of how the total rainfall is partitioned between the cumulative evaporation and drainage for each frequency for sand and clay (loam is not shown for clarity). From this figure, it is clear that clay evaporates more than sand. This trend is well known (e.g compare drying curves for sand, loam and clay in Ritchie, 1972 and Monteith, 1991) and is easily deduced from an understanding of the process of soil moisture flow: clay soils move more water upwards through the soil profile in response to gradients in potential while the water in sandy soils drains more readily leaving less water available for evaporation.

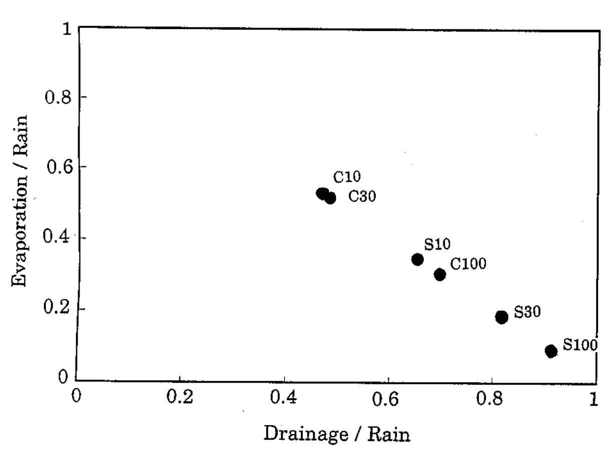

Fig. 2 *Drainage and evaporation as a fraction of total rainfall for sand and clay for the three frequencies (S10, S30, S100, C10, C30, C100) modelled by SWEAT.*

The second obvious feature of the nine cases illustrated in Fig. 2 is that the low frequency cycles have lower evaporation than the high frequency cycles. This is because in the low frequency cycles the water has time to move downwards away from the surface where the evaporation takes place.

The cumulative evaporation from SWEAT can be expressed as a percentage of the cumulative potential evaporation for each test case. The average of these percentages over the nine test cases is 64%. This statistic can be calculated for all of the models and will be referred to as the evaporation as a fraction of the potential evaporation.

The simple models do not include vapour flux. To test its significance, the maximum daily contribution to the vertical water flux crossing the 0.1 depth in SWEATwas calculated. Over all the soil types and all the tests, the maximum daily contribution it made was ten percent, which would mean only a few percent over the seasonal water balance. Thus, the exclusion of water vapour in the simple models does not alter the results of this paper significantly.

Table 3. Cumulative evaporation (mm) and errors $((E_{\text{simple model}} - E_{\text{SWEAT}})/\text{rain} \times 100)$ for equilibrium cycle

		10 day Evap. (mm)	Err. %	30 day Evap. (mm)	Err. %	100 day Evap. (mm)	Err. %
Sand	Pot. Evap.	27		86		304	
	SWEAT	17		27		42	
	4	18	2	21	–4	27	–3
	4mn	21	8	29	1	39	–1
	4dn	24	14	36	6	46	1
	4mx	24	14	38	7	48	1
	4β	20	6	21	–4	26	–3
	2a	15	–4	25	–1	44	0
	2b	27	20	63	24	80	8
	1	27	20	86	40	247	42
Loam	Pot. Evap.	26		80		291	
	SWEAT	26		63		111	
	4	26	0	53	–7	83	–6
	4mn	26	0	63	0	107	–1
	4dn	26	0	69	4	124	3
	4mx	26	0	69	4	141	6
	4β	26	0	55	–5	73	–8
	2a	22	–8	50	–9	106	–1
	2b	26	0	76	9	151	8
	1	26	0	80	12	277	34
Clay	Pot.Evap.	26		78		285	
	SWEAT	26		76		149	
	4	26	0	60	–11	106	–9
	4mn	26	0	65	–7	122	–6
	4dn	26	0	68	–5	135	–3
	4mx	26	0	70	–4	148	0
	4β	26	0	74	–1	100	–10
	2a	24	–4	60	–11	118	–6
	2b	26	0	72	–3	146	–1
	1	26	0	78	1	235	18

The performance of the simple models will be expressed as the difference between their predicted cumulative evaporation and that from SWEAT divided by the applied rainfall. This is expressed as a percentage and referred to as the error of the simple model.

MODEL 4

The cumulative evaporation predicted by Model 4 in the nine cases is given in Table 3. The results follow the trend predicted by SWEAT as described in the previous subsection reasonably well, with clay soils evaporating more than sandy soils, and evaporation from high frequency events being greater than that from lower frequency events. The error of Model 4 averaged over the nine cases is 4.7%, with all but one of the cases underpredicting the evaporation. The evaporation predicted by Model 4 as a fraction of the potential evaporation is 57% (cf 64% from SWEAT).

Sensitivity to evaporation formulation.

Table 3 shows the results using Model 4 using a β type formulation (labelled 4β). The use of this formulation (Eqn. (10)) rather than a α-type formulation (Eqn. (9)) for the calculation of evaporation has no significant effect, with evaporation changing by an average of just 2% of the total rainfall. The error of this model averaged over the nine cases was 4.1% with all but one of the cases underpredicting the evaporation.

Sensitivity to fimite difference method.

Table 3 shows the results using Model 4 but with Eqns. (12) (4mn), (13) (4dn) and (14) (4mx) in place of (11) (4) to calculate the conductivity. In Eqn. (11), the conductivity is a function of the average soil moisture weighted towards the value of the upper layer. During the evaporative phase, this will always be lower than the mean soil moisture. By comparison, if Eqn. (12) is used where the conductivity is a function of the mean soil moisture, then the upward movement of water is greater and evaporation is increased. In this case, the evaporation is 63% of the potential which is very similar to the results of SWEAT. The error using Model 4mn averaged over the nine cases is 2.7% (cf. 4.7% using Model 4). Using either Eqn. (13) or (14) where the conductivity is calculated at higher values of soil moisture during the evaporative phase, the model overpredicts the evaporation, with evaporation at 68% and 69% of the potential respectively.

Sensitivity to thickness and number of model layers.

The cumulative evaporation predicted by the Models 1, 2a and 2b are given in Table 3. As with Model 4, both Model 2a and 2b performed best when Eqn. 12 was used to calculate the conductivity i.e. at the mean soil moisture. Results with the models using Eqn. 12 are reported here.

Figures 3a, b and c show the values of the total evaporation as a fraction of the total potential evaporation for the three soil types at the three frequencies of the five models. The results of SWEAT show that the evaporations during the high frequency cycles are equal to the potential evaporation, while the evaporations in the low frequency cycles are less than the potential evaporation. Model 2b underestimates the evaporation for each of the frequencies and for each soil type. Model 1 overestimates the evaporation for each of the frequencies and soil types apart from the 10 day cycles where the evaporation is at potential. Model 2a overestimates the evaporation from sand and loam while Model 4 follows the results of SWEAT most closely.

Figure 4 shows the errors in predicted evaporation for the three soil types averaged over the three frequencies. It can be seen from this graph that Model 4 gives the best results and Model 1 gives the worst. Model 2a gives a good result for clay (average error 1.3%) and Model 2b gives a good result for sand (average error 1.7%). The two layer models are equally, but opposite, in error in their predictions for loam (average errors 5.7% and 6% respectively). Presumably, the optimum top layer depth for loam lies somewhere between 0.1 and 0.5m. If one wanted to use a two-layer model rather than a four layer model, one could use the thick top layer model for the clay and loam and the thin top layer model for the sand, in which case the average error is only 2.9% (cf 2.7% for Model 4).

It is interesting to note that, using a force-restore type model, Noilhan and Planton (1989) found the opposite result: that the top layer depth should increase with increasing coarseness. This discrepency underlines the fact that the rule is model dependent and does not represent a physically real phenomenon.

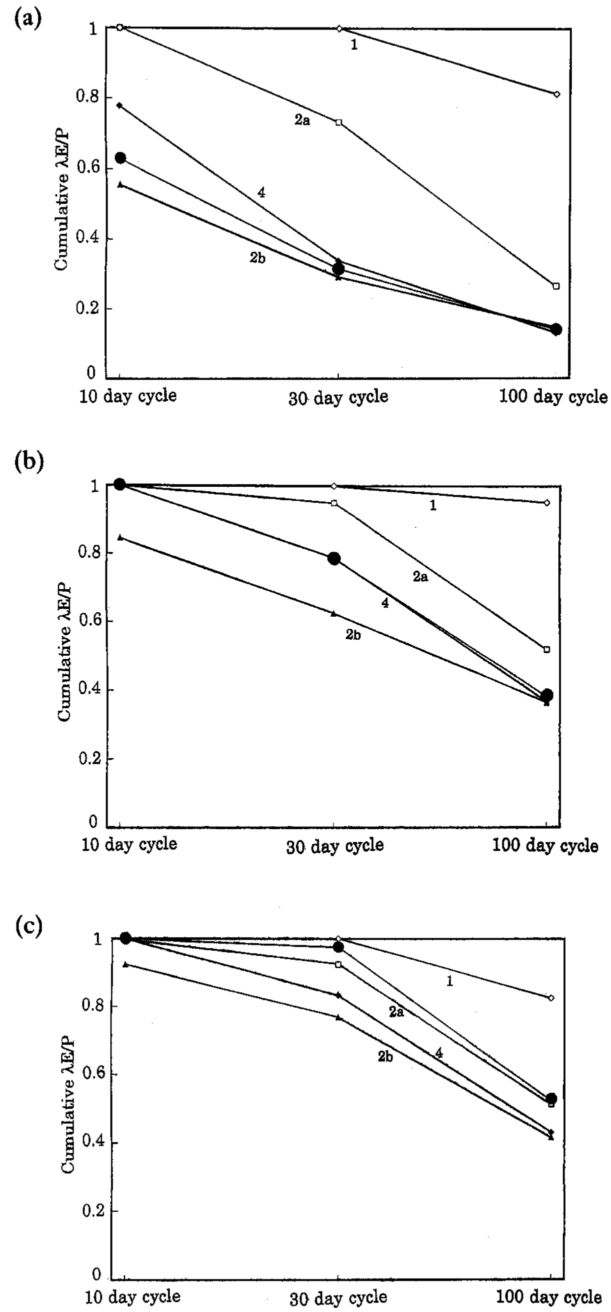

Fig. 3 *Total evaporation as a fraction of the potential evaporation for the three frequencies predicted by SWEAT (solid circle) and models 1 (open diamond), 2a (open square), 2b (triangle) and 4 (closed diamond) for (a) Sand, (b) loam and (c) clay.*

Conclusions

A fine layered soil model, forced with simulated climate data, was used to generate the corresponding evaporation

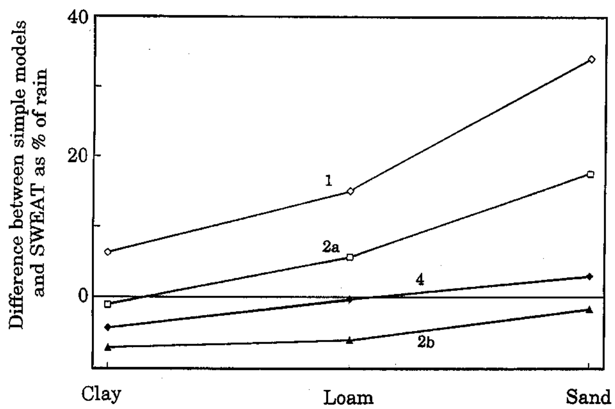

Fig. 4 *Average difference between models 1 (open diamond), 2a (open square), 2b (triangle) and 4 (closed diamond) and SWEAT for the three soil types given as a percentage of the applied rainfall.*

which in turn was used as a test against which simpler soil models were compared. This method of testing simple soil models proved valuable, as several climate types and soil types could be studied.

The results of the four layer soil model compared reasonably well with those for the fine layered model, but tended to underpredict the evaporation (average error of 4.7%). It was not possible to alter this result significantly by changing the evaporation formulation. However, it was possible to increase the evaporation by altering the finite differencing method and reduce the average error to 2.7%. It would therefore seem that the most important aspect of the simple soil model for predicting long term water balances is the vertical transfer of water through the soil profile, rather than the method of extracting the water from the top layer.

Two 2-layer models were assessed, one with a top layer of 0.1m and one with a top layer of 0.5m. The thinner top layered model performed well for sandy soils, while the thicker top layered model performed well for clay soils. The two layer model could replicate the results of the four layer model in terms of accuracy if the top layer thickness could vary with the soil type (average error using thin top layer for sand and thick top layer for loam and clay 2.9%).

The single layer model overpredicted the evaporation for all soils (average error 19%).

Appendix. Obtaining the parameter A used in Equation 10

In order to test the sensitivity of the evaporation to the evaporation formula, a new equation was required. Since the equation was being used in a sensitivity test, realism was not a high priority. It was decided to use SWEAT simulations as 'data', and thus increase the chances of a good model result. Several functions of the average soil moisture over the proposed top layer were plotted against evaporation, and the best result was found with the hydraulic conductivity. The final methodology is described below.

The information used to obtain values of A in Table 1 for the three soil types (sand, loam and clay) and the three top layer depths (0.1, 0.5 and 2.2m) is taken from the equilibrium cycles of SWEAT described in the Tests and Results sections. For daytime hours only (09:00 to 17:00 hrs) and for hours when evaporation is less than 80% of the potential evaporation, the vertically averaged value of water content of SWEAT over the top 0.1, 0.5 and 2.2 m is used to calculate the hydraulic conductivity using Eqn. (4). The hydraulic conductivity roughly maps against evaporation in straight lines going through the origin, with slopes that depend on the depth of averaging and the soil type only and not on the rainfall frequency. As an example, Fig. A1 shows evaporation against Kg calculated from the mean soil moisture in the top 50 cm of SWEAT for a loam for the 30 and 100 day cycles. (The evaporation in the 10 day cycle was always above 0.8P). A straight line was fitted by eye for each soil type and each depth. Since only a sensitivity of the evaporation to the formula is required, such a crude method of obtaining the parameter is valid.

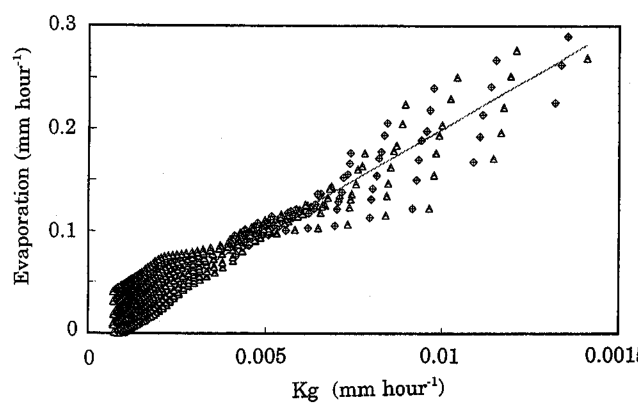

Fig. A1 *Evaporation plotted against Kg calculated from the average water content in the top 50 cm of SWEAT for loam for the 30 day cycle (diamond) and the 100 day cycle (triangle).*

Nomenclature

A	Dimensionless constant in calculation of evaporation from simple soil models (Eqn. (14))
b	Soil parameter which describes the form of the soil water release characteristic
c_p	Specific heat capacity of air at ambient pressure (J kg^{-1} K^{-1})
$D_v(z)$	Water diffusivity in soil (m^2 s^{-1})
dz_1	Depth of soil layer above interface (m)
dz_2	Depth of soil layer below interface (m)
$e^*(z)$	Saturated water vapour concentration (kg m^{-3})

e_0^*	Saturated water vapour concentration at T_0 (kg m^{-3})
e_a^*	Saturated water vapour concentration at T_a (kg m^{-3})
e_a	Water vapour concentration at z_a (kg m^{-3})
E	Evaporation flux (kg m^{-2} s^{-1})
g	Acceleration due to gravity (= 9.8 m s^{-2})
G	Ground heat flux (W m^{-2})
h(z)	The relative humidity in the soil pore space
h_0	The relative humidity in the top soil layer
H	Sensible heat flux (W m^{-2})
K(z)	Hydraulic conductivity of soil (kg sm^{-3})
K_0	Hydraulic conductivity of top soil layer (kg sm^{-3})
K_s	Saturated hydraulic conductivity (kg sm^{-3})
P	Potential evaporation (W m^{-2})
Q_l	Flow of liquid water through soil profile (kg m^{-2} s^{-1})
Q_v	Flow of water vapour through soil profile (kg m^{-2} s^{-1})
r_a	Aerodynamic resistance from surface to height z_a (sm^{-1})
R	Net radiation (W m^{-2})
T(z)	Temperature in soil (K)
T_0	Temperature of soil surface (K)
T_a	Temperature at z_a (K)
z	Depth into soil (m)
Δ	Slope of saturated water vapour with temperature (kg m^{-3} K^{-1})
η	Dimensionless vapour flow enhancement factor
$\theta(z)$	Water content of soil layer (m^3 m^{-3})
θ_0	Water content of top soil layer (m^3 m^{-3})
θ_1	Water content of layer above the interface (m^3 m^{-3})
θ_2	Water content of layer below the interface (m^3 m^{-3})
θ_s	Saturated water content (m^3 m^{-3})
θ_w	Water content at wilting point (m^3 m^{-3})
θ_c	Water content at critical point (m^3 m^{-3})
λ	Latent heat of vaporisation (J kg^{-1})
λE	Latent heat flux (W m^{-2})
ρ	Density of air (kg m^{-3})
$\psi(z)$	Matric potential of the soil (J kg^{-1})
ψ_s	Saturated matric potential (J kg^{-1})

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