Modeling soil moisture: A Project for Intercomparison of Land Surface Parameterization Schemes Phase 2(b)

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Abstract. In an intensive investigation of soil moisture simulation in land surface schemes, a number of numerical experiments was conducted with 14 representative schemes and the results compared with Hydrological and Atmospheric Pilot Experiment - Modelization du Bilan Hydrique (HAPEX-MOBILHY) data. The results show that soil moisture simulation in current land surface schemes varies considerably. After adjustment of land surface parameters, the disagreement in soil moisture for a 1.6-m soil layer remains around 100 mm. Correspondingly, the range of variation in predicted annual cumulative evaporation as well as total runoff plus drainage is around 250 mm (annual precipitation being 856 mm for HAPEX-MOBILHY). The partitioning of surface available energy into sensible and latent heat fluxes is closely coupled to the partition of precipitation into evaporation and runoff plus drainage. Although, on average, the range of variation in net radiation is about 8 W m\(^{-2}\), that of both the latent and sensible heat fluxes is twice as large. These disagreements are related to different causes but attempts to establish the link between the outcome and the responsible mechanism has had only limited success to date because of the complex interactions embedded in the schemes. This study implies that different schemes achieve different equilibrium states when forced with prescribed atmospheric conditions and that the time period to reach these states differs among schemes; and even when soil moisture is fairly well simulated, the processes (particularly evaporation and runoff plus drainage) controlling the simulation differ among schemes and at different times of the year. These results suggest that prescription of land surface scheme physics may have to be a function of the type of predictions (short-term weather forecasting, mesoscale modeling or climate ensembles) required as well as the underlying scheme formulation and that scheme simulations must be validated for all components of the prediction.

1. Introduction: PILPS and Soil Moisture Simulation

Budyko [1956] proposed a simple land surface scheme for parameterizing the interaction between the atmosphere and the land surface. The parameterization provides the boundary conditions for global climate models. The last decade has seen a rapid development of more sophisticated schemes and a rapid expansion in their applications in atmospheric, hydrological, and ecological modeling. However, it is in general not clear how reliable the schemes are and whether the host models are sensitive to the accuracy of the parameterizations.

Since 1992, the Project for Intercomparison of Land Surface Parameterization Schemes (PILPS) has been responsible for a number of complementary sensitivity tests [Pitman et al., 1993] for improved understanding of land surface schemes. The progress and future activities of the project are described in detail by Henderson-Sellers et al. [1995]. The science plan time lines of PILPS are as shown in Figure 1.

Because of the critical importance of soil moisture in atmospheric, hydrological, and ecological models, an intensive investigation of soil moisture simulation in land surface schemes was conducted within the framework of PILPS: the Soil Moisture Simulation Workshop (November 14-25, 1994, Macquarie University, Sydney) comprising PILPS Phase 2(b). The main goals of the workshop included the following: (1) quantification of the differences in soil moisture predictions among land surface schemes, and (2) investigation of whether dif-
PILPS SCIENCE PLAN TIMELINES

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Figure 1. PILPS science plan timelines.

Differences occur because of theory, numerical implementation, coding, or choice of parameters. A number of numerical tests were carried out with 14 representative land surface schemes (Table 1) and the outcomes compared with data from the Hydrological and Atmospheric Pilot Experiment – Modelization du Bilan Hydrique (HAPEX-MOBILHY).

It is naïve to expect that such a comparative study should provide detailed explanations for specific features of all schemes, or provide a firm judgment whether one type of parameterization is superior to others. Intercomparison is difficult because:

1. the participating schemes are developed based on different concepts and with different levels of complexity depending on the intended application of the schemes. The schemes can be divided into those for global climate models, Biosphere Atmosphere Transfer Scheme (BATS) [Dickinson et al., 1992], Bare Essentials of Surface Transfer (BEST) [Pitman et al., 1991], Canadian Land Surface Scheme (CLASS) [Verseghy, 1991; Verseghy et al., 1993], CSIRO Soil-Canopy Scheme (CSIRO9) [Kowalczyk et al., 1991], Schématisation des Échanges Hydrauliques Interface Biosphère-Atmosphère (SECHIBA2) [Ducoudre et al., 1993], Simplified Simple Biosphere Model (SSiB) [Xue et al., 1991], Variable Infiltration Capacity scheme (VIC) [Liang et al., 1994], bucket (BUCKET) scheme [Manabe, 1969]; for mesoscale models, Interaction Soil Biosphere Atmosphere (ISBA) [Noilhan and Planton, 1989], Land Surface Parameterization Scheme (LAPS) [Mihailovic et al., 1993], Parameterization for Land-Atmosphere-Cloud Exchange (PLACE) [Wetzel and Boone, 1995]; and for ecological models, Biogeochemical scheme (BGC) [Running and Hunt, 1993], Biome scheme (BIOME2) [Haxeltine et al., personal communication, 1994], and CENTURY [Parton et al., 1993]. Each scheme is intended to capture the important aspects of complicated land surface processes relevant to the host model. It is virtually impossible for the individuals responsible for analyzing the results to understand all the details of all schemes.

2. The schemes have a different history in their development. Some schemes are mature and well tested, while others may need further tests and adjustment.

3. More fundamentally, land surface schemes are systems of coupled nonlinear differential equations. The nonlinearity of the schemes makes it very difficult to...
determine the causality between the scheme outcome and the scheme details.

However, the PILPS Phase 2(b) study is important in determining the degree of disagreement among the bulk of participating schemes, identifying the areas where improvements are required and providing stimulating suggestions for possible improvements. Certain behavioral aspects of the schemes can be explained to some extent. It must be recognized that this work, as part of PILPS, represents a process for scheme improvement. Through their involvement in the process, the scheme developers identify specific problems in their schemes and develop strategies for improvement. A large number of examples demonstrate the importance of this process. These specific problems, such as errors in coding, inadequate parameterization and inadequate scheme structure, are different in nature. Therefore it is inappropriate to discuss these problems in the present paper; instead, they must be addressed separately (e.g., Special Issue of Global and Planetary Change, edited by Henderson-Sellers [1995]).

This paper documents the general results obtained in the Soil Moisture Simulation Workshop. Section 2 summarizes the basic differences in theory among schemes, which provides a basis for the design of the experiments and the interpretation of results. In sections 3 and 4, respectively, the HAPEX-MOBILHY data set and the numerical experiments are described. The results are presented in section 5 and the conclusions are in section 6.

2. Theory of Soil Moisture Simulation in Land Surface Schemes

The basis of all schemes tested in this study is the one-dimensional conservation equations for temperature and soil moisture

\[
\begin{align*}
\frac{\partial \theta}{\partial t} &= -\frac{1}{C} \frac{\partial G}{\partial z} \\
\frac{\partial w}{\partial t} &= \frac{1}{\rho_w} \frac{\partial Q}{\partial z} + s_w
\end{align*}
\]

(1)

where \( \theta \) is soil temperature, \( C \) is volumetric soil heat capacity, \( w \) is volumetric soil water content, \( \rho_w \) is the density of liquid water, and \( s_w \) is a sink term which includes runoff and transpiration. (The temperature sink term is zero, if there is no phase change in the soil water). The vertical heat flux, \( G \), obeys a simple flux-gradient relationship, and the vertical soil water flux, \( Q \), obeys Darcy's law. A land surface scheme is the algorithm required to solve this system of equations for a particular soil layer configuration. The parameterizations occur in the boundary conditions and in the treatment of the sink terms. The upper boundary conditions at the atmosphere and land surface interfaces include sensible and latent heat fluxes.

It is not helpful to discuss all the detailed differences among a large number of schemes, because it is impossible to determine the effect of these differences on the overall performance of the schemes which consist of complicated nonlinear interactions between many components. Nevertheless, the differences in scheme configuration and those in parameterization of individual components are the two major categories of differences worthy of consideration.

2.1. Structural Differences in Soil Moisture Simulation

The structural differences are mainly reflected in the number of soil layers, canopy layers, and the linkage between various components of a scheme. Most schemes use a single layer canopy treated as a "big leaf," except the bucket model which does not have a canopy component. Thus as far as soil moisture simulation is concerned, the major difference in model structure lies in the number of soil layers.

Conceptually, the schemes can be considered as bucket-type single-layer schemes, force-restore-type two-layer schemes and diffusion-type multilayer schemes. Schemes developed for ecological purposes may not fall into these categories.

Single soil layer models. The water balance equation for the active soil layer of depth \( d \) (often assumed to be 1 m) is the integrated form of (2)

\[ \rho_w \frac{dW}{dt} = P_r - E - R - D_r \]  

(3)

where \( W \) is soil moisture averaged over depth \( d \), \( P_r \) is precipitation rate, \( E \) is evaporation, \( R \) is runoff, and \( D_r \) is drainage. Single layer models have two distinct features. First, runoff is commonly assumed zero if soil moisture is smaller than a critical value \( W_c \), but equals the surface water flux if the soil moisture is larger than \( W_c \). Second, there is a direct feedback between evaporation and soil moisture of the total soil layer, and the hydraulic diffusion process which influences the distribution of water within the soil layer and the availability of soil water for evaporation is ignored. Consequently, rapid fluctuations in evaporation and surface soil moisture cannot be accurately described.

Force-restore models. A two-layer force-restore model has a thin top layer of depth \( d_1 \) and a total soil layer of depth \( d_2 \). The prognostic equations for soil moisture in the two layers are

\[
\begin{align*}
\frac{\partial W_1}{\partial t} &= -C_1 \frac{E_g - P_r}{\rho_w d_1} - C_2 \frac{W_1 - W_{1s}}{\tau} \\
\frac{\partial W_2}{\partial t} &= -E_{tr} - P_r \frac{E_{tr} + P_r}{\rho_w d_2}
\end{align*}
\]

(4)

where \( W_1 \) and \( W_2 \) are soil moistures in the top and the deep soil layer, respectively, and \( W_{1s} \) is that when gravity balances the capillary force; \( E_g \) is evaporation from the bare ground and \( E_{tr} \) is the transpiration rate; \( C_1 \) and \( C_2 \) are coefficients and \( \tau \) a time constant of 1 day. The force term \((-C_1(E_g - P_r)/\rho_w d_1)\) describes the
rapid response of \( W_1 \) to precipitation and evaporation and the restore term \( (C_2(W_1 - W_{eq})/\tau) \) describes the supply of soil moisture from the deep soil layer which responds slowly to the atmospheric forcing.

In contrast to the bucket model, the force-restore model has two distinctly different time scales in soil moisture simulation and a profoundly different feedback between evaporation and soil moisture. In addition, the force-restore model allows runoff from the surface, the top soil layer and the deep soil layer and the simulation of soil moisture is now coupled with the canopy transpiration process. The force-restore method is used in CSIRO9 and ISBA.

**Multilayer diffusion type models.** Most multilayer schemes have three layers which give a better resolution of root distribution and better handling of the recharging flow from deep soils. The evolution of the depth averaged soil moisture of soil layer \( i \) obeys the integrated form of (2)

\[
\frac{dW_i}{dt} = \frac{Q_i - Q_{i-1}}{\rho_w d_i} + \frac{S_{W_i}}{\rho_w} \tag{6}
\]

where \( S_{W_i} \) is vertically integrated for layer \( i \), which includes the water loss via transpiration and horizontal runoff; the moisture fluxes between the soil layers are determined (in principle) by Darcy's law. Among the schemes tested in the workshop, BATS, BEST, CLASS, LAPS, and SSSB use the diffusion method for moisture in a three-layer soil and PLACE solves the Richards' equation in a five-layer soil. The treatment of the sink term is important, because it not only involves the distribution of roots in soil layers, but also the relationship between canopy transpiration and horizontal runoff.

**Other soil moisture schemes.** VIC [Liang et al., 1994] uses two soil layers for soil moisture simulation, but the upper layer is designed to represent the dynamic behavior of the soil that responds to rainfall events, and is thicker (0.5 m) than the upper layer in the force-restore models. The lower layer is used to characterize the seasonal soil moisture behavior. Roots can be specified for both layers. Water can flow from the upper layer to the lower layer, but there is no upward moisture flux between the two soil layers.

SECHIBA2 uses a two-layer soil model in which the depth of the layers evolves through time. This evolution is driven by the "top-to-bottom" filling (due to precipitation) and drying (due to evapotranspiration) algorithm described by Choisnel [1984]; no explicit diffusion is allowed either between the two layers or at the bottom of the soil, so that it is equivalent to a bucket for runoff and drainage.

In BGC, BIOME2, and CENTURY, water can flow from the upper layer(s) to the lower layer(s) but there is no upward moisture flux within the soil. The water content in each layer is calculated by the water budget of the layer at each time step. The number of layers is two in BIOME2 (similar to VIC), three in BGC (similar to BATS), and up to eight in CENTURY.

### 2.2. Soil Moisture and Soil Temperature

The treatment of the interaction between soil moisture and soil temperature depends very much on the structure of each scheme. For a bucket model, the vertically integrated conservation equation for soil temperature can be simplified to

\[
\frac{\partial T}{\partial t} = \frac{R_n - H - \lambda E}{C_d} \tag{7}
\]

assuming the heat flux at the lower boundary of the soil layer is zero, where \( R_n \) is net radiation, \( H \) is sensible heat flux, and \( \lambda \) is the latent heat of vaporization. Therefore for a bucket model, evaporation is the major pathway for coupling soil moisture and soil temperature.

For schemes with more than one soil layer and explicit treatment of canopy processes, the interaction between soil moisture and soil temperature is very complicated. Although evapotranspiration remains the pathway for interaction, it now involves a canopy water reservoir, transpiration and differences in canopy, and bare soil albedo. It is difficult in general to identify how this interaction will impact on the performance of a scheme, because of the nonlinear relationships involved.

#### 2.3. Differences in Parameterization

Evaporation, transpiration, and runoff plus drainage determine the soil moisture budget and these components are parameterized very differently in the participating schemes.

**Evaporation.** It is assumed in all schemes that evaporation is proportional to a scaling evaporation, \( E_p \). One method of calculating the potential evaporation is the aerodynamic resistance formulation

\[
E_p = \rho (q_{sat} - q_a)/r_a \tag{8}
\]

where \( \rho \) is air density, \( r_a \) is aerodynamic resistance, \( q_{sat} \) is saturation specific humidity and \( q_a \) is the specific humidity of air. BATS, BEST, BUCKET, ISBA, LAPS, CLASS, PLACE, SSSB and SECHIBA2 use the aerodynamic formulation for calculating the potential evaporation. CSIRO9, BGC, VIC and CENTURY use the Penman-Monteith formulation and BIOME2 uses the Priestley-Taylor formulation. The Priestley-Taylor, the Penman-Monteith, and the aerodynamic formulations are not fundamentally different. The Penman-Monteith formulation assumes that the aerodynamic resistance for heat transfer and evaporation is identical and takes into account the effect of advection on evaporation. It reduces to the Priestley-Taylor formulation, if the advective effect is neglected. \( E_p \) estimated from the Penman-Monteith formulation is somewhat smaller than that estimated by using (8) [e.g. Garratt, 1992, chapter 5].

For unsaturated soils, the actual evaporation, \( E_g \), differs from the potential evaporation. Three methods, the \( \alpha \) method, the \( \beta \) method and the threshold method, are
commonly used for its calculation:

\[
E_g = \begin{cases} 
\frac{\rho(\alpha q_{sat}(T_g) - q_a)}{r_a} & \alpha \text{ method} \\
\beta E_p & \beta \text{ method} \\
\min\{E_p, E_c\} & \text{threshold method}
\end{cases}
\]

where \( \alpha \) and \( \beta \) are functions of soil moisture. The threshold formulation implies that evaporation proceeds at the potential rate until the soil moisture is sufficiently depleted, then evaporation is determined by the water flux from the soil \( E_c \). The \( \alpha \) and \( \beta \) formulations have the same physical interpretation as the threshold formulation and can be reduced to the latter if \( \alpha \) and \( \beta \) are adequately chosen (e.g., \( \alpha = \exp(-\psi - g) \) with \( \psi_g \) being the soil water potential of the top soil layer, \( \beta = 1 \) for \( E_p < E_c \) and \( \beta = E_c/E_p \) for \( E_p \leq E_c \)). The difference in evaporation schemes, therefore, lies in the estimation of \( \alpha \), \( \beta \) and \( E_c \).

Among the 14 schemes, BATS, PLACE, and BIOME2 use supply and demand formulation; BEST, BUCKET, CSIRO9, SECHIBA2, VIC, and CENTURY use the \( \beta \) formulation, while ISBA, LAPS, SSiB and CLASS use the \( \alpha \) formulation.

**Transpiration.** Transpiration is a physiological process associated with photosynthetic activities, which involves the transfer of water from soil through the roots, stems, branches, and leaves. The parameterization of transpiration is achieved by introducing a canopy resistance as a measure of the effectiveness of moisture transfer. For fully vegetated surfaces, transpiration is described by

\[
E_{tr} = \frac{\rho(q_{sat}(T_c) - q_a)}{(r_a + r_{st})}
\]

with \( r_{st} \) being the bulk stomatal resistance or bulk canopy resistance.

In most of the schemes, the stomatal resistance of a leaf, \( R_{st} \), is calculated and the bulk stomatal resistance, \( r_{st} \), is obtained by assuming that

\[
r_{st} = R_{st}/LAI
\]

where \( LAI \) is leaf area index. \( R_{st} \) is modified from a minimum leaf stomatal resistance by considering several constraints. For instance, the expression used in ISBA [Noilhan and Planton, 1989] is

\[
R_{st} = R_{st,min}F_1F_2^{-1}F_3^{-1}F_4^{-1}
\]

where \( F_1, F_2, F_3 \) and \( F_4 \) are, respectively, functions representing the effects of photosynthetically active radiation, soil moisture, vapour pressure deficit of the atmosphere, and air temperature on the stomatal resistance. More functions can be used in the above expression if more constraints are to be applied.

Depending on how the functions are specified, the expression for stomatal resistance can be very different. More importantly, depending upon how this parameterization is implemented in a specific scheme, a
comparison of transpiration becomes extremely difficult [Mahfouf et al. 1995].

Runoff and drainage. Runoff plus drainage is closely connected with the configuration of the soil layers. As illustrated in Figure 2, the schemes tested in this study can be divided into four groups. SECHIBA2 and the bucket model are the one-layer models with only one drainage process and a pseudosurface runoff; BEST, BIOME2, CSIRO9, ISBA, and VIC are two-layer models with flow out from the sides and/or the base; BGC, BATS, CLASS, LAPS, and SSiB are three-layer models with disparate boundary conditions; and CENTURY and PLACE have more than three layers, also with disparate boundary conditions. Some schemes with two or more layers explicitly include moisture diffusion between soil layers, while others (BGC, BIOME2, CENTURY, and VIC) do not permit upward diffusion.

In terms of the drainage and subsurface flow formulations, the 14 models can be classified into two major types: those keyed to values of intermediate soil moisture (field capacity and/or wilting point) and those which apply a (continuous) nonlinear function relating soil moisture to key diffusive parameters such as hydraulic conductivity and water potential [Wetzel et al., 1995]. While most schemes key their drainage to field capacity, PLACE and VIC allow the soil to drain without limit, with an asymptotic approach to zero soil moisture during a very long dry period. The nonlinear soil water functions vary widely from model to model, including empirical relationships derived from large-scale catchment hydrology, soil column studies, laboratory work, and theory.

3. The HAPEX-MOBILHY Data Set and Surface Parameters

3.1. The Data Set

The HAPEX-MOBILHY data set, which forms the basis of the verification, is chosen for the following three reasons:

1. A data set needs to offer long periods (years) of high-resolution measurements of atmospheric fluxes, atmospheric forcing, soil moisture, hydrological fluxes, biomass accumulation and surface properties (soil type, vegetation, and surface aerodynamic properties). The HAPEX-MOBILHY data set is reasonably complete and is of relatively high quality.

2. The HAPEX-MOBILHY data set can be used by all schemes without great numerical difficulties.

3. Two of the workshop participants (J. Noilhan J.-F. Mahfouf) have many years of experience with the data set and detailed understanding of its accuracy and reliability.

The HAPEX-MOBILHY data set consists of weekly soil moisture measurements down to 1.6 m at 0.1-m intervals and energy flux measurements during the Intensive Observation Period (May 28 to July 3, 1986) together with a full year’s atmospheric forcing measurements, including downward shortwave radiation, downward infrared radiation, precipitation, air temperature, wind speed, surface pressure, and specific humidity. Details of the data set are given in a series of publications documenting the HAPEX-MOBILHY experiment [e.g., Goutorbe et al., 1989; Goutorbe and Tarrieu, 1991; Goutorbe, 1991].

The HAPEX-MOBILHY data used in this study have been prepared by J.-F. Mahfouf and J. Noilhan, and have been used on several occasions for calibration of ISBA by, for instance, Mahfouf [1990] and Jacquemin and Noilhan [1990].

The data were obtained from HAPEX-MOBILHY at Caumont (Samer 3, 43°41' N, 0°6' W, mean altitude 113 m). Detailed information on the SAMER network and the site can be found in work by Goutorbe [1991]. Most of the forcing data were taken from Caumont, particularly during the Intensive Observation Period. If data at Caumont were missing, measurements from neighbouring meteorological stations were used. Therefore the forcing data may not be fully consistent with the validation measurements for short and intermittent time periods. However, this inconsistency in the data should not have a significant effect on the intercomparison and validation of land surface schemes.

The chosen location is a soya crop field. Soya plants start to grow in May and are harvested at the end of September. Although HAPEX-MOBILHY was conducted in a heterogeneous area, the immediate surroundings of Caumont can be considered as uniform on a scale of several hundred metres. For the HAPEX-MOBILHY area at large, surface fluxes reveal the signature of the two main ecotypes: coniferous forest and crops (Samer 3 represents one of the crops). Analysis of soil moisture also splits soil texture into two broad categories: sand and loam. The soil type at Caumont is loam. The parameters used for characterizing the land surface are summarized in the instructions for experiment 1 (see appendix).

For schemes with two or more layers, a quantitative description of root distribution is necessary. HAPEX-MOBILHY data do not include observations of roots. Thus the quantification of root distribution cannot be based on measurements but on the experience that soya plant has its root system concentrated in the first 0.5 m of soil. The crop height and zero displacement height are also empirically derived, but land surface schemes are insensitive to these two parameters. Albedo is based on radiative measurements which revealed a nearly constant value of 0.2 during the year.

The measurements of soil moisture were made using neutron sounding probes, every week at every 0.1 m from the surface down to 1.6 m. Details of soil moisture measurements using neutron probes, including theory, sensor calibration, and data manipulation are as described by Cuenca and Noilhan [1991].

Various terms of the surface energy balance recorded...
by the SAMER station every 15 min are available for the Intensive Observation Period at Caumont. Net radiation, ground heat flux, and sensible heat fluxes are directly measured, while the latent heat flux is the residual term required to close the surface energy budget. According to the assessment of Goutorbe [1991], the accuracy of the flux measurements is possibly around 15% at short time scales and around 10% at longer timescales (for instance, monthly).

The data set is not fully self-consistent, in particular between soil moisture and evaporation measurements. From the water budget equation, the cumulative evaporation can be expressed as

$$\int_{t_0}^{t} Edt = \int_{t_0}^{t} P_r dt - \int_{t_0}^{t} dm \quad (12)$$

if runoff plus drainage is negligible (which is possibly true for the Intensive Observation Period), where $E$ is evaporation, $P_r$ is precipitation and $m$ is the total amount of water in the soil layer. Figure 3 compares the cumulative evaporation estimated from the above equation with that estimated from the latent heat fluxes. The inconsistency amounts to 25 mm for the intensive observation period.

3.2. The Parameters

The parameters used in this work are given in the appendix and it suffices here to make two comments. Monthly mean leaf area index (LAI), fractional vegetation cover (FVEG), overall surface roughness length ($z_0$), canopy roughness length ($z_{dc}$), zero displacement height ($z_d$), and the height of canopy ($h_c$), are as specified in the appendix. These quantities are interpolated to smaller time intervals when required (see section 4).

The roots of soya plants were assumed to be shallow and are distributed mainly in the top 0.5 m. The year was divided into the bare soil period (January to April, October to December), the transition period (May) and the growing season (June to September). For the bare soil period, there were no roots; for the transition period, it was assumed that the top 0.1-m soil layer contains 70% of the roots and the soil layer between 0.1 to 0.5 m contains the rest, that is, 30%; for the growing season, 60, 30 and 10% roots were assumed to be in the soil layers 0-0.1 m, 0.1-0.5 m, and 0.5-1.6 m, respectively.

4. Numerical Experiments

Fifteen numerical experiments conducted for the workshop are listed in Table 2. The details about the design, purpose, and rationale of these experiments are reported by Shao et al. [1995]. A land surface scheme is understood as comprising three basic components for the treatment of bare soil transfer processes, canopy transfer processes, and soil thermal and hydraulic processes. A control experiment was conducted, followed by three other types of experiments: bare soil evaporation tests (experiments 2a1 and 2a2), sensitivity test for drainage (experiment 2c, 2c1) and transpiration test (experiment 3), in an attempt to compare the three basic components of land surface schemes. For the purpose of this study, it is sufficient for us only to describe the control experiments, experiment 2c and 2c1 in some detail.
Table 2. List of Numerical Experiments Conducted for the Soil Moisture Workshop

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Control experiment with preworkshop version of schemes</td>
</tr>
<tr>
<td>2a</td>
<td>Comparison of bare soil evaporation formulations</td>
</tr>
<tr>
<td>2b</td>
<td>Comparison of evaporation and top layer soil moisture feedback</td>
</tr>
<tr>
<td>3</td>
<td>Comparison of transpiration formulations</td>
</tr>
<tr>
<td>4</td>
<td>Comparison of soil hydraulic treatment for bare soil</td>
</tr>
<tr>
<td>5</td>
<td>Comparison of soil hydraulic treatment for vegetated soil</td>
</tr>
</tbody>
</table>

**Preworkshop Experiments**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Control experiment with surface aerodynamic parameters specified for every time step</td>
</tr>
<tr>
<td>12</td>
<td>Control experiment with wilting soil moisture set as the minimum soil moisture measured in top 0.5-m soil layer</td>
</tr>
<tr>
<td>13</td>
<td>Control experiment with a new set of soil hydrological parameters</td>
</tr>
</tbody>
</table>

**During-workshop Experiments**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>Sensitivity test for leaf area index</td>
</tr>
<tr>
<td>15</td>
<td>Control experiment with updated version of schemes</td>
</tr>
<tr>
<td>2a1</td>
<td>Comparison of bare soil evaporation formulations in updated schemes</td>
</tr>
<tr>
<td>2a2</td>
<td>Comparison of bare soil evaporation with specified drag coefficient</td>
</tr>
<tr>
<td>2c</td>
<td>Sensitivity test for drainage parameterization</td>
</tr>
<tr>
<td>2c1</td>
<td>Sensitivity test for drainage parameterization</td>
</tr>
<tr>
<td>31</td>
<td>Comparison of evapotranspiration formulations in updated schemes</td>
</tr>
<tr>
<td>6</td>
<td>Sensitivity test for transpiration</td>
</tr>
</tbody>
</table>

4.1. Control Experiments (Experiments 1, 11, 12, and 13)

Among these experiments, experiment 1 is the pilot control experiment, while experiments 11, 12, and 13 are the improved ones conducted after a preliminary analysis of experiment 1. The purposes of the control experiment are to quantify the differences among the schemes, to verify the simulations against observations and to provide a reference for the other experiments conducted as part of the workshop.

Experiment 1 was first compared with the HAPEX-MOBILHY data and it was found that the disagreement between the simulations and the observations can be reduced if more strictly specified parameters for the land surface are chosen (see section 6). Experiments 11, 12, and 13 were carried out for this purpose.

**Experiment 11.** In experiment 1, the aerodynamic properties of the surface were specified by the monthly averages of leaf area index, aerodynamic roughness length, zero-displacement height, and fractional vegetation cover. The low resolution of the aerodynamic parameters (specified for every month) is inconsistent with the high resolution of the atmospheric forcing data (specified every 30 min). Several schemes, especially those for ecological models, were found sensitive to the resolution of leaf area index.

In experiment 11, the above aerodynamic parameters are specified for every time step under the assumption that LAI and vegetation height increase linearly in the first two months of the growing season with the maximum LAI being 4 and vegetation height being 1 m. The fractional vegetation cover \( f_{\text{veg}} \) is derived from LAI using the relationship,

\[
f_{\text{veg}} = 1 - e^{-c \text{LAI}}
\]

where the coefficient \( c \) is set to 0.6 which is appropriate for soya crops. The aerodynamic roughness length and zero displacement height are derived from LAI and \( h \) from the empirical relationships suggested by Raupach \[1994\].

**Experiment 12.** For several schemes, the choice of wilting point, \( W_{\text{wilt}} \), strongly influences soil moisture prediction. In experiment 1, \( W_{\text{wilt}} \) is assumed to be 0.2 \( m^3/m^3 \) which corresponds to the observed minimum soil moisture averaged over the total 1.6 m soil layer. However, the observed minimum soil moisture averaged over the top 0.5-m soil layer, which is assumed to contain most of the roots (90% is assumed in the experiments), was less than 0.2 \( m^3/m^3 \). Experiment 12 is the same as experiment 11, except that \( W_{\text{wilt}} \) is assumed to be 0.12 \( m^3/m^3 \) corresponding to the observed minimum soil moisture in the top 0.5-m soil layer.

**Experiment 13 and 14.** Since soil moisture in the
top soil layers may be influenced by evaporation, it was estimated based on work by Cosby et al. [1984] that the most appropriate value for $W_{wilt}$ for the HAPEX-MOBILHY experiment site is 0.15 m$^3$/m$^3$. On the basis of the soil texture, taken at the Caumont site (sand, 37%; silt, 46%; clay, 17%), the multiple linear regression analyses described by Cosby et al. [1984] were used to determine soil water potential, saturation soil water potential and saturation soil hydraulic conductivity. The soil hydraulic parameters used for experiment 13 are as specified in the appendix. Experiment 14 is as experiment 13 but with halved leaf area index.

4.2. Sensitivity Test for Drainage (Experiment 2c, 2c1)

Soil moisture is determined by precipitation, evaporation, and drainage. The different treatments of drainage in land surface schemes may lead to profound differences in soil moisture. Experiments 2c and 2c1 are drainage sensitivity tests in which the amount of drainage and the residence time of water in the soil layers are investigated. Experiments 2c and 2c1 are performed for the HAPEX-MOBILHY bare soil period (first 120 days) with the surface and soil parameters as specified for experiment 13. Evaporation was assumed to be zero, and precipitation was assumed to be 5 and 10 times that of the observed values for experiment 2c and 2c1, respectively. Detailed results from these experiments are reported by Wetzel et al. [1995].

5. Results

In this section, a quantitative assessment of soil moisture simulation by the participating schemes is provided. The importance of this work lies in the investigation of the disagreement, and thus the assessment of the capability of land surface schemes for soil moisture simulation. Several general problems are discussed, such as the energy and soil moisture budget, scheme equilibration and scheme sensitivity to the choice of parameters. The details of individual schemes are not reviewed, since they are discussed in detail in a series of papers to be published elsewhere. Most of the conclusions are based on experiment 13 (Table 2), the final control experiment of the workshop, since the results of experiment 2a1, 2a2, 2c, 2c1 and 3 have been discussed by Mahfouf et al. [1995], Wetzel et al. [1995] and Desborough et al. [1995]. The results from LAPS are excluded from discussion because of numerical difficulties, but have been adequately discussed by Mihailovic and Rajkovic [1995].

5.1. Different Schemes, Different Predictions

The results show that the different schemes produced profoundly different predictions of soil moisture. The predicted total soil moisture for the 1.6-m soil layer from experiment 13 is compared with the HAPEX-MOBILHY measurements in Figure 4, with ±10% error margins. (The error margins are indicative, but according to previous studies [e.g., Mahfouf, 1990; Cuenca and Noilhan, 1991] the ±10% error margins for the soil moisture measurements are not unreasonable). In comparison with the HAPEX-MOBILHY measurements, all schemes correctly describe the annual cycle of soil moisture variation in a qualitative sense: because of frequent rainfall and low evaporation, the soil remains wet for the first four months of the year with the soil moisture close to the field capacity; as precipitation decreases and the available energy for evaporation increases, the soil water decreases at the beginning of the growing season (early May) and the soil is driest between August
and October; and after October the soil becomes increasingly wet. However, Figure 4 reveals a significant quantitative disagreement among schemes and with observations. Soil moisture predictions from five schemes (BATS, BIOME2, BGC, ISBA, and VIC) are in the best agreement with observations for most times of the year. For the bare soil seasons, the disagreement between the schemes is approximately 70 mm, while during the growing season, the disagreement between the schemes is approximately 100 mm. Compared with HAPEX–MOBILHY observations, most schemes under-predict soil moisture for most times of year, especially for the growing season.

The comparison of soil moisture in the root zone is illustrated in Figure 5. Again, there is broad agreement between predictions and observations. One out-
Figure 7. Net radiation, sensible heat flux, latent heat flux, and ground heat flux predicted by BATS from experiment 13 against those from HAPEX-MOBILHY observations.

Standing feature of Figure 5 is that, in contrast to total soil water content, most schemes overpredict root zone soil moisture for the growing season. For the top 0.1-m soil layer (not shown), both the simulations and the measurements contain more high-frequency fluctuations which make validation more difficult.

The results shown in Figures 4 and 5 imply that, for the growing season, the majority of schemes underpredict soil moisture for deep layers (below 0.5 m), while overpredicting soil moisture for the upper layers (above 0.5 m). It is possible to hypothesize that the distribution of roots for many of these schemes may have been specified inappropriately, with too many roots in the deep soil and too few roots in the top soil. It can also be speculated that too much upward diffusion of soil moisture is responsible for the poor simulation. However, a quick examination of BATS, BIOME2, BGC, ISBA, and VIC shows that these schemes may have produced “good” moisture prediction for different reasons: BIOME2, BGC, and VIC do not allow upward diffusion (Figure 2), BATS has specified zero roots in its deep layer (0.5 to 1.6 m), while ISBA is a two-layer scheme (0-0.1 m and 0.1-1.6 m). On the other hand, schemes which produce soil moisture simulations in less good agreement with the observations appear to be responding to a range of causes.

The schemes which predicted soil moisture in good agreement with observations do not necessarily predict energy fluxes also in agreement with observations, while schemes which predicted soil moisture in poor agreement with observations may predict energy fluxes much better. As an example, Figure 6 compares the half-hourly averages of surface energy fluxes predicted by BATS for the first 20 days of the Intensive Observation Period with the HAPEX-MOBILHY measurements. Despite the excellent soil moisture prediction throughout the year, in particular for the Intensive Observation Period, the quantitative disagreement between the predicted and observed energy fluxes is obvious, apart from net radiation (Figure 7). Several more examples for comparing energy fluxes are shown in Figure 8. Likewise, the good soil moisture prediction by VIC is accompanied by the relatively poor prediction of fluxes. On the other hand, the best agreement between predicted and observed energy fluxes is given by CSIRO9, while the agreement between its soil moisture and observations is less satisfactory, in particular for the top 0.5-m soil layer. It will be recalled that the HAPEX-MOBILHY data are not fully self consistent as shown in Figure 3 which indicated a higher than expected evaporation. The self inconsistency of the observed data, obviously contributed to, but cannot be used to fully explain, the dilemma encountered above.

5.2. Different Schemes, Different Budget

Water budget. The soil moisture budget equation for the total soil layer can be rewritten explicitly as

$$\rho_w \frac{dW}{dt} = P_r - E - R - D_r \quad (14)$$

All schemes tested here model the transfer of energy and water in one (vertical) dimension. This one-dimensional
assumption is valid if soil properties in the horizontal direction are reasonably homogeneous. Although the one-dimensional assumption, strictly speaking, requires that runoff (divergence of horizontal water flux) becomes zero, all schemes employ an ad hoc runoff term for soil moisture adjustment.

An integration of the water budget equation from time $t = 0$ to $t$ gives

$$m(t) - m(0) = IP_r(t) - IE(t) - IR(t) - ID_r(t)$$

where $IP_r(t) = \int_0^t P_r dt$ is the time integral of $P_r$ and $IE, IR$ and $ID_r$ are the integrals of $E, R$ and $D_r$, respectively. Since the simulated results are for the equilibrium year, we have

$$IE + (IR + ID_r) = IP_r$$

Figure 8. Sensible and latent heat fluxes predicted by CLASS, CSIOR9, SSiB, and VIC from experiment 13 plotted against HAPEX-MOBILHY observations.
if the integration is performed for 1 year.

Figure 9 shows that most schemes conserve water well. The variation of soil moisture with time is consistent with the soil moisture curves shown in Figures 4 and 5: there is an increase in soil moisture for the first 4 months, a depletion of soil moisture during the growing season, and an increase in soil moisture in the later part of the year.

However, more detailed analysis reveals that, although land surface schemes can simulate reasonably well at least the annual cycle of soil moisture variation, the soil moisture budget is achieved in very different ways. More precisely, the partitioning of precipitation into evaporation and runoff plus drainage is very different in different schemes. Some schemes achieve soil moisture simulation through large evaporative fluxes, while others have large runoff and drainage components.

The cumulative precipitation for HAPEX-MOBILHY is shown in Figure 10 (the annual total is 856 mm). Figure 11 shows the integration of total runoff (including surface and subsurface runoff) and drainage from the bottom of the soil layer with time, namely \((IR + IDr)\).
Figure 11 reveals a significantly different treatment of runoff plus drainage among the participating schemes. The total runoff and drainage difference among the models is as large as 200 mm for the year, varying from 100 to 300 mm. BGC, VIC, SECHIBA2, and BIOME2 predict the largest amount of runoff among all schemes, while BEST predicts the smallest. The 200-mm disparity occurred foremost in the first 4 months of the year and after this there is almost no change in the relative dispersion of the schemes. This result implies that the parameterizations used by different schemes are extremely different when the soil is wet.

A similar technique is applied to determine the annual evaporation as shown in Figure 10. Figure 10 shows a significant disagreement in the modeling of evapotranspiration which amounts also to about 200 mm. This result is consistent with Figure 11. Schemes with high runoff plus drainage (BGC, VIC, and BIOME2)
have the smallest amount of evaporation, while those schemes with small runoff and drainage (CSIRO9 and BEST) have the highest evaporation.

The partitioning of total precipitation into total evapotranspiration and total runoff plus drainage is shown in Figure 12 where $IE$ is plotted against $IR + IDr$. As can be seen from (16), all models should fall on a single line with a $-1$ slope and an intercept equal to the prescribed total precipitation, if they have the correct water budget. All schemes should map onto a single point if they have the same water partitioning. Figure 12 shows clearly that differences in water partitioning between models is extremely large.

**Surface Energy Budget.** Another partitioning in land surface schemes is that of the surface available energy into sensible and latent heat fluxes. Figures 13, 14, and 15 show the individual terms of the energy budget equation. Figure 13 shows that there is a reasonable agreement in the net radiation, and the scatter among most schemes is about 10 W m$^{-2}$ (CLASS has somewhat higher net radiation), due primarily to differences in surface radiative temperatures. There is a more profound difference in energy loss through sensible and latent heat transfer (Figures 14, 15). Figure 16 shows that the differences in the annual mean of sensible and latent heat fluxes are approximately 20 W m$^{-2}$. It is
easily understood from the energy budget equation that the annual mean sensible and latent heat fluxes should scatter along a diagonal straight line as indicated in Figure 16. Since schemes are in equilibrium with atmospheric forcing, the annual mean of the ground heat flux is zero and the surface energy budget equation is

\[ \overline{H} = -\overline{\lambda E} + \overline{R_n} \]

where the overbar represents an annual mean. Hence, \( \overline{H} \) and \( \overline{\lambda E} \) have a linear relationship, with the intercept being \( \overline{R_n} \) and a slope of -1. The scatter among the schemes can only be related to the difference in the available energy, \( \overline{R_n} \). The difference in \( \overline{R_n} \) is determined by the difference in surface radiative temperature, because albedo is specified as 0.2 for all schemes.

It is important to realize that the partitioning of sensible heat and latent heat fluxes is closely related to that of runoff plus drainage and evaporation: schemes with high runoff plus drainage inevitably result in low evaporation and high sensible heat flux, while schemes with low runoff plus drainage and high evaporation result in low sensible heat flux. The correlation between runoff plus drainage and sensible heat flux is positive. Thus surface energy fluxes can never be correctly predicted, unless the runoff plus drainage is correctly predicted. Despite these relationships between runoff plus...
drainage, evaporation and sensible heat flux, the link between these three quantities probably differs among the schemes. However, it is reasonable to suggest that different treatments in runoff plus drainage in different schemes is a key problem which leads to the differences in the energy partitioning.

5.3. Different Schemes, Different Equilibria

As can be seen from the soil moisture values shown in Figures 4 and 5, and indeed from any other variable, the disagreement among schemes starts from Day 1. This disagreement, together with all the other differences discussed above, reflects the different equilibrium status of a land surface scheme.

For the off-line tests, as considered here, land surface schemes are basically a set of discretized partial differential equations. Initial conditions required for the schemes are often not available. The approach taken in this study to avoid this problem is to allow all schemes to reach an equilibrium with the prespecified atmospheric forcing. In other words, the atmospheric forcing acts as a periodic force (with a 1-year period) and is applied repeatedly until all prognostic variables have the same behavior as for the previous year. The results presented in the previous sections are for the equilibrium year.

There are two reasons for looking at equilibrium results: (1) that it is necessary to remove the results from arbitrary initial conditions (in this case, fully saturated moisture stores) and (2) because the different equilibrium states reflect the intrinsic behavior of a scheme.

The definition of equilibration of land surface schemes needs continued refinement. In principle, equilibrium of a system should be defined according to the prognostic quantities. Therefore different criteria are required for schemes with different prognostic equations. Schemes with five prognostic equations require more parameters to describe equilibration than schemes with one prognostic equation. Yang et al. [1995] defined the equilibrium as

\[ \bar{X}(n+1) - \bar{X}(n) < 0.1 \text{W m}^{-2} \]

where \( \bar{X} \) is the annually averaged sensible or latent heat flux, and \( n \) denotes the year number of the model output. This is a pragmatic definition, but it may be insufficient. In the experiments investigated in this paper, an additional condition is also applied,

\[ |\sigma_x(n+1) - \sigma_x(n) | < 0.1 \text{W m}^{-2} \]

where \( \sigma_x \) is the standard deviation of \( x \). Despite the inadequacies of the above expressions, the equilibrium of a scheme is nevertheless defined.

The results presented in the previous sections show that schemes under the same atmospheric forcing reach very different equilibrium states. The influences on the equilibrium states of each scheme have not yet been fully evaluated, but it is certain that a combination of scheme structure, parameterizations, and choice of parameters are important.

A problem closely related to equilibrium is the response characteristic of a scheme, the speed with which a scheme approaches equilibrium with the changing external forcing (for instance, precipitation and solar radiation) and/or land surface parameters (such as leaf area index). The response characteristics are also determined by a combination of scheme parameters and the scheme structure. Obviously, the response time of a bucket model is different from that of a multilayer model. For a bucket model, the soil water throughput the soil depletes immediately as evaporation occurs (rapid response scheme), while for multilayer schemes, water in deep soil layers is depleted through diffusion to upper layers, and then evaporated from the surface. For the latter, water has a much longer residence time in the soil, during which time other processes (such as transpiration and runoff) are occurring. Therefore the differences in the scheme response characteristics are important to the behavior of the schemes.

The first indication of the different response times is the time required by the land surface scheme to reach an equilibrium. Yang et al. [1995] have already shown that spin-up times differ significantly among schemes and also for different initiation of schemes. Figure 17 shows the spin-up times (the number of years required for a scheme to reach the equilibrium with the atmospheric forcing). It appears that multilayer schemes, such as PLACE and CENTURY, require longer times to equilibrate. The picture for other schemes is less certain; for instance, ISBA and CSIRO9 are both two-layer schemes, while the spin-up time for ISBA is 1 year only, CSIRO9 needs 3 years to reach the equilibrium.

![Figure 17. Number of years required for selected schemes to achieve equilibration with prespecified atmospheric forcing.](image-url)
Therefore the equilibration time of the schemes determined by a combination of factors of number of layers and how the parameterization is carried out. Further detailed interpretation is not possible on the basis of the evaluations undertaken in this series of experiments.

The response characteristics are important and explain some detailed different behavior among schemes. Experiment 2c1 is a very interesting experiment which deserves discussion. In this experiment, the precipitation is specified to be 10 times that of the observed precipitation for the first 60 days, and then from day 61 to day 120 and throughout the period, no evaporation is allowed. Wetzel et al. [1995] discussed some aspects of this experiment, but what deserves more attention is that the different response characteristics have caused the different behavior of the schemes to the specified precipitation. To illustrate this proposition more clearly, we only consider total soil moisture predicted by BATS and ISBA (for different parameterizations of runoff plus drainage see Shao et al. [1995]. Figure 18 shows that BATS is a slower responding scheme than ISBA. Compared to BATS, the soil moisture predicted by ISBA increased more rapidly when there was precipitation and also decreased more rapidly for the dry period.

The different pattern of soil moisture in this example is caused by the different treatment in runoff plus drainage. It is readily understood that the differences will propagate to other aspects of the scheme behavior. If evaporation were to be taken into account, it would be expected that ISBA would have produced higher evaporation than BATS for the wet period (first 60 days) and lower evaporation for the dry period (last 60 days).

The difference in equilibrium states makes the comparison of scheme performance in a subannual period (e.g., the bare soil period or the growing season) very difficult, since these are inseparable entities in a complete cycle. For this reason, the flux measurements for a subannual period is of limited value in achieving a judgment as to how good the performance of a scheme is. For example, evaporation in the growing season will be dependent on the soil moisture at the beginning of the growing season, which in turn is determined by the performance of the scheme for the bare soil season. An attempt to evaluate the determinants of the equilibrium states and the response characteristics of a scheme is not possible on the basis of the experiments described here, even though a suite of 17 simulation sets were undertaken during the course of this intercomparison (Table 2).

### 5.4. Different Schemes, Different Sensitivities

Land surface parameters are difficult to determine and this is especially true for soil moisture simulation on a global scale. Even for the workshop experiments, for which first-hand information of surface aerodynamic characteristics, vegetation, and soil properties is available, an adequate specification of surface parameters remains a formidable task. To understand the sensitivity of land surface schemes to land surface parameters is not only important for studying the behavior of these schemes, but also important for the evaluation of soil moisture "products," such as global soil moisture maps. In this study, much attention was paid to the choice of better surface aerodynamic parameters, leaf area index, and soil hydraulic parameters, especially the wilting point soil moisture and the wilting point soil water potential. The control experiment was run four times (experiments 1, 11, 12, and 13) in order to achieve a better agreement between soil moisture predictions and observations and to understand the sensitivity of land surface schemes to these parameters (Table 2).

The setting of parameters for a particular site depends not only on the condition of the site, but also on the physics a scheme represents. The setting of wilting point is a useful example. Wilting point, \( W_{\text{wilts}} \), is the soil moisture below which plants will under water stress. In land surface schemes, it is usually assumed that for soil moisture below \( W_{\text{wilts}} \), transpiration decreases to zero. This is realized by increasing the stomatal resistance to infinity. In (11), \( F_2 \), the function representing the effects of soil moisture on stomatal resistance, is given by

\[
F_2 = \begin{cases} 
1 & W_2 > W_c \\
\frac{W_2 - W_{\text{wilts}}}{W_c - W_{\text{wilts}}} & W_{\text{wilts}} \leq W_2 \leq W_c \\
0 & W_2 < W_{\text{wilts}} 
\end{cases} 
\]  

(17)

In experiment 1, the saturation soil moisture is set to 0.439 m\(^3\)/m\(^3\) (the maximum amount of water is 702.4 mm for the 1.6-m soil column), and the wilting point is set to 0.2 m\(^3\)/m\(^3\) (corresponding to 320 mm of water in the 1.6-m soil column). The wilting point value was set to the lowest soil moisture averaged over the 1.6 m soil layer according to HAPEX-MOBILHY data, which occurred during the vegetated period (June to Septem-

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**Figure 18.** Soil moisture variations from experiment 2c1 between BATS and ISBA for the first 120 days.
In the top 0.5-m soil layer which contains a major proportion of roots, the HAPEX-MOBILHY observations show a drying period with the soil moisture content substantially lower than 0.2 m$^3$/m$^3$. The soil water in the top 0.5-m is between 50 and 75 mm, or in terms of soil moisture content 0.1 to 0.15 m$^3$/m$^3$, much lower than the suggested wilting point value of 0.2 m$^3$/m$^3$. Considering the major root zone being in the top 0.5 m, the choice of $W_{wilt}$ = 0.2 seems to be too high and a wilting point around 0.15 appears to be more appropriate.

2. The effect of the wilting point on the performance of soil moisture simulation can be clearly seen in some schemes such as BATS. In experiment 1, simulated soil moisture of BATS agrees well with the observations for the wet seasons (January to June), but is higher than observed soil moisture for the cropping period. This is mainly because the top soil of BATS is too wet (about 0.2 m$^3$/m$^3$). The minimum soil moisture content in BATS is limited by choosing the wilting point as 0.2, and BATS is unable to predict drier soil since transpiration is switched off at the wilting point.

Some schemes showed a significant improvement in soil moisture prediction by choosing a smaller $W_{wilt}$. As an example, Figure 19 shows the soil moisture simulation of BATS for experiments 1, 11, 12, 13, and 14. In experiments 11 to 13, BATS showed significantly better soil moisture simulation in the root zone. This improvement is attributed to the change of $W_{wilt}$ (from 0.2 to 0.15). With respect to the soil moisture simulation in the total soil layers, BATS showed greater sensitivity to $W_{wilt}$ and a significant improvement in soil moisture simulation from experiment 11 to 13 compared with the HAPEX-MOBILHY observations.

As mentioned above, the tuning of $W_{wilt}$ was based on the argument that 90% of the roots are within the top 0.5-m soil layer and the measured soil moisture for this layer is less than 0.2 m$^3$/m$^3$. Obviously, the tuning of $W_{wilt}$ was necessary and effective for models that distinguish the top 0.5-m soil layer from the deeper soil layers. However, for single layer schemes (bucket and SECHIBA2), the root distribution is assumed to be homogeneous in the vertical and the simulation is representative of the whole soil layer. For these models, the choice of $W_{wilt}$ as 0.2 m$^3$/m$^3$ (the minimum of the depth averaged soil moisture over 1.6 m for the year) rather than 0.15 m$^3$/m$^3$ (the minimum of the depth averaged soil moisture over 0.5-m for the year) is probably more appropriate. The inappropriate choice of $W_{wilt}$ for bucket and SECHIBA2 in experiment 13 is possibly the reason that the soil moisture simulated by these two schemes for the total 1.6-m soil layer was lower than the measured values for the growing season (Figure 20). Figures 19 and 20 show that parameters for different schemes should be chosen not only according to the condition of the site, but also to the physics a scheme represents.

The difference in sensitivity among schemes to the choice of parameters is further illustrated in Figures 21 and 22. In Figure 21, the cumulative runoff plus drainage of four schemes (BATS, ISBA, PLACE, and VIC) is plotted against the cumulative evaporation, while in Figure 22, the cumulative latent heat flux is shown against the cumulative sensible heat flux. In
these examples, BATS and PLACE responded strongly to the change in wilting point, while ISBA and VIC showed weaker responses. The interpretation of these different sensitivities must be left for studies dealing with individual schemes. It is emphasized here that the choice of parameters has a major impact on the simulation of soil moisture and that the requirement for the accuracy of the parameters differs significantly among schemes.

6. Conclusions

Land surface schemes are profoundly different in structure and in the treatment of various land surface processes such as evaporation, transpiration, and runoff plus drainage. From the PILPS Phase 2(b) experiments, it was possible to quantify the disagreement in soil moisture simulation and other related variables against one set of observational data. It was shown that large differences occur even for simulations run with high quality atmospheric forcing data and carefully chosen parameters. It seems probable, therefore, that the prediction of soil moisture in climate change, weather forecast or hydrological simulations cannot yet be considered reliable when the forcing data are much less accurate and the information available for specifying land surface parameters is crude.

The preworkshop control run (experiment 1) revealed a soil water disagreement of about 200 mm among the schemes [Shao et al., 1995] and this disagreement in soil moisture was accompanied by differences in evaporation, transpiration, sensible heat fluxes, and in runoff plus drainage. The disagreement in simulated soil moisture and other simulated variables was reduced in experiment 13 compared to experiment 1 after improvement in schemes and adjustment in land surface parameters, especially in those characterizing the soil hydraulic properties (wilting point, saturation soil water potential, and saturation soil hydraulic conductivity),

Figure 20. SECHIBA2 simulated soil moisture from experiments 1 and 13 in the total 1.6-m soil layer against HAPEx–MOBILHY data.

Figure 21. Cummulative runoff plus drainage versus cummulative evaporation from experiments 1, 11, 12, 13, and 14, for BATS, ISBA, PLACE, and VIC.
and in the parameters characterizing the surface properties (leaf area index, fraction of vegetation cover, vegetation height, aerodynamic roughness length, and zero displacement height). The scatter in soil moisture for the total soil layer (1.6 m) is about 70 mm for the bare soil period and 100 mm with a maximum of 143 mm in the growing season in experiment 13, compared with about 200 mm for the full year with a maximum of 240 mm for experiment 1. Thus the range in the "improved" control experiments remains large, even after more careful and consistent choice of parameters. The process of intercomparison emphasizes that characteristics for each scheme have to be selected with a knowledge of the scheme physics as well as the site’s biochemistry.

Most land surface schemes tested in PILPS Phase 2(b) conserve water. However, the partitioning of sensible and latent heat fluxes (in the surface energy budget equation) and the partition of evaporation and runoff plus drainage are profoundly different among the schemes as shown in Figure 16 and Figure 12. It was observed that, despite the significant improvement in the agreement of soil moisture prediction in experiment 13 compared to experiment 1, there was no significant improvement in the scatter of evaporation and runoff plus drainage.

For most participating land surface schemes, surface energy is conserved. However, the partitioning of surface energy fluxes, which is closely coupled to the partitioning of evaporation and runoff plus drainage, differs profoundly among schemes. Although, on average, the difference in net radiation \((\frac{1}{a} \int R_n dt)\), with \(a\) being 1 year) is about 8 W m\(^{-2}\), that of latent heat fluxes is approximately 17 W m\(^{-2}\) and that of sensible heat fluxes is of the same magnitude. In terms of energy transfer, these differences correspond to 250 MJ m\(^{-2}\) per year for net radiation transfer and 536 MJ m\(^{-2}\) per year for latent and sensible heat fluxes.

Other important differences in land surface schemes are embedded in detailed parameterizations of individual processes, choice of parameters, and numerical implementations. To study the individual processes that are controlling these differences, further experiments were conducted to evaluate: (1) evapotranspiration, (2) bare soil processes and (3) runoff plus drainage. Detailed investigations are presented by Mahfouf et al. [1995], Desborough et al. [1995], and Wetzel et al. [1995].

Two important sources of divergence have been identified during the workshop which need to be addressed in future studies. These are the combined effects of (1) different equilibrium and response times and (2) different energy and water partitioning. The equilibration response characteristics are determined by a combination of parameters within the schemes and the scheme structure. Land surface schemes under the same atmospheric forcing reach very different equilibrium states and achieve equilibration after different periods of forcing. One consequence is that the validation data, which

Figure 22. Cumulative latent heat flux versus cumulative sensible heat flux from experiments 1, 11, 12, 13, and 14, for BATS, ISBA, PLACE, and VIC.
are often limited to a couple of weeks or months, cannot be effectively applied when atmospheric forcing is applied repeatedly until all prognostic variables have exactly the same behavior as the previous year. Energy partitioning (i.e., the partitioning of available energy between surface sensible and latent heat fluxes in the surface energy budget equation), and water partitioning (i.e., the partitioning of precipitation between evaporation and runoff plus drainage in the water budget equation), are two closely coupled and fundamental aspects of land surface schemes. A major problem identified in PILPS Phase 2(b) is the way the surface energy budget and water budget are achieved differently by various schemes. A reasonable simulation of soil water can be achieved through very different partitioning of evaporation and drainage: in some schemes, soil moisture simulation is dominated by evaporation while other schemes achieve the same soil moisture by allowing more drainage (Figure 12) and thus the energy partitioning among land surface schemes is also significantly different (Figure 16). Hence although the emphasis of land surface schemes developed for atmospheric models is the energy partitioning, and the emphasis of land surface schemes for hydrological and ecological models is water partitioning, the two partitions should be treated as inseparable entities in all land surface schemes.

It is not possible on the basis of PILPS intercomparisons alone to conclude whether these differences are related to the philosophy and basic structure of land surface schemes, or to the details of parameterizations and to land surface validation data. However, it is clear that intercomparisons such as these are valuable both to individual scheme developers and to the community as a whole.

Appendix: Instructions for Workshop Numerical Experiments

Experiment 1: The Control Experiment

Parameters. Monthly averages of surface aerodynamic parameters and roots distribution should be as specified in Table A1. Other parameters should be set consistently with those specified in Table A2.

Soil layers. Soil layers are specified as one-layer models, 0-1.6 m; two-layer models, (top layer) 0-0.1 m and (second layer), 0.1-1.6 m; three-layer models, (top layer) 0-0.1 m, (second layer) 0.1-0.5 m, and (third layer) 0.5-1.6 m.

Atmospheric forcing. The HAPEX–MOBILHY atmospheric forcing data are available at 30-min intervals for 1 year. The forcing data are as listed in Table A3.

Execution. To execute initialize for 00:00 January 1 and set all soil water stores as saturated. Then set canopy water store as zero and set snow mass as zero, and set all temperatures at 279.0 K. After initialization, advance the initialized variables prognostically as the simulations progress and run the scheme to equilibrium by looping through the forcing data.

Experiment 11, 12, and 13: New Control Experiments

Experiment 11, 12, and 13 are as for experiment 1, but for experiment 11 specify wilting soil moisture, $W_{wilt}$, as 0.2 and soil water potential at wilting point $\psi_{wilt}$ as -28 m, for experiment 12 specify $W_{wilt}$ as 0.12 and $\psi_{wilt}$ as -506 m, and for experiment 13 specify $W_{wilt}$

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<td>3</td>
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<tr>
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<td>0</td>
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<td>a</td>
<td>a</td>
<td>b</td>
<td>c</td>
<td>c</td>
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LAI, leaf area index; FVEG, fractional vegetation cover; $z_0$, overall surface roughness length; $z_{oc}$, canopy roughness length; $z_d$, zero displacement height; $h_c$, height of canopy. Also, a indicates no roots, b indicates 70% roots in layer 0-0.1 m and 30% in layer 0.1-0.5 m, and c indicates 60% roots in layer 0-0.1 m, 30% in layer 0.1-0.5 m, and 10% in layer 0.5-1.6 m.
Table A2. Albedo, Soil Hydraulic Parameters and Reference Height of Atmospheric Forcing

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<th>Description</th>
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<td>Albedo</td>
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<tr>
<td>Canopy albedo for visible light</td>
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<tr>
<td>Canopy albedo for NIR light</td>
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</tr>
<tr>
<td>Albedo of snow for visible light</td>
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<tr>
<td>Albedo of snow for NIR light</td>
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<tr>
<td>Emissivity for all substances</td>
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<td>Soil type</td>
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<td>Soil water field capacity</td>
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<tr>
<td>Saturation water potential</td>
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</tr>
<tr>
<td>Saturation water content</td>
<td>0.439 (m^3/m^3)</td>
</tr>
<tr>
<td>Saturation conductivity</td>
<td>5.1e-6 (m/s)</td>
</tr>
<tr>
<td>Clapp-Hornberger parameter b</td>
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<tr>
<td>Height of atmospheric forcing</td>
<td>2 m</td>
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</tbody>
</table>

Saturation soil moisture 0.446
Saturation soil water potential -0.3 m
Clapp and Hornberger parameter b 5.66
Saturation hydraulic conductivity 4e-6 m s\(^{-1}\)
Field capacity 0.32 m\(^3\) m\(^{-3}\)

Use leaf area index (LAI), canopy height (h), fraction vegetation cover (FVEG), overall roughness length (z_0), zero displacement height (z_d) as interpolated values (Table A4) based on monthly averages.

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References


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