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Land-atmosphere interaction

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Introduction

The basic elements of land-atmosphere interaction (LA-I) are the exchanges of moisture and energy between these two systems. Historically, many of the important aspects of this interaction have been treated in the areas related to micrometeorology, agriculture and forest meteorology, planetary boundary layer, and hydrology. More recently, LA-I has also become recognized as important for studies of biogeochemical cycling, climate, mesoscale meteorology, and numerical weather prediction. Initial recognition of the importance of LA-I in these latter areas extends back at least two decades, but major advances have occurred over the period covered by this review. Land has been recognized as, in principle, a major element of the climate system since the initiation of the World Climate Research Programme (WCRP), and land was included in simple form in even the earliest General Circulation Model (GCM) climate studies.

The present review emphasizes advances in understanding of land interactions as part of the climate system, but also touches on related questions. For a contemporary view of Climate System Modeling, cf. *Trenberth* [1992]. Also, *Prinn* [1994] reviews atmospheric chemistry as part of the climate system including land interactions, and *Mooney and Koch* [1994] address the issue of effects of rising concentrations of CO_2 on terrestrial vegetation.

Fluxes of moisture and heat from the land surface determine the overlying distributions of atmospheric temperature, water vapor, precipitation, cloud properties, and hence the downward radiative fluxes at the surface. For example, *Koster and Suarez* [1994] find in decadal GCM simulations that inclusion of an interactive land surface leads to substantially greater interannual variability of precipitation over both tropical and mid-latitude land than does observed ocean temperature variations. How the coupling between land and atmosphere depends on the formulation of the land and atmospheric processes as represented in models is now being explored. Some of the general aspects of this question are common to study of ocean-atmosphere interactions.

What especially distinguishes the land question is the differences between land and ocean surfaces. A much wider range of surface moisture and temperature conditions is realized over land in proceeding from arid to moist climatic zones and from tropical to polar climates. The relatively low heat capacity of the land surface and its limited capacity for water storage imply much stronger diurnal variations in surface conditions over land than over the ocean, and more direct responses to changing atmospheric inputs of energy and moisture as cloud properties and precipitation change. First GCM climate models were averaged over the diurnal cycle, but now most include a diurnally varying sun [e.g., *Randall et al.*, 1991].

The limited capacities for heat and water storage over land, combined with the heterogeneous nature of underlying soils, vegetation, and slope, imply potentially large heterogeneities in sensible and latent fluxes. Whether these fluxes, on the average, differ drastically from fluxes from an assumed homogeneous surface, what mesoscale circulations they might drive, and how these might affect large-scale conditions are crucial questions now being explored.

Land Processes and Their Modeling

A wide variety of land-surface models have now been developed that gives a response of land climate variables to atmospheric conditions. Some are general enough to match the wide range of conditions provided by a global model; others are intended for more regional or local applications. There is much similarity and overlap between models, and they all attempt to treat many of the same processes. Most such models have been constructed from elements of earlier models. However, there are also some substantial differences in objectives and details between models. New land-surface parameterizations have been developed by *Xue et al.* [1991] and *Wood et al.* [1992].

The Project for Intercomparison of Land-Surface Parameterization Schemes (PILPS) has been developed through the WCRP Global and Energy Water Experiment(GEWEX) program to provide systematic comparisons between all participating land-surface schemes [*Henderson-Sellers et al.*, 1993b; *Pitman et al.*, 1993]. For prescribed atmospheric inputs over an annual cycle and presumably the same surface description, different schemes provide a wide range of portioning between sensible and latent fluxes. At least some of this variability can be ascribed to the wide variety of vegetation treatments and soil depths between the different models.

The Atmospheric Modeling Intercomparison Program (AMIP) project [*Gates*, 1992] is providing a database of multi-year climate simulations from a wide variety of GCMs, allowing intercomparisons between

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land processes in a completely coupled framework. *Randall et al.* [1992] intercompare surface fluxes over the ocean for coupled models for prescribed increments of ocean surface temperature. A wide range of evaporative fluxes was found between models, even under these simple conditions, a conclusion that is being replicated for studies over land. *Milly* [1994] has studied the question as to what parameters are most important for determining the annual runoff to precipitation ratio. Key parameters are Budko's index of dryness, which is the ratio of annual net radiation determined potential evapotranspiration to precipitation, the soil water holding capacity, and the arrival rate of storms. Seasonal and stochastic variations of precipitation rates, potential evapotranspiration, and storm arrival rates are also significant.

Betts et al. [1993] have compared averaged fields and fluxes from the First ISLSCP [International Satellite Land-Surface Climatology Project] Field Experiment (FIFE) for summer and fall of 1987 (next section) with surface output from the European Centre for Medium-Range Weather Forecasts (ECMWF) model. A number of substantial defects in the model were thus revealed. The use of a 0.07 m slab soil layer unshaded by vegetation gave soil heat fluxes that are much too large. The use of 0.07 and 0.42 soil layers for water storage, with prescribed wetness values below, gave zero evapotranspiration over a period when daytime fluxes greater than 50 W/m^2 were observed. Model solar fluxes exceeded those observed by approximately 10%. The treatment of land in this and other global Numerical Weather Prediction (NWP) models has a substantial impact on the land surface climatic data inferred from such models, which are widely used for diagnostic studies. There is commonly a high bias in surface solar radiation in climate models [*Dickinson and Kennedy*, 1991; *Garratt*, 1994].

Milly and Dunne [1994] have carried out GCM sensitivity studies with soil water capacity varying from 0.01 to 1.2 m. They find approximately a 10% increase in global evapotranspiration for each doubling of the soil water capacity. About half of this atmospheric water increase is added to land precipitation and half to oceanic. *Lakhtakia and Warner* [1994] have made comparisons of simulations of a mesoscale model with a simple 'bucket' model versus a soil-vegetation land model. *Bonan* [1994] has examined the dependence of land climatologies in Community Climate Model Version 2 (CCM2) on model resolution and concludes that improving resolution does not contribute noticeably to reducing discrepancies between modeled land-climate and observations.

Questions of Scaling and Heterogeneity

Inputs of land to the atmosphere occur in models on spatial scales of tens to hundreds of km. Yet many, if not all, of the land processes determining these inputs occur on substantially smaller spatial scales, from leaf to field or, at most, landscape spatial scales. Initial parameterizations of land surfaces in climate and mesoscale models have assumed homogeneous conditions of the land surface over a model grid square, either with some particular assumed surface type or an average over the actual surface types. Recent studies have modified land-surface parameterizations to include some aspects of heterogeneity and have studied what differences result from the inclusion of such heterogeneities. In particular, *Koster and Suarez* [1992] and *Avissar and Pielke* [1989] have proposed representing the land surface within a model in terms of a mosaic of homogeneous surfaces, each being some fraction of the total grid square. Prognostic variables, such as soil moisture and soil temperature, are then carried separately for each of these subelements. Other studies have emphasized the importance of the spatial variability of precipitation and soil moisture and have proposed statistical parameterizations to include such [e.g., *Johnson et al.*, 1993]. *Eltahir and Bras* [1993a] have shown, in addition, the importance of spatial variability of rainfall interception and suggested a statistical parameterization for that.

Avissar [1992] further suggests the need for probability distributions for a wide range of surface parameters, including leaf area index, topographic roughness, and stomatal conductances. *Bonan et al.* [1993], using another land-surface model, consider the dependence of surface fluxes on statistical distributions of parameters. They find a considerable sensitivity to these assumptions but that the greatest sensitivity is to leaf area index. *Avissar* [1993] has reported on observed variability of stomatal conductances. *Collins and Avissar* [1994] and *Li and Avissar* [1994] have carried out additional sensitivity studies for statistical distributions of parameters and report greatest sensitivity to variability of stomatal conductance, roughness, and, in the latter case, leaf-area index. *Seth et al.* [1994] consider treating heterogeneity of precipitation and land surface elements in terms of a submesh under a given GCM grid square, and also find sensitivity to details of these distributions.

Another question [*Pielke et al.*, 1991] is the importance and parameterization of mesoscale circulations for vertical fluxes from the surface. *Dalu and Pielke* [1992] indicate with a linear perturbation approach that such fluxes should be comparable to the fluxes from small-scale motions conventionally parameterized in large-scale models. More detailed analyses and parameterizations of this issue have been developed by *Zeng and Pielke* [1994] and *Pielke et al.* [1994].

The need for appropriate data is at least as great a practical difficulty as is the conceptual formulation of land processes. *Webb and Rosenzweig* [1993] describe a new soils database for use with climate models. Contributions of remote sensing to provide better data are described below.

Progress is being made toward incorporation of adequately realistic land processes in NWP models. Various surface moisture stores (prognostic variables) are part of these prescriptions and are currently entirely model-generated, as derived from modeled precipitation, radiative and other surface fluxes. The patterns and intensity of the precipitation producing floods in the United States in the summer of 1993 were apparently sensitive to antecedent soil moisture [*Betts et al.*, 1994]. However, considerable advances are being made in approaches, in part based on remote sensing, to provide observations that can be assimilated with model values. Methods to provide surface radiative fluxes from a network of operational satellite sensors have been developed under the auspices of the WCRP GEWEX SRB (surface radiative budget) initiative. *Pinker and Laszlo* [1992] and *Darnell et al.* [1992] have developed algorithms suitable for this purpose. Use of earth radiation budget satellites (i.e., Earth Radiation Budget Experiment [ERBE]) for determining surface radiation has also been developed [e.g., *Breon et al.*, 1994]. An ISLSCP/GEWEX project has just begun to develop a global data set for soil moisture and evaporation using surface observations of precipitation, satellite infrared surface radiative fluxes, and ECMWF assimilated surface meteorological fields as inputs and with a number of land surface schemes from various participants. This project includes an extensive validation effort using whatever observations are available.

Smith et al. [1994] use 4-1/2 months of preceding surface meteorological data and surface radiation estimated from cloud cover to initialize soil moisture in a mesoscale model. Time-varying surface temperatures can be closely related to evapotranspiration. *Tarpley* [1994] uses geostationary satellite data on the morning increase of surface temperatures to estimate, for clean sky conditions, evapotranspiration over related sites in Kansas. *Gutman* [1944] describes the land surface data sets now routinely available from National Oceanic and Atmospheric Administration (NOAA) operational satellites.

The use of remote sensing to derive surface biophysical properties as needed for climate and NWP models has made substantial advances in the context of FIFE, over Konza Prairie, Kansas, as reported in *J. Geophys. Res., 97, D17* and summarized by *Sellers and Hall* [1992]. *Sellers et al.* [1992] demonstrate with the FIFE data that surface canopy conductances are nearly linearly proportional to near-infrared minus visible reflectance differences and can be readily monitored by satellite. *Shuttleworth* [1994] reviews the overall past and future field programs being carried out as part of GEWEX. Methods are also being developed to characterize different land cover types by remote sensing globally and at the level of detail needed in climate models [e.g., *Running et al.*, [1994].

Characterization of Regional LA-I Processes

Ultimately, importance of LA-I is expressed through its role in determining various regional climate systems. U.S. efforts over the period of review have addressed modeling of LA-I over the U.S. through the use of mesoscale models integrated for time periods of up to several years and with prescribed lateral boundary conditions from either NOAA or ECMWF forecast initialization archives or from global climate simulations. *Giorgi et al.* [1994a,b] have reported on a multiyear simulation with the Mesoscale Model 4 (MM4) driven by climate model output and described precipitation, soil moisture, evapotranspiration, and runoff. The mesoscale model evidently substantially corrects a large positive bias in the average U.S. precipitation, but maintains a relative excess over the western U.S. Whether the overall reduction in precipitation is a result of differences in model resolution or some other feature of the mesoscale model is not known. This question is important because many, if not most, GCMs appear to have a high bias in their overall land precipitation [e.g., as analyzed by *Schultz et al.*, 1992]. Model evapotranspiration and soil moisture were found to be in substantial disagreement with observational data. However, the only observations used for the latter were observed monthly precipitation; furthermore, the comparison data are derived from a much cruder surface model than that used by *Giorgi et al.* [1994a,b].

Efforts have also continued to examine the LA-I consequent to a hypothetical complete deforestation of the Amazon. *Nobre et al.* [1991] obtained not only substantial reductions in evapotranspiration with deforestation but an even larger reduction in precipitation. *Dickinson and Kennedy* [1992] and *Henderson-Sellers et al.*[1993a] have addressed this climate response with the National Center for Atmospheric Research (NCAR) CCM1 model. Both studies also find precipitation decreases to be considerably larger than decreases in evapotranspiration (ET). Other models, however, may give less pronounced results. Further insights into the mechanisms underlying the numerical results can be provided by analytic studies with mechanistic models. *Eltahir and Bras* [1993b] developed a simple model interpreting earlier numerical simulations. Their model assumes that increased surface temperature increases precipitation but that reductions in precipitation produce a positive feedback that further reduces precipitation. This model neglects the effects of possible changes in boundary layer structure on precipitation.

Henderson-Sellers et al. [1993a] have argued the need for a considerable equilibration time for the model soil moisture changes and have carried out the integration for a substantially longer period (6 years) than did previous studies. They also argued for a substantially smaller change in surface roughness (i.e., degraded brush rather than degraded grassland) as the assumed end-state of forest conversion. An observational attempt to detect effects of Amazon deforestation [*Chu et al.*, 1994] gave a negative result. Scaling the effects inferred in complete deforestation studies to the relatively small amount of deforestation that has occurred up to now suggests an effect too small to be detectable above natural fluctuations. Moreover, understanding of what are the natural, long time-scale fluctuations within regions is weak, and the effect of patchy partial deforestation would not necessarily simply scale from results for complete deforestation.

One of the popular arguments for the importance of the Amazon forest for rainfall is its contribution of approximately 50% recycled rainfall. *Brubaker et al.* [1993] have analyzed the water budget of the Amazon and other regions and find only 30% of the water is recycled. This disagreement seems to lie, in part, in definitions. Their definition would give a recycling coefficient of 33% if the net water flux into the basin were equal to the basin evapotranspiration, as required for average precipitation to be double runoff (as approximately observed). Past authors have argued these conditions, and the smallness of transport out of the basin because of surrounding highlands implies a 50% recycling coefficient. Isotopic analyses have seemingly supported this result, but the correct answer depends on what fraction of land evapotranspiration is transported outside of the basin. Further analyses have been carried out by *Eltahir and Bras* [1994] who derive a recycling coefficient between 25% and 35% and explicitly argue that much of the evapotranspired water is carried out of the basin. They do not give details of their data analysis.

Further studies have addressed the question of the dependence of Sahelian rainfall on surface vegetation cover, soil moisture, and albedo. *Xue and Shukla* [1993] have carried out GCM sensitivity studies for this region that support the earlier inferences of positive feedbacks between albedo increase/vegetation decrease and reduced ET. *Lare and Nicholson* [1994] have also studied this question with observations and diagnostic modeling. They find an association between dry Augusts over the Sahel and a decrease in the strength of the African Easterly Jet, a system responsible for bringing rain-producing disturbances. *Dirmeyer* [1994] has studied, with numerical simulations and an idealized continent, the response of precipitation over the summer period to dormant vegetation or initial dry soil. He finds that either can lead to a drought.

Modeling of the summer Indian monsoon is another LA-I issue that has been addressed. *Fennessy et al.* [1994] have studied the sensitivity of precipitation in this system to various land boundary conditions. They find the greatest sensitivity to the prescription of orography, some dependence on initial soil moisture (for 90-day integrations started from 2 June), and little dependence on the details of the prescribed vegetation cover. Mechanisms of atmospheric heating and the boundary layer over the Tibetian Plateau have been addressed by *Yanai and Li* [1994].

Variations of precipitation amounts and distributions over a hypothetical tropical continent, in response to varying degrees of prescribed surface wetness, have been examined by *Cook* [1994]. She shows that with an idealized continent, longitudinal patterns of precipitation are obtained similar to those observed and that these patterns shift and precipitation is reduced as greater dryness is assumed.

Impacts

Precipitation and runoff calculated by climate models suffer various deficiencies because of their low spatial resolution and incomplete process treatment. Thus, efforts have continued to compensate for these shortcomings in the use of model output through inclusion of additional process parameterizations.

The use of model output to determine river flows has been addressed by *Miller and Russell* [1992] and *Liston et al.* [1994]. *Gao and Sorooshian* [1994] have developed a statistical procedure using observational data to transform climate model precipitation into a realistic frequency and intensity distribution.

Robock et al. [1993] discuss the general use of GCM simulations, with their common errors, for use in the study of required impacts of future climate change. They suggest a new procedure for the combination of GCM output with climate information in order to produce future scenarios, even when the GCMs give poor regional simulations.

The Next Four Years

Research over the last four years has considerably furthered understanding of LA-I. Further progress is expected over the next four years in understanding what the most appropriate formulation for land processes in climate and NWP models is, how these processes operate in the climate system, and how they can be specified by remote sensing data. These ideas will be synthesized with four-dimensional data assimilation systems for improved model initializations and generation of better land surface-atmosphere climatologies. Progress should also occur in understanding how land processes couple back to atmospheric processes, and the details of their atmospheric response. The focus provided by GEWEX programs over this period should help to considerably promote these advances.

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