The Project for Intercomparison of Land-surface Parameterization Schemes

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Abstract

The Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) is described and the first stage science plan outlined. PILPS is a project designed to improve the parameterization of the continental surface, especially the hydrological, energy, momentum, and carbon exchanges with the atmosphere. The PILPS Science Plan incorporates enhanced documentation, comparison, and validation of continental surface parameterization schemes by community participation. Potential participants include code developers, code users, and those who can provide datasets for validation and who have expertise of value in this exercise. PILPS is an important activity because existing intercomparisons, although piecemeal, demonstrate that there are significant differences in the formulation of individual processes in the available land surface schemes. These differences are comparable to other recognized differences among current global climate models such as cloud and convection parameterizations. It is also clear that too few sensitivity studies have been undertaken with the result that there is not yet enough information to indicate which simplifications or omissions are important for the near-surface continental climate, hydrology, and biogeochemistry. PILPS emphasizes sensitivity studies with and intercomparisons of existing land surface codes and the development of areally extensive datasets for their testing and validation.

1. Introduction to current land surface schemes

The practical importance of studying climate derives from the dependence of people on the processes that occur at the atmosphere–land interface. Relatively little attention, however, has yet been paid by the climate modeling community to the accurate prediction of land surface climates. A prerequisite for this prediction is a better understanding of the sensitivity of the overall climate system to land surface processes and the sensitivity of land surface climates to perturbations in the overall climate.

The World Meteorological Organization (WMO)–Commision for Atmospheric Sciences (CAS) Working Group on Numerical Experimentation (WGNE) and the science panel of the GEWEX Continental-scale International Project (GCIP) have agreed to launch a joint WGNE/GCIP Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) (Henderson-Sellers and Dickinson 1992). The principal goal of this project is to achieve greater understanding of the capabilities and potential applications of existing and new land surface schemes in atmospheric models. The scope of PILPS will be increased by the development of a concurrent project aimed at improving the parameterizations of carbon exchanges between the atmosphere and the continental surface to be organized by the International Geosphere Biosphere Programme's task force on Global Analysis, Interpretation and Modelling (IGBP/GAIM; Moore 1993).

The current generation of soil–vegetation–atmosphere transfer schemes (SVATs) reveals commonality in aim, design, and use. They study the interaction of energy, momentum, and water flux between the surface and its overlying atmosphere. These models may be regarded as one dimensional: only layers in the vertical (z) direction are considered. While they are generally designed to be used in three-dimensional models, processes that occur in the soil–vegetation–snow–atmosphere system of one grid square are not affected by what happens in neighboring grid squares. The inclusion of vegetation is a marked difference from the earlier so-called bucket schemes (Manabe 1969) in which a near-surface layer of soil is modeled as a bucket that can be filled by precipitation and snowmelt (if any) and empties by evaporation and by runoff; the latter occurs only when the bucket is full. Its other attribute is that the evaporation rate is a linear function of the amount of water in the bucket below some critical value. In SVATs, vegetation is treated as a separate layer, scaling (usually linearly) from a size of normal leaves up to a grid square of sizes ranging from 50 x 50 km to 500 x 500 km. Usually only three land components (soil, snow, and vegetation) are treated explicitly; land ice and lakes and other land covers are neglected (cf. Pitman 1991). Carbon fluxes

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are as yet included in only a few climate SVATs, although there are many current ecological models that deal with carbon uptake and release (e.g., Collatz et al. 1991).

Validation of all aspects of the performance of the available (and proposed) schemes is clearly required but is largely limited by lack of observed data especially over large enough areas. The first stages of PILPS will encompass 1) the preparation of improved and spatially extensive data (e.g., Vinnikov and Yeserkepova 1991) and also 2) comparison of the behavior of the existing schemes in agreed prescribed conditions. A necessary part of validation and intercomparison is the identification of the relative importance of different parameters and formulations within existing and proposed land surface schemes (e.g., Dickinson et al. 1991).

It is not anticipated that a single "best" or fully validated land surface scheme will emerge. Rather, the aim is to explore alternative models in ways compatible with their authors' or users' goals and to increase understanding of the characteristics of these models in the scientific community. Early results will be important in support of the "operational path" of the GCIP implementation plan, which seeks to make early improvements in land surface parameterizations of atmospheric models before the beginning of the GCIP Intense Observational Period (IOP) in 1995.

The design of PILPS and its first-stage science plan was discussed by participants at the first PILPS meeting held in June 1992 in Columbia, Maryland. There was agreement to a multistaged intercomparison process including:

- documentation of existing models,
- description of the sensitivity of existing models,
- framework for intercomparison of participating models,
- data development for initial intercomparisons,
- stand-alone (or off-line) intercomparisons,
- identification of a sound means of scheme validation (including development of adequate observational datasets),
- intercomparisons using one single-column atmospheric model, and (ultimately)
- model intercomparisons coupled to (at least) one mesoscale model and one general circulation model (GCM).

The phases of PILPS will follow a systematic and staged intercomparison and evaluation procedure. Objectives include an improved and community-wide documentation; intercomparisons and evaluations derived from the existing literature, from previous experiments, and from personal communication within the community; and intercomparison by means of the execution of agreed simulations by *all* PILPS participants. Evaluation of agreements and differences and, ultimately, validation with agreed observed data will be by the same means.

The first PILPS workshop (24–26 June 1992) generated 1) descriptions of existing models (those listed in Table 1 have already been volunteered by their authors or users) and 2) details of sensitivity experiments already conducted (Henderson-Sellers and Brown 1992). These reviews, together with the data-needs identification, formed the basis for PILPS phase 1 (Table 2). The ensuing discussions set the scene for phases 2 and 3 of the science plan. During the meeting, participants reported on their current model and existing sensitivity experiments in a common framework. Sections 2–4 outline this framework. Additional contributions to this documentation are welcome. (See the end of this article for details about participation in PILPS.) PILPS workshops and planning meetings were held in conjunction with the Southern Hemisphere Conference on Meteorology and Oceanography (Hobart, Australia, 29 March to 2 April 1993) and the IAMAP/IAHS Symposium (Yokohama, Japan, 11–23 July 1993).

2. Framework for the documentation of land surface schemes

a. Characteristics

Model developers and users participating in PILPS are invited to describe their model(s) by explaining how each of the important parameters are calculated (or ignored). Model descriptions should include information about

1) the spatial area represented/representable by the scheme,

2) the representation of subarea heterogeneity (if any),

3) the time step(s) of the scheme and of the output, and

4) the required temporal (and spatial) resolution of data for forcing and validation.

Many of the individual parameters that might be used in land surface schemes can, at best, be established only at local sites for specific vegetation, soil, and terrain conditions. Thus, it is probably pointless to seek validation of all the parameters that might or might not be in a given land surface parameterization. Rather, it is important to identify the basic functions of the treatment and the inputs needed from the rest of the climate model for the land process parameterization to function correctly. From the viewpoint of climate modeling, validation of these basic functions and

TABLE 1. Existing schemes to be included in PILPS.

Acronym	Name	Reference
—	Bucket scheme	Manabe (1969)
SiB	Simple Biosphere model	Sellers et al. (1986)
BATS	Biosphere–Atmosphere Transfer model	Dickinson et al. (1986, 1992)
—	UKMO	Warrilow et al. (1986)
BEST	Bare Essentials of Surface Transfer	Pitman (1988) Pitman et al. (1991)
—	GISS	Abramopoulos et al. (1988)
ISBA	Interaction Soil–Biosphere–Atmosphere	Noilhan and Planton (1989)
—	NMC/MRF	Pan (1990)
CLASS	Canadian Land Surface Scheme	Verseghy (1991)
—	ECMWF	Blondin (1991)
SECHIBA	Schematisation des Echanges Hydriques à l'Interface entre la Biosphere et l'Atmosphere	Ducoudre et al. (1992)
LSX	Land surface exchange	Pollard and Thompson (1992)
LEAF	Land–Ecosystem–Atmosphere Feedback	Lee et al. (1992)
PSUBAMS	Penn State Univ. Biosphere Atmo. Model Scheme	—
CAPS	Coupled Atmosphere–Plant–Soil model	(Cuenca, personal communication)
—	Hamburg/Max Planck	—
—	CSIRO/Aspendale	—
—	NMC/Mesoscale	—
AGROMET	Agrometeorological model	Moore et al. (1991)
PU-1	Princeton University-1	—
VIC	Variable Infiltration Capacity	Wood et al. (1992)
—	Mosaic-SiB	Koster and Suarez (1992)
SSiB	Simple SiB	Xue et al. (1991)
—	Column model for storms	(Wetzel, personal communication)
—	JMA/SiB	Sato et al. (1989)

inputs on the spatial scale resolved by the model is an important goal.

Most land surface schemes have five key elements that primarily involve the surface calculations—canopy conductance, aerodynamic resistance, albedo, water holding capacity and runoff—and three which involve, at least in part, coupling with the atmospheric model—precipitation, radiation, and the planetary boundary layer. Also important are software engineering questions relating to the code, its development, transferability, and compatibility. The first of these topics is reviewed in this section and the coupling and code aspects are considered in section 3. Examples are taken from a subset of the PILPS-participating schemes: the Biosphere–Atmosphere Transfer Scheme (BATS) (Dickinson et al. 1986, 1992), the Simple Biosphere scheme (SiB) (Sellers et al. 1986), Simple SiB (SSiB) (Xue et al. 1991), the Goddard Institute for Space Studies (GISS) Model (Abramopoulos et al. 1988), the Bare Essentials of Surface Transfer (BEST) (Pitman 1988; Pitman et al. 1991; Yang 1992), Interaction Soil–Biosphere–Atmosphere (ISBA) (Noilhan and Planton 1989), the U.K. Meteorological Office (UKMO) Model (Warrilow et al. 1986), and the Canadian Land Surface Scheme (CLASS) (Verseghy 1991).

TABLE 2. PILPS first three phases.

Phase 1: First workshop

- description of existing models
- reports on existing sensitivity studies
- framework for intercomparison of models

Phase 2: Intercomparisons and data development

- stand-alone (or off-line) comparisons
- data development for intercomparisons

Phase 3: Coupled intercomparisons and validation

A. Single-column model selection
   Data needs for forcing/validation
   Method of intercomparison: disseminate SCM or collect PILPS codes

B. Mesoscale model selection
   Data needs for forcing/validation
   Method of intercomparison

C. GCM model selection
   Data needs for validation and input
   Method of intercomparison

b. Water content (of soil and canopy)

Water holding capacity is the maximum water depth that can be held in a soil column and be exchanged with the atmosphere on a time scale of a few years or less. This term is most obvious in the simple bucket models; for example, the original soil-water parameterization of Manabe assumed a capacity of 0.15 m everywhere over land (Manabe 1969). More detailed treatments represent soil moisture in terms of the water density (mass of water per unit soil mass), with water draining in the soil according to Darcy's law (Darcy 1856). This adds additional dimensions to the concept of water holding capacity, but generally it is possible to define a field capacity and wilting point (both as densities in kg kg^{-1} or m^3 m^{-3}) such that the water holding capacity is the difference of these terms multiplied by the depth to which water is extracted in the soil (i.e., rooting depth when plants exist). The specification of this rooting depth over large regions is just as problematical as specifying a bucket depth, so it is best approached with intelligent guessing. One question is whether there is a need to include shallow-water tables; another issue that should be addressed is the slow diffusion from deeper soil levels on an annual and longer time scale to represent the effects of long-term droughts better [as recently attempted by Rind et al. (1990) for global warming scenarios]. An additional question is whether a broad enough parameterization can be formulated to capture the behavior of a mixture of bare soil and vegetated land adequately. Sensitivity studies suggest that the effective water holding capacity of soils in a climate model should be accurate to considerably better than a factor of 2 to avoid serious errors from this term (Wilson et al. 1987a).

Prognostic variables for describing soil moisture vary in current schemes; for example, in BATS, the soil moisture content is measured in terms of water equivalent depth d_w in meters. In the GISS SVAT, the mass of liquid water per unit lateral area in the soil layer, which is a product of water density and the depth, that is $d_w\rho_w$ (kg m^{-2}) is determined. ISBA measures actual volumetric soil moisture, X (m^3 m^{-3}). In SiB and BEST, soil moisture wetness (W) is a ratio of actual volumetric soil moisture (X) in a layer to its value at saturation (X_s), where W is dimensionless. In the UKMO SVAT and CLASS, soil moisture terms are products of water density and actual volumetric soil moisture and are also called soil moisture concentration, in units of kilograms per meters cubed. All these are essentially the same and related through

$$W = \frac{X}{X_s} = \frac{X\rho_w}{X_s\rho_w} = \frac{d_w/D}{X_s} = \frac{d_w}{D_w} = \frac{\rho_w d_w}{\rho_w D_w}, \quad (1)$$

where D = depth of soil layer (m); D_w = soil moisture capacity (m).

Under a series of assumptions, for example, a spatially homogeneous soil layer with no horizontal water movement and no melting or freezing within it, vertical movement of soil water will follow Darcy's law. This flux–gradient method is used in all the PILPS SVATs reviewed here. All of them, therefore, treat more or less the same processes when calculating soil water. They include, for instance, the forcing (throughfall, canopy drip, and snowmelt), surface soil evaporation, surface runoff, capillary and gravitational drainage, and transpiration by the canopy. Unique to BEST and CLASS, at least among the eight models reviewed here, is their explicit treatment of the frozen soil-water budget. (A newer version of the GISS SVAT, not yet documented in the literature, includes frozen soil moisture.)

All models treat the canopy vegetation water store with the same governing equations. BATS, BEST, GISS SVAT, and ISBA use the same method proposed by Deardorff (1978) to calculate the wet fraction of a canopy, that is, the 2/3 power law,

$$L_w = (W_{dew}/W_{DMAX})^{2/3}, \quad (2)$$

where L_w = fractional area of leaves covered by water,

W_{dew} = water store on the surface of canopy, and W_{DMAX} = maximum water the canopy can hold.

In SiB, it is prescribed as

$$L_w = \begin{cases} (W_{dew}/W_{DMAX})\ \text{e}\cdot(T_c) > e_a \\ 1 \qquad\quad \text{e}\cdot(T_c) \le e_a, \end{cases} \tag{3}$$

where $e_*(T_c)$ = saturation vapor pressure at canopy temperature, T_c (mb), and e_a = vapor pressure in canopy air space (mb). [Changes of symbols have been made for the fraction and water stores from the original in Sellers et al. (1986).] A similar approach is also used in the UKMO SVAT but with different conditions.

The maximum water store held on the canopy has been specified differently. In the earlier version of BATS, the UKMO SVAT, and ISBA, $W_{DMAX} = 0.2 \times 10^{-3} A_v L_{SAI}$ (m), whereas in the new version of BATS (BATS1e), GISS SVAT, and SiB (Sellers et al. 1989) it equals $0.1 \times 10^{-3} A_v L_{SAI}$, (m). In BEST, it is set to $0.2 \times 10^{-3} A_v \min(3, L_{SAI})$ (m), which becomes the same as that in BATS1e, SiB, and the GISS SVAT for $L_{SAI} = 6$, representative of a full canopy.

c. Canopy (vegetation) conductance

Canopy transpiration, sometimes called dry canopy evaporation (Morton 1984), is a physiological process associated with water transfer from the soil through roots, stems, branches, and leaves. The canopy conductance (or its reciprocal, resistance) measures the effectiveness of this moisture transfer. Basically, all SVATs use the same formulation of transpiration, based on assumptions used to derive Penman–Monteith's combination equation (see Penman 1948; Monteith 1973, 1981) but more closely related to a soil–plant–atmosphere model for transpiration proposed by Federer (1979).

In general, the canopy resistance term is a sum of an integrated stomatal resistance for the canopy and the bulk boundary-layer resistance for the canopy leaves. The transpiration is then limited by the supply of water from the roots and atmospheric conditions of demand. The canopy, for example, cannot transpire where there is dew on its surface, nor can it transpire when the soil moisture potential drops below the plant wilting point. The parameterizations of stomatal resistance, the dry fraction of transpiring canopy, and root-limiting factor (Cowan 1965), however, are different in the various SVATs.

Stomatal resistance is a subgrid-scale process that is difficult to parameterize while retaining sufficient generality for use in climate models. Although numerous factors determine leaf stomatal resistance, there are only five environmental conditions: solar radiation, temperature, vapor pressure deficit, leaf-water potential (soil-water potential), and ambient carbon dioxide, whose effects are commonly parameterized (Avissar and Verstraete 1990; Dickinson et al. 1991). Various schemes exist in the literature (e.g., Monteith et al. 1965; Jarvis 1976; Deardorff 1978; Hinckley et al. 1978; Federer 1979; Hillel 1980; Singh and Szeicz 1980; Molz 1981; Farquhar and Sharkey 1982; Grace 1983; Aston 1984; Jarvis and McNaughton 1986; Lynn and Carlson 1990). In the SVATs reviewed, the adopted schemes are generally simplified. After the stomatal resistance (r_s) of a leaf is calculated, the bulk stomatal resistance (r_c) is derived by assuming all the leaves of the canopy to operate in parallel using the analogy of Ohm's law. A quantity over a grid square is thus obtained by multiplying vegetation cover fraction (σ_f) to scale up from a canopy to a grid square.

In BATS (Dickinson et al. 1986, 1992), r_s is a function of minimum stomatal resistance, maximum stomatal resistance, (visible) solar radiation, leaf temperature, vapor pressure deficit (VPD), and soil moisture. These terms are expressed in a multiplicative form and for at least several canopy layers. The same approach has been followed in BEST and in ISBA. In ISBA, however, both VPD and carbon dioxide are omitted. In the GISS SVAT, a bulk canopy stomatal resistance is given by r_{smin}/LAI_e, where LAI_e is the effective leaf area index (LAI) used to account for the attenuation of radiation as light passes through the canopy and the coincident decrease in plant surface that is actively transpiring. Although no functional relationships for radiation, temperature, or humidity were published for this scheme, we are advised that the current version does include dependence on solar radiation and temperature. In the UKMO SVAT, a constant value of the stomatal resistance is used. In SiB (Dorman and Sellers 1989), a more elaborate formulation of r_c is used in which a sophisticated account of PAR flux within the canopy is considered.

In general, there are some common uncertainties in the aforementioned formulations for bulk stomatal resistance (Dickinson et al. 1991); for example, in SiB the values of species-dependent constants and the parameters that determine the stress factors for temperature, vapor pressure deficit, and leaf-water potential are not readily available. They must be determined from complex physiological experiments, and more advanced theories need to be established.

d. Aerodynamic resistance

Surface roughness is the basis for determining the aerodynamic drag coefficient, C_D, for a surface. In the early GCMs, C_D for land was specified as 0.003, which is a typical value over short vegetation and for conditions of neutral stability. Sensitivity studies suggest

that this term should be specified correctly over regions of land to accuracies of a few tenths of a percent. To achieve this accuracy, it is necessary to represent drag coefficients in terms of surface similarity theory, where transfer coefficients for momentum, heat, and moisture are determined from a roughness length, z_o, and the thermal stability of the near-surface air. It may be necessary to distinguish between coefficients for momentum, heat, and moisture. In particular, all subgrid-scale roughness elements and topography may contribute to momentum transfer but only those on the scale of individual vegetation elements to heat and moisture transfer.

Parameterization of vegetation properties related to canopy architecture determines significant features of the treatment of vegetation for evapotranspiration.

Recently, some canopy and soil schemes have begun to include the uptake, storage, and release of carbon through carbon dioxide exchanges with the atmosphere. These subschemes will be increasingly important as physical models are coupled to biogeochemical models.

The total surface of photosynthesizing leaves (LAI) and stem surfaces (SAI) influences canopy resistance and transfer of heat from the canopy to the atmosphere. The flux of PAR normal to leaf surfaces as required for stomatal parameterizations depends on canopy and leaf architecture. Furthermore, the net radiative loading over the surface of a given canopy element depends on these properties. Most models assume that energy transfers within the canopy are sufficiently rapid to allow the canopy to be treated as a single layer for heat, but the assumption of a single surface is probably too inaccurate for the PAR dependence of stomatal resistance.

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e. Albedo

Canopy albedo determines the fraction of incident solar radiation that is absorbed. Sensitivity studies show that albedo changes by greater than 0.02 are significant for surface fluxes and temperature. Because the spectral mix of atmospheric radiation may change with changing atmospheric conditions and surface reflectances have a strong spectral dependence, it may be necessary to represent albedos spectrally; the minimum division is between the visible and near-infrared parts of the solar spectrum. Furthermore, albedos depend on solar geometry, which is significant for determining the diurnal variation of solar heating. Current model parameterizations of surface albedo are largely inferred from some limited surface measures for various kinds of vegetation canopies. Satellites are, in principle, the only means of establishing surface albedos globally; however, but they do not directly give albedos but rather a bidirectional reflectance. Thus, validation of surface albedo parameterizations may be simplified if they can be represented in terms of bidirectional reflectances.

For canopy temperature calculations, the degree of complexity of schemes used is much lower than that adopted for calculating canopy albedo. For example, in SiB, a reasonably realistic two-stream approximation has been used to calculate albedo, and five components of solar flux are considered. In contrast, a single temperature is assigned to the whole canopy with a single prescribed canopy heat capacity. This limitation will influence the calculation of stomatal resistance since it is a function of vapor pressure deficit that is in turn dependent on leaf temperature. The ground has one temperature for ground cover and bare soil, and each soil layer has a temperature.

Similar approaches are also used in BATS and BEST for calculating canopy temperature except that the heat capacity is assumed to be zero. GISS SVAT specifies heat capacities but differentiates canopy temperature for wet and dry surfaces. It calculates surface temperatures and soil temperatures for shielded and bare portions of land, separately. In contrast, the UKMO SVAT links canopy and soil with a single temperature.

Two schemes are commonly used for calculation of soil temperature: the slab model and the force–restore method. A slab model assumes layers with fixed thermal properties. Heat conduction equations are solved for the temperature using a finite-difference method or finite-element method. Its accuracy is increased when the number of layers is increased but, generally, the computational cost restricts the number of layers. The UKMO SVAT employs four layers, while the published GISS SVAT and CLASS have three layers, which seems to be a minimum. (An updated GISS scheme now uses six layers.)

The force–restore method is formulated from an analytical solution of the soil heat-conduction equation under assumptions of periodic forcings and homogeneous medium (Carslaw and Jaeger 1959; Van Wijk

1963; Deardorff 1977, 1978; Lin 1980; Dickinson 1988). It has two prognostic variables: one that interacts (rapidly) with the forcing term and one that responds (slowly) with the storage term. The scheme is now efficient to use but does not handle vertical heterogeneities as simply as slab models and has been adopted in BATS, ISBA, and SiB, though earlier versions of SiB included the slab model (Sellers et al. 1989).

The force–restore method is highly accurate for the diurnal component of forcing but inaccurate for shorter and longer time scales. Its success depends on the maximum power at the diurnal period, relatively small temperature response at shorter periods, and insensitivity of surface temperature to soil heat flux at longer periods. Dickinson (1988) takes account of the contribution from snow and soil moisture to the heterogeneity and proposes a generalized force–restore method with a seasonal cycle included, which has been added in an updated version of BATS. In BEST, Cogley et al. (1990) used a combination of force–restore method and finite-difference method to solve the multilayer soil temperatures, taking into account the contribution to the thermal coefficients from snow, soil minerals, soil water, and air.

f. Runoff

Runoff parameterizations are likely to have to depend on soil moisture and properties of the incident precipitation. Given these, they may also depend on characteristics of soils and topography. There exists a good theoretical foundation for the vertical infiltration of water in soil, given soil hydraulic properties. There are intrinsic difficulties, however, in parameterizing slope effects to determine runoff in a climate model. Furthermore, soil properties are highly heterogeneous both horizontally and vertically, so that specifying them as constants over a model grid square or in a soil column is problematical. Change of soil hydraulic properties with depth may strongly affect runoff and is a key ingredient of the popular TOPMODEL for hillslope runoff (e.g., Beven and Kirby 1979). Freezing of soil can have a major effect on runoff and hence soil moisture.

Runoff tends to be treated as a diagnostic variable in current land surface models (including those more advanced ones reviewed here) and generally is regarded as the excess of water in the soil reservoir. This excess amount plays no further part in the host model's hydrological cycle, though in CLASS an attempt has been made to save surface runoff (overland flow) as ponded water between time steps (Verseghy 1991). In most GCMs, "runoff" has referred only to overland flow (e.g., Manabe 1969; Washington and Meehl 1984; Hansen et al. 1984; Mitchell et al. 1987), while in more advanced SVATs, it now also includes the gravitational drainage (e.g., Dickinson et al. 1992). Since there are no rivers or lakes with variable levels in climate models, runoff cannot be used to increase lake levels or strengthen river flows. These simplifications may be reasonable in view of the omission of treatment of subgrid-scale distribution of topography and horizontal water flow processes. Input of land runoff has just begun to be used to alter the salinity of the ocean in oceanic GCMs (OGCMs).

In BATS, surface runoff is dependent on the net water flux (i.e., effective precipitation rate minus evaporation) at the surface, the wetness of the soil layer, and the soil surface temperature (e.g., above or below the freezing point). The total runoff is equal to the sum of the surface runoff and the subsoil drainage. In SiB, runoff is defined as precipitation excess (i.e., effective precipitation rate on soil surface minus the infiltration into the upper soil moisture store) plus gravitational outflow from the lowest soil moisture store. BEST has a similar approach except that it also includes overflow in each soil layer. ISBA has a simpler approach by ignoring the drainage down to the water table. In CLASS, runoff is specifically referred to the gravitational drainage. In the UKMO and GISS SVATs, the treatment of surface runoff is more advanced in that the local rate of throughfall of water from the canopy to the surface is assumed to be exponentially distributed and to be occurring only over a fractional area of the grid square (Warrilow et al. 1986; Gregory and Smith 1990).

In all SVATs, the calculation of retained water on the canopy surface (including leaves and stems/trunks) is analogous to the bucket model for soil moisture content though a more general drip formulation developed by Massman (1980). A universal water holding capacity on the canopy surface is equivalent to the soil field capacity. The water storage falls because of canopy evaporation as discussed above and rises because of intercepted rainfall or dew formed onto the surface. The excess amount of water beyond the maximum water storage is moved into canopy drip, which is equivalent to the soil surface runoff.

In most SVATs (e.g., BATS, BEST, and ISBA), the intercepted rainfall is simply a proportion of incident precipitation above the canopy according to the calculated vegetation cover fraction. In SiB, this is calculated in an analogous way to the exponential attenuation of radiation through the canopy for a vertical flux and black leaves (Sellers et al. 1986), and the drip is formulated considering the subgrid-scale precipitation (Sato et al. 1989). A similar approach is used in the updated version of the UKMO SVAT (Gregory and Smith 1990). This concept is very important because the drip, unlike the surface runoff, is still a contributory factor in the host model's hydrological cycle, that is, a

water input to the soil-water budget. Therefore, its magnitude will affect the infiltration and evaporation at the surface. Pitman et al. (1990) have demonstrated the importance of this process using a version of BATS following Warrilow et al. (1986) and Shuttleworth (1988b).

3. Coupling to host model(s)

a. Datasets required

Provision of digital datasets of vegetation types and soil properties is an indispensible part of using and testing SVATs. The chosen number of vegetation and soil types, the assignment of the dominant type for each grid cell, and the derived secondary parameters for each type, however, are still in a "trial and error" stage. The sensitivity of land surface parameterization schemes to the chosen procedure(s) has not yet been adequately explored (Skelly et al. 1992). In particular, the sensitivity of the schemes to the aggregation procedure used to transform the data from the original resolution (say, 1° x 1°) to the required host model resolution has been given very little attention (see, however, Abramopoulos et al. 1988).

It is certainly true that a wide variety of approaches has been used to specify vegetation and soil data. For example, it may be noted that Matthews' (1983, 1984, 1985) vegetation dataset is used, in part, in generating the data for at least four SVATs: BATS, SiB, SSiB, and GISS SVAT. However, the application of these data varies from scheme to scheme. BATS, for example, also uses the Wilson and Henderson-Sellers vegetation dataset (Wilson and Henderson-Sellers 1985). The SiB model mainly uses the Kuchler (1983) vegetation dataset, while the GISS SVAT uses only Matthews' data. In BEST and UKMO SVAT, only Wilson and Henderson-Sellers' data are used.

The soil datasets are different in many schemes, except BATS, BEST, and UKMO SVAT use the same data of Wilson and Henderson-Sellers (1985), although FAO/UNESCO (1974) is the main data source for all schemes.

As for the secondary parameters, most of them can be estimated by numerical and field experiments (Sellers and Dorman 1987; Noilhan and Planton 1989; Sellers et al. 1989), while some of them can be inferred from satellite observations (Tucker and Sellers 1986). Many, however, still have to be "inferred by intelligent guessing as guided by the literature" (Dickinson et al. 1986). Dorman and Sellers (1989) undertook an interesting study to provide a mutually consistent climatology of surface albedo, surface roughness, and the minimum stomatal resistance on a 1° x 1° grid by running their SiB submodels with prescribed PAR and wind velocity. Their dataset may be used in GCMs that do not have biophysically based SVATs.

b. Precipitation

Precipitation can be the dominant determinant of evapotranspiration in semiarid regions; that is, if runoff is negligible over a long enough time average, all the water put into the soil must evaporate. Where runoff does occur, the ratio of the runoff to the precipitation is strongly dependent on antecedent soil moisture, on the local intensities and durations of the precipitation, and indirectly on the removal of precipitation by interception. Snow is important as a form of stored water, creating a high surface albedo and a thermal insulator for the underlying soil; seasonal soil freezing and permafrost are significant influences on surface energy balance and a major perturbation on soil hydrology.

Subgrid heterogeneity of precipitation has begun to be discussed recently, although it seems likely that subgrid parameterization within climate models "will always remain the Achilles' heel of numerical climate simulation" no matter how fine the model's resolution (Entekhabi and Eagleson 1989).

Precipitation, especially convective rainfall, was the first variable to be studied using a statistical approach to subgrid-scale heterogeneity. As is well known, the size of a grid square in most climate models is large enough to include a number of convective storms. Consequently, there must be great spatial variability of distribution of precipitation over a grid square. However, GCMs assume precipitation uniformly covers each of the grid squares that leads to an unrealistic estimation of canopy drip, soil moisture, infiltration, runoff, and evapotranspiration. Eagleson and his coworkers have conducted theoretical and observational studies on the relationship between convective storms and the spatial distribution of surface wetting (Eagleson and Wang 1985; Eagleson et al. 1987). Their researches were mainly for a catchment area. Warrilow et al. (1986) assumed that precipitation falls on a proportion, μ, of the grid area, and within this proportion, the local precipitation rate P_l is represented by a probability distribution function (pdf) of an exponential form as

$$f_p(P_l) = \frac{\mu}{P}\exp\left(\frac{-\mu P_l}{P}\right), \tag{4}$$

where P_l = local point precipitation rate; P = grid square area-averaged precipitation, a prognostic variable from climate models; $f_p(P_l)$ = probability distribution function; and μ = fraction of a grid square receiving precipitation. Then the (area-averaged) runoff rate may be derived accordingly.

A similar approach for simulating canopy interception of precipitation was adopted by Shuttleworth (1988a), who derived the area-average runoff rates (i.e., drip) from the canopy and the effective surface infiltration rate.

The aforementioned schemes have been incorporated into BATS for sensitivity tests over the Amazon rainforest region by Pitman et al. (1990). They found that surface variables, especially evaporation and runoff, are very sensitive to precipitation regimes. Sato et al. (1989) have used a similar exponential pdf for precipitation and canopy interception in SiB and made GCM studies with this version of SiB. Thomas and Henderson-Sellers (1991) have applied the methods of both Warrilow et al. (1986) and Sato et al. (1989) in a regional hydrological study using observational data collected in the Hunter Valley of southeastern Australia. They found that both methods match the seasonal and annual series of wetting depth but not the daily or hourly series.

Entekhabi and Eagleson (1989) further generalized Warrilow et al.'s (1986) approach, using a gamma pdf for soil moisture,

$$f_s(s) = \frac{\lambda^\alpha}{\Gamma(\alpha)} s^{\alpha-1}\exp(-\lambda s), \quad \lambda,\alpha,s > 0, \qquad (5)$$

where s = soil wetness, λ,α = parameters determining the variance of the mean $E(s)$.

For precipitation, an exponential form like Eq. (4) is used, which is a simplification of the Γ pdf when $\alpha = 1$. Based on both P_l and s and the deterministic equations describing basic soil moisture physics, they then derived a number of grid-square-averaged dimensionless quantities including surface runoff ratio (surface runoff to grid-square mean precipitation), infiltration rate, bare soil evaporation efficiency (ratio of actual to potential evaporation), and transpiration efficiency.

In their derivations, two components (Horton and Dunne) of surface runoff are considered. Horton runoff, or infiltration excess overland flow, is generated due to the excess of precipitation intensity over soil infiltration capacity at a point (Freeze 1974). It accounts for only a small fraction of the surface runoff contribution to streamflow. Dunne runoff, or saturation excess overland flow, is caused due to the occurrence of precipitation over saturated and impermeable surfaces. It is largely responsible for the rapid response of streams to precipitation (Dunne and Black 1970). The derived dimensionless quantities are useful to determine the key variables such as runoff, infiltration, bare soil evaporation, and transpiration for a grid square. Given a grid-square mean precipitation that is supplied from the host climate model, for example, the actual runoff of a grid square is obtained as a product of the runoff ratio and the grid-square mean precipitation.

Entekhabi and Eagleson (1989) found that by having such formulations, runoff and evapotranspiration rates are very sensitive to the fraction of surface wetting and the spatial variability of the soil moisture. Some SVATs (e.g., GISS) now incorporate fractional surface wetting, but the importance of such schemes for SVATs and for GCMs has not yet been investigated.

c. Radiation

Solar radiation, as the most variable term in net surface radiation, is crucial for determining evapotranspiration in well-watered regions. Indeed, the whole idea of a "potential evaporation" from land surfaces hinges on this strong solar control. Within climate models, incidence of solar radiation varies most with cloud properties but also with atmospheric water vapor and aerosol loading. Diurnal mean values are needed over a model grid point to an accuracy of order of 10 W m^{-2} (e.g., Dickinson 1989).

Owing to the diurnal variations of incident radiation flux and its subsequent partition into sensible and latent fluxes, SVATs require that their host model includes a diurnal cycle. Most SVATs expect input of incident shortwave radiation in at least two parts: in particular, split at 0.7 μm. The SiB model has the most complex requirement among all the schemes reviewed here with regard to the incident radiation flux from a host model: five components must be provided for use in the radiative transfer calculations in the canopy. In SVATs, the radiation transfer is generally calculated every time step, while in many global host models calling routines for radiation are executed at much longer time intervals in order to save computer time.

d. Planetary boundary layers

The planetary boundary layer mediates the exchange between the surface air and the rest of the atmosphere. Under unstable convective conditions, transport of surface properties will be insensitive to rates of mixing within the planetary boundary layer; on the other hand, under stable conditions with slow mixing, fluxes from the surface will modify the properties of the overlying surface air that in turn will modify significantly the surface fluxes.

The height of the lowest host model level is an important factor for SVATs. In calculating the turbulent transfers of momentum, sensible and latent fluxes between the surface, and the lowest model level, some assumptions (e.g., that the fluxes are constant with height) must be made. This approximation can

hold only over flat and homogeneous surfaces (below 100 m), while from this level to the top of the planetary boundary layer (PBL), the fluxes change with height. In SiB, however, the conventional surface-layer theory of momentum transfer is modified when a canopy is present with different processes being considered separately within the canopy and above the canopy.

Most GCMs currently treat the PBL in a very simple fashion. Generally, a small number of model layers are located within the PBL, and processes occurring within it are heavily parameterized with large-scale prognostic variables. On the other hand, most mesoscale models pay greater attention to computations of PBL processes. A lowest model level < 100 m seems necessary, and improved resolution PBL models may be needed in order for the GCM to be fully compatible with some SVATs.

On the practical side, it is important to understand how coupling to an alternative host model can be accomplished. All proposed code intercomparisons, including PILPS, would be facilitated by code developers adhering to the "rules for interchange of physical parameterizations" described by Kalnay et al. (1989). Plug-compatible land surface schemes (and indeed host models) are highly desirable. A major problem for PILPS is likely to be the difficulty of disentangling the land surface schemes from the boundary-layer schemes of their first host models.

4. The intercomparison framework for PILPS

The first PILPS meeting formed the basis for the development of consistent documentation of, at the least, all the schemes listed in Table 1 and included reports on existing sensitivity studies (e.g., Ducoudre and Dickinson 1991; Yang 1992). More importantly, it allowed the construction of the framework for the systematic intercomparisons indicated in Table 2 and identified the need for systematic data development for evaluation and, ultimately, validation of the land surface schemes.

a. Framework for the description of existing land surface sensitivity studies

A vital part of modeling is validation and sensitivity testing. The question considered is, "Do plausible perturbations to the values of the parameters of the model result in a significant perturbation to the model output?" PILPS participants are invited to describe sensitivity studies that have already been conducted with their land surface scheme under the headings listed in Table 3.

The typical model sensitivity experiment evaluates the impact of changing each of the parameter values in turn (usually between two extreme values that represent the range of likely values for that parameter). Conclusions are drawn from a comparison of the magnitudes of the residuals, defined as the differences between the perturbed experimental results and the "control" (the control being the experiment that uses the "standard" values for the parameters). For N parameters being perturbed, the set of residuals, r_i (i = 1 to N) is examined and it is concluded that the outliers in this set represent parameters to which the model is sensitive. Consequently, the values of these parameters should be more carefully specified in future experiments than those to which the model is less sensitive.

Using this methodology, the ith experiment has one perturbed parameter value (the ith) and $N - 1$ unperturbed parameters. This "one factor at a time" approach is often viewed as "the" scientific method of experimentation (Daniel 1976, p. 2). Such experiments testing the sensitivity of land surface parameterization schemes include Wilson et al. (1987a,b), Abramopoulos et al. (1988), Mahfouf and Jacquemin (1989), and Pitman et al. (1990).

In contrast, industrial experimentation has long realized the potential weakness of perturbing a single parameter at a time (Daniel 1976; Box and Bisgaard 1987; Gunter 1989) since such a methodology ignores multifactor interactions. Inclusion of higher-order interactions can also be considered to be analogous to the fitting of multidimensional "response surfaces."

TABLE 3. Organizational framework for PILPS for existing land surface sensitivity studies.

Scheme(s): name(s), vintage, reference(s)
Type of sensitivity study: one-at-a-time, factorial
Mode of study: fully coupled, off-line, other
Number of parameters: all, selected, reasons
Range imposed on parameters: e.g., +10% of normal, extremes
Environment studied: e.g., tropical forest, tundra
Outcomes: statistical significance, physical interpretation

Evaluation of multifactor interactions is accomplished by using factorial experimentation, in which a matrix of experimental runs is set up, individual numerical (or empirical observational) experiments are executed, and the results are analyzed for effects (either main factor effects, or factor interactions, or both) (e.g., Henderson-Sellers 1992a,b).

An alternative to the factorial method is the adjoint means of assessing sensitivity (e.g., Hall 1986). This method has been shown to be of value for climate models but may be less readily extendable to the assessment of land surface schemes since the technique depends on the solution of a set of adjoint equations derived from a differential form of the scheme's equations (Hall and Cacuci 1983). Many of the current land surface schemes contain parameterizations that are not differentiable.

Sensitivity testing of land surface schemes has usually (cf. Henderson-Sellers 1992a,b) been by means of the standard one-at-a-time method in which a suite of tests is conducted in one of two forms:

1) coupled into the planned host model (GCM or other)

2) stand-alone (or off-line) with all the required information prescribed and unchanging

The former method is fully interactive and is an ultimate tool but it is costly in computational time and the results are often difficult to evaluate. The latter method is attractive because it is cheap and interpretation is easier.

Development of land surface schemes by off-line testing, prior to their incorporation into their host model(s), is now an established methodology. Such off-line testing is an efficient and effective means of examining the sensitivity of the schemes to initialization, atmospheric forcing, and internal parameterization because it does not permit feedbacks between the climate and the land surface. This type of experimental method is therefore unacceptable if interactive simulations (e.g., of the impacts of deforestation) are the goal but is useful if information is sought about the sensitivity of the schemes themselves (Pitman et al. 1990; Dolman and Gregory 1992). An intermediate route exploiting single-column models for sensitivity testing has been developed by some groups (e.g., Koster and Eagleson 1990).

b. Intercomparison framework

To develop an agreed intercomparison, understanding, and validation framework, a number of issues must be addressed. The question of how to "drive" the various participating schemes is to be resolved by a staged approach in which stand-alone intercomparisons become the basis for PILPS phase 2 with coupled intercomparisons forming the major component of phase 3 (Table 2). The objective in phase 1 is to compare simulations of runoff, soil moisture, latent and sensible heat fluxes, and carbon exchange; the latter being organized through IGBP/GAIM.

As the comparison is to be carried out using prescribed forcings, the modeling of feedback to a host model cannot be assessed. The use of recorded data, however, implies that, regardless of outputs from the surface models (sensible and latent heats), the inputs (measured variables such as precipitation, solar radiation, longwave radiation, temperature, mixing ratio, wind, and surface pressure) for the next time step will always be correct. Although the simulation of feedback and the reliability of the surface models when linked to, say, a GCM cannot be directly assessed, comparing the models in the stand-alone mode can provide guidance on the ability of land surface schemes to simulate runoff and soil moisture—information that is of great importance to hydrologists, agricultural scientists, and water resources managers. At the very least, it will provide a better understanding of the differences between simple rainfall–runoff models (Crawford and Linsley 1966; Askew 1989; Hromadka et al. 1992) and the more complex land surface schemes.

The tasks associated with phase 3 of PILPS are potentially much more difficult to accomplish. The PILPS Science Plan calls for a two-staged approach employing first a single agreed simple atmospheric model such as a single-column model or mesoscale model or both.

Later, it is planned to couple a small number of the PILPS-participating schemes into a single GCM for the third stage of phase 3. An alternative or complementary analysis process or both are to use results from schemes coupled into their "normal host" GCM. This aspect of PILPS may, it is hoped, form part of an Atmospheric Model Intercomparison Project (AMIP) analysis subproject.

A crucially important issue for PILPS is to establish what output (e.g., energy fluxes, moisture exchange, or flow from an area and perhaps carbon store) is most valuable to intercompare and, equally importantly, what output can be most adequately validated. Rainfall–runoff models, for example, usually use a daily time step and require little or no vegetation or soil information. These models produce daily outputs of total runoff, soil moisture, and evaporative and sensible heat fluxes. Such rainfall–runoff models are typically developed with a view to adequate simulation of recorded streamflow and therefore require validation over basins, though these can be of variable areal extents. Land surface schemes generated for GCMs could be similarly validated, though it is often claimed that an important feature of these models is the diurnal

TABLE 4. List of observed data for validation of SVATs.

ARME	2 yrs	Shuttleworth et al. (1984a,b)	point (forest)
FIFE	5 months	Betts (personal communication)	15 km × 15 km
HAPEX	3 months	André et al. (1986)	3 locations (2 crops, 1 forest)
Murray	2 yrs	McMahon (personal communication)	Basin-scale
Russian	14 yrs	Vinnikov and Yeserkepova (1991)	50 stations

cycle in energy and moisture fluxes that would not be intercompared if output were to be evaluated only on a daily time step. Indeed, the issues of time scales and space scales required for input and appropriate to validation are crucial to the success of the PILPS intercomparison.

Another important and related issue is the length of time for which models must be integrated before any intercomparisons are made. This will probably differ depending on whether the models are being operated in a stand-alone mode or coupled to an atmospheric host model and will certainly also be a function of the complexity of the scheme parameterizations.

c. Datasets required for PILPS

The datasets to be used for PILPS must, at a minimum, represent a long enough time period so that models sensitive to initialization can be equilibrated prior to comparison or validation or both using the nominated data. This is likely to pose significant problems, as very few comprehensive and adequately validated land surface data exist (Table 4). An alternative (that will be tested in the earlier phases) is to repeat time series of observations many times. The PILPS Science Plan identifies four datasets that have already been used by the land surface simulation community and that could be made widely available. These data represent field observations from the Amazon Region Micrometeorology Experiment (Shuttleworth et al. 1984a,b; Shuttleworth et al. 1985; Shuttleworth 1988a,b), the Hydrological Atmospheric Pilot Experiment (André et al. 1986), the First ISLSCP Field Experiment (Sellers et al. 1988), and an agricultural area in a semiarid region of Australia (Murray). There are as yet no adequate high-latitude data, although it has been suggested that observations from BOREAS or long-term observations made in Russia might be used (Vinnikov and Yeserkepova 1991). None of these datasets are for large enough areas that they can be deemed to represent current GCM grid areas (which typically extend across two or three degrees in latitude and longitude).

PILPS data requirements will have to be based on the experience of those land surface scheme developers or users who have already used these or similar datasets. An exemplar of exploitation of field data is the calibration of SiB, BEST, and BATS for the Amazon tropical forest (Sellers et al. 1989; Yang 1992; Dickinson 1992). The SiB study involved the model author, users, and observational field scientists. These studies were also valuable because they identified aspects of the climate and biophysiology that must be observed in order to provide a complete observational dataset for calibration.

One meteorological parameter that was not observed for most of the 2-yr period of Amazonia data retrieval (cf. Henderson-Sellers et al. 1987) was cloud amount and type. This omission from the dataset meant that Sellers et al. had to use monthly climatological averages of cloud fraction for Manaus from Ratisbona (1976) irrespective of the time of day or day of the month both to calculate spectral and angular fluxes (only total incoming shortwave was measured) and to estimate downward longwave radiative flux [using the empirical expression given by Monteith (1973)]. Another land surface parameterization scheme author has identified considerable sensitivity of his scheme (BATS) to the cloud amount and type predicted by the host GCM (Dickinson 1989; Shuttleworth and Dickinson 1989).

These gaps in the observational record and identified sensitivities of one or more schemes to the missing data need to be borne in mind. The optimization procedure employed by Sellers et al. (1989) yields estimates of parameters and process rates that are representative of a relatively large area (they believe of the order of 10^4–10^6 m^2) rather than the spatial scale of individual leaves or plants. It might be valuable to develop such optimizing and areal aggregation schemes further, since these spatial scales are more appropriate to the continental-to-regional scale of practical value in climate models.

5. Invitation to participate in PILPS

At present, the primary mandate of PILPS is to document, compare, and improve the parameterization of the exchanges of energy and moisture at the

continental surface of the earth. The WGNE/GCIP Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) is *not* a "beauty contest." It is a community effort to improve understanding, methods of testing, and, ultimately, applicability of land surface schemes. The ultimate goal of PILPS is to identify inadequacies in current parameterization schemes and to propose solutions. Equally important is the other primary goal of identifying data gaps and proposing the means of acquiring these data at appropriate temporal and spatial resolutions. It is anticipated that PILPS will also serve a useful role for the biogeochemical community. To the extent that current land surface schemes include carbon uptake/release components, these will be incorporated into the PILPS program as a joint activity with the International Geosphere Biosphere's Global Analysis, Interpretation and Modelling Project (IGBP/GAIM) that will benefit both the physical/hydrological and the biogeochemical modeling communities.

Acknowledgments. This review was supported in part by grants from the Australian Departments of Employment, Education, Training and of Arts, Sport, Environment and Territories; by the Model Evaluation Consortium for Climate Assessment; and by the NASA Earth Observing System program. This is Contribution No. 92/11 of the Climatic Impacts Centre. A. H-S. is especially grateful to the University of Arizona Global Change Program and the National Center for Atmospheric Research, where her recent research visit to the United States was spent. For more information on PILPS contact the chair (AH-S) of the Organizing Committee at the address given on the title page (fax +61 2 805 8428; email ann@mqmet.cic.mq.edu.au).

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