Land Surface Hydrology in a General Circulation Model: Global and Regional Fields Needed for Validation

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Introduction

For the last two decades most General Circulation Models *(GCMs)* have included some kind of surface hydrology submodel. The content of these submodels is becoming increasingly complex and realistic. It is still easy to identify defects in present treatments. Yet, to improve our ability to model the contribution of land hydrology to climate and climate change, we must be concerned not with just the surface hydrology submodel *per se,* but also with how it works in the overall context of the GCM.

Suppose we had a "perfect treatment" of land hydrological processes in a GCM. Incorporated into any present GCM, we would most likely obtain a simulation of the land hydrological cycle that did not appear very realistic in the light of various observational measures we might apply. The purpose of this paper is to discuss what aspects of a GCM, other than the surface parameterization, must work right for a satisfactory simulation of the land hydrological cycle to be achieved. This theme is illustrated with previously unpublished modeling simulations with the National Center for Atmospheric Research *(NCAR)* Community Climate Model *(CCM).*

It is usually difficult to judge model correctness unless the more critical aspects can be judged against independent observations. In the present context, a number of regional and global data sets are just becoming available whose use is essential for model validation. We compare these observed and model fields. The GCM simulates climate through a more-or-less detailed simulation of individual weather processes and other short time-scale atmospheric variability, including the diurnal cycle.

Modeling Framework

The Biosphere Atmosphere Transfer Scheme *(BATS)* (Dickinson 1984; Dickinson *et al.* 1986) has been developed for interfacing a detailed land model with a GCM. That is, it must provide an adequately realistic parameterization of land interactions with climate and transfer information on these interactions between the rest of the GCM and its parameterization. Whereas the physical content of parameterizations is usually given the most attention, the linkages with the rest of the model are at least as crucial for effective applications in climate modeling simulations. Programming questions such as efficiency, flexibility, and documentation are important but are not mentioned further here. Rather, we address the issue of what subset of the rich information generated by a land package should be saved for further analysis for purposes of model validation and as "hooks" for study of climate impacts.

In: J.L. Betancourt and V.L. Tharp, editors. 1991. *Proceedings of the Seventh Annual Pacific Climate (PACLIM) Workshop, April 1990.* California Department of Water Resources. Interagency Ecological Studies Program Technical Report 26.

BATS has been developed in the context of several GCMs, albeit all at the National Center for Atmospheric Research. Although it is intended to be as portable as possible, it makes some assumptions about the overlying atmosphere that limit its direct applicability to some GCMs. In particular, it assumes, for the purpose of calculating surface conditions and fluxes, that the GCM provides information on atmospheric fields within a surface-mixed layer representable through Monin-Obukhov similarity theory. This assumption requires that the lowest model gridpoint be within the first hundred meters or so of the atmosphere. The layer structure of the CCM with this point, at about 70 meters above the surface, is barely adequate for this purpose; during nighttime and polar conditions, the surface-mixed layer can, in reality, shrink to a few tens of meters, but sensible and latent fluxes are relatively weak under these conditions. Thus, without a further planetary boundary layer model, BATS is not applicable to those GCMs whose lowest atmospheric layer is "thick"; that is, about a kilometer or more in thickness.

The fields of horizontal wind, atmospheric temperature, and water vapor mixing ratio are provided from the lowest atmospheric level of the GCM. Surface pressure is an additional prognostic variable of the atmospheric model. Furthermore, the overlying column of atmosphere provides to the surface: precipitation, thermal infrared fluxes, and modification of prescribed top-of-the-atmosphere flux of solar radiation. How well GCMs generate the spatial and temporal distribution of precipitation and solar radiation may be their most serious limitation in realistically representing the surface hydrological processes.

For example, Dickinson (1989) and Shuttleworth and Dickinson (1989) note a significant excess of model incident solar radiation compared to observations in the Amazon at a field site near Manaus. They suggest this excess solar radiation as a prime candidate explanation for the simulation of excess interception by the model canopy, along with differences between the model temporal distribution of precipitation and that which occurs at a local site.

The atmospheric model we use here is the NCAR CCM, Version 1 (Williamson *et al.* 1987), which was developed from an earlier CCM0 based on an Australian model and is similar in structure to those used by Manabe at Geophysical Fluid Dynamics Laboratory. These models are pseudospectral, with spectral-space horizontal-coordinates for the hydrodynamical calculations. This approach is efficient and accurate for the wind and temperature calculation but has undesirable properties (*e.g.*, negative mixing ratios) when used for water vapor. The present study uses the rectangular (R-15) spectral truncation, which maps to about a 4.5° latitude by 7.5° longitude mesh. The vertical differencing of CCM1 (Williamson 1988) was developed to ensure conservation of energy and still provide the good simulation of the lower stratosphere given by CCM0.

The standard CCM1 includes a simple moist convective adjustment, presumed to give convective precipitation as well as precipitation from stable-layer saturation. Cloud cover is calculated. Radiation interacts with ozone, water vapor, carbon dioxide, and oxygen. Solar radiation is reflected in the atmosphere by the clouds, with optical properties a function only of model layer, and by Rayleigh scatter. In general, the treatment of clouds and their radiative interaction is much less satisfactory than the quite accurate treatment of clear-sky radiation.

The only changes we have made in the atmospheric model discussed here for use with BATS is:

- We split the solar spectrum at 0.7μm to distinguish visible and near-infrared albedo over land; and
- We use a diurnal cycle of solar radiation with surface fluxes over land calculated every 0.5-hour (the model time step), solar atmospheric heating every 3 hours, and longwave heating at the standard 12-hour frequency.

The assumption of a reduced frequency for evaluating atmospheric radiative heating has traditionally been used by most models for computational economy. It suffers from presumably small lack of energy conservation.

The BATS parameterization version 1E, has been "frozen" from further development for establishing its performance coupled to the CCM1 described above. It represents the surface over a CCM grid square as a soil partially shaded by a vegetation canopy. Soil texture is specified for each such square, and from that are inferred hydrological properties — in particular, hydraulic conductivity and soil water potential as functions of soil moisture content. The most severe hydrological limitations of the soil representations are the assumptions that precipitation and soil properties are uniform over the grid square and that soil drainage through the three layers (surface, root, and subroot zone) is only vertical. We iterate the point that, however unrealistic these assumptions may be, they can be a less severe source of error than that from inadequacies of the atmospheric model. The current unrealistic soil assumptions mentioned here should be removed in model improvements. BATS includes the dominant processes of evapotranspiration, including a standard treatment of the environmental dependence of stomatal resistance, a simple model for effective root resistance depending on soil water potential, and a treatment of evaporative losses by canopy interception. Another function of BATS and other such land parameterizations is to define the surface roughness for turbulent exchange and the surface albedo for absorption of solar radiation.

From the viewpoint of fluxes of solar radiation, the BATS canopy is viewed as a continuous distribution of absorbers. However, for other energy fluxes and energy balance as a whole, it is parameterized as a single layer.

Surface Radiative Forcing and Hydrological Response in a Model Climate Simulation

The CCM1/BATS 1E model summarized in the previous section was integrated over six annual cycles (about 10^5 time steps), a relatively modest integration with today's computational resources. The purpose of such a control integration is to validate the model performance against observations. The simulation of atmospheric winds and temperatures for the NCAR CCMs has been shown to be reasonable in many studies. BATS does not have any major impact on these features, so we restrict ourselves here to previously unexamined questions of surface energy balance, where the verdict is not so positive.

Figure 1 shows the time series for model global average net solar radiation absorbed and thermal infrared radiation emitted, at the top of the atmosphere. Values for 4 months of Earth Radiation Budget Experiment *(ERBE)* data are indicated by ×s. From this viewpoint, the model infrared flux appears to be about 10 W m^{-2} too high, and the model solar fluxes appear to be about 15 W m^{-2} too high, corresponding to a model underestimation of global albedo by 0.03-0.04. Note, however, that the annual average ERBE solar fluxes apparently exceed the infrared flux by 5 W m^{-2}, so the model-absorbed solar exceeds outgoing infrared by about 10 W m^{-2}.

Possible difficulties with the model's treatment of solar radiation are further explored by examining the simulated results over a specific region, selected here to be centered over the United States. To see variations over the seasonal cycle, we average surface fields over the central United States (30°-50°N, 80°-105°W) and average each month over the final five years. Figure 2 summarizes radiative fluxes and evapotranspiration. The seasonal cycle of surface solar radiation over this region is an order of magnitude larger than that of net thermal infrared and so dominates the total net radiation.

Figure 3 shows similarly the model's simulated soil moisture on the surface (top 10 cm) and in the root zone (roughly 1 meter, but dependent on vegetation type) and model precipitation over the averaging region. The fourth quantity, moisture ratio, shows the root zone water variation between a field capacity (gravitational drainage of 2 mm/day) and wilting point (soil water potential of 15 hPa) normalized by this range. The soil moisture is out of phase with the precipitation, because net radiation and, hence, evapotranspiration have a larger seasonal variability (Figure 2) than does precipitation.

Figure 4 compares model runoff with observations. Model runoff is somewhat high, corresponding to the excess model precipitation. The model has two peaks, whereas the observations show a single summer peak. Some of the differences may be definitional; that is, model runoff is realized locally, whereas observations refer to runoff from major basins, which is smoothed and lagged in time relative to local runoff. However, the September peak in model runoff definitely appears unrealistic. Correspondence between model and observed precipitation is not examined here. Such an examination would have to consider both mean patterns and the discrepancies between realistic and model spatial and temporal variability of precipitation.

Figure 5 shows model versus observed surface incident solar flux for July. The model pattern is smoother than that given by observations, but otherwise it is in reasonable agreement over the western United States. However, over the eastern United States, the model shows about 20% more solar radiation than observed — an unacceptably large difference. The relative contribution of clear-sky model albedos and that of clouds to this discrepancy can be estimated from the ERBE satellite data (*e.g.*, Ramanathan *et al.* 1989). Figure 6, also for July, compares model clear-sky absorbed solar radiation with ERBE data. Both show 380-400 W m^{-2} across the United States, and the model values are lower than the data at higher latitudes. Hence, the model treatment of clear-sky radiation cannot explain the excess solar radiation at the surface. Consequently, this excess must result from the model clouds not reflecting enough solar radiation. Figure 7 compares the model and ERBE solar cloud forcing.

The model cloud forcing is generally less negative than that indicated by ERBE. The discrepancies are concentrated into three areas.

Figure 1
GLOBAL MONTHLY AVERAGES OF MODEL ABSORBED SOLAR RADIATION VERSUS THAT OBSERVED FOR ERBE FOR APRIL, JULY, AND OCTOBER 1985 AND JANUARY 1986

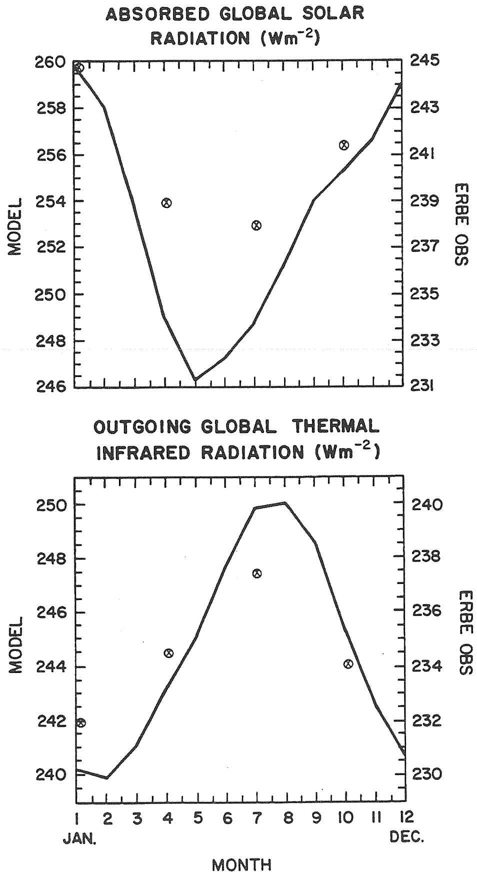


Figure 2
MONTHLY AVERAGED MODEL SURFACE RADIATION BALANCE QUANTITIES AND EVAPOTRANSPIRATION
(Averaged Over the Indicated Box)

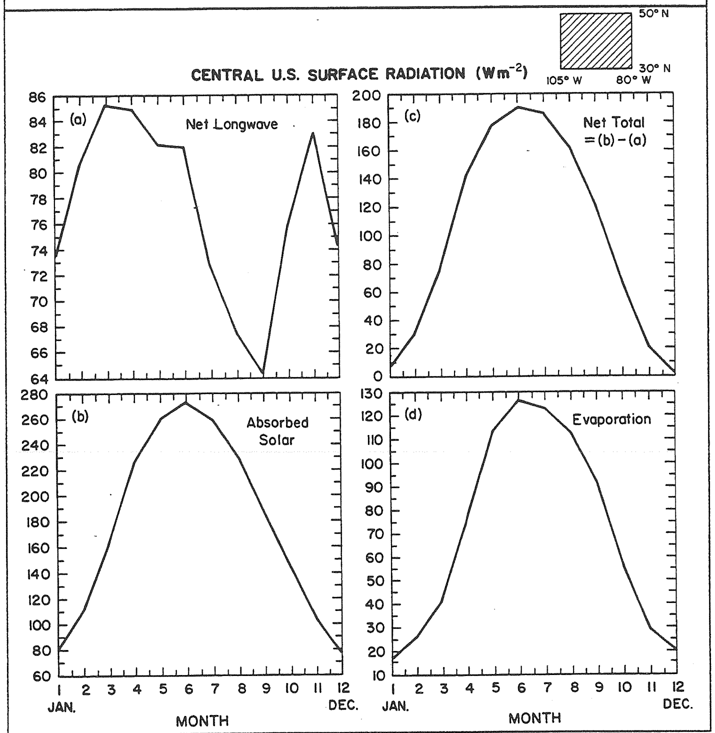
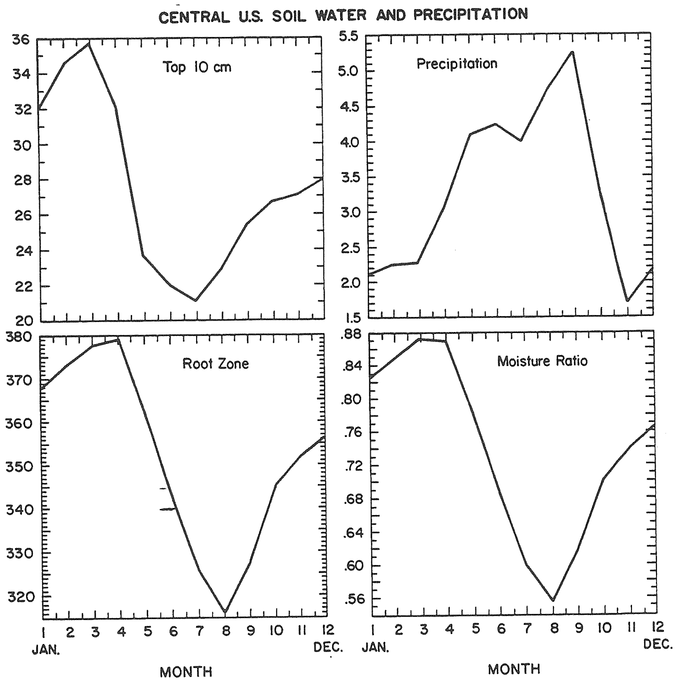


Figure 3
MONTHLY AVERAGED MODEL SOIL MOISTURE AND PRECIPITATION
(Averaged Over the Indicated Box)



- Off the West Coast, the model shows cloud forcing between 0 and –20 W m^{-2}, whereas the data is in the range of –60 to –80 W m^{-2}. This difference is accounted for by the model's failure to reproduce the low stratus decks in that region.
- Over the eastern states, the model gives about –40 W m^{-2}, whereas the data show –60 to –80 W m^{-2}.
- Over northeastern Canada, the model shows –40 to –60 W m^{-2} and the data show –80 to –100 W m^{-2}. Evidently the model clouds over eastern North America reflect only about half as much solar radiation as is observed.

Conclusions

We argue that the surface hydrology in General Circulation Models may be limited in accuracy by shortcomings in their simulations of relevant atmospheric quantities — in particular, precipitation and surface radiation depending on cloud radiative forcing. We illustrate this possibility through an analysis of some of the output fields of a simulation

Figure 4
MONTHLY AVERAGED RUNOFF

Observations were provided by Professor G. Thomas of University of British Columbia from a data base he has collected.

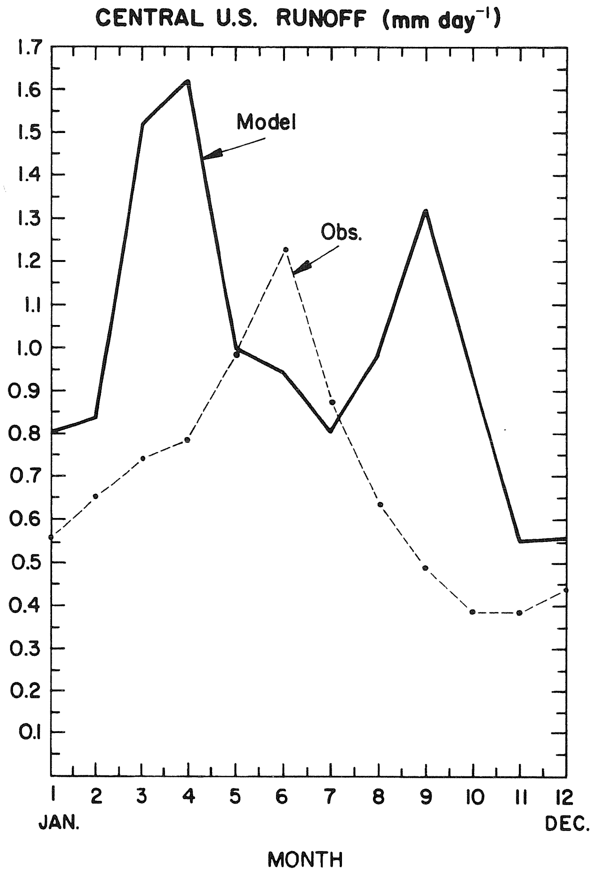
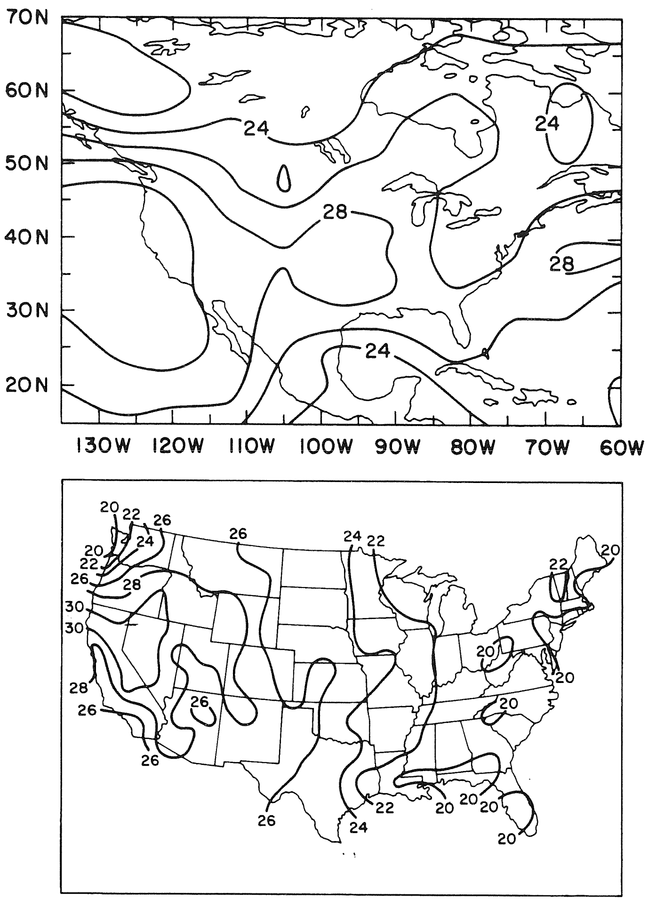


Figure 5
INCIDENT JULY SOLAR RADIATION
AT THE SURFACE (MJ m^{-2} day^{-1})

Top frame is for model average. Bottom frame is from an atlas prepared by Solar Energy Research Institute (1981).



with a diurnal cycle version of the NCAR Community Climate Model. Over a global average, the model shows a small excess of absorbed solar radiation, about 10 W m^{-2}. The excess of absorbed solar radiation appears to be much larger over certain regions, including eastern North America.

Model surface radiation over the eastern United States exceeds that observed by about 20%. This excess is associated with a deficit in model cloud reflection of solar radiation as seen in a 40 W m^{-2} discrepancy in solar cloud forcing over eastern North America. Analysis of model surface energy and hydrological parameters over a box over the central states shows a close correspondence between net radiation and evapotranspiration. The seasonal cycle of soil moisture appears to be driven more by the seasonal cycle of evapotranspiration than that of precipitation. Hence, for this region at least, errors in model surface net radiation are likely to give comparable errors in all the other surface hydrological parameters.

Figure 6
MODEL AVERAGE JULY CLEAR-SKY ABSORBED SOLAR RADIATION OVER NORTH AMERICA *(top frame)* VERSUS ERBE JULY 1985 *(bottom frame)*

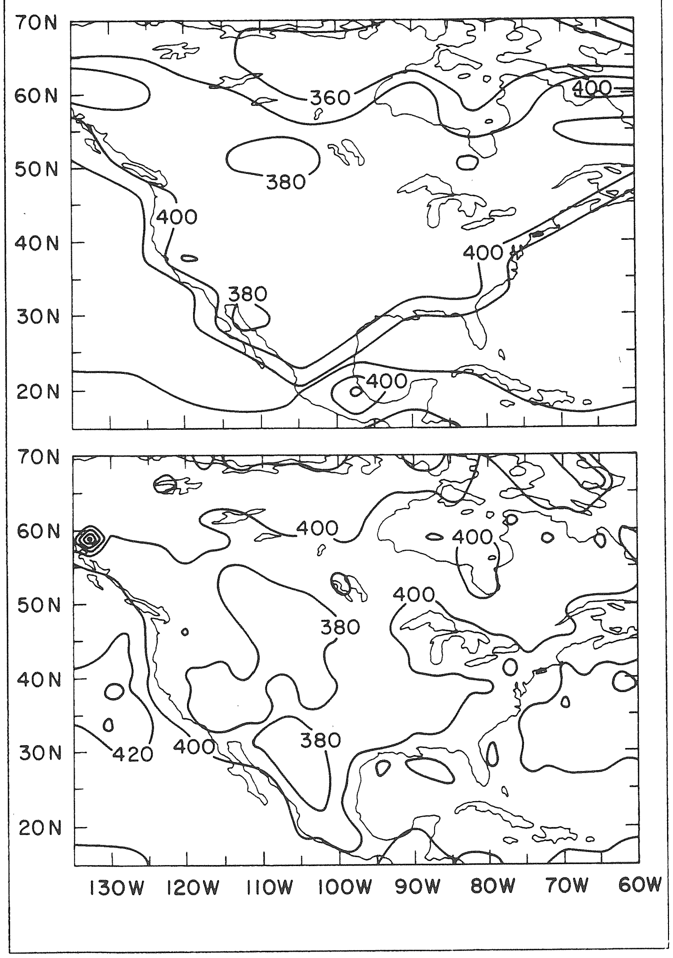
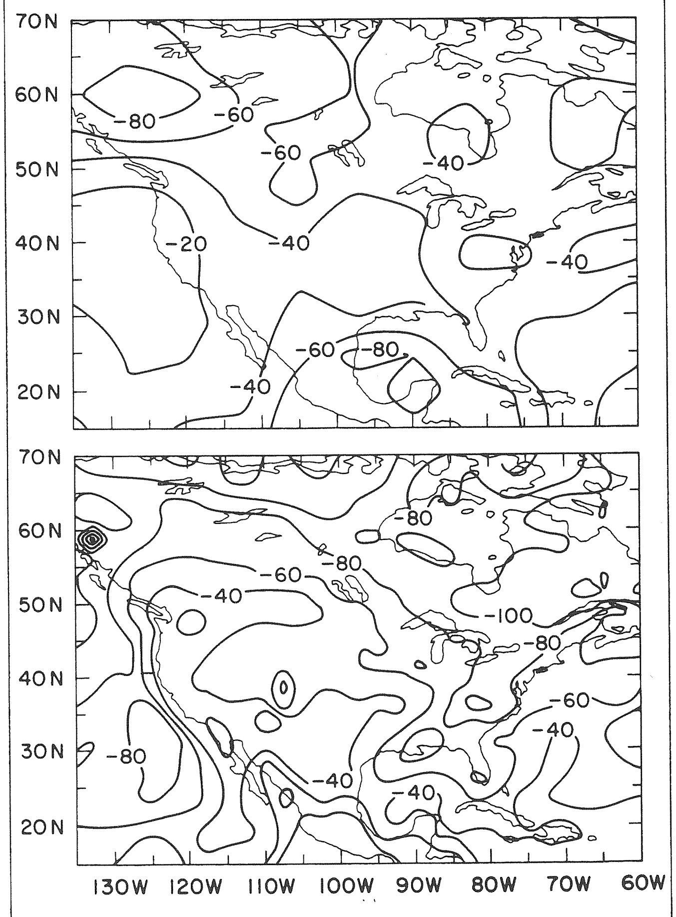


Figure 7
MODEL AVERAGE SOLAR CLOUD FORCING OVER NORTH AMERICA *(top frame)* VERSUS ERBE JULY 1985 *(bottom frame)*
The solar energy reflected to the top of the atmosphere minus that found in the absence of clouds.



Acknowledgments

We thank G. Thomas for providing the observational runoff data shown in Figure 4; B. Briegleb for providing the ERBE data in CCM format shown in Figures 1, 6, and 7; and S. Shearer for preparing the manuscript.

We are also grateful to Kluwer Academic Publishing, The Netherlands, for granting permission to use this material.

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