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Global change and terrestrial hydrology—a review

By ROBERT E. DICKINSON*, *National Center for Atmospheric Research***, *Boulder, Colorado, USA*

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ABSTRACT

This paper reviews the role of terrestrial hydrology in determining the coupling between the surface and atmosphere. Present experience with interactive numerical simulation is discussed and approaches to the inclusion of land hydrology in global climate models are considered. At present, a wide range of answers as to expected changes in surface hydrology is given by nominally similar models. Studies of the effects of tropical deforestation and global warming illustrate this point.

1. Introduction

Terrestrial hydrology is the state and dynamics of water at the land surface. How terrestrial hydrology will change with global change has long been recognized as a key practical question. However, we are just beginning to achieve an understanding of how it acts as a strongly interactive component of the global system. This understanding is being developed through two approaches: (a) exploring the role of land water in numerical simulations of the climate system and climate change, and (b) examining what must be done to adequately represent land hydrological processes in global models. Progress in this complicated question requires both these approaches. Interactive numerical simulations are required in order to discuss the most important feedbacks and limitations in our current approaches, and we must continue to explore different and possibly improved treatments of land hydrology, if only to better understand the strengths and limitations of current ones.

2. Role of land water in numerical simulations

A climate model with an atmospheric hydrology cycle must on the average evaporate as much water from the surface as it precipitates from the atmosphere in order to conserve water and energy. However, the presence of runoff precludes such a balance over land alone. That is, the evaporative cooling as a major determinant of summertime land temperatures depends not only on precipitation but also on how the surface portions this input into evaporation and runoff. This portioning in turn depends on how net radiative energy is divided between latent and sensible fluxes. Past conventional wisdom has largely ignored potential feedbacks of land on the atmosphere, but with increasing understanding from modeling simulations of these exchanges, we can begin to appreciate what might happen. The most common approach has been to study the effect of an arbitrary, though perhaps physically motivated, change in surface energy or hydrological processes. The study of the effect of postulated large increases in surface albedo became popular following the Charney et al. (1977) suggestion that this might represent a positive biophysical feedback. A large number of other such studies of arbitrarily assumed changes have been reviewed by Mintz (1984). Of these I mention only that of Shukla and Mintz (1982). They considered two scenarios, an earth with either perfectly wet or completely dry continents, and simulated July conditions. They found dry continents could have temperatures as much as 20°C warmer than if they were wet, and that large reductions in continental rainfall might occur.

Current studies are attempting to formulate

* Now at Institute of Atmospheric Physics, University of Arizona, USA

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more realistic change scenarios, though perhaps still hypothetical, in conjunction with more realistic treatments of the land surface physics. I consider in the following section three kinds of such scenarios.

3. Current questions regarding land-atmosphere interaction

Physical changes of continental land surfaces disrupt global energy flows by relatively small amounts compared to the effects of increasing trace gases (Dickinson, 1986). Therefore, their influence on climate is likely to be most pronounced on a regional scale. From the viewpoint of testing climate models and readily distinguishing signal from noise, it is best to study the effects of relatively large changes. It is desirable to study not only realistic changes but also the sensitivity to arbitrary changes in model parameters to establish better the effects of the process parameterization.

3.1. Large-scale land use change

Since the initial Charney studies, the question of the effect of land use changes on rainfall in the Sahel region of Africa has been the subject of considerable further study. Possible changes of albedo seem to be considerably less than were initially assumed by Charney (e.g., Gornitz, 1985) so that feedback with surface evapotranspiration has taken on comparable or greater significance for that question (e.g., Walker and Rowntree, 1977). Furthermore, numerical simulations and statistical studies suggest that the observed variations in rainfall may be largely forced by natural variations in ocean temperature anomalies (Owen and Folland, 1988; Parker et al., 1988). In sum, the evidence for significant climate impacts from human changes of the land surface in the Sahel appears to still be weak.

Tropical deforestation may be easier to relate to climate change. Observational evidence of a link between local rainfall and deforestation is considerable (Meher-Homji, 1991) though not necessarily very convincing. However, removal of a forest on the scale of a continent is probably not impossible and is a large enough change that numerical simulation should be able to find effects that stand out over natural variability. Earlier studies of this question treated deforestation as simply a question of increasing albedo, that is, a version of the Charney hypothesis. However, observational studies of the hydrological cycle over the Amazon basin have suggested to various authors (e.g., Salati, 1987) that the forest has a major role in the cycling of water between surface and atmosphere so that forest removal might severely disrupt the local hydrological processes. Testing of this hypothesis requires land surface models that can adequately distinguish between the micrometeorological effects of a forest versus whatever it might be replaced by and that can adequately couple these changes to a climate model.

Three recent studies have addressed the question of Amazon deforestation with detailed enough treatments of land surface processes designed to make this distinction (Dickinson and Henderson-Sellers, 1988; Lean and Warrilow, 1989; Shukla et al., 1990). We abbreviate these references as DHS, LW, and SNS. All these papers assumed a complete conversion of the Amazon forest to grassland; the exact domain converted differed somewhat between the papers of different spatial resolution and land cover data bases for the different models. All studies implemented their deforestation by increasing the surface albedo, decreasing its roughness, and by changing soil properties to reflect the change, i.e., decreased rooting depth and increased maximum infiltration rates, etc.

Precise comparison of the differing assumptions about this change is made difficult by the fact that the latter two reports were quite brief and leave out significant details. However, all report what they assumed to be the increase in albedo in converting forest to grassland: LW 0.05, DHS 0.07 and SNS 0.09. A factor of two range in the value of other key input parameters is also likely, and symptomatic of the shortage of observational information needed to specify more accurately what actually would be expected to change. These differences were probably not crucial at the time since, as I now discuss, quantitative and qualitative differences between the model simulations have been significantly larger than differences in input parameters.

The results of all three studies are similar, but only in a very broad sense. Some differences may derive from differences in experimental design besides that of the surface input parameters mentioned above. The DHS study suffered from being able to analyze only a single year of simulation and from its use of a model with relatively low resolution (R-15, i.e., about 4.5° latitude by 7.5° longitude); the LW study from use of a less detailed land model (but with a 3-year simulation and twice as fine a horizontal mesh as DHS), and the SNS simulation also from only a single year of simulation, noninteractive clouds and a glitch in their prescription of seasonality of sea surface temperature. All these studies indicated increases in surface temperature in the range of 1–4°, which is opposite in sign to that which would be expected with the albedo change alone. Vegetation must maintain a large surface-air temperature drop to maintain comparable sensible heat fluxes, hence giving the increase of temperature with shorter vegetation. The reduction in evapotranspiration ranges from about 150 mm for a year in DHS to about 500 mm in SNS.

An even more striking contrast is seen in the differences in precipitation. The DHS study found no obvious differences in precipitation except for some suggestion of a lengthening of the dry season. However, both the SNS and LW papers report large reductions in rainfall, about 500 mm per year in LW and about 650 mm per year in SNS. Finally, reported runoff ranges from an *increase* of the order of 100 mm per year in DHS to *decreases* of about 150 mm per year in SNS and LW, respectively. Thus, the Amazon countries might be warned of either floods or extreme reductions in riverine water supply, depending on which model result was accepted. The differences in runoff are explicable primarily in terms of the differences in simulated rainfall.

These disagreements are instructive in pointing out the variety of answers possible from land-atmosphere coupled models which have been only loosely validated and which involve surface processes whose dynamics and interaction are not yet thoroughly analyzed or understood. For example, it is not yet clear whether with conversion of forest to grassland, a reduction in evapotranspiration is inevitable or conversely, whether under some conditions, an increase is possible. Rowntree (1988) suggests through an analysis with the Penman-Monteith equation that this might be a delicate issue with either sign possible.

To help clarify the issue of possible rainfall change with Amazon deforestation, a new simulation has just been completed at NCAR, making the same assumptions as DHS but with more recent model versions, i.e., the NCAR Community Climate Model version (CCM1) coupled to the version 1e of the Biosphere Atmosphere Transfer Scheme (BATS1e). Three years of deforested Amazon (again at R-15 resolution) gives mean rainfall reduction in agreement with the LW and SNS studies. Quantitatively, the mean changes in rainfall, evapotranspiration and runoff are quite close to those of LW.

3.2. *Coupling to global warming*

In a number of studies (most recently, Manabe and Wetherald, 1987) Manabe and collaborators have raised the issue of a potential summer drying out of mid-continental areas with a "greenhouse warming". They find this conclusion to be a consequence of an earlier period of snow melt, extending the period where their evapotranspiration exceeds the sources of surface water, plus a northward shift in the belt of maximum summer rains. They have consistently found this result through a number of versions of their model.

Some other modeling groups, in particular Washington and Meehl (1988) of NCAR, have not found summer drying. What is especially surprising is that both groups have used superficially nearly the same model for both atmosphere and surface components. They have both worked with low resolution (R-15) spectral GCMs with the same layer structure, same convection scheme, and both with conceptually the same 0.15 m bucket model for soil moisture. In principle, only the vertical differencing algorithms, subgridscale mixing, and cloud-radiation parameterizations differ. Meehl and Washington (1988) have examined the simulated soil moistures given by both models. They find that their lack of a summer drying follows from their calculated values of soil moisture being much lower than those of Manabe; indeed the Washington and Meehl maximum winter soil moisture is much lower than the Manabe and Wetherald minimum summer soil moisture. Consequently, the Washington and Meehl soil moisture increases much more in the winter with the increased precipitation of "greenhouse warming" than does that of Manabe and

Wetherald, so more drying is required for it to fall below the present climate values. Their soil moisture is also undoubtedly limited in the extent of its summer drying by its present climate already being nearly "bone dry".

Mitchell and Warrilow (1987) carried out sensitivity studies with the British Meteorological Office GCM to further explore the issue of summer drying. Their standard model simulations reproduced results similar to those of the model of Manabe and Wetherald. However, in one simulation they were able to eliminate the summer drying effect. They did this by introducing a simple model for the effects on hydrology of winter soil freezing, a process neglected in the usual bucket model hydrology. They assumed that as long as soil was frozen, no rainfall or snow melt would infiltrate into the soil but rather would instantaneously run off. With this assumption, they found that the earlier spring melt season with global warming would increase the bucket water and ameliorate the midsummer dryout.

At first glance, their assumption as to immediate runoff with frozen soil seems contradicted by the boggy wet characteristics of large areas in northern latitudes following snow melt, and for much of the summer over areas of permafrost. However, these features result from impeded drainage through the bottom of the root zone as a result of frozen soil, whereas surface runoff in the spring can indeed be rapid. In the context of the bucket model, the bucket capacity could be increased by the impeded drainage in the presence of frozen soil at the bottom of a soil column as well as decreased by frozen soil at the surface. Thus, it is problematical as to what would be the net effect of soil freezing on the sensitivity of soil moisture to global warming.

3.3. Natural variability

The climate system undergoes major interannual variations that have large effects on atmospheric rainfall, hence terrestrial hydrology. Simulating the origin of such variations and examining their feedbacks with land processes could be a useful approach for validating some aspects of the behavior of the coupled atmospheric-land system in climate models. Year-to-year variations in tropical monsoon behavior have strong feedbacks with terrestrial hydrology.

The issue of land feedbacks on Sahel drought has already been mentioned. The large variations of rainfall in the tropics that occur because of the El Niño cycles is another such question. In particular, there are large natural variations in rainfall in the Amazon region; a convincing simulation of these variations could be a useful validation for a model intended to simulate tropical deforestation.

A current research focus at NCAR and elsewhere is the simulation of the drought of the spring of 1988 in the central part of North America. Over this period, many climate regions reported all-time low precipitation for one or more months. Trenberth et al. (1989) have hypothesized this drought to result from an arrangement of tropical sea-surface temperatures (SSTs) referred to as La Niña, that is, a cold anomaly in the Eastern Pacific over the equator and a warm anomaly northward off of the equator. Numerical simulations are in progress at various institutions to simulate the drought either in an extended forecast mode or as a climate simulation. Recent forecast mode simulations have shown significant skill in predicting the anomalous high pressure over North America (Palmer and Brankovic, 1989; Kalnay et al., 1990).

Simulations in a climate mode [at NCAR with CCM1 coupled to the BATS land parameterization model at R-15 resolution and for SSTs observed for 1987–1988] have so far not been successful in supporting (or disproving) the hypothesis of control by SSTs. The rainfall simulation in the controls of low resolution models has been too poor in the eastern Pacific for a definitive test to be possible. Trenberth and Branstator (1991) suggest the following criteria must be met for a GCM to say anything definitive regarding the role of tropical SST anomalies in determining the 1988 North American drought: (i) reasonable climatological rainfall distribution and rates, especially in the ITCZ; (ii) a good mean distribution of horizontal winds in 3-dimensions for correctly guiding tropical Rossby waves; (iii) a realistic vertical heating profile, especially in tropical convection, and reasonable low-level divergence and rainfall to correctly simulate the atmospheric forcing; (iv) reasonable climatology and terrestrial hydrology over North America—including cloud feedbacks—to properly simulate the drought. Meeting all these criteria in climate simulations is a severe test for current GCMs.

4. Components of a land surface model

The atmospheric components of a climate model must provide the surface with fluxes of solar and thermal infrared radiation and precipitation in the form of rain or snow and near-surface values of wind vector, air temperature and humidity. Water conservation is imposed by transferring the water applied to the surface either into storage by soil reservoirs or into losses by evapotranspiration or by runoff. The total radiation absorbed by the surface is balanced by emission of thermal infrared radiation, by the latent heat loss associated with the evapotranspiration, or by fluxes of sensible heat, and by diffusion of thermal energy into the soil.

The original Manabe bucket model for the above processes was supposed to evaporate at the same rate as a wet surface (zero canopy resistance) during well-watered conditions, hold a maximum water, typically 0.15 m, which corresponds to the available soil water, that is, the water in the rooting zone at some average field capacity minus that still present at some average wilting point. However, since it did not include the process of diffusion of water in soils or canopy resistance, its evaporation rates are unrealistic both for bare soil (after a very brief period at the rate of atmospheric demand) and for vegetated areas. Evaporation from most bare soils, in reality, is greatly reduced after the loss from the surface layer of about 1 cm of water.

Vegetation acts as a completely wet surface only during and immediately following precipitation when its foliage is wet. Otherwise, it has two important controls: (a) it can extract soil water from a greater depth than would evaporate from bare ground; (b) it retards the rate of evapotranspiration from the potential rate through resistance by the stomates to molecular diffusion of water.

All existing surface parameterizations of land are based on the same underlying principles. That is, they all give fluxes of heat and moisture proportional to the differences between the temperature and saturated water vapor pressure at the surface versus that of the lowest overlying model layer. What distinguishes different treatments is how they determine the proportionality factors in these relationships, referred to as "conductances", and how they model the surface temperatures (which also determines the saturated vapor pressure). Since over the range of a model grid square there are numerous distinct surfaces taking different temperatures, one necessary decision is how to lump the actual surfaces into a small number of model surfaces. The traditional bucket model has assumed only a single such surface, but this assumption cannot be realistic for both vegetation and bare soil because of the physically distinct processes that determine conductances for these two surface types. Consideration of an additional multiplicity of surfaces may be needed to allow for subgrid spatial variations of surface types and precipitation.

The two most advanced schemes distinguishing between vegetation and soil that have been used in GCM simulations are the Simple Biosphere Model (SiB) developed by Piers Sellers and collaborators (Sellers et al., 1986) and the NCAR BATS model (Dickinson et al., 1986). Both these treatments have multiple soil layers but parameterize the canopy with single temperature values. The essential feature in their canopy treatments is the parameterization of an integrated stomatal conductance; for tall vegetation this conductance becomes rate limiting for evapotranspiration and gives much more realistic Bowen ratios during midday conditions than do the bucket models. The feedbacks from those parameterizations impact model planetary boundary layers and precipitation dynamics.

5. Discussion

Terrestrial hydrology has been reviewed as a component of global climate models and as an output of considerable practical importance. As more realistic simulations are sought, more realistic parameterizations of the governing processes become necessary. With increased realism comes increased complexity. Much more clever analyses and sensitivity studies are needed to clarify what these parameterizations do.

There is some evidence, as discussed in this paper, that similar or even identical treatments may give a wide diversity of results when integrated as components of different climate models. How can we find out what causes these differences? When two versions of the same computer program give widely different answers, we usually start exchanging subroutines and other pieces of code until we have tracked down the source of the discrepancy. Development of GCM programs that are sufficiently modular, portable, and documented to allow such analyses between different models would require much more attention given to the software engineering aspects of the models than has been done up to now.

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