Land Surface Modeling and Its Application in Regional Study

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ABSTRACT

This paper describes the coupled Eta model, a NCEP regional weather forecast model, and the Simplified Simple Biosphere Model (SSiB), a biosphere model, and its application in regional simulation studies. The Eta model and SSiB exchange heat, momentum, and radiation fluxes.

In a case study, the coupled model's performance is evaluated, and its simulations are compared with observational data and reanalysis data. The results from the Eta/SSiB are also compared with those from the Eta/Bucket model. Both models have conducted three months 48 hour simulation for June, July, and August 1993, a heavy flood summer in the US. The monthly and seasonal means from the simulations in both model runs are compared.

The Eta/SSiB produces more realistic monthly mean precipitation over US and the flood areas. The improvements are mainly manifested in the intensity of the heavy rainfall and its spatial distribution. The results demonstrate that even with a short term simulation, while initial conditions are dominant, more realistic presentation of surface processes could improve the monthly and seasonal means of regional precipitation simulation for summer 1993.

1. Introduction

Climate sensitivity studies have shown that changes in land surface characteristics, such as albedo, surface roughness length, vegetation properties, and soil properties, substantially alter the terrestrial hydrologic system at global, regional and meso scales. Similar to ocean studies, in which distinct features in the sea-atmosphere interactions in different oceans are identified, substantial effort needs to be made to identify the specifics of the mechanisms and the influence of the land surface processes in different parts of the world for land surface studies.

During the past decade, using coupled atmosphere-biosphere models, studies have explored the effects of surface hydrology-atmosphere interactions over different continents. For example, using a Center for Ocean-Land-Atmosphere Studies general circulation model (COLA GCM) coupled with a biosphere model, the Simplified Simple Biosphere Model (SSiB, Xue et al, 1991), studies have demonstrated that land cover degradation in the Sahel may cause regional climate anomalies, consistent with observed decadal and seasonal anomalies in the hydrologic cycle in equatorial northern Africa. These anomalies are mainly manifested in drought, higher surface temperature, reduced soil moisture (Xue and Shukla, 1993, Xue, 1997), and decreased river discharge (Oki and Xue, 1998). In East Asia, a study has shown that land degradation may also influence the anomalies of the East Asian summer monsoon (Xue, 1996).

North American studies have shown that local conditions (e.g., soil wetness) and local processes (e.g., evapotranspiration) are important in determining the amount of summertime precipitation (see for example, Beljaars et al., 1996, Pielke et al., 1997). However, in a 1993 flood simulation (Pan et al., 1996), the inclusion of a more sophisticated land model produces rainfall response similar to a simple surface parameterization. In addition, Giorgi et al. (1996) find that local effects associated with surface evaporation play only a minor role in the 1993 US flood and the 1988 drought simulations. But later, it is discovered that this finding is influenced by the domain choice in the model (Seth and Giorgi, 1998).

In a North American land-atmosphere interaction study (Xue et al., 1996b), the systematic prediction errors in the COLA GCM in summer simulations are coincident with the agricultural region in central US. These errors are caused by the false prescription of the crop vegetation phenology in the surface model (SSiB) applied in the GCM. A series of numerical experiments designed to investigate the impact of crop area vegetation and soil properties on the prediction also reveal very pronounced and persistent effects of the land surface on the atmospheric variables at and near the surface during the North American summer. These effects, however, are limited to the area of the anomalous land surface forcing. The results of the study demonstrate that land surface processes play a significant role in the North American climate. Therefore, adequate land surface models and accurate land surface information are essential in North American climate studies.

In this paper, the biosphere model, SSiB (Xue et al. 1991, 1996c), is coupled and tested in the NCEP regional Eta coordinate forecast model. The Eta model and SSiB have evolved over the last decade and have been widely used in various studies. The Eta model has been used as the primary short-range weather forecasting tool at NCEP and at many other national weather services and research institutions all over the world. The performance of the model and its components have been carefully and continuously scrutinized by many researchers (e.g. Mesinger et al., 1990, Betts et al. 1997).

2. Biosphere Model (SSiB)

The SSiB is a bio-physically based model of land-atmosphere interactions and is designed for global and regional studies. It is intended to realistically simulate the controlling biophysical processes and to provide fluxes of radiation, momentum, sensible heat and latent heat to general circulation models and regional models. SSiB, which is a simplified version of SiB (Sellers et al., 1986), is used to represent land surface processes in the Eta model. It is consisted of three soil layers and one vegetation layer. The model predicts soil wetness (the fraction of soil water content to saturation) for three soil layers; temperatures on the canopy, surface soil layer, and deep soil layer; snow depth on the ground, and intercepted water at the canopy. Deardoff's force-restore method (1977) is used to predict the fast response (surface) and the slow response (deeper) soil temperatures. In the soil model, water movement is described by a finite-difference approximation to the diffusion equations. The soil layers receive water from precipitation and snow melting, and provide water for evaporation from bare soil and transpiration from canopy. The surface runoff and drainage are produced in the surface soil layer and bottom soil layer, respectively. In addition, each soil layer produces runoff whenever it is saturated. The governing equation for the interception water stores is based on the water conservation equation. SSiB describes the vegetation complex of 12 biomes (Dorman and Sellers, 1989), each of which represents some averaged (typical) soil and vegetation characteristics.

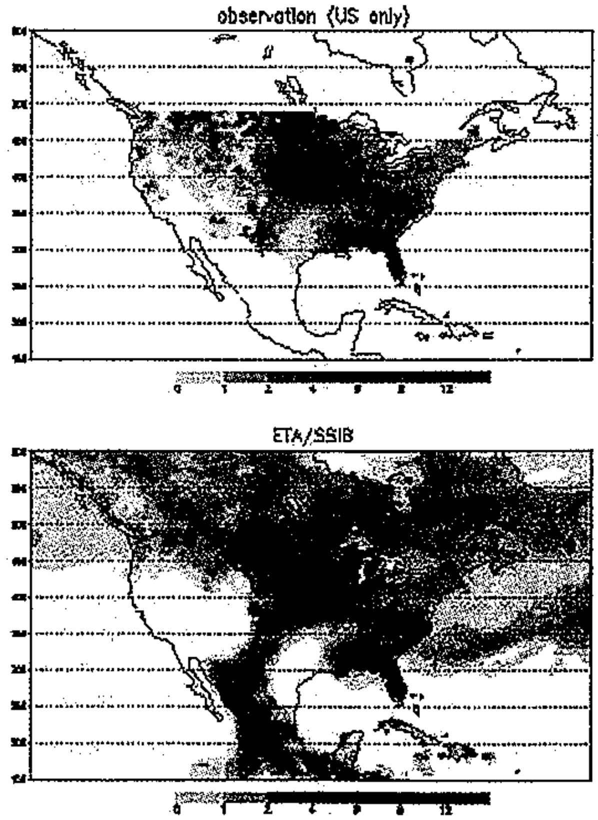
In a coupled model, vegetation distributions (normally through a vegetation map) need to be specified first. An appropriate set of vegetation parameter values is specified based on vegetation types and month of the year. In SSiB, the diurnally varying surface albedos are calculated based on vegetation and soil properties, solar zenith angle, and snow depth. The effect of surface albedo on the reflected short wave radiation from the surface in turn influences the surface energy balance and the surface skin temperature, which is related to canopy temperature and soil surface temperature. The skin temperature is used to derive the upward long wave radiation from the surface.

In addition to radiation flux exchanges, heat and momentum fluxes are also exchanged between the land surface and the atmosphere. The surface stomatal resistance and aerodynamic resistances are calculated based on the vegetation properties and environmental variables at the lowest atmospheric model layer as well as the land surface. These variables include photosynthesis flux and soil moisture, wind field, temperature, and humidity. The resistances control the energy partitioning into latent heat and sensible heat fluxes.

An off-line SSiB has been validated and calibrated using data measured from various vegetation types and regions in the world. In an off-line model, field measurements specify the atmospheric conditions that serve as the driving force in SSiB. Fluxes, surface temperature, and soil moisture simulated by SSiB are compared with observations. (For example, Xue et al., 1996c, Xue et al., 1996a). These comprehensive off line tests have helped us to understand the mechanisms of land surface processes under different surface and climate conditions, and have paved the way for more complex interaction studies in coupled models.

3. Case study - July 1993

After coupling the Eta model with the SSiB, the coupled model was first tested for the summer 1993 period. The NCEP/NCAR reanalysis data are used as atmospheric initial conditions, lateral boundary conditions, and surface boundary conditions of the Eta model in this study. The surface boundary conditions from reanalysis include sea surface temperature and sea ice. They are not updated for a 48 hour forecast. The lateral boundary conditions are updated every six hours and impose to model grid points only in the two outermost lines in the model domain.



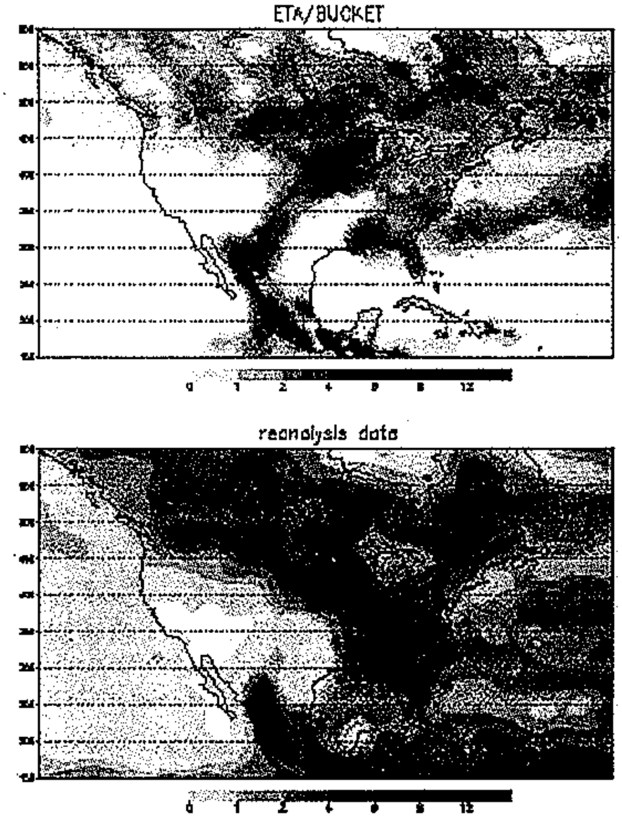


Figure 1 July 1993 mean average daily precipitation (mm/day): (a) Observation (US only); (b) Eta/SSiB simulation; (c) Eta/CNTL simulation; (d) reanalysis.

The 1993 flood in the mid US developed in June and peaked in July. Figure 1a shows the observed July US rainfall. The data is obtained from the NCEP Climate Prediction Center based on some 5000 rain gauge stations in the US and is used to calculate the forecast scores. Central US is the area most severely affected by the flood. The core area of heavy precipitation is located at about 40 degree north and 95 degree west. Southeast US, along the coast of the Gulf of Mexico, also experienced heavy rainfall. On the other hand, most of Texas and Oklahoma received little rainfall. It is seasonally dry west of the Rocky Mountains. Because there are very few station data available in Canada and Mexico in this data set, the precipitation distribution outside US is not able to provide enough information for comparisons and is masked out in Figure 1a. In fact, Mexico also experienced heavy rainfall in summer 1993.

The rainfall from the reanalysis data is shown in Fig 1d for comparison. The wind field, atmospheric temperature, and humidity in the reanalysis data are used as lateral boundary conditions to drive the regional model. The reanalysis data capture the general features of the July rainfall spatial distribution. The heavy rainfall in central US and southeast US are simulated. The simulation, however, is much weaker in central US and overly strong in Florida and Georgia.

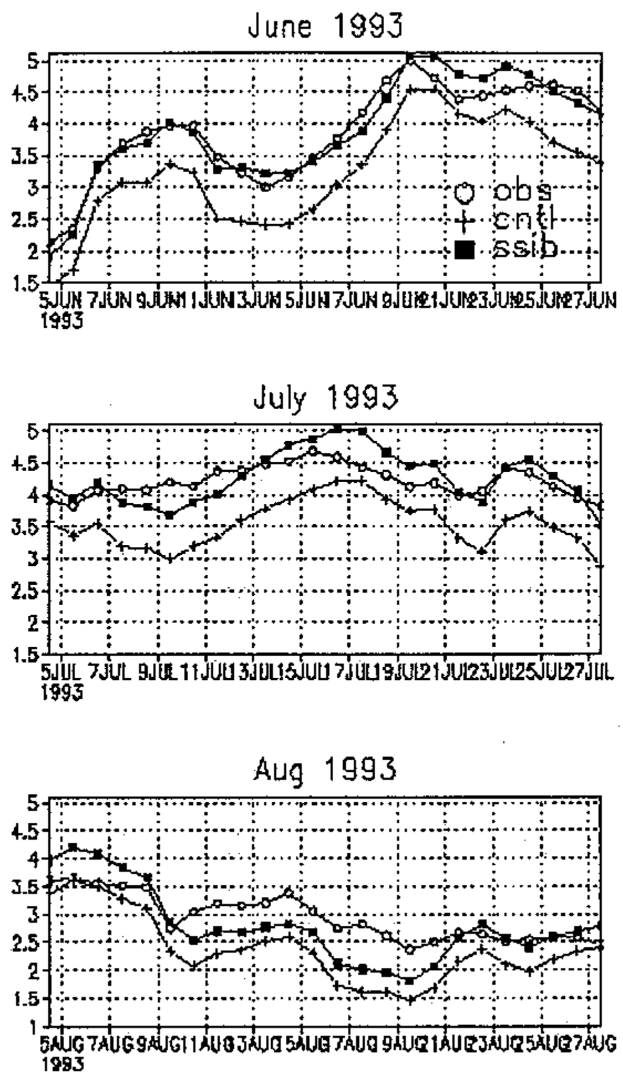


Figure 2 Five day running mean of observed and simulated precip (mm/day) averaged from 250W to 180W and 50N to 30N.

Both the Eta/CNTL and the Eta/SSiB produce better results than the reanalysis data (Figures 1c and 1b). The Eta/CNTL substantially reduces the reanalysis data's wet bias in southeast US. However, the rainfall reduction in southeast US is too much. Meanwhile, the simulated rainfall over the upper Mississippi Basin is too week compared with observation.

The Eta/SSiB produces better rainfall simulations in both the flood area and southeast US than the reanalysis data as well as the Eta/CNTL Case. In regions most affected by the flood, with precipitation in excess of 12 mm/day, the Eta/SSiB simulation is closer to observation than the Eta/CNTL simulations, although the intensity is still weaker than observed. The normal June-July-August (JJA) precipitation totals between 1961-1990 for the Central Plains and the UMRB are about 300mm (i.e., about 3mm/day). In 1993, the major flood area with precipitation in excess of 4mm/day expand from Central Plains to North Dakota. The second highest precipitation is located in North Dakota and Montana. The simulation results are consistent with observations.

Another heavy precipitation area, along the coast of North Carolina, South Carolina, Florida, Alabama, and Mississippi, and the dry areas in most part of Texas and Oklahoma are also well simulated by the Eta/SSiB. The Eta/SSiB and the Eta/CNTL produce similar results for the Mexican flood simulations. It indicates that land surface processes may have less impact on the rainfall there. A weakness in both the Eta SSiB and the Eta/CNTL is in the Gulf of Mexico. There is a clear contrast between land and ocean. Rainfall generally is confined over the land and islands in the simulations. But observational data from Xie and Arkin (1997, not shown), which cover the ocean, show that there are rainfall over the Gulf as appeared in the reanalysis data (Figure 1d).

The improvement in the Eta/SSiB is persistent throughout the three month simulation. Figure 2 shows the 5 day running mean of precipitation for the 24 hour simulation for June, July, and August, 1993. The averaging area covers most rainy regions from longitude 80 degree to 110 degree West and latitude 30 degree to 50 degree North. This area will be referred to as the test area. The Eta/CNTL has a clear systematic low bias in the three month simulation. This dry bias not only appears in the three month simulations, but also in other Eta/Bucket model simulations (for example, see Part I, and Berbery and Rasmusson, 1999). The Eta/SSiB has no obvious bias for the first two months. In August, when the rainfall becomes lower, the Eta/SSiB is too wet at the beginning of the month and quickly becomes drier than the observations in the middle of the month.

The test area's average July mean rainfall from the 24 and the 48 hour simulations are 4.15, 4.74, 3.42, and 4.12 mm/day for observation, reanalysis, Eta/Bucket simulation, and Eta/SSiB simulation, respectively. The monthly variation is incorrect in the reanalysis data, which has the rainfall peak in June rather than in July. Although both the Eta/SSiB and the Eta/CNTL produce the correct trend for the monthly variations, the Eta/SSiB's three monthly means are closer to the observed than the Eta/CNTL. With the exception of July 1993, the Eta/SSiB's 48 hour simulations are better than the Eta/CNTL's 24 hour simulations. In both case studies, the results are drier for the 48 hour simulations than the 24 hour simulations. The Eta/CNTL reduces rainfall by about 5 - 10%. The Eta/SSiB reduces rainfall by about 10% in June and August and more than 20% for July 1993. The differences in 24 hour and 48 hour forecasts for the 1993 summer are also found in other model.

By and large, the Eta/SSiB improves the simulations, but this improvement does not change the general patterns of the rainfall spatial distribution evident in the Eta/CNTL simulations.

4. Summary

In this study, a coupled Eta/SSiB model is developed and tested. A comprehensive atmosphere model, a robust PBL, a land surface model with an explicit vegetation canopy, and a proper coupling methodology are essential for land-atmosphere interaction studies. A vegetation map derived from remote sensing and other ancillary data are used to specify the surface vegetation distribution. The surface model provides the upward radiation, heat, and momentum fluxes at the surface to the atmosphere through PBL.

Despite the dominant role initial conditions exert on the short term simulations, this study is able to demonstrate the importance of using realistic presentation of surface processes in improving the monthly and seasonal means of regional simulation for summer 1993, by using two different surface schemes and corresponding initial soil moisture in the Eta model. The improvements are mainly manifested in the intensity of the heavy precipitation and its spatial distribution. In addition to precipitation, the surface temperature simulations are also evaluated (not shown). In most part of the US, the Eta/SSiB simulates reasonable surface temperature. However, in western part of the US mountain region, the Eta/SSiB has cold bias at nights.

Reanalysis data are used in this study. Our results show that a coupled atmosphere-biosphere regional model with reanalysis data as initial and boundary conditions has the potential to provide a more realistic simulation of precipitation in extreme climate events.

References

Berbery E. H. and E. M. Rasmusson, 1999: Mississippi moisture budgets on regional scale. Mon. Wea. Rev., in press.

Beljaars, A. C. M., P. Viterbo, and M. J. Miller, 1996: The anomalous rainfall over the United States during July 1993: Sensitivity to land surface parameterization and soil moisture anomalies. Mon. Wet. Rev., 124, 362-383.

Betts, A.K., F. Chen, K.E. Mitchell and Z.I. Janjic, 1997: Assessment of the Land Surface and Boundary Layer Models in Two Operational Versions of the NCEP Eta Using FIFE Data. Mon. Wea. Rev., 125, 2896-2916.

Deardorff, J.W., 1977: Efficient prediction of a ground surface temperature and moisture with inclusion of a layer of vegetation. J. Geophys. Res., 83, 1889-1903.

Dorman, J.L. and P. Sellers, 1989: A global climatology of albedo, roughness length and stomatal resistance for atmospheric general circulation models as represented by the Simple Biosphere Model (SiB). J. Appl. Meteor., 28, 833-855.

Giorgi, F., L.O. Mearns, C. Shields, and L. Mayer, 1996: A regional model study of the importance of local versus remote controls of the 1988 drought and the 1993 flood over the central United States. J. Climate, 9, 1150-1162.

Mesinger, F., A. I. Janjic, S. Nickovic D. Gavrilov and

D. G. Deaven, 1988: The step-mountain coordinate: Model description and performance for cases of Alpine Lee cyclogenesis and for a case of an Appalachian redevelopment. Mon. Wea. Rev., 116, 1493-1518.

Oki, T., and Y. Xue, 1998: Investigation of river discharge variability in Sahel desertification experiment. Preprint of Ninth Symposium on Global Change Studies, 259-260.

Pan Z., E. Takle, M. Segal, R. Turner, 1996: Influences of model parameterization schemes on the response of rainfall to soil moisture in the central United States. Mon. Wea. Rev., 124, 1786-1801.

Pielke, R.A., T.J. Lee, J.H. Copeland, J.L., Eastman, C.I., Ziegler, and C.A. Finley, 1997: Use of USGS-procided data to improve weather and climate simulation. Ecological Application, 7, 3-21.

Sellers, P.J., Y. Mintz, Y.C. Sud, and A. Dalcher, 1986: A simple biosphere model (SiB) for use within general circulation model. J. Atmos. Sci., 43, 505-531.

Seth A. and F. Giorgi, 1998: The effects of domain choice on summer precipitation simulations and sensitivity in a regional climate model. J. Climate, 11, 2698-2712.

Xue, Y., P. J. Sellers, J.L. Kinter III, and J. Shukla, 1991: A Simplified Biosphere Model for Global Climate Studies. J. Climate, 4, 345-364.

Xue, Y. and J. Shukla, 1993: The influence of land surface properties on Sahel climate. Part I: Desertification. J. Climate , 6, 2232-2245.

Xue, Y., 1996: The Impact of desertification in the Mongolian and the Inner Mongolian Grassland on the regional climate. J. Climate, 9, 2173-2189.

Xue, Y., H.G. Bastable, P. A. Dirmeyer, and P.J. Sellers, 1996a: Sensitivity of simulated surface fluxes to changes in land surface parameterization -- a study using ABRACOS data. J. Appl. Meteor., 35, 386-400.

Xue, Y., M.J. Fennessy, and P.J. Sellers, 1996b: Impact of vegetation properties on U.S. summer weather prediction. J. Geophy. Res., 101, D3, 7419-7430.

Xue, Y., F. J. Zeng, and C.A. Schlosser, 1996c: SSiB and its sensitivity to soil properties --- a case study using HAPEX-Mobilhy data. Global & Planetary Change, 13, 183-194.

Xue, Y., 1997: Biosphere feedback on regional climate in tropical North Africa. Quart. J. Roy. Met. Soc, 123, B, 1483-1515.