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Surface soil moisture parameterization of the VIC-2L model: Evaluation and modification

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Abstract

HAPEX–MOBILHY data, consisting of one year of hourly atmospheric forcing data at Caumont (SAMER No. 3, 43.68°N, 0.1°W) were used repeatedly to run the two-layer Variable Infiltration Capacity (VIC-2L) land-surface scheme until the model reached equilibrium in its water and energy balance. The equilibrium results are compared with one year of weekly soil moisture measurements at different depths, the estimated latent heat fluxes for 35 days of the intensive observation period (IOP), and the accumulated evaporation, runoff and drainage for the entire soya crop season. The latent heat flux comparisons show that VIC-2L tends to underestimate the evaporation due to the low soil moisture in its upper layer. The soil moisture comparison shows that the total soil water content is well simulated in general, but the soil water content in the top 0.5 m is underestimated, especially in May and June. These comparisons suggest that the lack of a mechanism for moving moisture from the lower to the upper soil layer in VIC-2L is the main cause for model error in the HAPEX–MOBILHY application. A modified version of VIC-2L, which has a new feature that allows diffusion of moisture between soil layers, and a 0.1 m thin layer on top of the previous upper layer, is described. In addition, the leaf area index (LAI) and the fraction vegetation cover are allowed to vary at each time step in a manner consistent with the rest PILPS–RICE Workshop, rather than being seasonally fixed. With these modifications, the VIC-2L simulations are re-evaluated. These changes are shown to resolve most of the structural deficiencies in the original version of the model. The sensitivity analysis of the new version of the model to the choices of soil depths and root distribution show that the evapotranspiration and soil moisture at the model equilibrium state are more sensitive to the root distribution than to the soil depth.

1. Introduction

The development of surface hydrological schemes appropriate for large scale water and energy balance modeling, including representing the surface in general circulation models (GCMs) used for climate and weather prediction, requires a careful balance between computational ease and accurate representation of the physical processes. The representation of the soil column and the infiltration parameterization is particularly important because of their direct effects on a model's vertical distribution of soil moisture. Soil moisture determines whether the soil column can meet the atmospheric demand for moisture; either at the surface (bare soil evaporation) or in the root zone (transpiration). The evapotranspiration, along with net radiation, then essentially determines the sensible and ground heat fluxes. Thus, models which have insufficient soil moisture to meet evapotranspiration demands have sensible heat fluxes and

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surface temperatures which are too high, and within a coupled land–atmospheric model, boundary layers that are too deep.

There are three important aspects of the specification of the soil column and the infiltration and evaporation parameterizations within a land surface hydrology scheme. These are: (1) the handling of spatial variability in soil characteristics within the area being modeled; (2) the number of soil layers and their water holding capacities; (3) the parameterization of soil water drainage and diffusion. Different land surface parameterization schemes have addressed these aspects in different ways. For most of the current models, the most common assumption is that spatial heterogeneity in soil properties is ignored, leading to a 1-dimensional infiltration representation.

Stamm et al. (1994) proposed using a model that has variable infiltration capacities (VIC) within an area, but represents a particular point as a single layer. The results presented in Stamm et al. (1994) suggested that a single layer soil model may be insufficient for land surface schemes. Thus, Liang et al. (1994) extended the variable infiltration capacity model to two layers (VIC-2L), along with other features. This version of VIC-2L, when tested using FIFE and ABRACOS observed data, performed well (Liang, 1994). The VIC-2L model as developed by Liang et al. (1994) includes, in addition to a parameterization for spatial variability of the infiltration capacity, evaporation from different vegetation types, bare soil evaporation, and two soil layers with drainage from the upper layer into the lower layer, which in turn produces slow drainage and subsurface flow, but ignores the diffusion of moisture between the soil layers. In addition, the soil moisture dynamics near surface (e.g., the upper 10 cm), which is particularly dynamic during summer periods, was not included in the model structure. Further testing of VIC-2L has been performed under the auspices of PILPS.

This paper describes the findings from the PILPS–RICE HAPEX workshop held in Sydney, Australia in November 1994, and the modifications of VIC-2L. In particular, the performance of VIC-2L is analyzed for the workshop control experiment run. As a result of the model structural deficiency in the control run, the soil column representation is modified to include a top thin soil layer, and the soil water diffusion parameterization between soil layers, which are discussed in Sections 3 and 4.

2. Control experiment analysis of VIC-2L

The control experiment used in the PILPS–RICE workshop was designed to allow comparisons of different land-surface schemes, using the same meteorological forcing data (Goutorbe, 1991; Goutorbe and Tarrieu, 1991; Shao et al., 1994), and the same prescribed land-surface parameters (Raupach, 1994; Shao et al., 1994) and soil characteristics (Cosby et al., 1984) for HAPEX–MOBILHY. In the control experiment, each scheme used the one year meteorological forcing data repeatedly until it reached an equilibrium in its water and energy balance. Since the climatology at HAPEX–MOBILHY is quite similar each year, the detailed available observations during certain periods of the control year provides a good basis for the model verification and validation at each model's equilibrium state (Shao et al., 1994). These observations include soil moisture measurements at different soil depths, the estimated latent heat fluxes during the 35-day intensive observation period (IOP), the accumulated evaporation, and runoff and drainage at different accumulation times. Soil moisture was measured weekly (by neutron probes) for the entire year. During the IOP (from day 148 through day 182), the net radiation, sensible heat flux, and ground heat flux at 15 minute intervals were also measured. The latent heat flux was then derived as the residual of the energy balance equation (Goutorbe, 1991). The accumulated evaporation, and runoff and drainage right for the entire growing months of the soya crop were derived from the water balance equation (Shao et al., 1994).

The goal of the control experiment analysis of VIC-2L performance is to identify weaknesses in the model and to improve it. The major features of VIC-2L related to the soil moisture simulation are the two soil layers in the subsurface soil column. The surface is described by n land cover types ($n = 1,2,3, \cdots N$). Associated with each land cover class is a single canopy layer (if not bare soil), upper soil layer and lower soil layer. The upper soil layer is designed to represent the dynamic response of the

soil to rainfall events, and the lower layer is used to characterize the seasonal soil moisture behavior. The lower layer only has a short-term response to rainfall when the upper layer is saturated, therefore, it tends to separate the subsurface flow from storm quick response. Drainage to the lower layer from the upper layer is based on the hydraulic conductivity of the upper layer. In the Liang et al. (1994) version of VIC-2L used at the workshop, there was no diffusion process. Therefore, water cannot move upwards from the lower layer even when it is more moist, except by vegetation roots which penetrate into the lower layer.

The VIC-2L subsurface flow and drainage formulation is an empirical relationship derived from large scale catchment data. The parameters included in the empirical equation would be better represented if there were more hydrologic information available for the HAPEX field site. One aspect of the formulation that bears testing is that it allows the soil to drain to zero asymptotically during a very long dry period (see Liang et al. (1994) for details).

Fig. 1 shows the comparisons of the observed soil moisture contents for the total (1.6 m) and top (0.5 m) HAPEX–MOBILHY soil column with VIC–2L model simulations. The VIC-2L reproduces the total soil moisture dynamic change over the year reasonably well. However, in the top 0.5 m soil column, the VIC-2L significantly underestimates the soil moisture during June and July. Fig. 1 indicates that, compared to observations, VIC-2L has less water in the top 0.5 m soil column, while it keeps more water in its lower soil layer (0.5–1.6 m) during June and July. Therefore, the model evapotranspiration during those months suffers greater soil stress than the observations indicate. Fig. 2a compares accumulated evaporation during the IOP (from May 28 to July 3) between the model and the observations. As expected, VIC-2L underestimates the observations by about 30 mm out of a total of 126 mm for the IOP. The model and observations are close for the first 25 days, but they diverge thereafter as the upper layer becomes excessively dry. The total evaporation for the growing season is estimated to be 320 mm (Mahfouf et al., 1996-this issue), while VIC-2L only evaporates 291.1 mm. The major reason for the consistent underestimation of evaporation is the lack of a mechanism for upward diffusion of soil moisture in VIC-2L. As discussed earlier, the soil moisture content in the lower layer in VIC-2L is higher than observed during the critical period, but is lower than the observations in the upper layer (i.e., the top 0.5 m). Therefore, the problem of losing water too

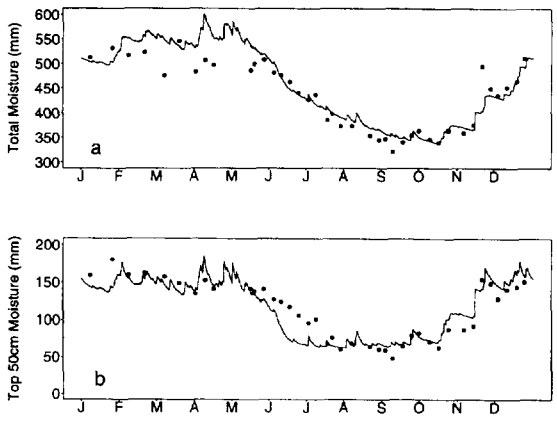

Fig. 1. Comparison of soil moisture in: (a) total 160 cm soil layer; and (b) top 50 cm soil layer. The dots are HAPEX weekly observations for the respective layers and the solid line is the control experiment (i.e., Exp. 13) from the original version of VIC-2L.

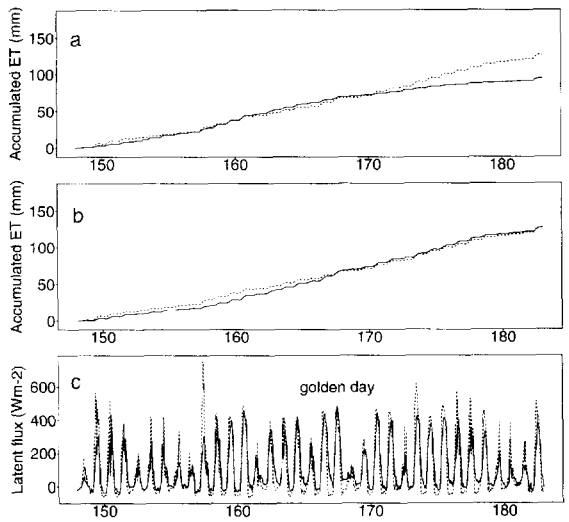

Fig. 2. Comparison of evaporation during the IOP (from day 148 to day 182): (a) accumulated evaporation between the observations (dotted line) and the original version of VIC-2L (i.e., Exp. 13) (solid line); (b) accumulated evaporation between the observations (dotted line) and the modified version of VIC-2L (solid line); (c) time series of latent heat flux between the observations (dotted line) and the modified version of VIC-2L (solid line).

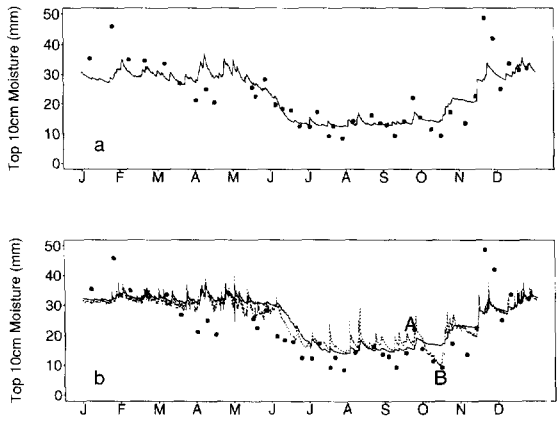

Fig. 3. Comparison of soil moisture in the top 10 cm soil layer: (a) between the weekly observations and the control experiment (i.e., Exp. 13) from the original version of VIC-2L; (b) between the weekly observations and the control experiment from the modified version of VIC-2L. The dots are HAPEX weekly observations for the top 10 cm, the solid line is the soil moisture derived from the top 50 cm soil moisture, and the dotted line is the soil moisture from the top 10 cm.

quickly in the upper soil can be resolved if diffusion caused by the soil moisture gradient between the soil layers is accounted for.

Another reason for the rapid decrease of model evapotranspiration at the end of IOP is the use of monthly average values for LAI and fractional vegetation coverage. At the workshop, it was recognized that the monthly LAI and fractional vegetation coverage cannot represent the changes in vegetation structure of the soya crop during its rapid growing period in May and June. Therefore, a time series of LAI and the fractional vegetation coverage was generated (see Shao et al., 1994) by using the following relationship:

$$C_v = 1 - e^{-c \cdot \mathrm{LAI}} \quad (1)$$

where C_v is the fractional vegetation coverage, and c is a coefficient related to the vegetation type (0.6 for soya crop).

Fig. 3a compares the soil moisture of the top 0.1 m over the year. The VIC-2L only had upper layer (top 0.5 m) and lower layer (0.5–1.6 m), and thus the top 0.1 m soil moisture was derived by multiplying the volumetric soil moisture of the upper layer (top 0.5 m) by a depth of 0.1 m. It is seen that the significant underestimation of upper layer soil moisture in June and July in Fig. 1b disappears in Fig. 3a. This indicates that the soil moisture characteristics in the top 0.1 m are very different from those in the top 0.5 m, and thus the average volumetric soil moisture from the upper layer cannot represent the soil moisture of both the top 0.1 m layer and the upper layer (0.5 m) well at the same time. Also, the derived top 0.1 m soil moisture shows a much smoother variation than the observations. In fact, the measured weekly soil moisture data (at 0.1 m increments from the surface to 1.6 m, Shao et al., 1994) indicate that the volumetric soil water content of the top 0.1 m is smaller than the average of the upper 0.5 m, (especially during the period of April–July), and that it has a larger range than the average of the upper 0.5 m. Also, the 0.1 m increment soil moisture observations (not shown) have significant differences based on variations in the volumetric soil moisture content. Generally, the volumetric soil moisture content differences among each 0.1 m increment from 0.1 to 0.6 m, and from 0.6 to 1.6 m, are smaller than those from the surface to 0.1 m. Therefore, it seems that a three soil moisture layer representation might improve the VIC-2L model performance.

Based on the analysis of the results from the control experiment and the HAPEX observations, it is clear that there are two major weaknesses in VIC-2L. These are the lack of moisture diffusion process between soil layers and the lack of a top thin layer to capture the dynamic behavior of soil moisture content. In this paper, the VIC-2L model is modified by including those two features, and evaluated using the HAPEX–MOBILHY data.

3. Modification of VIC-2L

In this section, the two major modifications to VIC-2L are described. The new version of the model consists of an upper layer, which is partitioned into a top thin layer and a thicker layer (referred to as upper thicker layer hereafter), and a lower layer (see Fig. 4).

3.1. Bare soil

Assuming that there is no lateral flow in the top thin layer and the upper thicker layer, the movement

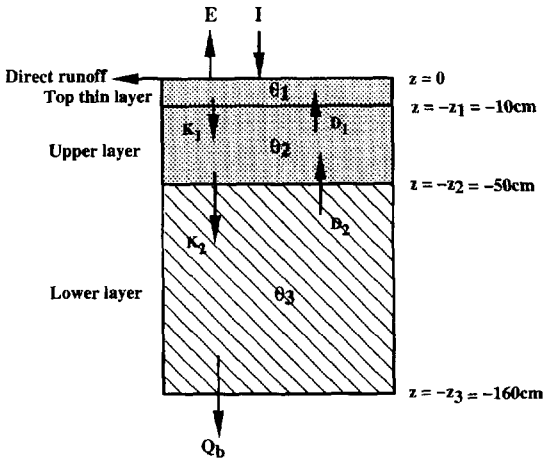

Fig. 4. Schematic representation of the three-layer structure of VIC (modified version of VIC-2L) for bare soil case. D_1 and D_2 represent the diffusions between the soil layers, and K_1 and K_2 represent the drainages between the soil layers.

of moisture can be characterized by the one-dimensional Richard's equation:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(D(\theta)\frac{\partial\theta}{\partial z}\right) + \frac{\partial K(\theta)}{\partial z} \tag{2}$$

where θ is the volumetric water content, $D(\theta)$ is the soil water diffusivity, $K(\theta)$ is the hydraulic conductivity, and $|z|$ represents the depth of soil (see Fig. 4).

Integrating Eq. (2) over the top thin layer of depth z_1, and taking into account atmospheric forcing, we obtain (Mahrt and Pan, 1984),

$$\frac{\partial\theta_1}{\partial t}\cdot z_1 = I - E - K(\theta)|_{-z_1} - D(\theta)\frac{\partial\theta}{\partial z}\bigg|_{-z_1} \tag{3}$$

where

$$\theta_1 = \frac{1}{z_i}\int_{-z_1}^{0}\theta\,\mathrm{d}z \tag{4}$$

where I is the infiltration rate, and E is the evaporation from bare soil.

Integrating Eq. (2) from $z = -z_2$ to $z = 0$, we obtain,

$$\frac{\partial\theta_2}{\partial t}\cdot z_2 = I - E - K(\theta)|_{-z_2} - D(\theta)\frac{\partial\theta}{\partial z}\bigg|_{-z_2} \tag{5}$$

where

$$\theta_2 = \frac{1}{z_2}\int_{-z_2}^{0}\theta\,\mathrm{d}z \tag{6}$$

As in the original version of VIC-2L, the soil surface is characterized by a variable infiltration capacity curve, which is expressed as,

$$i = i_{\mathrm{m}}\left[1 - (1 - A)^{1/b_{\mathrm{i}}}\right] \tag{7}$$

where

$$i_{\mathrm{m}} = (1 + b_{\mathrm{i}})\cdot\theta_{\mathrm{s}}\cdot|z| \tag{8}$$

where i and i_{m} are the infiltration capacity and maximum infiltration capacity with a dimension of length respectively, A is the fraction of the area for which the infiltration capacity is less than i, b_{i} is the infiltration shape parameter which is a measure of the spatial variability of the infiltration capacity, and θ_{s} is the soil porosity. The parameter b_{i} is best determined using hydrologic information (especially streamflow) at the site, which were not available. Because of the lack of site specific data, b_{i} was determined based on past calibration experience and the suggested range from Dumenil and Todini (1992).

The direct runoff (Q_{d}) is calculated by applying Eq. (7) to the entire upper layer, rather than just to the top thin layer of depth z_1. The direct runoff can be then expressed as,

$$Q_{\mathrm{d}}\cdot\Delta t = P\cdot\Delta t - z_2\cdot(\theta_{\mathrm{s}} - \theta_2),\ i_0 + P\cdot\Delta t \geq i_{\mathrm{m}} \tag{9}$$

$$Q_{\mathrm{d}}\cdot\Delta t = P\cdot\Delta t - z_2\cdot(\theta_{\mathrm{s}} - \theta_2) + z_2\cdot\theta_{\mathrm{s}}\cdot\left[1 - \frac{i_0 + P\Delta t}{i_{\mathrm{m}}}\right]^{1+b_{\mathrm{i}}},\ i_0 + P\Delta t \leq i_{\mathrm{m}} \tag{10}$$

where Δt is time step which is taken as one hour in the model calculation, P is the precipitation rate, and i_0 is a specific point infiltration capacity of i that corresponds to the soil moisture at that time step.

The reason for not calculating the direct runoff based on the top thin layer depth is that it has a very small water holding capacity (i.e., $\theta_{\mathrm{s}} z_1$). Therefore, unless the soil column is strongly stratified within

the top thin soil layer, applying Eq. (7) to the top thin layer would tend to produce an overly flashy storm runoff response.

The infiltration rate I, which is the difference between the precipitation (or throughfall if there is vegetation coverage) that reaches the soil surface and the surface runoff (Q_d), can be expressed as,

$$I = P - Q_d \tag{11}$$

Bare soil evaporation (E) is calculated in the same way as in the original VIC-2L, except that the available soil moisture is determined by the soil moisture content in the top thin layer (z_1), rather than the entire upper layer of depth z_2. The bare soil evaporation is expressed as,

$$E = E_p \left\{ \int_0^{A_s} \mathrm{d}A + \int_{A_s}^{1} \frac{i_0}{i_m \left[1 - (1 - A)^{1/b_i} \right]} \mathrm{d}A \right\} \tag{12}$$

where E_p is the potential evaporation rate calculated by Penman-Monteith's formulation for a free water surface (Shuttleworth, 1993), A_s is the fraction of the bare soil that is saturated (i.e., the fraction of area corresponding to i_0), and i_m is calculated by using $|z| = z_1$ in Eq. (8).

When the soil is unsaturated, the drainage and the diffusion terms [Eqs. (3) and (5)] between soil layers are calculated based on the Clapp-Hornberger relationships (Clapp and Hornberger, 1978) between the volumetric soil water content and soil hydraulic conductivity, and the diffusivity and water potential. In the original version of VIC-2L, the drainage was calculated by using the Brooks-Corey relationship (Brooks and Corey, 1964) between the soil moisture content and the hydraulic conductivity. The Brooks-Corey relationship is similar to the Clapp-Hornberger relationship, but it has one additional parameter, the residual soil moisture content. Ek and Cuenca (1994) did a sensitivity study on the choice of Clapp-Hornberger "B" parameter, and found that the surface fluxes and boundary-layer development are sensitive to B value. Because the B parameter and other parameters related to the soil characteristics used in the workshop are based on Cosby et al. (1984), it is more consistent to use the Clapp-Hornberger relation to calculate the drainage and diffusion between soil layers. When the soil is unsaturated, water is diffused upward from the lower soil layer if it has higher volumetric soil moisture content; otherwise, water is diffused downward from the upper soil layer. If the volumetric soil moisture is the same in the two soil layers, there is no diffusion. When the upper soil layer is saturated, the drainage to the lower layer follows the saturated hydraulic conductivity.

For the lower soil layer, it is assumed that there are both drainage from the unsaturated part (which is not explicitly delineated) and subsurface flow from the water table. Since VIC-2L does not explicitly compute a water table depth, these terms are lumped together, and are calculated by an empirical formulation derived from large scale catchment hydrology as in the original version of VIC-2L. Thus, the water balance equation including diffusion between soil layers for the lower layer can be expressed as,

$$\frac{\partial \theta_3}{\partial t} \cdot (z_3 - z_2) = K(\theta)|_{-z_2} + D(\theta) \frac{\partial \theta}{\partial z}\bigg|_{-z_2} - Q_b \tag{13}$$

where

$$\theta_3 = \frac{1}{z_3 - z_2} \int_{-z_3}^{-z_2} \theta \, \mathrm{d}z \tag{14}$$

and Q_b is the subsurface flow plus drainage. It is worth noting that Eq. (11) does not have an evaporation term, since it is assumed that bare soil evaporation occurs only from the top thin layer. However, for vegetated areas, Eq. (11) will include evapotranspiration if the vegetation roots penetrate into the lower layer. Eqs. (3), (5), and (13) were solved using a finite difference scheme at an hourly time step.

3.2. Vegetation

For vegetated areas, the soil column is represented in the same way as bare soil areas as above. The only exceptions are that bare soil evaporation is replaced by transpiration which may occur from both the upper and lower layers depending on the vegetation type and the root distribution. Also, precipitation is replaced by throughfall. In addition, the upper soil layer is divided into wet soil and dry soil. In this

case, the transpiration from the wet soil is not subject to the soil stress, while the transpiration from the dry soil will subject to a larger soil stress compared with the original VIC-2L version. The way of incorporating different vegetation covers and bare soil and the other features of VIC-2L are the same as described in Liang et al. (1994).

As discussed in the previous section, the time series of LAI and fraction vegetation coverage, instead of their monthly values, are used for May and June. In the following section, the results from the modified VIC-2L are analyzed and discussed.

Since the upper soil layer is designed to represent the dynamic behavior of soil moisture to rainfall events, and the lower layer is designed to characterize the seasonal soil moisture behavior, it is not possible to determine the depths for each of the soil layers uniquely at the HAPEX site. In the original version of VIC-2L control experiment, the depths of the upper (0.5 m) and lower (0.5–1.6 m) layers were determined based on general knowledge. To be consistent with the original soil layer depths, the depths of the upper layer ($z_2 = 0.5$ m) and the lower layer ($z_3 - z_2 = 1.1$ m) are kept the same. The top thin layer depth is taken as $z_1 = 0.1$ m.

4. Results and discussion

By incorporating the modifications described above, the control experiment was re-run keeping all parameters as in the original control run, except for the three parameters in the Q_b formulation, which were slightly adjusted in this re-run to reflect the observations that almost no runoff and drainage were observed at the HAPEX–MOBILHY site during and after the growing season. As discussed by Wetzel et al. (1996-this issue), the empirical formulation of Q_b which is based on large scale catchment hydrology would benefit if a more explicit hydrologic characterization of the HAPEX field site were available. It should be noted that the three parameters in the Q_b formulation were not specified at the workshop for the original control experiment, they were instead arbitrarily chosen since no information that would allow, for instance, baseflow recession estimation was available. Therefore, the slight adjustment of the three parameters in the new control experiment seems defensible given the observed absence of baseflow.

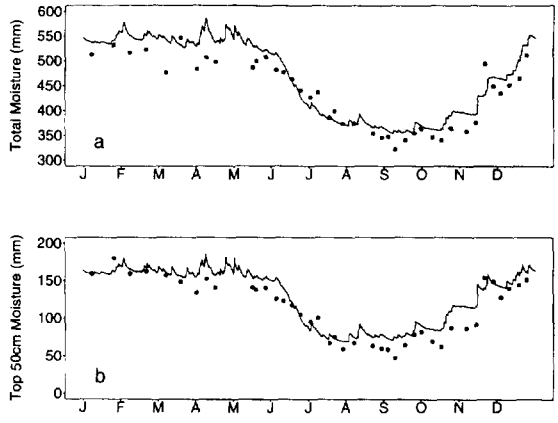

Fig. 5. Comparison of soil moisture in: (a) total 160 cm soil layer; and (b) top 50 cm soil layer. The dots are HAPEX weekly observations for the respective layers and the solid line is the control experiment from the modified version of VIC-2L.

Fig. 5 compares the soil moisture contents of the total (1.6 m) and the upper (0.5 m) layers for the new results of VIC-2L and the observations. The new results reproduce the soil moisture dynamic change over the year quite well in both soil layers. The significant underestimation of the soil moisture in the top 0.5 m during June and July in the original VIC-2L results no longer exists, while the performance of the total soil moisture is similar to the original VIC-2L results. The obvious improvement of the soil moisture in the top 0.5 m in June and July suggests that the lack of a diffusion mechanism in the model was the major problem in the previous results. Since there is more water available for the soya crop to transpire in the modified VIC-2L, the accumulated evaporation for the IOP and the growing season (from day 148 to day 273) increased from 94.1 mm and 291.1 mm to 126.6 mm and 315.6 mm, respectively. The observed data discussed by Mahfouf et al. (1996-this issue) give an accumulated evaporation of 126 mm and 320 mm for the IOP and the growing season (from day 148 to day 273) respectively. The soil moisture content of the total 1.6 m layer at the beginning of the growing season does not change much, as expected, from 518.0 mm to 519.1 mm, but the position of VIC-2L moves

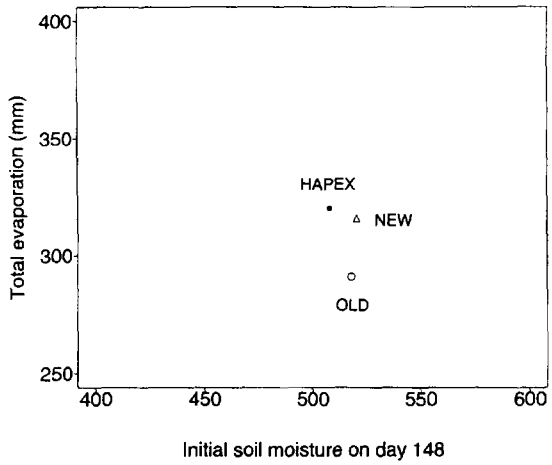

Fig. 6. Comparison of the total soil moisture at the beginning of the IOP against the total evaporation from day 148 to day 273.

toward the observations as shown in Fig. 6, since the total evaporation is increased by a significant amount.

Fig. 2b shows the accumulated evaporation for the IOP. The modified VIC-2L model results are significantly improved in accumulated evaporation during the IOP. In the original VIC-2L results, the evaporation is close to the observations for the first 25 days, and then it decreases dramatically because of increased soil moisture stress. With the diffusion process, however, the problem of drying out the upper layer is mitigated.

It is worth pointing out that, using monthly LAI and fraction vegetation coverage, the difference in total evaporation for the IOP (not shown here) is less than 6 mm out of 126.6 mm for the modified VIC-2L. However, the evaporation tends to occur more before the middle of June and less after that date as compared with continuously varying LAI and fractional vegetation coverage. This is because the monthly LAI and vegetation fraction values were taken to be the mid-June values. These results indicate that the monthly values can give a reasonable simulation of the total amount, but not of the time series when the vegetation is undergoing rapid growth.

The hourly time series of latent heat flux from the modified VIC-2L is shown in Fig. 2c (solid line). In the same figure, the latent heat flux obtained as the residual of the energy budget (dotted line) is also shown for comparison. From the figure, it is seen that the modified VIC-2L model compares well with the observations in general, although both underestimates and overestimates occur. In the original VIC-2L control experiment, the simulated evaporation on the golden day (June 16) was only about half of that observed, while this day is simulated quite well in the modified VIC-2L. Tuning of the VIC-2L model parameters would almost certainly improve the latent heat flux simulations.

Fig. 7 shows the accumulated evaporation and total runoff for the entire year. Compared with the control experiment from the original VIC-2L, the annual evaporation increases from 565.7 mm to 614.8 mm mainly due to the addition of the diffusion process. Consequently, the annual total runoff decreases from 290.8 mm to 241.7 mm. In addition, due to the adjustments of the parameters in the empirical subsurface and drainage formulation, more than 90% of the annual runoff now occurs before the IOP, while it was 72% before the IOP in the original VIC-2L. This indicates the importance of having hydrologic information about the runoff and drainage formulation (e.g., baseflow data), even if it is quite general.

Fig. 3b compares the top 0.1 m soil moisture between weekly observations (dots) and the modified VIC-2L simulation (dotted line). The soil moisture obtained by multiplying the volumetric soil moisture content of the upper layer by the soil depth of 0.1 m (solid line) is also shown in Fig. 3b. From the figure,

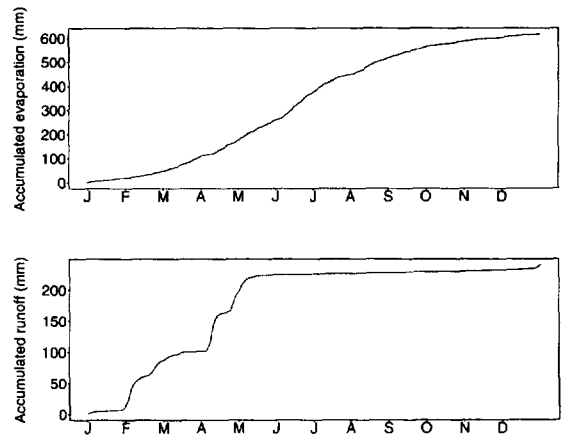

Fig. 7. Accumulated evaporation and total runoff for the control experiment from the modified version of VIC-2L.

Table 1
Sensitivity analysis of evaporation and soil moisture to root distribution and soil depth

	Ctrl. Case		Case 1		Case 2		Case 3		Case 4	
	Value	Err. (%)	Value	Err. (%)	Value	Err. (%)	Value	Err. (%)	Value	Err. (%)
Yr. ET (mm)	614.8	0.2	601.2	2.4	566.1	8.1	672.1	−9.1	631.2	−2.5
Yr. R (mm)	241.7	−0.5	255.3	−6.2	290.4	−20.7	184.4	23.3	225.3	6.3
IOP ET (mm)	126.6	−0.5	118.1	6.3	118.7	5.6	133.6	−6.0	132.4	−5.1
GS ET (mm)	315.6	1.4	300.8	6.0	268.2	16.2	392.1	−22.5	349.7	−9.3
W at GS (mm)	519.1	−2.2	520.4	−2.5	519.1	−2.2	515.4	−1.5	515.4	−1.5
W at Yr. (mm)	547.6	−6.8	551.5	−7.6	550.5	−7.4	477.1	6.9	517.9	−1.0

it is seen that the dotted line simulates the top 0.1 m soil moisture dynamic change much better than the solid line. For example, in May, June and July, the soil moisture (dotted line) can be depleted to near the observations (i.e., dots), while the solid line is always above the observations. Another example is shown around the period of late September to the middle of October, indicated by points between *A* and *B* in the figure. It is seen that the dotted line (top thin layer) can simulate the high moisture at point *A*, and also the depletion of soil moisture from point *A* to point *B*, but the solid line cannot. When there are rainfall events, the soil moisture increases quickly, which is represented by the spikes in the figure. When there is no rainfall, the soil dries out gradually. As for the solid line, its behavior is much more damped than the dotted line, since it represents the average soil moisture dynamics of the top 0.5 m

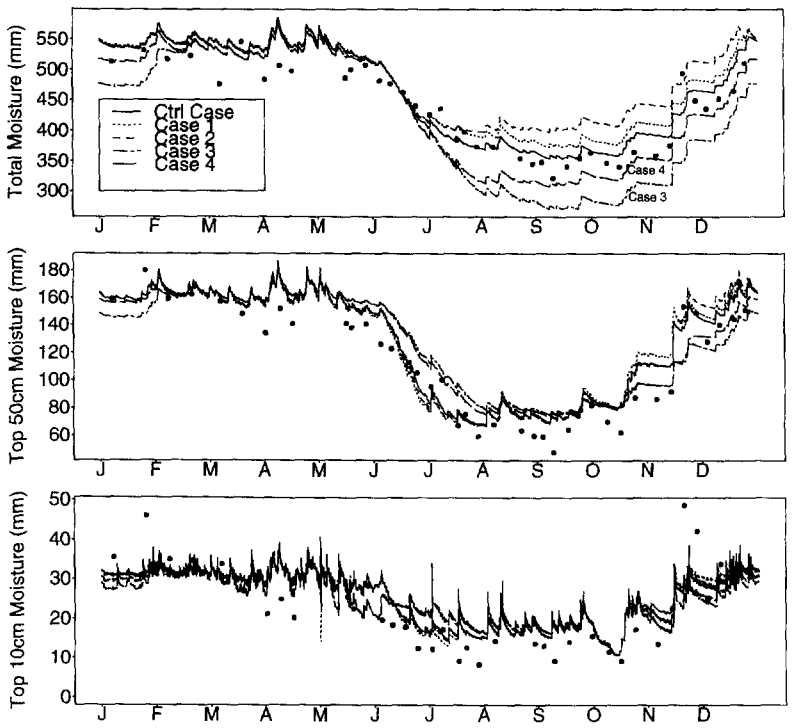

Fig. 8. Comparison of soil moisture among the four sensitivity cases and the control experiment case with the modified version of VIC-2L. The dots are HAPEX weekly observations for the respective layers.

soil layer. The inclusion of the top thin layer representation illustrates that it is important to capture the soil dynamics near the surface. It should be pointed out that although it appears that the original VIC-2L compares better with the observations in Fig. 3a, the solid line in Fig. 3a is obtained from the volumetric soil moisture content of the upper layer of the original VIC-2L which is too dry during June and July as shown in Fig. 1b.

As mentioned earlier, the choice of the depths of the upper and lower layers for VIC-2L is not unique. The depths could be more reasonably determined if there were some information about the behavior of the soils within the area of interest. However, such information is usually hard to get, especially for global or regional applications, such as inclusion of the land-surface scheme in the GCMs. Therefore, it is important to study the sensitivity of the model performance to the choice of soil depths. Four sensitivity cases were conducted: Case 1, $z_2 = 0.4$ m, with 90% roots in the upper layer and 10% in the lower layer; Case 2, $z_2 = 0.5$ m, with 100% roots in the upper layer; Case 3, $z_2 = 1.1$ m, with 90% roots in the upper layer and 10% in the lower layer; Case 4, $z_2 = 1.1$ m, with 100% roots in the upper layer.

The annual total evaporation (Yr. ET), runoff (Yr. R), the total evaporation for the IOP (IOP ET) and the growing season (from day 148 to day 273) (GS ET), the soil moisture in the 1.6 m soil column at the beginning of the equilibrium year (W at Yr.) and the growing season (W at GS) are listed in Table 1 for the control experiment case (Ctrl. Case) and the above four sensitivity cases with the modified version of VIC-2L. Table 1 also includes their errors (Err) relative to the observations. Since there was no observed soil moisture in the 1.6 m soil layer at the beginning of the control year (i.e., the equilibrium year), the soil moisture on the 7th day of the control year was used to calculate the relative errors. The positive sign in Table 1 indicates that the model-simulated values are smaller than the corresponding observations. The soil moisture in the top thin layer (0.1 m), upper layer (0.5 m), and total layer (1.6 m) from the four sensitivity cases are shown in Fig. 8, and are compared with the control experiment case and also the one year observations. The relative changes of soil moisture in the 1.6 m, top 0.5 m, and top 0.1 m soil column for each case are seen clearly in Fig. 8. Also, it is seen that the changes of soil depths and crop root distribution in each layer have the least effect on the soil moisture in the top thin soil layer, but the largest on the soil moisture in the total soil layer (1.6 m).

In Case 1, it is seen (Table 1) that when the depth of the upper layer is reduced by 0.1 m, the evaporation during the IOP, growing season, and over the year is reduced respectively, and the major decrease occurs during the growing season. This is because soil depth determines the available soil moisture for transpiration. With the decrease of soil depth in the upper layer which contains 90% of the roots, less soil moisture is available for transpiration. The total soil moisture at the beginning of the growing season and the equilibrium year changes insignificantly in this case. Compared with the observations, the relative errors are all less than 8% in this case.

In Case 2, all of the roots are in the upper layer (0.5 m), thus the available soil moisture for crop transpiration is significantly reduced. As expected, the evaporation decreases, especially during the growing season by 47.4 mm compared with the control experiment case (315.6 mm). The effect to the total soil moisture at the beginning of the growing season and the equilibrium year is not significant. The annual total runoff is increased due to the decrease in evaporation. The relative errors in this case are much larger than in Case 1, with the largest being about 20%. The results of Case 1 and Case 2 indicate that the choice of soil depth is not as sensitive as the choice of distribution of crop roots to the evaporation, runoff, and soil moisture.

In Case 3, 90% of roots are in the upper layer, and 10% in the lower layer as in the control experiment case (Shao et al., 1994, p. 30). However, the depth of the upper layer is increased to 1.1 m from 0.5 m in the control experiment case. Therefore, the available soil moisture for the crop roots is increased significantly from the control experiment. Table 1 shows that the transpiration during the growing season increased by about 76 mm from 315.6 mm in the control experiment case. The annual evaporation reaches 672.1 mm, and the annual runoff decreases to 184.4 mm. As the result of the large moisture depletion due to the significant increase in transpiration, it takes longer to recover the total soil moisture. Therefore, the soil moisture at the beginning of the

equilibrium year is drier than the control experiment case. The total soil moisture at the beginning of the growing season in each case, however, does not vary much. This is because the soil moisture is refilled during the bare soil evaporation period. The relative errors are as large as 23% in both the growing season transpiration and annual runoff in this case.

In Case 4, the depth of the soil in each layer is the same as in Case 3, but the crop roots are limited within the top 1.1 m soil layer only. The relative errors are significantly reduced from Case 3, although the growing season transpiration is still overestimated by 9.3% (Table 1).

This sensitivity study indicates that although the available soil moisture for evaporation and runoff is determined by both the root distribution and the soil depth, the evapotranspiration and soil moisture at the model equilibrium state are more sensitive to the root distribution than to the soil depth. If information about the vegetation root distribution is available, reasonable evaporation and soil moisture can be simulated even if there is little information about the model soil depth. In other words, this sensitivity study seems to suggest that the model equilibrium state is more closely related to the crop root distribution than to the soil depths if all of the model parameters are kept the same.

5. Conclusions

The results of the control experiment using HAPEX–MOBILHY data with the modified VIC-2L model show that the addition of the diffusion process to VIC-2L is important to achieve realistic results for the months with low soil moisture. Although the model improvements were tested only using the HAPEX data, it is believed that they should benefit applications to other seasonally dry climates where the difference of soil moisture between soil layers are significant. For humid areas, the addition of the diffusion may not be as important.

Comparisons of the top thin layer and the full upper layer show that the soil moisture dynamics cannot be represented well by an average behavior of the soil moisture from the upper layer. The reason is that the upper layer cannot characterize the quick response that a surface thin layer experienced due to changes in surface conditions.

The use of monthly LAI and fraction of vegetation coverage during the vegetation rapid growing period introduce errors in the time series of evaporation, although the accumulated evaporation amount over a long period are not affected significantly. Therefore, it is necessary to use the time series of LAI and fraction of vegetation coverage if short time series of evaporation are to be simulated.

Finally, evapotranspiration and soil moisture at the model equilibrium state are more sensitive to the root distribution than to the soil depth if all of the model parameters are kept the same, although the available soil moisture is determined by both the root distribution and the soil depth.

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