LAND SURFACE PROCESSES

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1. Introduction

Through their regulation of water and energy transfer between the land and atmosphere, the dynamics of terrestrial water stores are an important boundary condition for the global water cycle at weather and climate timescales. The basis for a concerted integrated research effort is now provided by breakthroughs in techniques to observe: (1) global and regional precipitation, (2) surface soil-moisture, (3) snow, (4) surface soil freezing and thawing, (5) surface inundation, (6) river flow, and (7) total terrestrial water-storage changes, combined with better estimates of evaporation. As the primary input of water to the land surface, precipitation defines the terrestrial water cycle. The partitioning of this precipitation between infiltration (and subsequently evapotranspiration) and runoff is determined by surface physics, vegetation, snow and soil-moisture conditions, and soil-moisture dynamics.

Accurate initialization of land surface moisture and energy stores in fully-coupled climate system models is critical for seasonal-to-interannual, climatological and hydrological prediction because of their regulation of surface water and energy fluxes between the surface and atmosphere over a variety of time scales. Subsurface moisture and temperature stores exhibit persistence on seasonal-to-interannual time scales; together with external forcing and internal land surface dynamics, this persistence has important implications for the extended prediction of climatic and hydrologic extremes. Because these are integrated states, errors in land surface forcing and parametrization accumulate in subsurface moisture and temperature stores, which lead to incorrect surface water and energy partitioning. However, many innovative new land surface observations are becoming available that may provide additional information necessary to refine and constrain the physical parametrizations and initialization of land surface states critical for seasonal-to-interannual prediction. These constraints can be imposed in three ways. First, by forcing the land surface primarily by observations (such as precipitation and radiation), the often severe atmospheric numerical weather prediction land surface forcing biases can be avoided. Second, by employing innovative land surface data assimilation techniques, observations of land surface storages (such as soil temperature and moisture) can be used to constrain unrealistic simulated storages. Third, the land surface physical parametrizations themselves are improved through the use of observed parameters, and through the data assimilation process where model states are constantly being evaluated against observations.

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2. Land surface modelling

Figure 1 shows recent advances in understanding soil-water dynamics, plant physiology, micrometeorology, and the hydrology, all of which control biosphere-atmosphere interactions. These advances have spurred the development of land surface models, whose aim is to represent in a simple, yet realistic way, the transfer of mass, energy, and momentum between a vegetated surface and the atmosphere (Dickinson *et al.*, 1993; Sellers *et al.*, 1986). Land surface model predictions are regular in time and space, but these predictions are influenced by model structure, errors in input variables and model parameters, and inadequate treatment of sub-grid scale spatial variability. Consequently, land surface model predictions of land surface hydrology and land surface states are much improved by the assimilation of land surface observations.

Three recent land surface models warrant further discussion. These are: (1) the Mosaic land model of Koster and Suarez (1992) and Koster *et al.* (1998), (2) the National Centers for Environmental Prediction, Oregon State University, United States Air Force, and Office of Hydrology, land surface model, called Noah, and (3) the Community Land Model.

The Mosaic land model addresses the problem of subgrid heterogeneity by subdividing each grid cell into a user-specified mosaic of tiles (after Avissar and Pielke, 1989), each tile having its own vegetation type and hence water and energy balance. Surface flux calculations for each tile are similar to those described by Sellers *et al.* (1986). Tiles do not directly interact with each other, but influence each other indirectly, by their collective influence on the overlying atmosphere. Like the plethora of land surface models that have been developed over the past decade (*e.g.* the Project for Intercomparison of Landsurface Parameterization Schemes, PILPS, participants, Henderson-Sellers *et al.* 1993), the Mosaic land model is well suited to modelling the vertical exchange of mass, energy and momentum with the overlying atmosphere, but includes a poor representation of lateral moisture movement, which significantly controls variations in soil water, surface energy fluxes and runoff. Recognizing this weakness, Koster *et al.* (2000) developed a new, catchment-based land surface model that includes a more realistic representation of hydrological processes, including the lateral transport of soil water through the subsurface. The catchment-based model, which relies heavily on concepts originally put forth by Famiglietti and Wood (1991) and Famiglietti and Wood (1994) (*i.e.* the Topmodel based Land- Atmsophere-Transfer-Scheme, TOPLATS) will represent a major advance in land surface models for the following two reasons. First, the Topmodel (Beven and Kirkby, 1979) topographically-based framework will result in improved runoff prediction, and consequently, more realistic catchment-scale water balance. Second, the downslope movement of moisture within the watershed will yield sub-catchment-scale variations of surface and unsaturated-zone moisture content, which will result in more realistic prediction of within-catchment variations in surface fluxes. Improved simulation of runoff will ultimately result in a more realistic flux of continental streamflow from the land to the oceans in the coupled model, and similarly, the within-catchment variations in surface fluxes result in more representative catchment-average exchanges with the atmosphere.

The Noah land model simulates soil moisture (both liquid and frozen), soil temperature, skin temperature, snow water equivalent, snow density, canopy water content, and the traditional energy flux and water flux terms of the surface energy balance and surface water balance. This model has been used in: a) the National Oceanic and Atmospheric Administration (NOAA) Office of Hydrology submission to the Project for Intercomparison of Landsurface Parameterization Schemes phase 2d tests for the Valdai, Russia site, b) the real-time, United States domain, Land Data Assimilation System, c) the coupled National Centers for Environmental Prediction (NCEP) mesoscale Eta model (Chen *et al*, 1997) and the Eta model's companion 4-dimensional Data Assimilation System, as well as in d) the coupled National Centers for Environmental Prediction global Medium-Range Forecast model and its companion 4-dimensional Global Data Assimilation System.

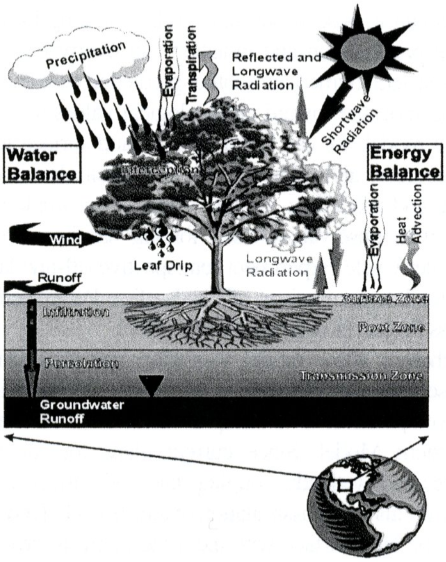

Figure 1: Land surface modelled processes.

The Community Land Model is being developed by a *grass-roots* collaboration of scientists who have an interest in making a general land model available for public use. By *grass roots*, we mean that the project is not being controlled by any single organization or scientist, but rather, the scientific steering is judged by the community. However, the project began at a sub-group meeting at the 1998 National Center for Atmospheric Research (NCAR) Climate System Model meeting, and it was implemented in the National Center for Atmospheric Research Climate System Model in early 2000. The Community Land Model development philosophy is that only proven and well-tested physical parametrizations and numerical schemes shall be used. The current version of the Community Land Model includes the best components from each of three contributing models: the Land Surface Model (Bonan, 1996), the Biosphere Atmosphere Transfer Scheme (Dickinson *et al.*, 1986) and Chinese Institute of Atmospheric Physics land surface model (Dai and Zeng, 1997). The Community Land Model code management is similar to *open source* in that, use of the model implies that any scientific gain will be included in future versions of the model. Also, the land model has been run for a suite of test cases including many of the Project for Intercomparison of Landsurface Parameterization Schemes case studies. These include the First International Satellite Land Surface Climatology Project Field Experiment (Kansas, USA), Cabauw (Netherlands), Valdai (Russia), Hydrological and Atmospheric Pilot Experiment in the Sahel (France), the Amazon Region Micrometeorology Experiment, and the Anglo-Brazilian Amazonian Climate Observational Study. These cases have not been rigorously compared with observations, but will be thoroughly evaluated in the Project for Intercomparison of Landsurface Parameterization Schemes framework.

3. Land surface modelling considerations

There are strong justifications for studying a land surface model uncoupled from atmospheric and ocean models. Coupling the land surface model to an atmospheric model allows the study of the interaction and feedbacks between the atmosphere and land surface. However, in coupled models the atmospheric model can impose strong land surface forcing biases on the land surface model. For example, biases in precipitation and radiation can overwhelm the behaviour of land surface model physics. In fact, several numerical weather prediction centres must "correctively nudge" their land surface model soil moisture toward climatological values to eliminate its drift. By using an uncoupled land surface model, we can better specify land surface forcing using observations, use less computational resources, and address most data assimilation development questions. The physical understanding and modelling insights gained from implementing distributed, uncoupled land-surface schemes with observation-based forcing has been vividly demonstrated in recent Global Energy and Water Cycle Experiment retrospective off-line land surface modelling projects known as the Project for Intercomparison of Landsurface Parameterization Schemes phase 2c and the Global Soil Wetness Project (Koster and Milly, 1997).

Runoff-routing schemes allow model validation and assimilation using ground-based and remote streamflow observations (Lohmann, *et al.*, 1996). Graham *et al.* (1999) and Olivera *et al.* (2000) describe the development of river transport methods for the National Center for Atmospheric Research Climate System Model. Since current plans for runoff routing models include a parametrization of lakes and wetlands, coupling the land surface models with the runoff routing transport scheme also may allow for assimilation of altimetry-derived water heights.

The interaction of the land surface with the atmosphere is strongly dependent on the scale at which it is modelled. It is well established that sub-grid variability can profoundly impact land-surface predictability. Therefore, the dependence of land surface predictions on spatial resolution and parameter aggregation can be assessed with multi-scale sensitivity experiments. Land surface model performance can vary widely over a range of spatial scales (typically land surface models are implemented on scales ranging from 1 to 200 kilometres). Parameters and forcing can be transferred between spatial scales using standard aggregation algorithms, along with simple interpolation. Scaling studies help to identify: (1) the sensitivity of land surface model predictions to spatial resolution, (2) mechanisms for relating and transferring results between spatial scales, and (3) the importance of sub-grid scale heterogeneity on land-surface storage estimation.

4. Remote sensing of the land surface

The emphasis of land surface data assimilation research is to assimilate remotely-sensed observations of the land surface that previous research suggests will provide memory to the land-atmosphere interaction. Remote observations of interest include: (1) temperature, (2) soil moisture (surface moisture content, surface saturation, total water storage), (3) other surface water bodies (lakes, wetlands, and large rivers) and (4) snow (areal extent, snow water equivalent). The remote sensing potential and availability of each of these quantities is described in more detail below.

Remote sensing of surface temperature is a relatively mature technology. The land surface emits thermal infrared radiation at an intensity directly related to its emissivity and temperature. The absorption of this radiation by atmospheric constituents is smallest in the 3 to 5 and 8 to 14 micrometre wavelength ranges, making them the best atmospheric windows for sensing land surface temperature. Some errors due to atmospheric absorption and improperly specified surface emissivity are possible, and the presence of clouds can obscure the signal. Generally, surface temperature remote sensing can be considered an operational technology, with many spaceborne sensors making regular observations (for example, the Landsat Thematic Mapper, Advance Very High Resolution Radiometer, AVHRR, the Moderate Resolution Imaging Spectroradiometer, MODIS, and the Advanced Spaceborne Thermal Emission and Reflection Radiometer, ASTER) (Lillesand and Kiefer, 1994). The evolution of land surface temperature is linked to all other land surface processes through physical relationships. These land surface process interconnections can be exploited in a data assimilation framework to constrain all of the predicted land surface states.

Remote sensing of soil moisture content is a developing technology, although the theory and methods are well established (Eley, 1992). Long-wave passive microwave remote sensing is ideal for soil moisture observation, but there are technical challenges involved in correcting for the effects of vegetation and roughness. Soil moisture remote sensing has previously been limited to aircraft campaigns (*e.g.* Jackson, 1997a), or analysis of the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I) (Engman, 1995; Jackson, 1997b). The Special Sensor Microwave Imager has also been successfully employed to monitor surface saturation/inundation (Achutuni and Scofield, 1997; Basist and Grody, 1997). The Earth Observing System Advanced Microwave Sounding Unit (AMSR) will provide additional C-band microwave observations that may be useful for soil moisture determination. The Tropical Rainfall Measuring Mission's Microwave Imager (TRMM-TMI), which is very similar to the Advanced Microwave Sounding Unit, is much better suited to soil moisture measurement (because of its 10 MHz channels) than Special Sensor Microwave Imager. All of these sensors have adequate spatial resolution for land surface applications, but have a very limited quantitative measurement capability, especially over dense vegetation. However, Sipple *et al.*, (1994) demonstrated that it is possible to determine saturated areas through dense vegetation using the Scanning Multichannel Microwave Radiometer (SMMR), which can greatly aid land surface predictions. Because of the large error in remotely-sensed microwave observations of soil moisture, there is a real need to maximize its information by using algorithms that can account for its error and that extend its information in time and space.

An important and emerging technology with respect to land surface observation is the potential to monitor variations in total water storage (ground water, soil water, surface waters (*e.g.* lakes, wetlands, rivers), water stored in vegetation, snow and ice) using satellite observations of the time variable gravity field. The Gravity Recovery and Climate Experiment (GRACE), an Earth System Science Pathfinder mission launched in 2002, will provide highly accurate estimates of changes in terrestrial water storage in large watersheds. Wahr *et al.* (1998) note that the Gravity Recovery and Climate Experiment will provide estimates of variations in water storage to within 5 millimetres on a monthly basis. Rodell and Famiglietti (1999) have demonstrated the potential utility of these data for hydrologic applications, including their application in large (>150,000 km^2) watersheds; and they further discuss the potential power of Gravity Recovery and Climate Experiment observations for constraining modelled water storage in land surface models when combined with surface soil moisture and altimetry observations. Birkett (1995, 1998) demonstrated the potential of satellite radar altimeters to monitor height variations over inland waters, including climatically-sensitive lakes and large rivers and wetlands. Such altimeters are currently operational on the European Space Agency Remote Sensing Satellite 2 (ERS-2), the Topex Poseidon satellite, the European Space

Agency Environment Satellite (Envisat), and the Jason 1 satellite (see chapter *Altimeter covariances and errors treatment*).

Key snow variables of interest to land surface understanding include area coverage and snow water equivalent. While the estimation of snow water equivalent by satellite is currently in research mode, snow areal extent can be routinely monitored by many operational platforms, including The Advanced Very High Resolution Radiometer, the Geostationary Operational Environmental Satellite (GOES) and the Special Sensor Microwave Imager. Recent algorithm developments even permit the determination of the fraction of snow cover within Landsat Thematic Mapper pixels (Rosenthal and Dozier, 1996). Cline *et al.* (1998), describe an approach to retrieve snow water equivalent from the joint use of remote sensing and energy balance modelling.

Precipitation is the most important forcing for the land surface. Since precipitation is not predicted in an uncoupled land surface model, it cannot be formally assimilated. However, we can perform sensitivity experiments to understand how errors in precipitation affect our ability to quantify the variability of terrestrial water.

Precipitation is generally poorly predicted by numerical weather prediction models because we have not mastered the complex prediction of cloud physics and dynamics, which can lead to gross errors in land surface simulations. Therefore, we generally replace these fields by observational products, when available. Unfortunately most high-quality long-term global land surface observations have been processed on monthly time scales for use in climate variability studies, and therefore lack the high temporal resolution required by land surface modelling efforts. These low temporal resolution observations can still be used to improve global land surface predictions by correcting the longer-term land surface forcing biases. Essentially, we use the numerical weather prediction surface fields as high-resolution temporal weights on the longer-term observation averages when high-resolution observed forcing is unavailable. It is recognized that the timing of forcing is also of particular importance in land surface prediction, and therefore state-of-the-art temporal and spatial downscaling techniques are explored to mitigate these effects. As our understanding of the various sources of precipitation information has matured, we have recognized that these sources have disparate and often complementary information. We are therefore exploring the use of a data assimilation analysis scheme to optimally merge the various precipitation observations prior to their use as land forcing. Assimilation of precipitation information to constrain an atmospheric model is also an area of active research that shows great promise for further reducing the errors in land surface forcing, but such precipitation assimilation is outside the scope of this book.

Two general categories of satellite-derived precipitation exist, each with severe limitations. However, it is generally acknowledged that they have less bias, and better location and timing of precipitation when compared to model estimates. The first category of satellite-based precipitation observation is Geostationary Operational Environmental Satellite Precipitation Index estimates (Arkin and Meisner, 1987). This very simple method uses the cloud infrared brightness to directly estimate precipitation using a lookup table. This method can provide hourly precipitation estimates, but is limited to convective precipitation structures in the 40 degrees North to 40 degrees South latitude band. The second category uses shortwave passive microwave, as available with the Special Sensor Microwave Imager instrument, the Tropical Rainfall Measurement Mission Microwave Imager, and the Advanced Microwave Scanning Radiometer, which are sensitive to cloud water vapour quantities and raindrops, and can therefore provide better estimates of precipitation. Because these satellites are not geostationary, their temporal coverage is limited. Many research groups have investigated the derivation of precipitation from this data using methods ranging from simple empirical systems to neural network techniques. The quality of precipitation estimates is expected to be highest from microwave sensors, moderate from Geostationary Operational Environmental Satellite Precipitation Index estimates, and lowest from the numerical model predictions. Generally, the best available precipitation observations are used, or the available observations are optimally merged following Houser *et al.* (1999). Additional corrections for each data type based on rain gauge and climatological information further increase the accuracy of remotely observed precipitation.

5. Land surface validation

Data that are assimilated are generally not useful for subsequent validation because they are not independent from the prediction. Therefore, we also want to compare against independent data sets, either *in-situ* or remote, as available. Some useful land surface validation observations are listed here:

(a) Regionally-averaged *in-situ* validation: Various *in-situ* land observations are available for direct validation of land surface predictions (*e.g.* the First International Satellite Land Surface Climatology Project Field Experiment, the Boreal Ecosystem-Atmosphere Study, the Southern Great Plains Experiments, the Cooperative Atmosphere Surface Exchange Study, the Mackenzie Global Energy and Water Cycle Experiment Study, and the Global Energy and Water Cycle Experiment Continental-Scale International Project).

(b) Streamflow validation: A streamflow routing algorithm (*e.g.* Lohmann *et al.*, 1996) can be used to facilitate validation of predicted states and fluxes via comparison with widely available streamflow observations.

(c) Surface temperature validation: Simulated surface temperature is dependent on model forcing, land surface characteristics, soil water storage, and internal model physics. Thus, surface temperature can provide an integrated assessment of land surface predictive quality. High quality land surface temperature observations are available from a large number of infrared instruments, such as the Advanced Very High Resolution Radiometer (Dubayah *et al.*, 1997).

(d) Snow extent and water equivalent validation: Snow cover information derived from Advanced Very High Resolution Radiometer, the Geostationary Operational Environmental Satellite and the Special Sensor Microwave Imager is available from various operational centres (Robinson *et al.*, 1993), and can be useful for evaluating the snow accumulation and melt processes. Further, validation data for model predictions of snow water equivalent are compiled by the National Weather Service National Operational Hydrologic Remote Sensing Center. These data include *in-situ* snow course measurements and airborne snow water equivalent measurements compiled in a gridded map format for the United States and Canada.

(e) Long-term budget partitioning validation: Over long time periods, the land surface model should estimate the correct partitioning of available surface energy into sensible, latent, and ground heat fluxes, and of precipitation into evaporation, runoff, and groundwater recharge . Relatively reliable estimates of these partitionings have been established for various sub-regions and watersheds, and will be a valuable check on performance.

(f) Model cross-validation: Comparing results between models that have different forcing, parametrizations, or resolution can provide additional validation.

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