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# Remote Sensing of the Land Surface for Studies of Global Change: Models – Algorithms – Experiments

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*The ISLSCP Workshop was held in Columbia, Maryland, 23–26 June 1992 with over 240 scientists and science managers attending. The goal was to assess the progress of the last decade in the areas of modeling, satellite data algorithm development, and field experiments. This article includes:*

- 1. A review of the state and direction of biosphere-atmosphere model development and an assessment of the data needs of the models. Models covering a large range of timescales were considered: energy–water–carbon (seconds to seasons); carbon cycles and biogeochemistry (days to years); and ecological structure and function (years to millennia).*
- 2. A reference to current satellite data algorithms and other global data sources. The areas covered in the workshop were: near-surface meteorology, surface radiation budget, precipitation, runoff, snow and ice, soils and soil moisture, and land cover type and land cover attributes. These are discussed in detail in other articles in this issue.*

- 3. A review of completed and planned major field experiments. The major experiments of the last decade are summarized and the lessons noted.*

*The participating scientists agreed on the need to rapidly assemble and circulate global data sets of variables and parameters required to initialize, force, and validate the global biosphere–atmosphere models. A prioritized list of data sets required to meet this need is set out and discussed. Lastly, initiatives taken by ISLSCP to satisfy these requirements are reviewed:*

## *Initiative I: Immediate Generation of High Priority Global Data Sets*

*Some essential global data sets are to be put together within 2 years and released to the community by mid-1994. These data sets will be mapped to a common spatial resolution ( $1^\circ \times 1^\circ$ ) and will cover the period 1987–1988.*

- 1. Vegetation: Global sets of vegetation-related parameters are to be generated with a monthly time resolution. Available AVHRR data sets are to be used as the basis for this effort, and algorithms will be applied to calculate fields of cover type, phenology, FPAR, and leaf area index. These fields can then in turn be used to infer other surface parameters such as roughness, albedo, biomass, etc.*
- 2. Hydrometeorology: Global meteorological fields retrieved from numerical reanalysis will be manipulated to provide near-surface forcing data sets for temperature, humidity, windspeed, etc. Observations of precipitation, runoff, and snow cover are to be worked up into easily accessible forms.*

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3. Radiation Budget: A closer interface with the International Satellite Cloud Climatology Project (ISCCP) and related projects will be pursued to obtain surface radiation budget components at higher spatial resolutions, as well as fields of incident PAR.
4. Soils: A small project was set in place with the goal of providing a useful soil type and properties data set for use by global modelers.

#### Initiative II: Improved, Follow-on Data Sets

The data sets specified in Initiative I are to be generated within a 2-year period. However, it is clear that great improvements could be made over this first data release which must rely on preexisting data sets and robust, available algorithms. Work was started to scope out what needs to be done to produce improved versions of all the Initiative I data sets within 5 years, by mid-1997.

#### Initiative III: Improved Communications within the Land Science Community

Future discussions within ISLSCP and between ISLSCP and other bodies will focus on the need to coordinate different research thrusts within the land science community, particularly the modeling, algorithm and field experiment work.

## INTRODUCTION

The ISLSCP (International Satellite Land Surface Climatology Project) workshop was held in Columbia, Maryland, 23–26 June 1992. Over the 3 days of the workshop, some 240 scientists and managers participated in presentations and discussions with the goal of rationalizing the different activities taking place in the areas of modeling, algorithm development, and field experiments. A complete account of the proceedings of the workshop can be found in Sellers (1992).

The workshop was tasked with reviewing progress in the area of land science, examining the role of remote sensing and setting future research directions. The need to scrutinize the links between modeling, algorithm development and field experiments was explicitly stated as part of the charge to the workshop (see Fig. 1).

The goals of the workshop were as follows:

- i. Review progress in the science, in particular the requirements and science issues addressed by land-atmosphere modelers.
- ii. Examine the role of remote sensing; in particular, assess the status of satellite data algorithms and what had been learned from field experiments.

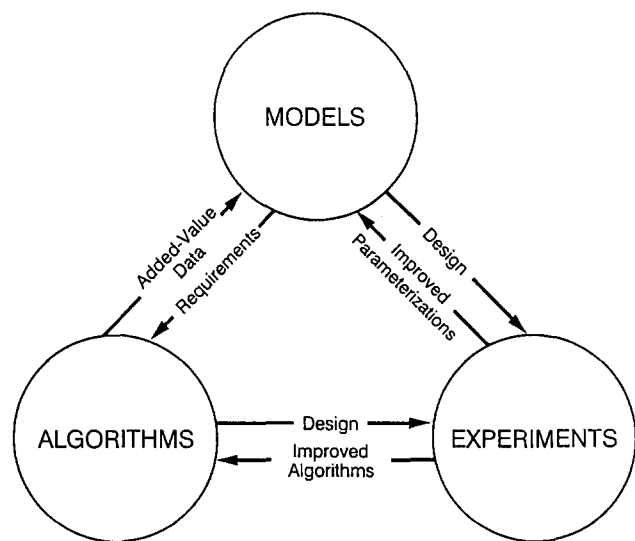


Figure 1. Relationships between different components of ISLSCP. The last few years have seen a weakening in the links between the three areas. The workshop was charged with: i) careful specification of modeling goals and requirements; ii) comparison of data requirements and algorithm limitations; iii) improving connections between model requirements, algorithm validation needs and experiment design.

- iii. Determine the next steps to be taken and assess future research directions.

## MODELING

Each of the three modeling areas was the subject of two invited talks: Water–Energy–Carbon (Dickinson, Running); Carbon and Biogeochemistry (Fung, Schimel); and Ecosystem Structure and Function (Field, Bonan). Five of these contributions are written up as articles in this issue. The science issues and data requirements of each class of models are summarized below.

### Water–Energy–Carbon

Articles by Dickinson (this issue) and Running et al. (this issue) cover this topic. These models are used to calculate the fluxes of water–energy–carbon at the land surface–atmosphere interface on time scales appropriate to global and mesoscale GCMs (i.e., seconds to seasons) (see Appendix for definitions of acronyms throughout) and on length scales of a few kilometers to several hundred kilometers. In most of these models, land surface parameters are specified as boundary conditions (e.g., vegetation type, biophysical properties, etc.) using data from ground-based surveys or from anecdotal sources. Generally, very little validation of the land surface prognostic variables (surface temperature, soil moisture) or diagnostic variables (e.g., surface conductance, evaporation rate, etc.) has been attempted. Satellite data could be used for both initialization and validation purposes (see Fig. 2). Improved models of this type

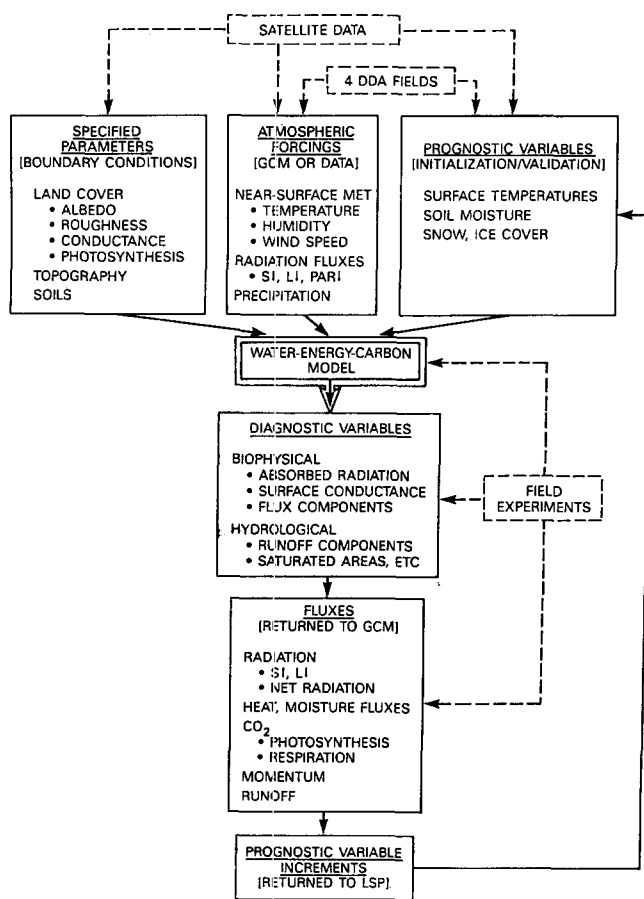


Figure 2. Schematic of relationships between water-energy-carbon models (forcings, fluxes), specified parameters (boundary conditions), prognostic variables (initialization, validation), and diagnostic variables (validation). The roles of satellite data and 4DDA products are also shown.

will be useful for numerical weather prediction and many aspects of climate simulation, including diagnostic studies of the effects of increased atmospheric CO<sub>2</sub> on continental hydrology and carbon fluxes.

Data are used by these models either as initial fields/boundary conditions (input), or for validation of model output. For a global model, global input data (initial conditions, boundary conditions) at the model resolution are an absolute requirement; the issue is the quality of what is available, and what is the degree of interpolation or fabrication that has to be done. Thus, for input data, coverage is a vital concern, with the availability of high quality analyzed products being a major practical consideration. Validation data, on the other hand, need not necessarily be global to be useful, but their accuracy and reliability are of paramount importance.

Atmospheric global models need input data to match the grid resolutions of 150 km expected within the next 5 years. For highly heterogeneous subgrid scale land surface processes such as evapotranspiration, grid cells may be subdivided by a fine mesh grid or by classes with weights proportional to area. This implies a requirement for maps or Geographic Information System (GIS) data sets at substantially finer scales, or at least joint-probability distributions, of land cover, soils, and, in mountainous regions, of slope and aspect. The required resolution is at least 50 km now and 24 km within 5 years. Where suitable data are unavailable, they simply have to be invented, resulting in reduced credibility for model performance and output.

A set of key variables are ranked in priority order in Table 1 and in the summaries below. The priority ranking is based upon the need for better modeling of the surface energy and water balance coupled with an estimate of the prospects for improvement in analyzed products over the next 5 years. Attention was concentrated on global data sets, especially but not exclusively those obtainable from existing satellite data streams, or those scheduled for launch within the next 3 years.

A. *Albedo, Incoming Solar Radiation, and PAR*: Albedo is usually treated as an input variable to atmo-

Table 1. Key Variables for Water-Energy-Carbon Models

	Requirements			Source / Accuracy		
	Spatial Res (km)	Temporal Res	Accuracy	4DDA	Satellite	Other
Albedo	250 × 250	Monthly <sup>a</sup>	± 0.02		± 0.03	Classification
SW <sub>surf</sub>	250 × 250	Monthly	± 10 W/m <sup>2</sup>		± 20 W/m <sup>2</sup>	
PAR	250 × 250	Monthly <sup>a</sup>	± 10 W/m <sup>2</sup>		± 20 W/m <sup>2</sup>	
LW <sub>net</sub>	250 × 250	Monthly <sup>a</sup>	± 10 W/m <sup>2</sup>	± 10 W/m <sup>2</sup>		
Evapotranspiration	250 × 250	Monthly <sup>a</sup>	± 0.3 mm/day	± 10 W/m <sup>2</sup>		
Precipitation	250 × 250	Monthly <sup>a</sup>	± 0.3 mm/day		± 50%	Surface observations FAO
Soil hydraulic properties	1-10	Once	—			
Roughness	250 × 250	Seasonal	± 300%			Classification
Topography and stream networks	1	Once	Consistent streams			USGS/DoD
Near-surface meteorology	250 × 250	Diurnal <sup>a</sup>	Varies	T, q, u		Surface observations

<sup>a</sup> Plus diurnal cycle and day to day variability.

spheric GCMs, whereas the modulation of the incoming solar radiation by clouds and aerosols is in principle a product of the GCM. Sensitivity experiments have shown that uncertainties in either variable equivalent to  $\pm 10 \text{ W m}^{-2}$  averaged over a month make a significant difference to simulated regional climates [see Nobre et al. (1991) and cited literature therein]. Currently, for global models, land surface albedo is inferred from crude land cover classifications on a scale of around 100 km (see, e.g., Dorman and Sellers, 1989). Reliable data are required on the scales described in Table 1. Incoming solar radiation at the surface can be modeled from the top of the atmosphere using optical imagery. Existing techniques at the research level are promising, but more work is required to produce satisfactory global products; for example, aerosols contribute a significant uncertainty. Data on incoming solar radiation should define the diurnal cycle and day-to-day variability, as well as the monthly mean.

Evapotranspiration is closely linked to photosynthesis, for which photosynthetically active radiation (PAR) is a primary driver. PAR differs from incoming solar radiation only in the spectral range ( $0.4\text{--}0.7 \mu\text{m}$ ), and is more directly related to what is measured by present satellite sensors. A product for PAR should be prepared routinely along with that for incoming solar radiation with the diurnal cycle described in addition to monthly means.

**B. Net Longwave Radiation:** Direct global-scale measurement of net longwave radiation to a useful accuracy ( $\pm 10 \text{ W m}^{-2}$ ; monthly mean) is highly desirable but is not believed possible at this time. Instead, the best strategy for now may be to use fluxes and near-surface temperature fields derived from atmospheric four-dimensional data assimilation (4DDA) models to calculate the upwelling and downwelling fluxes.

**C. Evapotranspiration:** Direct measurement of regional evapotranspiration rates is currently infeasible. The approach to estimating useful ( $\pm 0.3 \text{ mm d}^{-1}$ ; monthly means) fields is similar to that for longwave radiation; that is, assimilation modeling incorporating meteorological and satellite data. Current approaches are based on biophysical models that require information about vegetation cover. Large-scale field experiment data may represent the best validation information available, but obviously for only a few times and places.

**D. Precipitation:** Rainfall / snowfall are crucial inputs to the water balance of the land surface, but are highly variable in both space and time and very difficult to measure accurately. Significant differences in climate are associated with  $\pm 0.3 \text{ mm d}^{-1}$  monthly average, or 10% of actual precipitation where that is smaller, whereas present uncertainties on a regional scale in many places are on the order of at least on  $\pm 50\%$ . Spatiotemporal statistics of small scale variability can also be of great

importance to infiltration and runoff, which are inherently nonlinear processes.

**E. Soil Hydraulic Properties:** Soil porosity, hydraulic conductivity (preferably profiles), and soil depth directly affect the field capacity and the accessibility of soil moisture for different types of vegetation, which enter nonlinearly into the response functions. There are many issues in inferring this information from national soil maps, or from the survey data upon which such maps are derived, but even a "quick and dirty" globally consistent product would be preferable to what is available now.

**F. Surface Roughness and Topography:** Estimates of the evapotranspiration and sensible heat flux depend upon the aerodynamic conductance, into which the surface roughness parameters enters logarithmically. Thus variations of the roughness length  $z_0$  are probably significant only to a precision of a factor of 3 on a global scale. This can be inferred to a first approximation from a simple land cover classification with the spatial resolution requirements outlined above. Additional direct measurements of vegetation height would, however, be useful for validation purposes. On a landscape scale of 1–10 km, the process by which units of different size and roughness may interact through the atmosphere is currently a research issue, for which high resolution validation data sets are required in selected areas.

For momentum flux, on the other hand, the pressure drag associated with subgrid scale variations in topography may also be significant. Though methods for treating this in global-scale models are at present controversial, all depend on some knowledge of topographic slopes at a higher spatial resolution. Likewise, the energy budget and runoff from individual landscape units depend on slope and aspect, to a significant extent in hilly or mountainous regions. Attempts to balance water budgets by streamflow require accurate definition of drainage basins and the associated stream net. These factors define a requirement for a global digital elevation model, with a horizontal resolution of 1 km, and a vertical resolution sufficient to define a consistent stream net on this scale. Where the requisite data are unavailable, synthetic constructs that reflect statistically the characteristic structures of the surrounding geomorphological province should be considered instead.

**G. Near-Surface Meteorology:** Archives of ungridded daily surface weather observations taken from the Global Telecommunication System (GTS) at Washington (temperature, humidity, observer-estimated cloud amount and type, precipitation, wind), and four-dimensional data assimilation (4DDA) products from the operational meteorological agencies (including some estimates of surface fluxes) have become available.

Other variables for which there are significant requirements for improved data sets on a global scale, but no consensus on the priority ranking, include skin

radiating temperature, infrared emissivity, snow water content, snow line elevation, permafrost, surface wetness, and stream flow. In addition, there is a major need for better surface and boundary layer atmospheric data as input for land surface models of all types.

### Carbon and Biogeochemistry

The article of Schimel (this issue) addresses some of the issues and needs of this science area. Models developed by this community are used to describe the processes governing the fluxes of carbon and trace constituents between the atmosphere and the land biosphere, and between different pools within the land biosphere–soil system. The timescale of the models generally runs from days to many years. The climatic forcing for most of these models is provided by observations or GCM output, but the models are seldom directly linked to GCMs. The data requirements for these models parallel those discussed in the previous section except that more information is needed to initialize or prescribe biochemical aspects of the system (see Fig. 3). The models are important for studying the role of the land biosphere in the carbon cycle and for exploring the limits imposed by nutrients on the biospheric response to increased CO<sub>2</sub>.

The global carbon cycle will be a central theme of research in the biogeochemistry field over the next few years. Several considerations justify this perspective. First, the carbon cycle is the most obvious player in climate change. Second, measurements and analyses indicate that the sum of global carbon sources and sinks is out of balance (see, e.g., Tans et al., 1990; Enting and Mansbridge, 1991). Approaches for quantifying this imbalance are increasingly available and powerful. Third, the global carbon cycle can be viewed as a major integrator of our understanding of the global-scale fluxes of several elements, especially N, P, and S, as well as water and energy.

Table 2 lists some important quantities that influence several of the most important phenomena summarized above. Listed are quantities that may be observed directly (i.e., a straightforward algorithm may be used to translate sensor readings directly into quantities of interest), quantities that are required as inputs into process models that can be used to determine or predict phenomena of interest, and quantities that can be used to extrapolate direct measures or model predictions to large spatial and temporal scales.

Four kinds of products with the most potential for advancing modeling activities over the next 3–5 years are defined. In addition to the potential for advancing research, a second criterion was the feasibility of assembling useful global products, at reasonable cost, using existing technologies. The priority data sets concern:

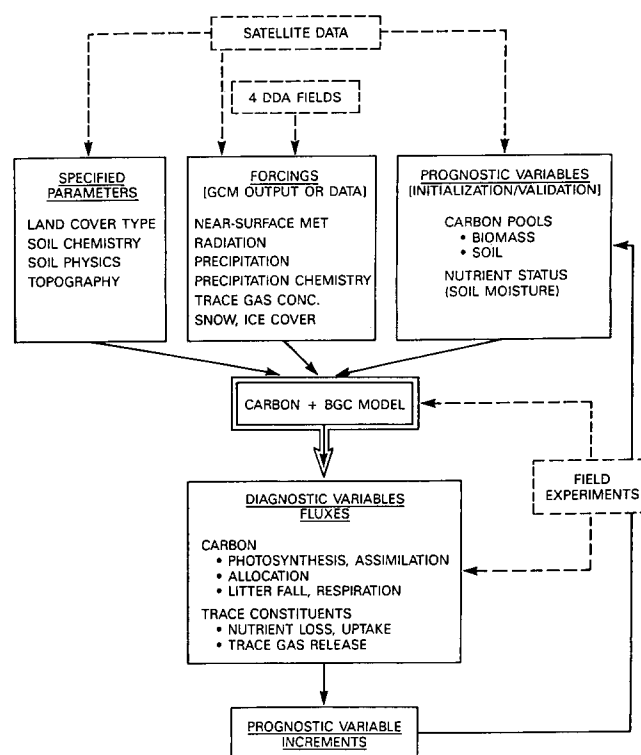


Figure 3. Schematic of relationships between global biogeochemistry models and atmospheric observations or calculations (forcings), specified parameters (boundary conditions), prognostic variables (initialization, validation), and diagnostic variables (validation). The roles of satellite data and meteorological observations and/or GCM output are also shown.

**A. Soils:** The determinants of soil texture (% sand, silt, clay), depth, gross mineralogy (clay type), and pH are needed at resolutions comparable to Advanced Very High Resolution (AVHRR) data (~10 km). Secondary properties that can be approximated given these primary data include water holding capacity and other hydraulic properties, soil organic matter content, and gas diffusion relationships. Organic matter (soil C and N) are also desirable as part of the primary data set for validation, since models must be employed to estimate organic matter given climate and texture. Higher resolution products would be preferable, but may not be feasible at this time.

**B. Topography:** Elevation, slope, and the distribution of aspects are critical at 1 km or better.

**C. Surface Climate:** Data requirements center on daily weather, including some resolution of the diurnal cycle. Critical variables include  $T_{\max}$ ,  $T_{\min}$ , precipitation, humidity, and radiation. Many of the data will come from surface observations. Satellite data bases could provide incident PAR, total solar radiation, and skin temperature, at spatial resolutions of 50–100 km.

**D. Vegetation:** To assess seasonal and interannual

Table 2. Remote Sensing Needs for Global Carbon Cycling and Terrestrial Biogeochemistry<sup>a</sup>

	<i>Plant Photosynthesis Respiration</i>	<i>Carbon Storage Vegetation and Soil</i>	<i>Decomposition (Soil Respiration)</i>	<i>Trace Gases CH<sub>4</sub>, N<sub>2</sub>O, NMHC</i>
Direct observation	C, H <sub>2</sub> O Fluxes	Land cover type Biomass Fires Particulate C exports	Soil CO <sub>2</sub> fluxes	Fluxes
Process modeling	Surface climate Greenness Sapwood volume Biochemical capacity Leaf area index Soil moisture	Biomass (root/shoot) Microbial biomass Soil organic matter Vegetation height Soil moisture storage	Organic matter chemistry Litterfall Soil texture Soil mineralogy Soil moisture	Organic matter chemistry Photosynthesis Soil moisture
Spatial/temporal Extrapolation	Greenness FPAR	Landscape heterogeneity Landcover type		Landcover type (esp. wetlands)

<sup>a</sup> The table lists some of the parameters that are most critical for the current generation of models and approaches. Each of these factors has a characteristic temporal scale over which changes are significant for biogeochemical studies. Soil texture changes slowly enough so that this need only be determined once. However, surface climate changes are large enough at daily or finer time scales to significantly alter trace gas fluxes. Measures of surface climate must therefore be made frequently enough to resolve the cycle. Intermediate repeat frequencies on the order of a few days are needed for determining vegetation classification, biomass, and FPAR. Repeat frequency will depend on model needs and is constrained by the availability of remote sensing resources. An order from low to high repeat frequencies may be as follows:

**LOW** **HIGH**  
soil type < veg. class < biomass < FPAR < surface climate

Similarly, the level of spatial resolution required to quantify processes scales roughly with the linearity of the response of the parameter to the underlying controllers. For example, photosynthesis scales fairly linearly with climate factors, while production of trace gases has a nonlinear relation with the degree of soil anaerobiosis. The degree of spatial resolution required for each process may be approximately ordered:

**COARSE** **FINE**  
P<sub>s</sub>, respiration < decomposition < C storage < trace gas production

variability, a corrected, calibrated 10-km AVHRR data set is critical. This data set can provide the basis for global, internally consistent maps of vegetation class, the fraction of PAR absorbed by the green canopy (FPAR), leaf area index (LAI), as well as a rough picture of aboveground biomass. One of the key needs for the short term is an approach to vegetation classification that is tuned to the requirements and strengths of the models. One method that appears promising involves identifying a small number of inherently different classes (perhaps six to eight), and modifying the parameters for each class on the basis of climate (see Running et al., this issue).

### Ecosystem Structure and Function

The articles of Bonan (this issue) and Field et al. (this issue) review this science area. These models are directed toward describing the changes in ecosystem structure and function over time in response to internal dynamics (succession, soil chemistry changes, etc.) or external forcing (disturbance, climate change, anthropo-

genic change). Most of these models address timescales ranging from months to millenia. Forcings are generally provided from meteorological observations or GCM output (as with the carbon and BGC models of the previous subsection), and validation is done almost exclusively with *in situ* observations and historical (e.g., palynology) analyses, diagnostic studies, and change detection (see Fig. 4).

The data needed to describe the structure and function of ecosystems are those required to determine land surface type and soil characteristics (Table 3). From these descriptors, parameters to drive functions describing plant conductance, carbon assimilation, and soil moisture and thermal regimes can be derived for use in land surface models. In all cases, the problems of traversing the scale gap between conventional ecological studies and regional or global scale processes is significant.

Tables 3 and 4 capture the needs of the ecological community for global scale modeling as well as they could be defined at the workshop. Clearly, many of the

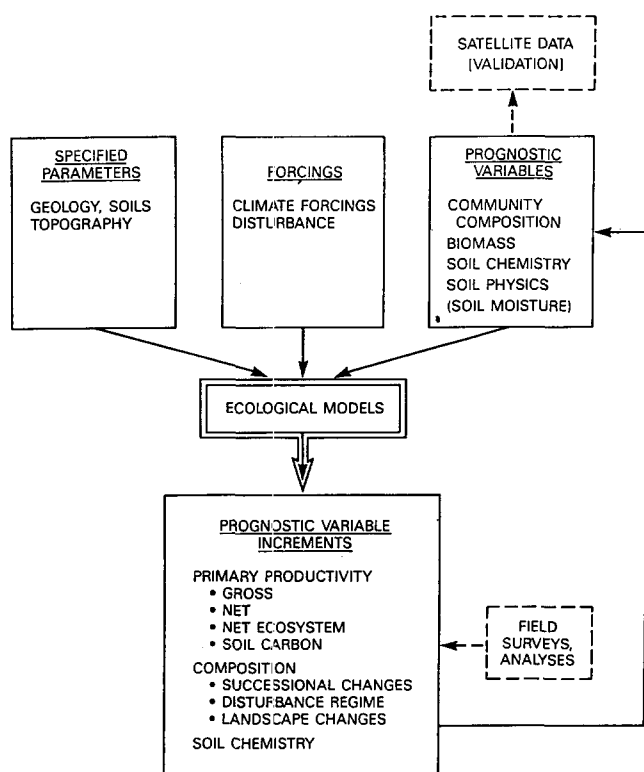


Figure 4. Schematic of relationships between ecosystem structure and function models and atmospheric conditions (forcing), specified parameters (initial conditions, forcing) and prognostic variables (validation). The roles of satellite and other data are shown.

variables listed cannot be specified globally using remote sensing or any other techniques at the required scales, at least not in the foreseeable future.

## ALGORITHMS AND EXPERIMENTS

After the discussions on the state and needs of the models, the workshop was reorganized into three new breakout groups. These were charged with assessing the state of current satellite data algorithms and with summarizing what has been learned from recent field experiments. Articles in this issue cover much of the presented material, and so only brief summaries are provided here.

### Algorithms for Atmospheric Forcings

Articles in this issue by Frouin and Pinker, Pinker et al., and Ellingson address the problems of retrieving surface radiation components from remotely sensed data. The article of Petty (this issue) reviews the current status of precipitation algorithms.

### Algorithms for Surface State

Articles in this issue by Hall et al., Norman et al., and Myneni et al. cover the methods and problems

associated with retrieving vegetation and surface energy balance components from optical and thermal data. The articles of Engman et al. (this issue) and Dobson et al. (this issue) deal with microwave (passive and active, respectively) remote sensing of soil moisture and land surface.

## Field Experiments

A number of field experiments have been designed and conducted under the auspices of ISLSCP. A brief summary of the major field experiments, an assessment of the major findings from these experiments, and an outline of major planned experiments is provided in Table 5 and in the text below. Prince (this issue) has contributed an article on one of these experiments, HAPEX-Sahel.

### Strategy for the Field Experiment Program

The initial strategy for the ISLSCP and allied field programs was focused on i) improving and upscaling the land surface parameterizations (LSPs) used in GCMs and ii) developing and validating means for using remote sensing to determine the climatically important properties of the land surface. It was recognized that while remote sensing had the potential to provide critically needed observations to initialize and provide boundary conditions for climate models, the actual algorithms to convert satellite observables into climatically important variables were primitive at best.

At the outset, there were vigorous discussions on how to develop an approach for scaling nonlinear processes over spatial scales which ranged from measurements made by surface instrumentation (1–10 m) to averages over the scale of a pixel (20–1000 m) to the scale of a GCM grid scale (100,000 m). In addition, biological and physical processes operate on timescales that are often incommensurate at any given scale, and which range from less than a second to hours or days over the scales to be modeled. It was also recognized that whatever algorithms were developed were likely to be biome-specific. Accordingly, it was desirable to conduct a series of experiments in a variety of regions around the world.

Lists of critical parameters are to be found elsewhere in this article, but the initial parameters were drawn strictly from the needs of GCM modelers attempting to improve biospheric parameterizations. In general, the accuracy requirements could be deduced from an overall goal of determining monthly average energy, heat, or water fluxes at the surface to  $\pm 10 \text{ W m}^{-2}$  over a GCM grid scale. This led to a need to understand surface albedo, surface roughness, bulk stomatal resistance, and soil moisture in the root zone. Direct and indirect methods were suggested using simple one-dimensional biospheric models, which used re-



Table 3. Surface Parameters Needed in Ecosystem Structure and Function Models

<i>Variable</i>	<i>Use in Parameterization</i>	<i>Temporal Scale</i>	<i>Spatial Scale</i>
Land cover type	Select functions for <ul style="list-style-type: none"> <li>• LAI/APAR</li> <li>• conductance</li> <li>• carbon assimilation</li> </ul>	—	Climate model dependent  1 × 1 km
Soil type	Initialize models for the following parameters <ul style="list-style-type: none"> <li>• field capacity</li> <li>• wilting point</li> <li>• hydraulic conductivity</li> <li>• heat capacity</li> <li>• thermal conductivity</li> <li>• rooting depth</li> </ul>	—	Climate model dependent  1 × 1 km
Phenology	Seasonality of LAI/APAR relationship  Could be used as a variable to help determine land cover classes	At least 1/4 of growing season cycle of principal plant form	Same scale as land cover type
Biomass	Help determine the following biomass parameters for a given land cover class <ul style="list-style-type: none"> <li>• standing aboveground biomass</li> <li>• fractional annual litter fall</li> </ul>	Assumed time, invariant once, characterized for cover type	Same as land cover type
Soil moisture profile	Initialize soil moisture models  Validate soil moisture models	Specified by initialization and validation schemes	By land cover type
Soil temperature profile	Initialize soil temperature models  Validate soil temperature models	Specified by initialization and validation schemes	By land cover type

motely sensed measures of the soil and vegetation condition, radiation fluxes, and precipitation.

Grasslands or agricultural areas with low relief and arid to semiarid regions were selected for much of the initial work, because of the relative simplicity of the remote sensing of their optically thin, erectophile plant canopies, the relative ease of instrumenting the low canopies, and the relative simplicity of the boundary layer flow over them.

#### *Major Field Experiments*

The first major experiment planned under ISLSCP (First ISLSCP Field Experiment; FIFE) was executed in 1987 on the Konza Prairie in Kansas. It was explicitly designed to address the scaling question over the range

from point measurements to that of a few AVHRR pixels (see Sellers et al., 1988; Sellers and Hall, 1992). A series of experiments conceived by the World Climate Research Programme, the Hydrologic Atmospheric Pilot Experiments (HAPEX), were also initiated at that time (see Andre et al., 1988; Schmugge and Andre, 1991). Although these were not initially designed for remote sensing purposes, an ISLSCP component was added. The first experiment in this series, HAPEX-Mobilhy was conducted in mixed forest and agricultural lands in south central France in 1986. HAPEX-Mobilhy sought to work at the scales ranging from 10 km to that of a GCM grid scale. The remote sensing component was not strongly oriented to the scaling issue.

Emerging from these two experiments was a clearer

**Table 4.** Additional Parameters Required To Describe Some Aspects of Structural and Functional Changes in Ecosystems

<i>Variable</i>	<i>Use</i>	<i>Temporal Scale</i>	<i>Spatial Scale</i>
Species composition of land cover types	Assess changes in structure with time and space Determine the emissions of some biogenic trace gases (e.g., some nonmethane hydrocarbons) Determine the ratio of C <sub>3</sub> to C <sub>4</sub> plants	Rate-dependent	Process-dependent—i.e., on the scale of disturbance/response function
Vertical structure of ecosystem	Assess total carbon exchange Assess biomass allocations Assess changes in ecosystem stratification	At least 1/4 of growing season	Dependent on level of stratification
Age structure	Determine dynamic turnover rate	Rate-dependent—annual or greater	On the scale of ecosystem composition
Disturbance	Determine rate of biomass turnover and changes in carbon allocation Determine rate of succession Determine sensitivity of land cover types to change	Dependent of the rate of disturbance	Dependent on the scale of disturbance
Canopy chemistry	Determine energy and photosynthetic efficiency	Subseasonal	On the scale of ecosystem composition
Decomposition	Determine rate and magnitude of production of biogenic trace gases	Subseasonal	By ecosystem
Standing water/degree of saturation	Determine the degree of anaerobiosis of ecosystem	Subseasonal	By ecosystem

approach to experiment design to provide for upscaling from the point to pixel scales and from pixel to GCM scales. These ideas were reflected in the HAPEX-Sahel experiment, which took place in the summer of 1992 and which was both a HAPEX and an ISLSCP experiment (see Prince et al., this issue; Goutorbe et al., 1994). The concepts were integrated to a lesser extent in the 1991 EFEDA (European Field Experiment in a Desertification-threatened Area) (see Bolle et al., 1993), and were fully implemented in the 1994 BOREAS (BOReal Ecosystem Atmosphere Study) and will be in subsequent ISLSCP experiments (see Sellers et al., 1993a, b).

Coverage of a range of biomes (grassland, agriculture, arid zone, boreal forest, tropical forest) will have been attained over a period of more than a decade. This

is partly because of limitations of funding, but also from the need for the scientific community to fully assimilate the results of these complex experiments. Reduction of field measurements which are not dependent on other measures may take months to a year, and the use of related measures and models to constrain parameters in the retrieval algorithms can take another year or more (see Sellers and Hall, 1992). Finally, synthesis of all results into regional scale modeling adds at least another year. A concern expressed by many participants in these experiments has been that, if anything, the experiments have been too closely spaced. Table 5 lists the locations (biomes) of each experiment. The emphasis on simpler, water-limited systems, and the short intervals between experiments is evident. Note that no exper-

Table 5. Completed and Planned Experiments Involving ISLSCP or Related Programs

<i>Experiment</i>	<i>Date of Field Phase</i>	<i>Location, Study Area Size</i>	<i>Primary Foci</i>	<i>Status / Lead Publications</i>
HAPEX-Mobilhy	1986	SW France 100 × 100 km	Energy-water exchange Mesoscale modeling	Data sets with investigators: Schmugge and Andre (1991) Andre et al. (1988)
FIFE	1987, 1989	Kansas, USA 15 × 15 km	Energy-water-carbon exchange Process studies, scaling Remote sensing science	Data sets on CD-ROM: Sellers et al. (1988) Sellers and Hall (1992)
KUREX	1991	Kursk, Russia	Energy-water-carbon exchange Remote sensing science	Data sets with investigators: Deering and Kozoderov (forthcoming)
EFEDA	1991	Central Spain 100 × 100 km	Energy-water-carbon exchange Process studies, scaling Remote sensing science	Data sets with investigators: Bolle et al. (1993)
HAPEX-Sahel	1992	Niger, Africa 100 × 100 km	Energy-water-carbon exchange Process studies, scaling Remote sensing science Mesoscale modeling	Data sets to be released in 1995: Goutorbe et al. (1994) Prince et al. (this issue)
BOREAS	1993–1994	Saskatchewan + Manitoba, Canada (1000 × 1000 km)	Energy-water-carbon exchange Carbon cycle and biogeochemistry Terrestrial ecology Process studies, scaling Remote sensing science Mesoscale modeling	Main field phase in 1994; data to be released in 1996–1997: Sellers et al. (1991) Hall et al. (1993) Sellers et al. (1993a)
GCIP	1995–2000	Mississippi Basin, USA 2000 × 2000 km	Energy-water exchange Scaling studies Mesoscale models Application of remote sensing	Planning in progress IGPO (1992)
AMAZON (LAMBADA- BATERISTA- AMBIX)	1998–2000	Amazon Basin, Brazil (3000 × 2000 km)	Energy-water-carbon exchange Carbon cycle and biogeochemistry Terrestrial ecology Process studies, scaling effects Remote sensing science Mesoscale modeling	Planning initiated: Sellers et al. (1993b)

iments have been planned for the tundra at this time. A discussion of the framework and results of the experiments listed in Table 5 may be found in Sellers (1992).

#### *Major Findings from the Field Experiments*

The experiments of the last few years have largely fulfilled their promise. The key findings can be summarized as follows.

**Radiation Balance:** Satellites (specifically GOES) can be used to estimate insolation to  $\pm 21.6 \text{ W m}^{-2}$ , incident PAR to  $\pm 8.2 \text{ W m}^{-2}$ , and net radiation to around  $\pm 50 \text{ W m}^{-2}$  (FIFE) (see Frouin and Gautier, 1990).

**Remote Sensing Science:** Sensor calibration errors can be dealt with so as to be a negligible part of the calibration/correction problem. Visible and near-infrared surface reflectances can be calculated to within 1% absolute or better using good atmospheric correction techniques (FIFE) (see Hall et al., 1992).

**Soil Moisture:** Surface soil moisture can be measured to within  $\pm 25\%$  relative accuracy using passive microwave techniques; however, there are problems in the retrieval whenever there is dense overlying vegeta-

tion or a litter layer (FIFE and HAPEX) (see Wang et al., 1992).

**Atmospheric and Surface Fluxes:** The atmospheric boundary layer over the land is more closely coupled (by a factor of 2) to the free troposphere than was previously thought (FIFE and HAPEX). Surface evaporative fraction is often relatively constant throughout the day; canopy level responses to incident PAR, vapor pressure deficit, and soil moisture are consistent with leaf-level studies and theory (FIFE) (see Betts, 1992).

**Measurement Technique Development:** LIDAR, aircraft and radiosondes provide comparable estimates of atmospheric boundary layer wind profiles and momentum transport. Flux aircraft can provide useful quantitative measures of surface flux (heat, water vapor,  $\text{CO}_2$ ), to around 5 km resolution, with systematic but well-understood underestimation (see Kelly et al., 1992; Gal-Chen et al., 1992; Desjardins et al., 1992). Net radiometers commonly disagree with each other up by up to 10%, depending on manufacturer (FIFE) (see Smith et al., 1992).

**Modeling:** Estimating surface sensible heat flux from radiometric surface temperatures is subject to many

sources of error; studies indicate that these lead to uncertainties on the order of  $150 \text{ W m}^{-2}$ . Visible and near-infrared reflectances can be used to calculate FPAR and hence canopy photosynthetic rates and maximum conductances to useful accuracies (see Hall et al., 1992). The models which link satellite-based reflectance fields, canopy FPAR, surface conductance, and evapotranspiration are almost linear and thus should be largely scale-invariant. This was validated using leaf-level, surface station, and airborne flux measurements combined with landsat data (FIFE). The whole question of scale integration of fluxes from point to region appears to be less problematic than feared at the outset of ISLSCP (HAPEX, FIFE) (see Sellers et al., 1992; Noilhan et al., 1991).

### DATA PRIORITIES FOR LAND SCIENCE

After the discussions on algorithms and field experiments, the original science groups (Water-Energy-Carbon, Carbon and Biogeochemistry, and Ecosystem Structure and Function) were briefly reformed to reassess their global data needs in light of what could realistically be provided given current technology and the likely resource base over the next few years.

The originally stated positions of each group are shown in Tables 1–4. As expected from the outset, the “more physical” data fields are specified as highest priority by the Water-Energy-Carbon Group while the ecologists placed more emphasis on vegetation dynamics and soil properties. The Carbon and Biogeochemistry priorities align themselves somewhere between the two other groups. However, an inspection of the tables sheds some interesting light on the reality of and perceptions about the desired data sets. In brief:

- (i) There is a very large overlap in terms of data requirements and associated data properties (resolution, frequency, etc.) as specified by the three groups.
- (ii) In most cases, the data sets exist in some form or another. However, they are not (or at least are not perceived to be) available to working scientists.
- (iii) Many data sets that are not currently available, for example, vegetation cover, FPAR, phenology, etc., could be generated and distributed with relatively little effort.

Table 6 is a prioritized consolidation of the data requirements of all three groups. Each of these data sets was reviewed with particular emphasis on what could be produced in the next two to five years. The data sets listed in Table 6 are ranked in a rough priority order on the basis of an approximate weighing of the priorities specified by each working group of each item.

This final ranking should be viewed as very rough; the error or uncertainty is probably on the order of  $\pm 1$  category. A set of four working groups were given the task of looking at the consolidated list of data sets in detail. These groups were titled “land cover,” “hydrometeorology,” “radiation,” and “soils”; their findings were summarized in Table 6 and are discussed below.

### Land Cover

Two streams of products were identified as critical for further progress in all areas of the science.

#### *Land Cover Classification*

Compilations of basic land cover classes have been provided for many years based on individually mapped areas. Unfortunately, the resultant statistics are apparently far from reliable (see Townshend, 1992). Moreover, if the areal extent of the cover classes is examined, the degree of correspondence between published classifications is found to be even more modest.

Other properties are similarly poorly known, such as primary productivity. Reliable observations are available for only a relatively limited number of areas, and these then have to be extrapolated in some way to the remainder of the Earth. Unfortunately, such extrapolations have often used global land cover class maps, as described above. Consequently, it is apparent that there is an urgent need to produce more reliable, internally consistent land cover products. The only realistic way in which such products can be produced is through the analysis of satellite data.

There remains a need for a consensus of the definition of categories of vegetation types for different purposes. Given the variety of needs for such categorical data, it is likely that different definitions of classes might well be needed according to the type of application. However, it may be that many different uses can cope with a core set of classes. The experience of the climate modeling community is worth acknowledging in this respect. In current biophysical land surface parameterization (LSPs), a large variety of vegetation characteristics are included, but experience with such models indicates that, although certain variables may be important, little is to be gained from anything but a very simple description of their properties. (For example, vegetation roughness does not need to be specified more precisely than three broad categories.) Hence knowing the distribution of around a dozen vegetation types may provide other modeling communities with sufficiently precise information given the current status of their models. Associated with the need for categorical data was a stated requirement for descriptors of landscape heterogeneity. The latter led to suggestions that vegetation communities might be described in terms of the proportion of different end-members.

Table 6. Consolidated, Prioritized Data Needs across the Science Areas: Water–Energy–Carbon and Biogeochemistry; and Ecological Structure and Function

Data Field	Domain	Spatial Resolution	Temporal Resolution	Source / Methodology	Action
Vegetation (cover type, phenology, disturbance, LAI, FPAR, etc.)	Regional and global	50 × 50 km to 1 × 1 km	Monthly	(1) AVHRR (2) Landsat, SPOT	(1) Use an existing AVHRR product for now (2) Support 1 × 1 km land surface data set effort (3) Revitalize efforts to correct data and apply algorithms to define biophysical parameters (1) Initiate work to process 4DDA products into usable data sets
Near-surface meteorology	Global	50 × 50 km	Diurnal cycle, monthly means	NMC, ECMWF, JMA, 4DDA and observations	
Precipitation	Global	100 × 100 km	Monthly means and selected days	WCRP-GPCP, operational met. agencies, surface data, thermal IR, 4DDA	(1) Implement NMC workshop to analyze surface network data (2) Check that the above is linked to WCRP-GPCP (3) Provide resources for gridding data if necessary
Radiation fluxes (S <sub>0</sub> , S <sub>1</sub> , L <sub>0</sub> , L <sub>1</sub> , PAR <sub>0</sub> )	Global	250 × 250 km to 50 × 50 km	Diurnal cycle, monthly means	GOES, METEOSAT, ERBE, AVHRR, TOMS, ISCCP, ESA, NASA analyses	(1) Define interested communities, dialog with ISCCP (2) Check regressions using Pathfinder data (3) Validate against long term data
Soils physics: texture, depth, porosity Chemistry: mineralogy, pH Topography	Global	100 × 100 km to 1 × 1 km	Once	FAO product and supporting material; new initiatives, notably IGBP	(1) Assign soil physics parameters to the FAO soil descriptor fields for now (2) Support new initiative, and encourage early deliveries
	Global	10 × 10 km to 1 km or better	Once	USGS, DMA, ERS-1	(1) Support efforts to release all data from DMA
Runoff	Regional to global	Catchment grid formats 50 × 50 km	Monthly	World Runoff Data Center in Germany	(2) Check across data sets for consistency (1) Strong encouragement to GRDC in Germany, enlist WMO support
Snow and ice	Regional to Global	25 × 25 km	Monthly	NOAA, NASA, Russian and Canadian agencies; SSM / I and surface observations	(2) Encourage continuous updating of the data set; gridding and averaged products (1) Apply existing techniques (2) Develop and apply improved algorithms and international communications links (3) Investigate use of SAR

### Land Cover Attributes

A number of important vegetation attributes vary spatially and temporally within as well as between vegetation classes. These include:

- Fraction of PAR absorbed by the vegetation canopy (FPAR)
- Leaf area index
- Gross primary productivity, biomass
- Ratio of  $C_3$ - $C_4$  species (by cover fraction)

Some of these parameters can be used to derive other fields; for example, leaf area index and FPAR can be used to estimate values of surface reflectance and roughness length.

As discussed in some of the articles in this issue, there are only a few data sources for this work (principally AVHRR but also Landsat, SPOT, and ERS-1), and there is no set of advanced but operationally robust algorithms that can be used to derive surface attributes. To meet the objective of producing global data sets within the near future, it is clear that most of the effort should be applied to the current and nascent AVHRR data sets.

### Hydrometeorology

In most cases, the required data sets exist somewhere in usable but not necessarily accessible forms. Each of the data sets was reviewed on a case-by-case basis.

(a) *Near Surface Meteorology:* The operational GCMs used by national/international organizations (NMC, ECMWF, JMA, etc.) all have four-dimensional data assimilation (4DDA) procedures which are mainly used for the initialization of forecast runs. Additionally, there are ongoing research efforts within NASA and NOAA, some of which are intended to support EOS by producing 4DDA fields.

These 4DDA fields of atmospheric variables (temperature, wind vector, humidity but also estimates of precipitation, radiation fluxes, heat fluxes, soil moisture, soil temperature, etc.) are in many cases the best global estimates currently available. They incorporate a combination of quality-controlled observations with time-and-space-filling provided by the model physics to yield gridded products which are suitable for use by scientists working in many disciplines. However, right now it is not easy for scientists to access the small subset of data required for their studies from the very large 4DDA archives held by most agencies, heroic efforts by ECMWF notwithstanding. In most cases, parameters are interpolated to standard pressure levels.

(b) *Precipitation:* The Global Precipitation Climatology Project (GPCP) was established in 1987 by World Climate Research Program (WCRP) to provide global fields of area / time averaged precipitation for the period 1986–1995. A combination of surface and satellite observations will be used to put together a data product

on a  $2.5^\circ \times 2.5^\circ$  grid with a monthly time resolution. Additionally, a variety of surface observation data sets and a few gridded products are held at the National Center for Atmospheric Research (NCAR). Legates and Willmott (1990) analyzed data from 24,000 surface stations and have produced a monthly mean,  $0.5^\circ \times 0.5^\circ$  product for the period 1920–1980, currently available on CD-ROM from NCAR. As yet, no  $1^\circ \times 1^\circ$  products exist for the last 10 years, nor (except for 4DDA statistics) is there an analysis of convective versus large scale rainfall components.

(c) *Runoff:* Runoff rates for selected catchments distributed around the world for the period 1965–1979 are held in a data base in Germany at the Global Runoff Data Center (GRDC). The runoff is defined in daily flow rate units per catchment. There is a need for gridded monthly data, also a need for the record to be brought up to the present for at least a few significant basins.

(d) *Snow and Ice:* There is only one operational product at the moment; the NOAA/NESDIS weekly snow cover map based on NOAA, GOES, and METEOSAT optical data. The SSM/I microwave sensor appears to have great promise for the production of regional products, but no agreed-upon algorithm is available as yet.

### Radiation

The International Satellite Cloud Climatology Project (ISCCP)  $250 \text{ km} \times 250 \text{ km}$  product is the only continuously generated data set available (see Schiffer and Rossow, 1983; Rossow et al., 1988; Darnell et al., 1992). The data are temporally aggregated for each month into eight 3-h bins per day to allow resolution of the diurnal cycle within the monthly mean data. An effort should be made to obtain estimates of downward surface PAR in addition to insolation and also to improve the spatial resolution of these products.

The provision of the longwave radiation components data is more problematical. Currently, the best available global information may be provided by 4DDA.

### Soils

(a) *Soil Physical and Chemical Properties:* Different analyses of the FAO  $1^\circ \times 1^\circ$  data base are all that are available for now. These have been used with other data to estimate the hydraulic properties of soil on a global scale (in most GCMs, soil depths is defined as a function of vegetation type). Rudimentary chemical information can also be assigned on the basis of the FAO data.

(b) *Soil Moisture:* Clearly, no technology exists for directly observing soil moisture fields globally. As present the best descriptions we have may be those provided by 4DDA.

It was proposed that the remote sensing community

involved with soil moisture determination be approached with a new set of challenges.

- i. Can time series of information on soil moisture be collated for a few critical areas for the purposes of model validation?
- ii. Can the available global data sets (principally SSM/I) be analyzed to yield at least qualitative maps of the spatial and temporal dynamics of surface soil moisture?

(c) *Topography*: There is an opportunity to provide much better topographical data to the community than currently available. The Defense Mapping Agency (DMA) data set could be released and compared with other data sets to yield a 10 km × 10 km product, adequate for most global and many regional modeling applications.

## SUMMARY AND RECOMMENDATIONS

The workshop assessed the progress made by ISLSCP and allied organizations in the areas of modeling, satellite data algorithms, and field experiments. Throughout there was an emphasis on tackling global scale problems in the context of Earth System Science. The findings of the participating scientists are summarized below.

### Modeling

The range of ongoing land-atmosphere modeling studies can be broken into three categories on the basis of process timescale.

*Water-Energy-Carbon*: These models are used to calculate the exchanges of water, energy, and carbon (photosynthesis and respiration) between the land surface and the atmosphere on relatively short timescales, on the order of seconds to seasons. On small spatial scales, they are used for hydrological and agricultural studies, on the global scale they are used to define the lower boundary fluxes for atmospheric general circulation models (GCMs) in which case they are loosely classified as land surface parameterizations (LSPs). The more realistic biophysically based LSPs implemented within GCMs over the last decade have been shown to produce better simulations of energy and water fluxes over the continents and thus should give rise to improved numerical weather prediction and climate simulation (see Betts et al., 1994; Noilhan et al., 1991; Sato et al., 1989). All of these models have suffered from two general weaknesses: First, it was not clear that the description of important flux-controlling processes, for example, heat and moisture transfer within the vegetation-soil-atmosphere system, could be credibly scaled up from models and

observations tested and/or conducted at very small scales up to the scales of LSP-GCMs; and second, no reasonable method exists to define the global state of the vegetation and soil moisture for either initialization or validation of the LSP-GCMs.

*Carbon and Biogeochemistry*: The models appropriate to studies of carbon and biogeochemistry (BGC) span intermediate timescales, on the order of days to several years. The important processes covered by these models include primary production, carbon allocation, decomposition, nutrient interactions and relation to the physical climate system (upstream) and ecosystem structure and function (downstream). It has been suggested that perturbations to the terrestrial carbon cycle, specifically an imbalance between photosynthesis and respiration which would lead to carbon sink/source anomalies, may play important roles in the rate and timing of atmospheric CO<sub>2</sub> increase over the next few decades (see Tans et al., 1990). This class of models suffers from many of the same kind of handicaps as the water-energy-carbon models discussed above; in particular, global forcing (atmospheric conditions) and surface state (photosynthetic capacity, carbon storage in the soil, etc.) data are not freely available.

*Ecosystem Structure and Function*: These models have a large overlap with the carbon and BGC models but span a wider range of timescales; most of these models have timesteps on the order of months to years and are run to describe ecological processes over periods of years to millenia. In large part, the models are forced by climate data but data on soil physical and chemical properties, topography, etc. are also used as part of the boundary conditions. Obviously, all data pertaining to land cover type, phenology, biomass, etc. are immensely useful for initializing and validating these models.

The three classes of models described above clearly originate from different scientific motivations and, to a large extent, from different science communities. However, they will all be essential for the study of global change and they all suffer from similar deficiencies, namely:

- i. *Scaling*: All of the models suffer from the so-called scale gap to varying degrees. Processes are studied in situ at small scales and very simple assumptions are used to aggregate the findings into parameterizations for use within regional or global scale modeling exercises.
- ii. *Data Needs*: Very few reliable, time-consistent, large-scale data sets exist in accessible form for

the purposes of initialization and validation of these models.

In the first ISLSCP meetings of 1983 and 1984, it was hoped that a combination of large-scale field experiments and a stream of satellite data products would be used to deal with these two issues. Research work conducted within and parallel to the field experiments would produce improved algorithms to generate the regional and global data sets.

### Algorithms

Satellite data algorithms that deal with land surface studies have been developed piecemeal under the aegis of the responsible government agencies. In 1987, an ISLSCP workshop reviewed the status of the algorithms [see Sellers et al. (1990) for a summary] and concluded that:

- i. Algorithms were available to calculate many of the important surface and atmospheric state variables required by modelers.
- ii. Very few of the algorithms had been thoroughly evaluated as to their accuracy and precision.
- iii. There is a lot of room for improvement in the current algorithms in terms of calibration, geometric correction and cloud screening procedures.
- iv. Very few of the algorithms have been tested sufficiently or are innately robust enough for routine operational use.

Since the 1987 workshop, some progress has been made in evaluating algorithm precision and accuracy, mainly as a result of studies sponsored by field experiments. However, virtually no progress has been made on the remaining issues, largely because considerable resources would have to be committed to address them effectively.

### Field Experiments

The ISLSCP field experiment initiative and some parallel activities performed by WCRP and other organizations were designed to address the issues described above.

The results from several experiments, including FIFE, HAPEX-Mobilhy, and others, were presented and discussed at the meeting. In broad summary, the principal findings were as follows:

- i. *Scaling Issues:* The problems of scaling soil-vegetation-atmosphere models from smaller scales up to scales of several kilometers do not appear to be as severe as originally feared. In general, the radiative transfer and mass and heat transport models used to describe processes on the scale of individual plants or small plots could be used to describe large-scale fluxes to acceptable accu-

racies while making use of very simple aggregative spatial integration techniques. In the experiments, explicit checks on these hypotheses were made possible by using a range of surface and airborne instruments to cover the scale range from a few centimeters out to several kilometers.

- ii. *Use of Satellite Data:* The field experiments permitted the collection of integrated data sets which allowed evaluation of the end-to-end procedures for calculating surface state parameters from exoatmospheric radiances. It was found that several components of the surface radiation budget (insolation, downward PAR, reflected shortwave) could be estimated from GOES with good accuracy and also that useful estimates of net radiation and downward longwave could be calculated. Satellite data were also used to calculate surface biophysical parameters, including FPAR, unstressed stomatal conductance, and unstressed photosynthetic capacity. These parameters have been used in simulation models to calculate the surface-atmosphere fluxes of carbon and water. Significantly, the remote sensing methodologies, the parameters, and the models themselves have been shown to be largely scale-invariant. This indicates that the local-scale models tested on the field experiment scale could be combined with large-scale satellite data sets to produce continental scale fields of energy and mass ( $H_2O$  and  $CO_2$ ) fluxes.

The field experiments succeeded in dealing with the two major issues that framed their design. The next task was to take the lessons learned from the experiments and apply them to improve models and to generate better data sets. It can be argued that the modeling community directly benefitted from the work: Several offline models and at least three operational GCMs utilize formulations that are based on field experiment results. However, it is also clear that the experimental results have yet to be used to generate improved large-scale data sets based on satellite data.

### Workshop Discussions and Assessments

At the risk of oversimplifying the issues, it can be concluded that the communities working on model development and on past and planned field experiments have their activities in hand. However, it was made clear that the availability and / or accessibility of global data sets was not considered to be satisfactory and that the activities of modeling, field experiments, and algorithm development / data set generation were in danger of becoming decoupled. These two issues are discussed in turn below:

Table 6 lists the most pressing data needs as specified by the working groups representing the three



classes of models discussed at the workshop. It is these high priority data sets that are perceived to be unavailable or inaccessible to the modeling community. Specifically:

- i. The 4DDA products (near-surface meteorology, radiation fluxes, soil moisture fields, etc.) have been generated by the operational meteorological agencies but the required information is expensive and difficult to extract from the product archives.
- ii. Very few satellite data products are actually available.
- iii. Other data sets based on surface survey work (soils, topography, runoff) are available but need a great deal of further analysis or reduction to make them directly useful to the modelers.

With regard to data accessibility, it is clear that with some effort the situation could be greatly improved. In most cases, such as the 4DDA products, soils information, topography, etc., it is more a question of agencies deciding to take the job and committing resources to see it through rather than the solution of difficult technical problems.

The situation with respect to data availability is different. Archives of satellite data certainly exist, in the form of instrument counts, exoatmospheric radiances, or, in some cases, atmospherically corrected surface radiances. Only in a handful of cases, for example, the ISCCP cloud products and the ERBE surface (clear-sky) albedo products, do we have global fields of surface or atmospheric parameters. For the satellite-based products specified in Table 6 (vegetation, incident PAR, insolation), the raw satellite data exist, but the processing has not been carried through to the production of global data sets of physical or biophysical parameters. However, all the necessary tools and materials for undertaking such a project are available: The data exist, many of the algorithms have been developed and tested using field experiment data, and the required data product list has been defined. What is required is an initiative to bring all of these things and the appropriate scientific expertise together to actually produce the global data sets. It was repeatedly pointed out that huge resources have been expended by agencies to design and launch satellite instruments, collect and archive the observations, and conduct the necessary investigations to understand and use the data. The final step, applying the science to produce global data sets of useful and usable parameters, is a clear priority and would be relatively cheap to execute, but has been done in only a few cases. These general assessments formed the basis for the specific recommendations of the workshop.

The second issue, that of the perceived decoupling of modeling, field experiment, and algorithm development activities is less easy to address by direct action

and is probably less responsive to a top-downwards management approach than is often believed. The problem may be best dealt with by more direct communication between the interested parties. At an informal level, this can be encouraged by holding interdisciplinary workshops at more frequent intervals than 5–7 years and specifically tasking them with addressing the gaps and bottlenecks existing between the science communities. On a formal level, the continuing involvement of modelers within field experiment design and algorithm working groups is essential.

Both of the above issues (data set availability / accessibility; scientific decoupling) are potential showstoppers for the future of much of Earth system science, particularly with regard to Earth Observing System (EOS). It was recognized that the major obstacles to progress in these areas had to be addressed within the next couple of years if the land science community is to reap benefits from scientific research connected with EOS.

### Workshop Recommendations

Three initiatives were put forward by the workshop. These cover the immediate generation of global data sets, the improvement of methodologies and algorithms for follow-on data sets and the improvement of communications between different elements of the Land Science community. These are discussed in turn below:

#### *Initiative 1. Immediate Generation of High Priority Global Data Sets*

It was proposed that some essential global data sets could be put together within two years, that is, by the summer of 1994, and released to the community. Existing or planned data management systems should be involved in this effort from the beginning. These data sets are listed in order of priority in Table 6 and shown schematically in Figure 5. The workshop made the following recommendations for the four areas of vegetation, hydrometeorology, radiation, and soils.

**Vegetation:** Global, monthly data sets of vegetation related parameters should be generated at good spatial resolution (100 km × 100 km or better is preferred) and monthly time resolution. The available AVHRR data should be used as the basis of this effort and algorithms applied to calculate fields of cover type, phenology, FPAR, and leaf area index (see Table 7A).

**Hydrometeorology:** Near-surface meteorological data sets should be extracted from the four-dimensional data assimilation (4DDA) streams generated by operational meteorological agencies. Specifically, near-surface temperature, humidity, wind vector, surface temperature, soil moisture content, radiation components, and precipitation should all be saved. Temporal resolution should be sufficient to resolve the diurnal cycle (preferably four or more reports per day) (see Table 7B).

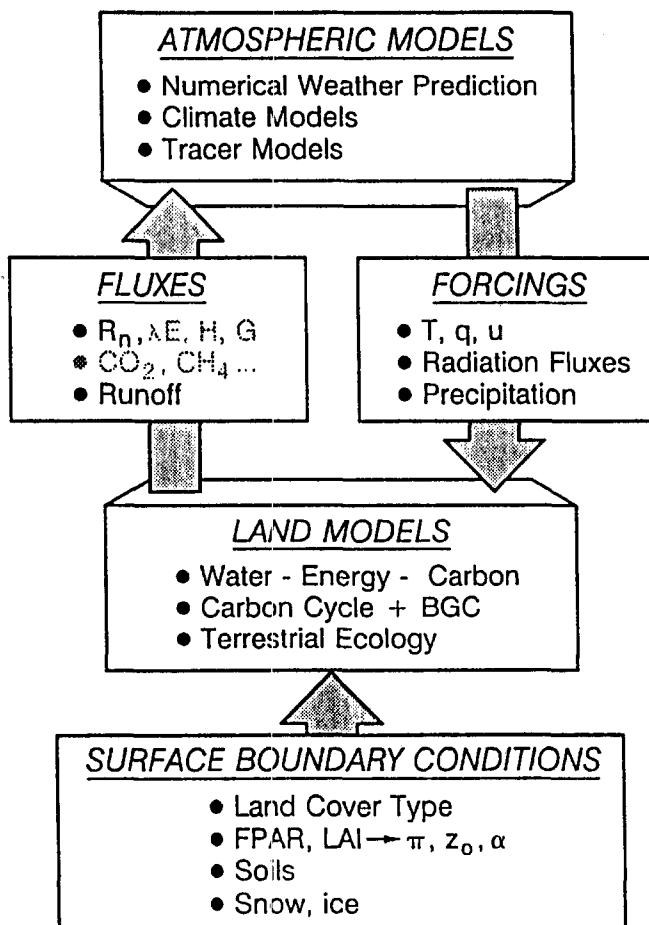


Figure 5. Schematic showing relationships between different kinds of atmospheric and land models. The Initiative I data sets are targetted at supplying the forcings, fluxes, and surface boundary conditions required to initialize, validate, and/or drive the land models in isolation from the atmospheric models. Initiative I should be successful in meeting all these requirements except for global-scale mass and heat fluxes, for which observations only exist for a few places and times, for example, large-scale field experiments.

A number of institutions hold archives of rainfall data. What is required is a gridded product (100 km × 100 km or better) with monthly time resolution and some information, direct or indirect, on the proportion of convective to large-scale precipitation. Runoff data is currently stored at the Global Runoff Data Center (GRDC) in Germany—these data should be processed to yield mm/day numbers (monthly means) for selected large catchments. This data subset would be of more direct use to modelers.

Lastly snow and ice data are currently collated by NOAA and NASA in the U.S. and also by Canadian and Russian operational agencies, largely from analyses of optical satellite data. The temporal resolution of the data should be sufficient to resolve weather-related changes in snow extent.

*Radiation:* There is a strong desire to have many

components of the surface radiation budget available at resolutions down to 50 km × 50 km, although it is clear the community could do good work with coarser resolution (250 km × 250 km) products. Again, the temporal resolution should be sufficient to resolve the diurnal cycle. The International Satellite Cloud Climatology Project (ISCCP) data sets insolation and incident PAR on a 250 km × 250 km grid with some effort. The continuing ERBE work will provide surface albedo estimates and the net surface shortwave budget on the same scale (see Table 7C).

*Soils, Soil Moisture, and Topography:* Global soils data sets with quantitative, even if only best-guess, soil physics, and soil chemistry information are needed. Soil texture, depth, porosity, mineralogy, and pH fields are required by most water-energy-vegetation and biogeochemistry modelers. A data set could be quickly generated based on the FAO global 1° × 1° data base and supporting or related information (see Table 7D).

Soil moisture information is very useful for validating all classes of models. It was recommended that the soil moisture remote sensing community be tasked with producing some global or regional products from existing information, such as SSM/I, even if this turns out to give only qualitative spatial and temporal patterns of soil moisture climatology, rather than precise information at a single point under ideal retrieval conditions. (These patterns would be very useful for checking 4DDA fields and other soil moisture estimates.)

Good topographic data sets are available but not easily accessible. Every effort should be made to extract the best available product from USGS and/or DMA and release it.

The above recommendations made for Initiative I were promptly followed up. During the year following the 1992 workshop, an ad hoc ISLSCP Science Steering Committee supported by staff at NASA/GSFC worked to put together a mutually consistent collection of data sets that would largely satisfy the needs expressed in Table 6. This effort will result in the issue of a CD-ROM in the middle of 1994. Table 7 lists the main data sets, their sources and some of their attributes. In comparing Tables 6 and 7, it will become clear that the stated requirements will be met except for those specifying soil chemical properties (which will hopefully be addressed by the latest IGBP-DIS initiative) and topography (which is being handled by a team at Eros Data Center as part of EOS). It should be noted that, as required, all the data are to be reformatted to a common 1° × 1° grid and will cover the same period, 1987–1988.

The Initiative I CD-ROM should be an invaluable resource for initializing, forcing, and validating all three classes of land model (see Fig. 5). For example, the International Geosphere-Biosphere Project (IGBP) may use the CD-ROM as a baseline initial condition and meteorological forcing data set for a global carbon model

Table 7. Types and Sources of Data To Be Collated onto the ISLSCP Initiative I CD-ROM<sup>a</sup>

A. VEGETATION: LAND COVER, BIOPHYSICAL PROPERTIES						
Parameter	Source Data			Temporal Coverage	Temporal Resolution	Data Source
	Spatial Resolution (deg)	Grid Description				
NDVI	1 × 1	Linear lat / lon	1 / 87–12 / 88	Monthly	AVHRR / GAC NASA / GIMMS	Los et al. (1994)
FASIR-NDVI	1 × 1	Linear lat / lon	1 / 87–12 / 88	Monthly	NDVI + vegetation classification	Sellers et al. (1994)
FPAR	1 × 1	Linear lat / lon	1 / 87–12 / 88	Monthly	FASIR + vegetation classification	Sellers et al. (1994)
LAI	1 × 1	Linear lat / lon	1 / 87–12 / 88	Monthly	FPAR + vegetation classification	Sellers et al. (1994)
Greenness	1 × 1	Linear lat / lon	1 / 87–12 / 88	Monthly	LAI (from above)	Sellers et al. (1994)
Surface roughness ( $Z_0$ ) (model-derived)	1 × 1	Linear lat / lon	1 / 87–12 / 88	Monthly	LAI + vegetation classification	Sellers et al. (1994)
Snow-free surface albedo (model-derived)	1 × 1	Linear lat / lon	1 / 87–12 / 88	Monthly	LAI + vegetation classification + soil reflectance	Sellers et al. (1994)
Clear-sky surface albedo (satellite-based)	4 × 5	Linear lat / lon	1 / 87–12 / 88	Monthly	ERBE data	Harrison et al. (1990)
Soil / litter reflectance (hybrid)	1 × 1	Linear lat / lon	1 / 87–12 / 88	Fixed	Vegetation classification + ERBE in deserts	Harrison et al. (1990)
Vegetation classification (surface survey)	1 × 1	Linear lat / lon	N / A	Fixed	Surveys of ecological literature, FAO archives	Sellers et al. (1994)
Vegetation classification (satellite-based)	1 × 1	Linear lat / lon	1 / 87–12 / 88	Fixed	Classification of NDVI	Kuehler (1983) Matthews (1984) DeFries (personal communication)
B. HYDROMETEOROLOGY						
B.1 NEAR-SURFACE METEOROLOGY, PRODUCED FROM ECMWF FOUR-DIMENSIONAL DATA ASSIMILATION						
Parameters are produced by ECMWF 4DDA at 1.125° resolution, on a regular lat / lon grid for the period 1 / 87–12 / 88, four times daily						
Surface temperature and pressure						
u-wind, v-wind, magnitude of wind vector						
u-wind stress, v-wind stress						
Net surface SW radiation						
Net LW surface radiation						
Temperature and dew point at 2 m						
Albedo						
Soil moisture						
Geopotential, temperature, and relative humidity at 500 hPa						
u-wind, v-wind, magnitude of wind, and direction of wind at 500 hPa						

## B.2. ADDITIONAL PARAMETERS TO BE OBTAINED FROM ECMWF FOUR-DIMENSIONAL DATA ASSIMILATION

Parameters are produced by ECMWF 4DDA at 1.125° resolution, on a regular lat / lon grid for the period 1 / 87–12 / 88, four times daily

Surface sensible heat flux, surface latent heat flux  
New SW radiation, and LW radiation at top of atmosphere  
u-component surface wind stress, v-component surface wind stress  
Snow depth

Pressure at mean sea level, surface geopotential  
Deep-soil wetness, deep-soil temperature

## B.3. MONTHLY OR FIXED PARAMETERS TO BE OBTAINED FROM ECMWF FOUR-DIMENSIONAL DATA ASSIMILATION

Parameters are produced or specified by ECMWF 4DDA at 1.125° resolution, on a regular lat / lon grid for the period 1 / 87–12 / 88, monthly or fixed

Surface roughness (monthly)  
Climate deep-soil wetness, and temperature (monthly)  
Land–sea mask (fixed)

## B.4. RUNOFF

### Source Data

Parameter	Spatial Resolution	Grid Description	Temporal Coverage	Temporal Resolution	Publications, Documentation
Flow rate	29 major rivers	Basin	1 / 87–12 / 88	Monthly	GRDC; data needs analysis

## B.5. PRECIPITATION

### Source Data

Parameter	Spatial Resolution	Grid Description	Temporal Coverage	Temporal Resolution	Publications, Documentation
Surface observations (gauged)	1 × 1	Linear lat / lon	1 / 87–12 / 88	Monthly	GPCP; land only
Merged gauged / satellite (IR-MW)	2.5 × 2.5	Linear lat / lon	1 / 87–12 / 88	Monthly	GPCP; global

## B.6. SNOW AND ICE

### Source Data

Parameter	Spatial Resolution	Grid Description	Temporal Coverage	Temporal Resolution	Publications, Documentation
Extent	150 to 200 km	Polar stereographic	1 / 87–12 / 88	Monthly	NOAA / NESDIS from NCDC Northern Hemisphere only
Snow depth	40 × 40 km	Eighth mesh grid	1 / 87–12 / 88	Monthly	Air Force ETAC from NCDC

## C. RADIATION

Parameters	Source Data			Temporal Coverage	Temporal Resolution	Publications, Documentation
	Spatial Resolution	Grid Description				
TOA net shortwave	Approximately 280 × 280 km	ISCCP equal area		1 / 87–12 / 88	Monthly means (8 × daily)	Staylor algorithm / Langley DAAC
TOA net shortwave	2.5° × 2.5°	Equal-angle lat / lon cells		1 / 87–12 / 88	Monthly means (8 × daily)	Pinker (personal communication)
TOA net longwave	Approximately 2.5 × 2.5°	Equal-angle lat / lon cells		1 / 87–12 / 88	Monthly means	Darnell (personal communication)
Surface net shortwave	2.5 × 2.5°	Equal-angle lat / lon cells		1 / 87–12 / 88	Monthly means (8 × daily)	Pinker (personal communication)
Net shortwave	Approximately 280 × 280 km	ISCCP equal area		1 / 87–12 / 88	Monthly means (8 × daily)	Staylor algorithm / Langley DAAC
Downwelling shortwave surface	Approximately 280 × 280 km	ISCCP equal area		1 / 87–12 / 88	Monthly means (8 × daily)	Staylor algorithm / Langley DAAC
Cloud fraction	Approximately 280 × 280 km	ISCCP equal area		1 / 87–12 / 88	Monthly means (8 × daily)	Staylor algorithm / Langley DAAC
Downwelling longwave surface	Approximately 2.5 × 2.5°	Equal-angle lat / lon cells		1 / 87–12 / 88	Monthly means	Darnell (personal communication)
Downwelling shortwave surface	2.5 × 2.5°	Equal-angle lat / lon cells		1 / 87–12 / 88	Monthly means (8 × daily)	Pinker (personal communication)
Downwelling PAR surface	2.5 × 2.5°	Equal-angle lat / lon cells		1 / 87–12 / 88	Monthly means (8 × daily)	Pinker (personal communication)

## D. SOILS (BY MAP UNIT)

Soil texture (three classes), slopes (three classes), and depths (three classes) are to be provided on a 1° × 1°, linear lat / lon grid by Bliss and Amer (personal communication) based on a reanalysis of the FAO data

<sup>a</sup> Note that: (i) All data are to be regridded onto a 1° × 1°, linear, latitude-longitude grid; (ii) The period covered will be the years 1987 and 1988, as far as possible. This period covers the maximum availability of some satellite data sets and also the FIFE field phase.

intercomparison exercise. Besides this and similar applications, the data set will provide a strong starting position for global studies that will help the community to prepare for the EOS data sets.

#### *Initiative II. Improved, Follow-On Data Sets*

The data sets specified in Initiative I are to be generated within a 2-year period, that is, with existing data and the available robust and simple algorithms. The resulting products will go some way towards satisfying the immediate needs of the modelers and will exercise every aspect of the data–algorithm–modeler pipeline as well as (hopefully) a data system or two en route. However, it is clear that great improvements could be made over this first data release, mainly in the areas of data correction, algorithm improvement, and validation. Some specific examples were discussed at the workshop.

**Vegetation:** Almost all of the steps in the land cover data processing/parameter retrieval activity could be improved for a follow-on data product, including calibration; radiometric, geometric, and atmospheric correction; treatment of BRDF; and the inference of biophysical qualities (see Fig. 6).

**Hydrometeorology:** As mentioned before, the major objective is to make available data sets (4DDA products, precipitation data, runoff data, etc.) more accessible. The 5-year objective should be to make the operational production of the useful data routine.

**Radiation:** Many improvements could be made in many areas. First, ISCCP products could be generated

at a higher spatial resolution than now (125 km rather than 250 km) for insolation and incident PAR at least. Second, close contact should be maintained with the Surface Radiation Budget (SRB) project activities ongoing at NASA/Langley Research Center, and elsewhere. Again, assessment of the accuracy and precision of higher spatial resolution products over the land surface should be emphasized. Third, a number of research areas should be encouraged; specifically, algorithm improvement for the determination of downward longwave fluxes, satellite calibration, surface validation, and validation of cloud radiation models.

**Soils:** A number of activities, including one sponsored by IGBP, are underway to produce improved soils information. Subsets of the resulting data sets should be analyzed to address the modeling needs described elsewhere in this article. The same goes for topographic and snow and ice data sets. With regard to soil moisture, efforts should be made to redirect some of the ongoing research towards the generation of the discontinuous regional or global scale data sets for model validation in addition to the basic research which has been underway for many years now. Even if the resulting data sets are spatially or temporally discontinuous, they are still useful.

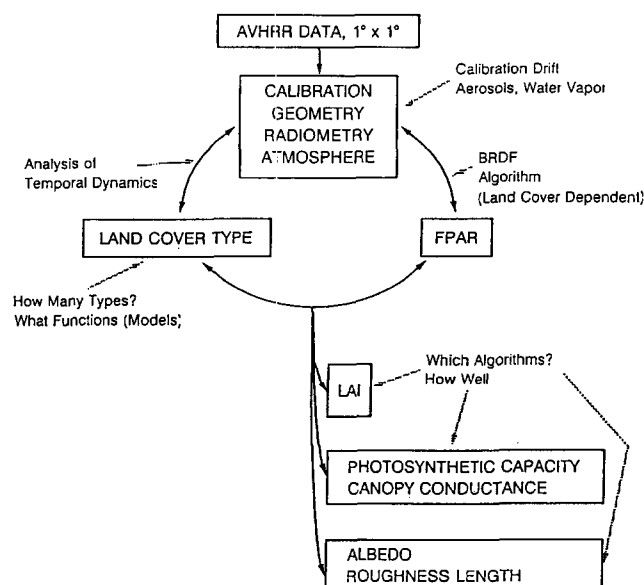
#### *Initiative III. Improved Communications within the Land Science Community*

The workshop highlighted the extent to which different but related research thrusts can become separated from each other even when it is obvious that there are strong mutual scientific interests at stake. It was recognized that coordinated top-down management initiatives could provide only part of the answer: It is equally important to provide regular forums where the different communities discuss their areas of overlap on a scientist-to-scientist basis. It was observed that many recent workshops had drifted into within-discipline discussions (e.g., wish-list writing, experiment design, etc.) with little time to focus on the so-called bottleneck issues (e.g., implementation of algorithms to produce global data sets, incorporation of late-developing model needs into experiment design, etc.). Clearly, these cross-cutting issues need explicit attention.

#### CLOSING REMARKS

The ISLSCP Workshop of 23–26 June 1992 succeeded in providing a forum at the working scientist level for assessing what had been achieved by the land science community over the last decade and what urgently needs to be done. It became clear that the participating scientists felt that the experiments and algorithm development efforts, though completely worthwhile in themselves, had failed to deliver global data sets to modelers working in the areas of energy–water–carbon exchange,

**Figure 6.** Processing steps and issues in moving towards a suite of land cover data sets derived from AVHRR data and other sources. Note that the derivation of FPAR is partially dependent on the assumed or derived type of land cover present and vice versa. Leaf area index and canopy biophysical properties are functions of both FPAR and land cover type.



carbon cycle and biogeochemistry, and terrestrial ecology. The needs of the modelers, the capabilities of the algorithms and the lessons learned from field experiments were reviewed, critiqued, and combined to produce a prioritized list of global data requirements that would meet the needs of the modeling community using source data from satellites, meteorological analyses, and analyses of surface survey work. As a consequence, ISLSCP has launched work to produce a preliminary global data set for release in mid-1994 (Initiative I), to be followed by a second more sophisticated product, to be released in 1997 (Initiative II), and will also work to improve communications among scientists working on models, algorithms and field experiments (Initiative III).

#### APPENDIX: ACRONYMS

4DDA	Four-dimensional data assimilation	GRDC	Global Runoff Data Center
AVHRR	Advanced Very High Resolution Radiometer	GSFC	Goddard Space Flight Center (NASA)
BGC	Biogeochemistry	GTS	Global Telecommunications System
CD-ROM	Compact Disc-Read Only Memory	HAPEX	Hydrology-Atmosphere Pilot Experiment
DAAC	Distributed Active Archive Center	IGBP	International Geosphere-Biosphere Project
DMA	Defense Mapping Agency	IGBP-DIS	IGBP Data and Information System
DOD	Department of Defense	IR	Infrared
ECMWF	European Center for Medium-Range Weather Forecasting	ISCCP	International Satellite Cloud Climatology Project
EFEDA	European Field Experiment in a Desertification-threatened Area	ISLSCP	International Satellite Land Surface Climatology Project
EOS	Earth Observing System	JMA	Japanese Meteorological Agency
ERBE	Earth Radiation Budget Experiment	LAI	Leaf area index
ERS-1	European Research Satellite-1	LaRC	Langley Research Center (NASA)
FASIR	Fourier-adjusted, solar zenith angle corrected, interpolated and reconstructed data	LSP	Land surface parameterization
FAO	Food and Agriculture Organization (UN)	METEOSAT	Meteorological Satellite (European geostationary platform)
FIFE	First ISLSCP Field Experiment	NASA	National Aeronautics and Space Administration
FPAR	Fraction of PAR absorbed by the vegetation canopy	NCAR	National Center for Atmospheric Research
GCM	General Circulation Model (of the atmosphere)	NDVI	Normalized difference vegetation index
GEWEX	Global Energy and Water Cycle Experiment	NMC	National Meteorological Center
GOES	Geostationary Operational Environmental Satellite	NOAA	National Oceanic and Atmosphere Administration
GPCP	Global Precipitation Climatology Project	PAR	Photosynthetically active radiation
		SAR	Synthetic aperture radar
		SPOT	Satellite Probatoire pour l'Observation de la Terre
		SRB	Surface Radiation Budget
		SSM / I	Special Sensor Microwave Imager
		TOMS	Total Ozone Mapping Spectrometer
		USGS	United States Geological Survey

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