

Large scale field experiments and modelling land surface processes : A review

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ABSTRACT

Land surface processes (LSP) have significant impact on climate variability at different time scales. General circulation models require worldwide information about terrestrial changes that are responsible for interactions between the atmosphere and land-surfaces. Various land-atmosphere monitoring programs have been undertaken in different ecosystems to develop, test and validate the LSP parameterisation schemes used in regional and global models. This paper presents an overview of the recent LSP associated field experiments, their accomplishments and the modelling activities to improve weather and climate forecasts. The problem of spatial integration of land-surface properties over a non-homogeneous land surface and especially the estimation of regional surface fluxes has been a central issue for all the land-surface experiments. Though satellite measurements provide the required inputs on real time to simulate the models, significant errors among them indicate the need for development of region specific coefficients to represent LSPs. There is also a need to intensify multi-disciplinary activities related to measurements, analysis and modelling of soil-vegetation-atmosphere interactions.

Key words : Land surface processes, Energy and moisture fluxes, Weather and climate modelling, Geosphere-biosphere.

Land surface processes (LSP) are those associated with the exchange of mass, momentum and energy between the land surface and the atmosphere. Exchange processes at the land surface-atmosphere interface on regional scale belong to the most sensitive components in the climate system. The small heat capacity of the land makes land-atmosphere interaction distinctly different from ocean-atmosphere interaction (Zeng and Neelin, 1999). The role of the land surface in controlling climate is still underestimated (Kabat *et al.*, 1998). This significant component of the land surface-atmosphere interactions governing the transfer processes

at smaller scales, has not been, adequately resolved by general circulation models (GCMs) for climate prediction (Moore *et al.*, 1993; Gedney *et al.*, 2000). Further, most of the problems in GCMs, including the prediction of monsoon precipitation (Gadgil *et al.*, 1998), come from the continental-scale atmosphere-land surface interactions and poor physical basis in representing the land surface as well as cloud / precipitation processes.

A wide variety of schemes to represent the LSP have been developed over the years (Garratt, 1993; Betts *et al.*, 1996 b). Recent studies have shown that major improvements

in climate modelling require availability of long-term flux data, unbroken time series, from representative surfaces (Viterbo and Beljaars, 1995).

In order to represent LSP in different ecosystems over large areas in the atmospheric GCMs, several extensive field measurement campaigns, of short duration, are under implementation. The primary objective of these experiments is to study the LSP and their interaction in different ecosystems with the cooperation of scientists from multi-disciplinary fields using modern instrumentation. For example, at Cabauw (The Netherlands), a continuous boundary layer monitoring program has been running since 1986 (Van Ulden and Wieringa, 1996). The measurement program includes profiles of wind, temperature, and moisture up to 200m from a micro-meteorological tower, as well as all components of the surface energy balance (Beljaars and Bosveld, 1997). Table-1 provides summary of recent field experiments on LSP, which indicates that intensive efforts are being made to study these processes at different ecosystems and geographical regions.

This paper briefly reviews the experimental plan, implementation strategy and the data generated in a few recent large-scale field experiments undertaken in different ecosystems. Some of the important results of these experimental data in understanding the prevailing variations in local and regional climate are presented. We also discuss the efforts to study the observational data including remote sensing to parameterize different LSP schemes in numerical weather prediction (NWP) models and the activities undertaken by multi-disciplinary groups to

improve weather and climate predictions at regional to global scales.

Large scale land surface process experiments

Long-term monitoring of surface fluxes is difficult and therefore the climatology of sensible and latent heat fluxes based on observations is virtually nonexistent. The World Climate Research Programme (WCRP) and the International Geosphere Biosphere Programme (IGBP) have provided the first sets of data and the first insights into the relevant processes, on local, regional and global scales (Shuttleworth, 1991). Well-known field experiments such as the HAPEX - Hydrological Atmospheric Pilot Experiments (Andre *et al.*, 1986, 1988, 1990, Goutorbe *et al.*, 1997); First ISLSCP (International Satellite Land-Surface Climatology Project) Field Experiment (FIFE) (Sellers *et al.*, 1992; 1996a; Sellers and Hall, 1992); Amazonian Regional Micrometeorological Experiment (Shuttleworth *et al.*, 1984); European International Project on Climate and Hydrological Interactions between Vegetation, Atmosphere and Land Surface (ECHIVAL) Field Experiment in Desertification - Threatened Area (EFEDA) (Bolle *et al.*, 1993), and Boreal Ecosystem - Atmospheric Study (BOREAS) (Sellers *et al.*, 1995, 1997), etc. have generated a wealth of data. Shuttleworth (1991) presented an overview of major experiments and main conclusions, until 1990.

The motivation for the HAPEX and FIFE type experiments came from the fact that land-atmosphere interactions are represented inadequately in the current GCMs on one hand and the need to calibrate satellite systems for global observations on the other. Of the

Table 1 : Large-scale land surface process experiments in different ecosystems

Acronyms	Name of the Experiment	Period of Study	Place / Country	Vegetation/ Climate
ABRACOS	Anglo Brazilian Climate Observation Study	1990-95	Brazil	Virgin rain-forest, Pastures
ARME	Amazonian Regional Micrometeo. Experiment	1980's	Brazil	Amazonian forest
BOREAS	Boreal Ecosystem - Atmosphere Study	1993-96	Canada	Boreal forest
BALTEX	Baltic Sea Experiment	1994-2001	Baltic	Temperate climate
EFEDA	European Field Experiment in Desertification threatened area	1991-95	Spain	Semi-arid climate
HAPEX-Mobilhy	Hydrological and Atmospheric Pilot Experiment	1986	France	Agricultural crops, forest vegetation
HAPEX - Sahel	Hydrological and Atmospheric Pilot Experiment in the Sahel	1991-93	Niger	Tiger bush, fallow bush grassland, millet fields
HEIFE	Hei Ho River Basin Field Experiment	1992-93	China	Arid to semi-arid, forest
GCIP	GEWEX Continental Scale International Project	1995-	Canada, USA	Prairie, forest, agriculture.
FIFE	First ISLSCP Field Experiment	1987-89	USA	Gallery forests, agriculture, grasses
IMGRASS	Inner Mongolia grassland Atmosphere Surface Study	1997-2000	Mangolia	Grassland
LASPEX	Land surface Processes Experiment over Sabarmati region.	1997-1998	India	Semi-arid, tropical agricultural land use
LBA	Large Scale Biosphere-Atmosphere Experiment	1996-2003	Brazil	Tropical rainforest
LITFASS	Lindenberg Inhomogeneous Terrain - Fluxes between Atmosphere and Surface : A long-term Study	1995-2001	Germany	Agricultural fields, forest and lake
NOPEX	Northern Hemisphere Climate Processes Land Surface Processes Experiment	1994-96	Sweden	Boreal pine forest
OASIS	Observation at Several Interacting Scales	1994-95	Australia	Semi-arid salt bush, Rainfed wheat
PILIPS	Project for Intercomparison of Land-surface Parameterization Schemes	1992-	USA	Grassland, deciduous forest
REKLIP	Regio Klima-Project	1990's	Germany	Coniferous forest, Agric. Land use

previous major land-surface experiments those of the HAPEX-type (mainly GCM-oriented) were focused on an area size of roughly 100 km by 100 km, whereas those of the ISLSCP-type (remote-sensing oriented) focused on much smaller areas on the order of 10 km by 10 km. HAPEX-Mobilhy, EFEDA, HAPEX-Sahel, CASES (Cooperative Atmospheric Surface Exchange Study) in the Walnut River Watershed (LeMone *et al.*, 2000), KUREX (Kursk experiment) in Russia and Hei-He River Field Experiment (HEIFE) in China are the most prominent examples of the former. The FIFE and LOTREX (Longitudinal land-surface traverse experiment) (Jochum *et al.*, 1990) are examples of the latter. Results from these experiments have been published (Schmugge and André, 1991; Wood, 1991; Special Issue on FIFE, Journal of Geophysical Research, November 1992). The BOREAS, NOPEX (Northern hemisphere land surface processes experiment), Global Energy and Water Cycle Experiment (GEWEX) Asian Monsoon Experiment (GAME), Tibetan Plateau Experiment (TIPEX) (Chen and Xu, 1999), and Land Surface Process Experiment (LASPEX) in the Sabarmati River Basin (Vernekar, *et al.*, 1999) are some other recent experiments at continent and river basin scale.

The hydrology-atmosphere pilot experiment in the Sahel (HAPEX-Sahel)

The HAPEX in the Sahel region (HAPEX-Sahel) is an international land-surface-atmosphere observation program that was undertaken in Africa. The Sahel forms the border of the Sahara desert, which is a major source of sensible heat for the atmosphere. Any extension or reduction of desert-like conditions due to fluctuations in the rainfall and vegetation of the Sahel are therefore likely to have strong feedbacks on

the general circulation through the energy balance and other processes (Goutorbe *et al.*, 1997; Mahrt and Ek, 1993). Further, HAPEX-Sahel was the first large-scale experiment where passive microwaves were fully investigated and retrieved parameters confronted with mesoscale and global circulation models (Goutorbe *et al.*, 1993).

The aim of HAPEX-Sahel was to make simultaneous measurements of relevant variables at the micro, meso and macro scales including remote sensing approach. Fluxes of water vapor were measured at the leaf, canopy, stand, landscape and $1^\circ \times 1^\circ$ grid scales. Similar designs were adopted for all aspects of the energy, water, and carbon balances. The heterogeneity of surface types and seasonal variation in the region are much greater than in the areas studied in any previous measurement campaign of this type. In order to obtain data for this large area, an extensive measurement program was undertaken including field, aircraft, and satellite remote sensing measurements, between 1990 and 1992. Intensive observational periods (IOPs) were undertaken for 8 weeks from mid to late growing season of 1992.

A three-layer hierarchy of sites were established in order to sample the study area and to provide the appropriate size and uniformity of sites needed for each of the wide variety of measurement techniques that were used in HAPEX-Sahel (Goutorbe *et al.*, 1997). First, one $1^\circ \times 1^\circ$ square was selected; second, three super sites were identified inside the $1^\circ \times 1^\circ$ square, each approximately 20 km by 20 km; third, within each super site, three or more sub-sites were selected, one in each of the principal landscape components of the super site. The sub-sites were divided into a

number of stands, one of which was generally a tower flux site, but others were used for other types of measurements (Lloyd *et al.*, 1997). Below the stand level, individual plants or specific soil sampling were conducted. This formalized sampling structure was intended to assist in the subsequent scaling of field measurements to the landscape and regional scales (Prince *et al.*, 1995).

Two ancillary sites were instrumented to improve the surface flux coverage of the $1^\circ \times 1^\circ$ area. Observations were also made from aircraft to bridge the gap between ground observations and satellite data. There were two roles for the aircraft; first, acquisition of data over the sub-sites and super sites to enable the relationships between the ground and airborne scales of measurement to be determined; second, measurements at the scale of the $1^\circ \times 1^\circ$ square, to scale the super site results to the entire study area.

The results from these observations indicated that surface-atmosphere interactions affect atmospheric processes on daily, monthly, and longer time scales. (Goutorbe *et al.*, 1994, Beljaars *et al.*, 1996 and also see Special Issues on HAPEX-Sahel, Journal of Hydrology Volume 188 and 189). These results were able to improve our understanding of the role of the Sahel on the general circulation, in particular the effects of large interannual fluctuations of land surface conditions in this region. These studies, in turn, developed ideas about how the general circulation is related to the persistent droughts that have affected the Sahel during the past 25 years or so (Monteny *et al.*, 1997).

Northern hemisphere climate processes land surface experiment (NOPEX)

The NOPEX was devoted to study the

land surface-atmosphere interaction in a northern European forest-dominated landscape (Lundin *et al.*, 1999). The NOPEX main study region, central Sweden is situated in the middle of the densest part of the northern European boreal forest zone and also centrally situated in the Baltic Sea drainage basin, the study region for the BALTEX project (Raschke *et al.*, 1998). The NOPEX was specifically aimed at investigating fluxes of energy, momentum, water, and CO_2 - and the associated dynamics - between the soil, the vegetation and the atmosphere, between lakes and the atmosphere as well as within the soil and the atmosphere on local to regional scales ranging from centimeters to tens of kilometers (Halldin *et al.*, 1998). The main objectives of NOPEX are

- (i) To study land-surface processes at a regional scale for a mixed land cover dominated by boreal forest by providing improved parameterization schemes of exchange of water, energy and carbon between the land surface and the atmosphere in hydrological and meteorological models from the meso-scale to global-scale.
- (ii) To undertake Integrated analysis of local and regional data for initialization and validation purposes,
- (iii) Development and testing of relevant algorithms for the remotely-sensed data and models for their sensitivity to the quality of input data, and to couple hydrological and atmospheric models in an interactive way.

The main field activities are conceived to strike a balance between the need to cover sufficiently long observation periods and the

amount of resources required to carry out field campaigns covering all relevant spatial scales. The long-term data-collection activities, the continuous climate monitoring (CCM) programme, form the backbone of the NOPEX field programme. Field activities like airborne deployments, intensive remote-sensing ground-truth data collection, and establishment of a network of micro-meteorological field stations, were coordinated in a series of concentrated field efforts (CFE). Research within the CFE and CCM brought together hydrologists, meteorologists, soil scientists, remote-sensing specialists, and researchers from other disciplines.

The CCM program is divided into Long-term catchment studies (LTCS), Soil-plant-atmosphere monitoring (SPAM) and Regional climate survey (RCS). Activities during the CFE are made up by: (a) Local-scale studies, (b) Regional-scale studies and (c) Remote sensing. A total of nine sites were selected for local-scale ground-based micro-meteorological measurements and are representative of the surrounding area, i.e., fetch conditions were ideal. The activities during the first two CFEs made use of established techniques and the emphasis was on the integration of these data with the regional-scale data.

The regional-scale studies are comprised of three distinct but complementary activities. Atmospheric states and fluxes at the meso-scale are probed by airborne and sounding equipment. Hydrological variability of states and fluxes at the regional scale is studied by undertaking a mixture of synoptic and catchment measurements of groundwater, soil moisture runoff, and precipitation in combination with weather-radar and physiographic data obtained from national

authorities and remote sensing. Remote-sensing activities include ground-truth, airborne recordings and data from satellites.

Observations covered the whole depth of the atmospheric boundary layer (ABL). An instrumented aircraft, radiosondes, tethered sondes, and pilot balloons were used. Data on ABL structure, important diurnal cycles (surface energy budget, inversion height), characteristics of the area and their influence on area-average fluxes were observed. Measurement activities are intimately linked with meso-scale modelling activities (Bringfelt *et al.*, 1999; Haldin *et al.*, 1999). The NOPEX initial results are as follows. The aircraft measurements of sensible heat fluxes were generally lower than those obtained from ground measurements. This discrepancy is partly explained by measured and modeled gradients in the lowest part of the atmospheric boundary layer. The evaporation fluxes could be aggregated from land-use weighed mast fluxes in the boreal forests. The effective exchange coefficients for momentum transfer seem to be independent of the averaging scale such that standard similarity theory and effective roughness lengths, of around 1.5 m, can be used to parameterise momentum flux (Molder and Lindroth, 1999). However, subgrid-scale heterogeneity must be explicitly resolved to predict correct grid-averaged surface fluxes (Haldin *et al.*, 1999). Zero-plane displacement was affected by wind speeds in a relatively dense rye canopy but not for spring barley, winter wheat and pasture (Matejka and Hortalova, 1999). Boreal forest-floor evaporation accounted for around 10% of the total stand evaporation with daytime rates between 0.1 and 0.6 mm per day (Constantin *et al.*, 1999). About 1 km scale soil moisture can be meaningfully deduced

from local-scale measurements at a few representative locations, required for coupled atmospheric-hydrological modelling. The physiographic features of lakes (depth, areal extent and shape) are needed to understand how a specific lake reacts to atmospheric forcing and feeds back to the atmosphere (see Special Issue on NOPEX, Agricultural and Forest Meteorology, 1999, Vol.98-99).

Lindenberg inhomogeneous terrain - fluxes between atmosphere and surface: a long-term study (LITFASS)

The LITFASS is an R&D project of the German Weather Service (GWS) being implemented during 1995 to 2001. The major scientific objective is to determine and to model / parameterize the area-averaged turbulent fluxes of momentum, heat, water vapour (and other trace constituents) over a heterogeneous landscape around Lindenberg meteorological observatory. These fluxes are expected to be representative for a horizontal scale of about 10 km, which corresponds to the grid length of the operational NWP model of the GWS (Foken *et al.*, 1997). An IOP on Cloud/Precipitation - Air/Land surface interaction experiment (LITFASS-98) was undertaken during May-June 1998. The scientific goals are as follows:

- (a) Collection of a complex meteorological/hydrological dataset for initialization, forcing and validation of high-resolution, non-hydrostatic meso-g-scale meteorological models,
- (b) Measurement of soil parameters, radiation components and turbulent fluxes over different types of land surface (meadow, agricultural fields, forest, lake) and collection of data for the validation of SVAT models,

- (c) Measurement of turbulent fluxes which are representative for different horizontal scales using point measuring devices and spatially integrating measurement systems,
- (d) Identification and assessment of processes and small-scale surface structures determining the energy and water cycles and the formation of clouds and precipitation over non-homogeneous terrain, and
- (e) Development and testing of data assimilation methods for remote sensing data and hydrological parameters.

The LITFASS-98 has produced a valuable, comprehensive data set for model simulations with different types of models (Beyrich *et al.* 1999, Beyrich, 2000). Behavior of the turbulent fluxes has been determined using a variety of techniques and methods covering six magnitudes of spatial sampling scales (measurements of profile, eddy-correlation, scintillometer, helicopter and aircraft measurements). The initial scientific results from LITFASS-98 are described by Beyrich (2000) and are summarized as follows.

The influence of local terrain and surface conditions on the mean atmospheric parameters tends to get mixed at about 150 m - 200 m above ground level under daytime convective conditions. The soil heat flux reached daytime maximum values typically between 50 Wm⁻² and 80 Wm⁻². In the forest, the daytime heat flux is always less than 25 Wm⁻² due to the limited amount of available energy below the canopy. The Intercomparison of the soil flux measurements in a depth of 5 cm at the forest site showed root mean square differences of less than 5 Wm⁻² and a relative

Table 2 : Land surface process models and associated model variables.
(Adopted from Land Surface Process Interaction Mission, Personal Communication)

PROCESSES	MODELS	MODEL VARIABLES
Heat and mass transfer at the land-atmosphere interface	<ul style="list-style-type: none"> • Soil Vegetation Atmosphere Transfer models • Planetary Boundary Layer models • Global Circulation model • Numerical Weather Prediction models 	Albedo
		Emissivity
		Long-wave irradiance
		Canopy and ground temperature
		Resistance to heat and mass transfer
Primary productivity	<ul style="list-style-type: none"> • Efficiency models • Canopy functioning models • Plant production and senescence 	Vegetation type
		Cover fraction
		FAPAR
		LAI
		LIDF
		Leaf chlorophyll content
		Leaf water content
		Stand density
		Phenology
		Soil type
Regional hydrological processes	<ul style="list-style-type: none"> • Distributed watershed models • Water conveyance and PBL dynamics • Sediment removal and transport • Chemicals transport and accumulation 	Cover fraction
		Vegetation type
		Soil type
		Soil surface status (residues, moisture, roughness)
		Evapotranspiration
		Snow cover, grain size
		Surface storage capacity
Land atmosphere exchanges of biochemical entities	<ul style="list-style-type: none"> • Soil organic matter turnover • Biogeochemicals input to water • Mineral nutrition 	Relative amount of fast and slow decaying biochemicals
		Ground temperature
		Soil moisture, water thickness
		Fresh water constituents
Establishment and dynamics of ecosystems	<ul style="list-style-type: none"> • Process models in stands • Transect models • Gap models • Spatial models • Dynamic global vegetation models • Canopy architecture dynamics models 	Spatial patterns of canopy architecture
		Soil type

deviation of 15% or less. The time evolution of friction velocity is characterized by a gradual increase until around noon, a pronounced minimum at around 14 UTC, and a sharp decrease after 16 UTC. The magnitude of the sensible heat flux is highest over the forest exceeding that over low vegetation. Friction velocity is slightly higher over the agricultural crops than over grass. On the contrary, the sensible heat flux is higher over grass than over the cereals, which is compensated by a lower latent heat flux. The micro-meteorological measurements revealed a non-closure of the local energy budget at different flux stations. The mean ratio between the available energy and the turbulent fluxes of sensible and latent heat is about 1.6, and increases with an increasing fraction of bare soil indicating the importance of the heat storage in the upper soil layers. The relative weights of the different surface types in forming the area-averaged flux and the possible contribution from mesoscale circulations or advective transports have still to be investigated.

Oklahoma atmospheric surface layer instrumentation system (OASIS)

Measurements at over 90 automated weather stations across Oklahoma State (USA), known as MESONET (Brock *et al.*, 1995) were used in the OASIS project (Richardson *et al.*, 1999) during 1997 to 2000. It is designed to enhance the MESONET's capability to measure boundary layer fluxes of sensible, latent, and ground heat as well as the radiation balance. The MESONET sites directly measure the net radiation balance and ground heat flux and indirectly estimate the sensible heat flux using similarity theory; and calculate latent heat flux as a residual from the conservation of energy equation. In

addition, nine of the 90 sites also used eddy correlation techniques to determine the sensible and latent heat fluxes and measured net radiation using a four-way net radiometer. The OASIS-98 field phase was designed to examine the accuracy of surface flux measurements during an eight week period (June to August, 1998) using the tower-based components of an integrated surface flux facility (Richardson *et al.*, 1999).

The initial results (of 30th July 1998) indicated the total available energy as 600 Wm^{-2} . Approximately 300 Wm^{-2} goes into the sensible heat flux while the remaining is split about evenly between latent and ground heat flux. At night, the magnitude of the flux imbalance is less than 10 Wm^{-2} while during the day, it is less than 90 Wm^{-2} , with a 24-hour average imbalance of 10 Wm^{-2} . The sensible heat flux estimated using the profile method agreed well with the eddy correlation measurements. Latent heat flux estimated as the residual from the energy balance equation agreed reasonably well with eddy correlation measurements.

Land surface process parameterisation and modelling

The land-surface atmospheric process models are broadly classified into five groups, viz

1. Heat and mass transfer at the land-atmosphere interface,
2. Primary productivity,
3. Regional hydrological processes,
4. Land-atmosphere exchange of biochemical parameters, and
5. Dynamics of ecosystems,

Table 2 describes various process models and their primary variables. Accuracy of these model variables are of crucial importance to achieve a realistic simulation of the low-level atmospheric properties, the planetary boundary layer (PBL) structure, cloud formation, rainfall, weather patterns, and the atmospheric circulation in general (M. Rast, 1999, personal communication).

Lal (2000) prepared monthly gridded ($1^\circ \times 1^\circ$) data sets on land surface characteristics of the Indian Subcontinent. The sensitivity experiments with these data sets demonstrated that vegetation exerts a mitigating influence on both the land surface and atmosphere. Also, simulation experiments with a Regional Atmospheric Modeling Systems (RAMS) suggest that the model performs better with an interactive biosphere-hydrological land surface.

Present-generation atmospheric and process-based hydrological models are very different in aim and scope and not easily coupled. Local advection and other sub-grid-scale phenomena are important for the parameterisation of the exchange of mass and energy between the atmosphere and the land surface in climate and weather models. However, atmospheric meso-scale modelling has proven to be a powerful and convenient tool to study results of the previous land-surface experiments and to study feedback processes between the land surface and the atmosphere (Bougeault *et al.*, 1991). Furthermore, it had been evident that surface and PBL processes are linked, making it necessary to measure and model the boundary layer and the energy budgets together (Raupach, 1991). Thus, improved understanding of surface-exchange or boundary layer processes was included among

the objectives of many scientific programs (Ex. IGBP-BAHC (Hutjes *et al.*, 1998), GEWEX (Coughlan and Avissar, 1996), PILPS (Henderson-Sellers *et al.*, 1993, 1995)). They have been successfully used to model the exchange processes of heat, water vapour and momentum over large areas. However, a fully coupled model for the atmosphere at a given spatial scale and the surface and subsurface is yet to be developed.

Numerical simulation of planetary boundary layer (PBL)

Several land surface schemes like ECHAM (Roeckner *et al.*, 1996), SECHIBA (Ducoudre *et al.*, 1993) etc., were designed for use in atmospheric GCMs to simulate the PBL. For example, 1D-simulation for July (Central Europe, grass) using the same initialization and the horizontal tendencies of humidity in the atmosphere simulated diurnal cycles of evapotranspiration, and convective precipitation events. Variations noted are due to the impact of land surface parameterisation on the atmosphere.

Project for intercomparison of land-surface parameterization schemes [PILPS]

The Project for Intercomparison of Land Surface Parameterisation Schemes (PILPS) is a joint activity by the GEWEX and the Working Group on Numerical Experimentation. PILPS has been operational since 1992 with the objective to improve the parameterisation of the continental surface, especially the hydrological, energy, and momentum exchanges, as represented in climate and NWP models (Henderson-Sellers *et al.*, 1993). Its approach is to facilitate comparisons (i) between models, and (ii) between models and observations, that will

help diagnose the shortcomings, and motivate improvements in the model schemes.

The implementation of PILPS consisted of five phases. Phase 0 was documentation stage. Phases 1 and 2 comprised of a suite of experiments, where land surface schemes are run in an off-line (i.e. not coupled with their host atmospheric model) and are forced with, and validated against, synthetic (Phase 1) and observational data (Phase 2). In Phase 1, over 30 participating models, which used one-year common data set, were compared with respect to partitioning of net radiation into latent and sensible heat, and of precipitation into evapotranspiration and runoff. In Phase 2, the emphasis was expanded from simple inter-comparison of models to evaluation with observed field data. The Cabauw experimental meteorological data for the year 1987 has been used as input to 23 land-surface flux schemes in climate and weather models (Chen *et al.*, 1997). Schemes were evaluated by comparing their outputs with long-term measurements of surface sensible heat fluxes, upward longwave radiation and total net radiative fluxes, and also comparing them with latent heat fluxes derived from a surface energy balance experiment (Henderson-Sellers *et al.*, 1995). The mismatch noted in the model outputs is attributed to point observation of fluxes, and there was not a good match between the areas represented by the fluxes and the catchment scale stream flow. Further, the catchment drainage area was much smaller than the study region, and therefore, the models' ability to simulate stream flow could not be rigorously evaluated. Another shortcoming of the previous Phase 1 and 2 series of experiments is the absence of data sets that allow testing of the effects of interannual variability.

In order to resolve the scale mismatch and to compare the ability of the models to simulate land surface energy and moisture fluxes, simulation experiments using a multi-year test period has been undertaken. The radiative and meteorological forcings for six catchments located throughout the Arkansas-Red basin, USA were used to adjust, or calibrate, model parameters. Phase 3 of PILPS is contained within Atmospheric Model Intercomparison Project (AMIP) (Gates, 1997) and was developed to assess the performance of land surface schemes coupled to their host atmospheric GCM. In phase 4 several land surface schemes are coupled to the same atmospheric GCM, to detail land-atmosphere interactions in numerical simulations.

Significant results of the model simulations (Chen *et al.*, 1997) are as follows. On an annual basis, the predicted surface radiative temperature exhibits a range of 2°K across schemes, consistent with the range of about 10 Wm⁻² in predicted surface net radiation. Most of the model values of monthly net radiation differ from the observations by less than the estimated maximum monthly observational error of ±10 Wm⁻². Annual means of sensible and latent heat fluxes, into which net radiation is partitioned, have ranges across schemes as 30 Wm⁻² and 25 Wm⁻², respectively. Annual totals of evapotranspiration and runoff, into which the precipitation is partitioned, both have ranges of 315 mm. These ranges in annual heat and water fluxes were approximately halved upon exclusion of three schemes that have no stomatal resistance under non-water-stressed conditions. Many schemes tend to underestimate latent heat flux and overestimate sensible heat flux in summer,

with a reverse tendency in winter. For six schemes, root-mean-square deviations of predictions from monthly observations are less than the estimated upper bounds on observation errors of $\pm 5 \text{ Wm}^{-2}$ for sensible heat flux and 10 Wm^{-2} for latent heat flux. Differences in boundary conditions used in various schemes are not sufficient to explain the large variance in soil moisture. However, many of the extreme values of soil moisture could be explained in terms of the particulars of experimental setup or excessive evapotranspiration.

International satellite land surface climatology project (ISLSCP)

The ISLSCP was established to promote the use of satellite data for the global land-surface data sets needed for climate studies. The objectives are

- (a) Demonstrate the types of surface and near-surface satellite measurements that are relevant to climate and global-change studies,
- (b) Develop and improve algorithms for the interpretation of satellite measurements of land-surface features,
- (c) Develop methods to validate area-averaged quantities derived from satellite measurements for climate simulation models, and
- (d) Prepare the groundwork for future operational production of land-surface data sets, which can be directly applied to climate problems.

The First ISLSCP Field Experiment (FIFE) was conducted over the period of 1987-1989 on the Konza Prairie in Kansas (Sellers

et al., 1988). The purpose of FIFE was to provide satellite data on land-surface states such as biomass, cover type and temperature; and land-surface processes such as transpiration and photosynthesis. The work of FIFE is being continued and extended to the Boreal Ecosystems-Atmosphere Study (BOREAS) in Canada (Sellers *et al.*, 1995). Sellers *et al.* (1996a, b) described the global data sets of surface boundary conditions and biophysical parameters.

The ISLSCP was accepted as a component of the GEWEX and continues to improve the representation of land surface processes in climate models, which is critical to the success of the GEWEX program (Sellers and Hall, 1992). The ISLSCP has thus played a key role in addressing further research in land surface processes, developing climate models, experimental design and implementation, and data set development.

The global soil wetness project (GSWP)

The Global Soil Wetness Project (GSWP) is an ongoing modeling activity of the ISLSCP and GEWEX. Soil wetness is an important component of the global energy and water balance, but it is unknown over most of the globe. Soil wetness is the reservoir for the land surface hydrologic cycle, a boundary condition for atmosphere, controls the partitioning of land surface heat fluxes, affects the status of overlying vegetation, and modulates the thermal properties of the soil. Knowledge of the state of soil moisture is essential for climate predictability on seasonal to annual time scales. Robock *et al.* (2000) described a Global Soil Moisture Data Bank, currently has soil moisture observations for over 600 stations from a large variety of climates around the globe.

The goals of GSWP are fourfold. The project is to produce state-of-the-art global data sets of soil moisture, surface fluxes, and related hydrologic quantities using remote sensing technique. It provides a means of testing and developing large-scale validation techniques over land. It serves as a large-scale validation and quality check of the ISLSCP data sets. GSWP is also a global comparison of a number of LSPs, and includes a series of sensitivity studies, which should aid future model development. The GSWP is to produce a 2-year global data set of soil moisture, temperature, runoff, and surface fluxes by integrating one-way uncoupled LSP models using externally specified surface forcings and standardized soil and vegetation distributions (Sellers *et al.* 1996a). Approximately one dozen participating LSP groups in five nations have taken the common ISLSCP forcing data to execute their state-of-the-art models over the 1987-1988 period to generate global data sets (Darnell *et al.* 1992, Dirmeyer *et al.*, 1999). The soil wetness data produced are also being tested within GCMs to evaluate their quality and impact on seasonal to interannual climate simulations (Dirmeyer *et al.*, 1998). A number of sensitivity experiments are intended to evaluate the impact of uncertainties in model parameters and forcing fields on simulation of the surface water and energy balances. Comparison among the model results is used to assess the uncertainty in estimates of surface components of the moisture and energy balances at large scales, and as a quality check on the model products themselves (Dirmeyer *et al.*, 1998).

Validation of operational numerical weather forecast models

Available datasets have been used to develop and validate different schemes of LSP

used in NWP models, in stand-alone condition. For example, Beljaars and Viterbo (1994) used Cabauw dataset to improve and test the land surface scheme in the European Centre for Medium-Range Weather Forecasting (ECMWF) model. Assessment of the land surface interaction of the ECMWF reanalysis using summer 1987 FIFE data showed greater improvements in the 1992 operational model (Betts *et al.*, 1998a). Utilising the same FIFE data set, the diurnal and seasonal cycles of the surface energy budget and boundary layer in the NCEP-NCAR (National Center for Environmental Prediction - National Center for Atmospheric Research) global reanalysis indicated the seasonal agreement to be quite good, reflecting the improvements in land-surface parameterisations in recent years (Betts *et al.*, 1996, 1997, 1998b). Simulation with a new land-surface parameterisation on a regional-scale weather forecast model, Bringfelt *et al.*, (1999) were able to mimic NOPEX measurements and produce Bowen ratios from forests twice as large as those from agricultural grid cells.

DISCUSSION

One of the largest uncertainties in the present-day global climate models resides with the understanding of the processes in the soil-vegetation-atmosphere-transfer (SVAT) system. Thus the main purpose of the LSP schemes in GCMs is to provide the atmosphere with surface fluxes of momentum, heat, and moisture with a view to decrease the uncertainty in climate prediction. Parameterisation of these fluxes is highly complex and include components for scaling of turbulent eddies, radiation, cloud formation, rainfall and, in a usually simplistic manner, the land-surface processes. However, even if the processes occurring at the interfaces of the

biosphere - geosphere system with the atmosphere and the ocean are well understood and parameterised on the very local scale, extending that knowledge to regional and global scales is still a complex problem. Strong coupling between these processes and the extreme heterogeneity of the geosphere - biosphere system render spatial aggregation very complicated. Thus, a major concern would be the scaling up of local processes to regional and global scales or vice versa.

The energy and moisture budgets and their partitioning at the land-atmosphere interface must be represented as accurately as possible in different process models. However, for testing and validation of these schemes in stand-alone mode, it is necessary to have a continuous time series of the atmosphere forcings (i.e. wind, temperature, radiation and precipitation) as well as continuous records of sensible and latent heat flux data. In view of the fact that success of atmospheric modelling effort is mainly dependent on the implementation of efficient land-surface schemes, simple and complex schemes have been developed over the years.

The problem of spatial integration of land-surface properties over a non-homogeneous land surface and especially the estimation of regional hydrology or surface fluxes, has been a central issue for all the major land-surface experiments. Many national and international field experiments are being organised in different ecosystems to provide reliable input data for development, testing and validation of land surface processes and their parameterisation schemes used in climate, hydrological and numerical weather prediction models at different time scales (Ex: meso-, regional-, and global scales). Spatially distributed information on the bio-geophysical

properties and temporal changes of the terrestrial ecosystems, as provided by satellites, are additional inputs to investigate surface/atmospheric exchange processes.

Although many meso-scale modelling studies have provided new insights, there is a clear need for more methodological studies of this type, preferably with a focus on relevant integration principles/aggregation rules. Intercomparison of results obtained from GCM experiments indicated large inter-model differences in the partitioning of sensible and latent heat fluxes at local and River-basin scale model integrations.

The land surface process experiment (LASPEX) over Sabarmati river basin in India is aimed at (i) improving our understanding of LSP over the semi-arid tropical region and (ii) to improve land surface process parameterisation in the global model used for medium range weather forecasting. LASPEX data sets at Anand, on diurnal variation of air and soil temperature with respect to solar radiation, indicated that during summer, there is a considerable lag in the temperature maxima with respect to solar radiation, as compared to the monsoon period (Pillai *et al.*, 1998). However, the diurnal and day-to-day variations of short-wave radiation and net radiation fluxes are predicted satisfactorily using one dimensional turbulent closure model (Satyanarayana *et al.*, 2000). This model well captured the daytime super-adiabatic lapse rate conditions and night time stable conditions in the first few tens of meters of the atmosphere during winter. There is a need to critically analyse the available LASPEX data to elucidate the processes underlying the monsoon variability at different spatial and temporal scales in the tropics.

Development of an integrated surface flux measurement program in different agro-climatic regions of India seems to be an essential requirement to improve our understanding of the processes responsible for the monsoon variability at different spatial and temporal scales. There is a need to intensify our efforts in multi-disciplinary activities related to measurements, analysis and modelling of land-vegetation-atmosphere interactions involved in the hydrological processes, land-atmosphere exchange of biogeo-chemical parameters and dynamics of ecosystem models for sustainable productivity.

Climate research at the interface between the atmosphere and land surface is undergoing a dramatic change in focus, driven by new societal priorities, emerging technologies, and better understanding of the atmospheric system. Further, there is a need to undertake field experiments to investigate the role of land-ocean-atmosphere interactions in climate variability at different time scales under non-homogenous terrain.

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