The Land Component of the Global Climate System with Adequate Spatial Resolution

Final Report
to the
Department of Energy

Project Number DE-FG02-91ER61216

Prepared by R. E. Dickinson, A. N. Hahmann,
X. Zeng, M. Chen, J. Vaughan, and B. A. Auvine

Robert E. Dickinson, P. I.
Institute of Atmospheric Physics
The University of Arizona, Tucson, AZ 85721

November 30, 1994

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
me

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Contents

1	Introduction	1
1.1	Overview	2
1.2	Progress milestones	3
1.3	Overall Development of CCM2/BATS	4
2	Surface Land Temperature and Radiative Fluxes Response of the NCAR CCM2/BATS Land Scheme to Modifications in the Optical Properties of Clouds (A. Hahmann)	9
2.1	Introduction	9
2.2	Radiative and Cloud Parameterizations in CCM2	11
2.2.1	Standard Model	11
2.2.2	Modification to the Cloud Optical Properties	12
2.3	Results	14
2.3.1	Global Averages	15
2.3.2	Geographic Distribution	16
2.4	Conclusions	21
3	Validation and Adjustment of Precipitation Simulated by CCM2/BATS over the Continental United States (M. Chen)	23
3.1	Introduction	23
3.2	Model Validation	25
3.2.1	Seasonal variation of daily precipitation	25
3.2.2	Diurnal variation of precipitation in August	25
3.2.3	Extreme Events	29
3.2.4	Hourly precipitation	31
3.3	Adjustment of intensity on grid scale	31
3.4	Disaggregation	36

3.4.1	Disaggregation method for hourly variable distribution	37
3.4.2	Disaggregation method for monthly stationary distribution	40
3.5	Summary	42
4	Development of a Fine-Mesh Model	43
4.1	Fine-Mesh Land Data Sets (J. Vaughan)	43
4.2	Prototype integration of the fine-mesh model (A. Hahmann)	44
5	Future Research Plans	49
5.1	Completion of linkages between fine-mesh and CCM2	49
5.2	Improvement of BATS model parameterizations	50
5.3	Parameterizability of subgrid-scale processes (X. Zeng)	52
5.4	Complete and refine fine-mesh atmospheric parameterizations	52
5.5	Sensitivity studies	53
6	References	55

List of Figures

1.1	Geographical distribution of July surface solar insolation differences (Wm^{-2})	6
2.1	Differences in July surface air temperature ($^{\circ}\text{C}$)	13
2.2	Geographical distribution of July surface air temperatures (K)	19
2.2	continued	20
3.1	a) Location of gauge stations; b) T42 Grid cells and locations of Regions A, B and C.	24
3.2	Amplitudes of diurnal variation of observed a) rainfall, b) intensity, and c) frequency; amplitudes of diurnal variation of simulated d) rainfall, e) intensity, and f) frequency in August.	27
3.2	continued	28
3.3	Distribution of a) observed and b) simulated maximum hourly precipitation, and distribution of c) difference between simulated and observed maximum hourly precipitation for August.	30
3.4	Correlation coefficients as a function of number of predictors for hourly intensity in August.	34
3.5	Comparison among observed, simulated and fitted hourly intensity in August for region A, B and C.	35
3.6	Probability density function of fractional coverage in Cell 2 in January.	38
3.7	a) Observed and b) simulated distribution of hourly precipitation in Cell 4 in January.	39
3.8	Sketch to illustrate the procedure of our disaggregation method for hourly variable distribution.	41
4.1	For South America, we show: a) the T42, b) the 0.5° land cover type, and c) a summary of the difference between these.	45
4.1	continued	46

4.2	Changes over South America between fine mesh and control simulation averaged over the coarse mesh for: a) skin temperature, b) surface air temperature, c) root zone moisture, and d) runoff. The contour interval is 0.5°C for a) and b), 2 cm for c), and 2 mm day^{-1} for d).	47
-----	---	----

List of Tables

2.1	Summary of Model Simulations	15
2.2	Comparison of Globally Averaged TOA Fluxes (Wm^{-2})	17
2.3	Comparison of Regionally Averaged Surface Air Temperatures (K)	18
3.1	Comparison of Daily Precipitation	26
3.2	Regression variables	33
3.3	Positions and Averages of Intensity	37

1. Introduction

The focus of the work done under this grant has been to couple global circulation models (in particular, the National Center for Atmospheric Research (NCAR) Community Climate Model Version 2 (CCM2)) to a land-surface model at a much finer mesh than that used for the atmospheric processes. The end objective has been to incorporate into the CHAMMP modeling system a state-of-the-art land model on a mesh independent of the atmospheric model resolution. Our objectives as stated in the original proposal have been to:

- Upgrade the Biosphere-Atmosphere Transfer Scheme (BATS) Version 1e code to current programming standards as implemented in CCM2, complete written documentation needed for BATS1e, carry out some research on improvements needed, and develop a design plan for the next-generation treatment (BATS2);
- Reprogram BATS1e to carry out its integrations over land in efficient vector loops and interface this code to CCM2, including input of required databases and formulation and programming for land output files, in order to be able to carry out land integrations over a 0.5° submesh, independent of the global model atmospheric resolution;
- Formulate and implement CCM2 schemes to provide statistically prescribed distributions of precipitation; develop a simple scheme to distribute atmospheric grid radiation incident at the surface onto the submesh elements, consistent with subgrid-scale cloudiness distributions as inferred from the subgrid-scale precipitation.
- Carry out one or more sensitivity studies with the above scheme implemented in CCM2, consisting of one or both of the studies of Amazon deforestation or the drought of 1988, depending on availability of previous control simulations;
- Develop graphical visualization procedures for scientific evaluation of the fine-mesh output.

1.1 Overview

Our efforts to date have been focused on obtaining a preliminary prototype formulation and integration of our fine-mesh treatment of CCM2/BATS. Considerable planning has gone into completion of efforts to provide an efficient community version of the standard CCM2/BATS code as the requisite starting point for the fine-mesh treatment. This aspect has been done in close collaboration with L. Bath, programmer for the Community Climate Model core program, and other collaborators at NCAR, in particular P. Kennedy, who carried out much of the effort to port the scalar version of BATS from CCM1 to CCM2, and A. Seth, who, as part of her University of Michigan thesis and through consulting activities supported by the present grant, did much of the development of the vectorized version of BATS and has pursued studies of the effects of fine-mesh BATS treatments on surface atmospheric exchange (Seth *et al.*, 1994). Progress has also been made toward formulation of the next generation version of BATS by collaboration with A. Henderson-Sellers on the international Project for Intercomparison of Land-surface Processes (PILPS) program. The currently frozen BATS is described in Dickinson *et al.* (1993).

Programmatic efforts at the University of Arizona have emphasized: development and graphical displays of the requisite fine-mesh land surface boundary conditions; the data structures required to carry out integrations on the land fine-mesh; the physical parameterization required to disaggregate model precipitation onto the fine-mesh; analyses of the NCAR 10-year control simulation of the frozen version of CCM2/BATS; implementation of changes in the cloud optical properties to mitigate excess incident solar radiation and temperatures over middle latitudes in Northern Hemisphere summer; and prototype development of the CCM2/BATS fine-mesh treatment, including a one-month integration and preliminary analyses of the results in terms of the effects of heterogeneity of land surface type on fluxes of sensible and latent heat to the atmosphere. In the next section, we summarize the current status of that effort.

1.2 Progress milestones

Listed below are our major progress milestones, along with the years of completion, supported wholly or in part by this project. They are discussed further in the following sections.

- BATS incorporated into CCM2 and integrated over several years at T42. Results analyzed as to success in climate simulation (1992).
- Documentation of the scalar version of BATS1e (current frozen version) completed and published as an NCAR Technical Note (1993).
- Vectorized version of BATS1e (VBATS) developed and passed on to CCM core group for implementation in CCM2 (1993).
- Robust VBATS version of CCM2/BATS developed and integrated for a ten-year control simulation, including analysis of its climatology, and released by NCAR as an option for community use (1993).
- Identification made of July Northern Hemisphere excess surface temperatures as the most serious present defect in the climate of the frozen version of CCM2/BATS. Analyses of comparisons with Earth Radiation Budget (ERBE), International Satellite Cloud Climatology (ISCCP), and Surface Radiation Budget (SRB) global data sets to interpret the biases as a result of a deficiency in cloud albedos and amounts. Development (in parallel with similar efforts by J. Kiehl and J. Hack on the non-BATS version of CCM2) of modifications to the CCM2 cloud optical properties to fix the diagnosed problem (1993).
- New five-year control simulation with CCM2/BATS carried out with the cloud optical property improvements and comparisons between the climate of this model and that of the frozen CCM2/BATS; decision made that the changes in cloud optical properties were a success (1993).
- Vectorized BATS (VBATS) code cleaned up considerably, including better conformance to CCM2 coding standards (1994).

- Understanding of the issue of parameterization of precipitation disaggregation advanced (1993).
- Land data set for BATS integrations developed at 0.5° resolution (1992).
- Preliminary data structures and linkages with CCM2 completed for the fine-mesh version of VBATS; tested with a one-month integration where the only difference from control is the fine-mesh representation of land cover (1994).
- Effects of the prototype one-month simulation analyzed and presented at the American Meteorological Society (AMS) Global Change Symposium and American Geophysical Union (AGU) Spring Meeting (1994).
- Write-up and submission of a manuscript to *Journal of Geophysical Research* describing the results of the improvements to the cloud optical properties in CCM2/BATS (1994).
- Published work in simulating fluxes from heterogeneous land surfaces in the *Journal of Geophysical Research* (1994).

1.3 Overall Development of CCM2/BATS

The first seven milestones represent progress in the development of a framework for use of the BATS code in CCM2. They include work done collaboratively with NCAR staff responsible for the overall progress in CCM2. We have carried out, under other sponsorship, an extensive analysis of various aspects of the surface climate simulation of CCM2/BATS. We have especially examined, in the context of a 10-year control simulation, how well the model reproduces monthly mean patterns of precipitation, temperature, and surface radiation. The model's most severe shortcoming for the simulation of land surface climate is an excess of surface solar radiation in the summer hemisphere, especially over Northern Hemisphere mid-latitudes in July. Figure 1.1a displays the differences in surface-incident solar flux between the CCM2/BATS control simulation and SRB (Whitlock *et al.*, 1993) observed values over the continents for July. Note the excess solar radiation (above 100 Wm^{-2}) over North America and the eastern part of the Asian continent. This excess surface solar radiation produces

temperatures that are as much as 5–10°C too warm. Guided by similar work being done by J. Kiehl and J. Hack at NCAR with the standard CCM2, we have modified the model's parameterization for prescription of cloud liquid water and generated an additional five-year control simulation. This simulation resulted in improved surface-incident solar radiation and temperatures. The average July differences in surface-incident solar flux between this new simulation and the SRB are displayed in Figure 1.1b. This new simulation is also in better agreement with ERBE and ISCCP data. This problem will be discussed in more detail in Chapter 2.

Other projects at The University of Arizona have been looking at the model monthly patterns of precipitation and runoff with emphasis on the U.S., where comparison data are most readily available. The current runoff parameterization in BATS is oversimplified and *ad hoc*. However, the ratio of runoff to precipitation appears to be at least as realistic as the precipitation itself. Hence, improvement in the model precipitation would appear to be of higher priority than improvement of runoff. The annual mean model precipitation averaged over land exceeds observational values by at least 50%. We examined whether there were any major temporal or geographical factors providing the bulk of these biases and have found none. In particular, the biases cannot be interpreted as either a coastal or a topographic effect. Some of the wintertime biases could be accounted for in terms of inadequate measures of snow in current observational climatologies. However, much of the bias is in summer or tropical conditions, where the most obvious unifying factor is that the precipitation is convective.

Improved surface temperatures and radiation give a modest improvement in model precipitation patterns. Some erroneous features in precipitation are likely a result of discrepancies between the low-resolution (T42) model and realistic topography. However, even allowing for all known sources of bias, there evidently is still an unexplained overall positive bias in land precipitation that is large compared to known oceanic discrepancies. We are beginning to explore the hypothesis that this positive bias in land precipitation is a consequence of some current flaw in the treatment of the coupling between land processes and moist convection. This flaw could very well involve the subgrid variations of land processes coupling to model

CCM2/BATS - SRB

RCCM2/BATS - SRB

Figure 1.1: Geographical distribution of the surface solar insolation differences (Wm^{-2}) between SRB and a) CCM2/BATS control simulation, and b) CCM2/BATS simulation with the modifications to the cloud liquid water parameterization for July. Contour interval of 20 Wm^{-2} .

subgrid-scale precipitation. The fine-mesh model begun here should be an important tool for further exploration of this aspect of the precipitation bias.

2. Surface Land Temperature and Radiative Fluxes Response of the NCAR CCM2/BATS Land Scheme to Modifications in the Optical Properties of Clouds (A. Hahmann)

2.1 Introduction

The coupling between the land surface and the atmosphere is becoming increasingly recognized as a key aspect of climate models. The atmosphere exerts strong controls over surface temperatures and moisture through its determination of incident surface radiation, precipitation, and near-surface vertical transports of heat and moisture. In turn, fluxes of heat and moisture from the land surface have major effects on the occurrence and properties of the clouds and precipitation that govern the atmosphere's control on the land surface. Because of the significant coupling between land and the atmosphere and the great variety of its manifestations in different locations and seasons, it is ultimately best studied in the context of a 3-D General Circulation Model (GCM) climate model.

The Biosphere Atmosphere Transfer Scheme, described most recently by Dickinson *et al.* (1993), was developed to represent land-surface processes in GCM climate models. Many other land process models with a comparable objective and similar features have also been proposed since the initial version of BATS was described by Dickinson (1984); and comparative studies of the performance of these schemes are being carried out through the PILPS program, as described by Henderson-Sellers *et al.* (1993b). Sensitivity studies have demonstrated substantial dependencies of model cloud properties and precipitation on the details of the land-surface boundary conditions. For example, several groups have studied the climate changes that might be expected with deforestation of the Amazon Basin. These studies (*e.g.*, Dickinson and Kennedy, 1992; Henderson-Sellers *et al.*, 1993a) have shown substantial decreases in the amounts of model precipitation with deforestation, in most cases by considerably larger amounts than the accompanying decreases in evapotranspiration. Thus, it appears that changes in land cover affect the atmospheric supply of water from the ocean.

After a long development period, the latest version of NCAR's Community Climate Model (CCM2) has become available for general use (Hack *et al.*, 1993). CCM2 improves substantially upon many aspects of earlier versions of the NCAR Community Climate Model, both in its physical and numerical formulation and in the quality of the software. However, the standard CCM2 includes only a minimum treatment of land-surface processes through inclusion of a diurnal cycle, an assumed soil model to provide thermal capacity for the diurnal heating, reasonably realistic prescribed albedos inferred from a land cover data set, and a prescribed "surface wetness" that varies geographically with land cover. For more detailed treatment of land, an optional inclusion of the latest version of BATS (BATS1e) is available. Numerical integrations of the BATS version indicate some serious deficiencies in the land simulation resulting from inadequate atmospheric inputs to the land surface, especially regarding the magnitude of incident solar radiation and in details of precipitation amounts and distributions.

The apparent increase in the importance of solar radiation absorbed at the land surface when a detailed land model such as BATS is included, along with the indication of problems resulting from excess solar radiation in the present and past versions of CCM (*e.g.*, Shuttleworth and Dickinson, 1989), have motivated us to examine here the details of absorbed solar radiation via simulations with several versions of CCM2. These versions include the standard CCM2, the standard CCM2 with BATS as its land surface component (CCM2/BATS), and the CCM2/BATS model with prescribed cloud optical properties, revised to provide improved agreement with observed solar radiation fluxes and land temperatures. We focus our description of the model simulations on July climatologies because they best illustrate the large excesses in simulated summer temperatures that result in CCM2 with BATS when excess solar radiation is provided from the atmospheric model to the land surface component. Observations from satellite platforms have become crucial sources of observational data for validating radiative fluxes in GCMs. For observational climatologies of radiative fluxes, we use ERBE data, which are now frequently used for similar studies, and also the recently released SRB data. This is the first time that this new data set, which provides a measure

of incident solar fluxes directly at the land surface, has been used to validate GCM simulated surface fluxes.

2.2 Radiative and Cloud Parameterizations in CCM2

Model fluxes for this study are obtained from several simulations with the latest version of the NCAR CCM2. The CCM2 is a global spectral model developed for a standard T42 horizontal truncation (approximately equivalent to a $2.8^\circ \times 2.8^\circ$ transform grid), with 18 vertical levels, and model top at 2.9 mb. The main differences between CCM2 and the earlier CCM1 version are an improvement of the key climate processes, including substantial changes in cloud and radiation (Hack *et al.*, 1993), moist convection (Hack, 1994), the planetary boundary layer (Holtslag and Boville, 1993), and transport (Williamson and Rasch, 1994). Especially relevant to this study have been changes made in the calculations of solar radiation and cloud amounts. The reader is referred to Hack *et al.* (1993) for a complete description of the standard CCM2 model.

2.2.1 Standard Model

The frozen version of CCM2 utilizes the δ -Eddington approximation to calculate atmospheric solar absorption using 18 spectral intervals (Briegleb, 1992). This radiation code allows for gaseous absorption by O_3 , CO_2 , O_2 , and H_2O , molecular scattering, and cloud water-droplet scattering and absorption. To account for cloud scattering and absorption, the parameterization of Slingo (1989) is used. For this scheme, the single-scattering properties of typical water cloud droplets (*i.e.*, cloud extinction optical depth, τ_c ; particle single-scattering albedo, ω ; and asymmetry parameter, g) are parameterized in terms of the cloud liquid water path (LWP) and the equivalent radius of the drop size distribution (r_e):

$$\tau_c = LWP \left(a + \frac{b}{r_e} \right), \quad (1a)$$

$$\omega = 1 - c - dr_e, \quad (1b)$$

$$g = e + fr_e, \quad (1c)$$

where $a \dots f$ are constant coefficients for 4 spectral ranges.

The computation of longwave radiation remains very similar to that in CCM1 (Kiehl *et al.*, 1987). In this scheme, the cloud emissivity is accounted for by defining an effective cloud amount for each model layer,

$$A'_k = \epsilon(p_k) A_k , \quad (2)$$

where A_k is the cloud amount at level k and the broadband emissivity, ϵ , is parameterized as

$$\epsilon(k) = 1 - e^{-\alpha \text{LWP}(k)} . \quad (3)$$

The $\alpha = 1.0 \times 10^{-4} \text{ m}^2 \text{ kg}^{-1}$ is an absorption coefficient based on observations by Griffith *et al.* (1980). In the standard CCM2, the cloud droplet effective radius is fixed at $10 \mu\text{m}$.

Cloud LWPs are computed from a prescribed cloud liquid water density (ρ_l):

$$\text{LWP} = \int \rho_l dz , \quad (4)$$

where

$$\rho_l = \rho_l^0 e^{-z/h_l} , \quad (5)$$

ρ_l^0 is equal to $1.8 \times 10^{-4} \text{ kg m}^{-3}$, z is the height, and h_l is a meridionally varying, but time-independent, empirically derived liquid-water scale height expressed as:

$$h_l = A + B \cos^2 \phi , \quad (6)$$

where ϕ is the latitude, $A = 1080 \text{ m}$, and $B = 2000 \text{ m}$.

2.2.2 Modification to the Cloud Optical Properties

An analysis of surface temperatures simulated for July over the Northern Hemisphere continents (Figure 2.1) shows a model temperature too warm by $5\text{--}10^\circ\text{C}$ when compared to the climatology of Legates and Willmott (1990). The possibility that this is due to an excess in

Figure 2.1: Differences in surface air temperature ($^{\circ}\text{C}$) between the ensemble July predicted by CCM2/BATS and the climatology of Legates and Willmott (1990)

surface incident solar radiation is confirmed by comparisons to the SRB climatology. Therefore, more realistic simulations of surface temperature require a reduction of surface incident solar radiation for this region and season.

A simple modification to the computation of cloud optical properties in the radiation parameterization was introduced, increasing the optical thickness of summer clouds while maintaining a simple analytic prescription. In this new scheme, the liquid water scale height [previously defined in Eq. (6)] was modified to

$$h_l = A' + B' \cos^2(\phi - \delta), \quad (7)$$

where δ is the solar declination angle, and the new values of the empirical constants are $A' = 1580$ and $B' = 1500$. Note that this modification not only increases the cloud LWPs in

high latitudes but also shifts maximum values toward the summer hemisphere through the dependence on the solar declination angle.

A number of observational studies (*e.g.*, Heymsfield, 1993) show significant differences in the cloud-drop number and effective radius distributions between maritime and continental regions. Kiehl (1994) suggests that the model representation of cloud optical properties should also reflect this behavior. To accomplish this, the equivalent radius of the drop size distribution [r_e in Eq. (1a) – Eq. (1c)], fixed at 10 μm everywhere in the standard model, was reduced to 5 μm over continental areas. Kiehl examined the effect of this assumption in the standard CCM2 but with a transition back to 10 μm for the high clouds. Through Eq. (1a) – Eq. (1c), a smaller effective radius for fixed LWP represents more droplets and larger effective cross section, hence larger cloud optical depth, larger particle single-scattering albedo, and less forward scattering through a reduction of the asymmetry parameter. All these factors contribute to an increase in the reflectivity of clouds in the modified version of CCM2/BATS. Kiehl (1994) found that reducing the droplet size over continents from 10 μm to 5 μm would reduce surface absorbed solar radiation by an amount of 20 to as much as 60 Wm^{-2} .

2.3 Results

Simulations using three different versions of CCM2 are used in this study. These three simulations are summarized in Table 2.1. The first simulation, labeled "CCM2", represents a 20-year integration (years 1–20) with the standard ("frozen") version of the CCM2 model. The simulation labeled "CCM2/BATS" refers to a 10-year integration (years 1–10) with the same standard version used in the "CCM2" simulation but with the land-surface processes computed using the BATS1e land model. These two integrations were performed by the Climate Modeling Group at NCAR and are fully described in Williamson (1993). Revisions to the cloud optical properties were introduced to the CCM2/BATS model, resulting in the simulation labeled "RCCM2/BATS" in Table 2.1.

Table 2.1: Summary of Model Simulations

Simulation	Description	Duration
CCM2	Standard CCM2	20 years (years 1-20)
CCM2/BATS	Standard CCM2 + BATS1e	10 years (years 1-10)
RCCM2/BATS	Standard CCM2 with revisions to cloud properties + BATS1e	5 years (years 6-10)

The RCCM2/BATS simulation was initialized from output fields of the CCM2/BATS simulation valid at 0000 GMT 7 August, year 5, and was integrated until 0000 GMT 1 January, year 11. The initial period from August 7 to December 31, year 5, is taken as a minimum "spinup" period and not used in the computation of monthly ensemble averages. Therefore, ensemble averages of the RCCM2/BATS simulation include monthly averages for years 6 to 10. For the CCM2 and CCM2/BATS simulations, ensemble averages are taken over the complete 20 and 10 years, respectively.

2.3.1 Global Averages

Globally averaged quantities are compared in terms of TOA total fluxes and cloud-radiative forcing (longwave, C_{IR} ; shortwave, C_S ; and net, C_{Net}) (Charlock and Ramanathan, 1985):

$$C_{IR} = F_{IR}^{clr} - F_{IR} , \quad (8a)$$

$$C_S = F_S - F_S^{clr} , \quad (8b)$$

$$C_{Net} = C_{IR} + C_S , \quad (8c)$$

where F_{IR} and F_S are the net upward longwave and net downward shortwave fluxes at the TOA, respectively, and F_{IR}^{clr} and F_S^{clr} are their respective clear-sky counterparts.

Table 2.2 summarizes the globally averaged TOA fluxes for ERBE (observed) and CCM2, CCM2/BATS, and RCCM2/BATS simulations, for both the annual average and individual monthly ensemble averages for January and July. The standard CCMs have annual and global average longwave and solar fluxes that are substantially larger than those observed by ERBE. In the CCM2 and CCM2/BATS simulations, longwave fluxes are larger than ERBE by 5.2 and 6.5 Wm^{-2} , respectively. This bias results in part from the absence of radiative effects of trace gases in the longwave computations. Inclusion of methane, nitrous oxide and the fluorocarbons, at present gas concentrations, would reduce the globally averaged longwave flux by approximately 2 Wm^{-2} (Kiehl *et al.*, 1994). Likewise, shortwave fluxes are larger than ERBE by as much as 9.3 Wm^{-2} in the CCM2 simulation. Resulting in part from the absence of atmospheric aerosol, this bias is correctable through changes in the specified cloud optical properties. Net fluxes are generally in better agreement with observed values than are their individual components, since longwave and shortwave fluxes tend to balance one another. The globally averaged cloud-radiative forcing values for the standard CCMs are in very good agreement with ERBE values, especially in the annual averages: the CCM2 and CCM2/BATS simulations net cloud-radiative forcing differ from ERBE by only 1.7 and -1.0 Wm^{-2} , respectively.

The errors in the monthly averages are considerably larger in July than in January for all globally averaged quantities of the CCM2 and CCM2/BATS simulations. Longwave fluxes are in somewhat better agreement with ERBE than are the shortwave fluxes.

2.3.2 Geographic Distribution

Figure 2.2 displays the July ensemble average surface air temperature for the Legates and Willmott (1990) climatology and for the three model simulations. Over North America, the surface air climatology (Figure 2.2a) displays the 290 K contour line along the border between the United States and Canada. In the CCM2 and CCM2/BATS simulations (Figures 2.2b and 2.2c) this contour level has expanded northward to cover most of the

Table 2.2: Comparison of Globally Averaged TOA Fluxes (Wm^{-2})

Annual	F_{IR}	F_S	Net	F_{IR}^{clr}	F_S^{clr}	C_{IR}	C_S	C_{Net}
ERBE	235.3	239.1	3.8	266.3	287.7	31.1	-48.6	-17.6
CCM2	240.5	248.4	7.9	271.4	295.1	30.9	-46.8	-15.9
CCM2/BATS	241.8	246.6	4.8	272.4	295.8	30.7	-49.2	-18.6
RCCM2/BATS	238.6	239.1	0.5	271.9	295.5	33.3	-56.4	-23.2

January	F_{IR}	F_S	Net	F_{IR}^{clr}	F_S^{clr}	C_{IR}	C_S	C_{Net}
ERBE	232.8	243.7	10.9	262.0	295.6	29.3	-51.9	-22.7
CCM2	236.4	253.8	17.4	267.5	305.2	31.1	-51.3	-20.3
CCM2/BATS	237.3	251.4	14.1	268.0	305.3	30.7	-53.9	-23.2
RCCM2/BATS	235.4	245.0	9.6	268.1	305.2	32.7	-60.2	-27.5

July	F_{IR}	F_S	Net	F_{IR}^{clr}	F_S^{clr}	C_{IR}	C_S	C_{Net}
ERBE	239.2	230.3	-8.9	269.6	277.4	30.4	-47.1	-16.7
CCM2	248.0	245.0	-3.0	276.6	287.0	28.6	-42.0	-13.4
CCM2/BATS	249.7	242.9	-6.8	277.8	286.8	28.1	-44.0	-15.9
RCCM2/BATS	245.5	234.0	-11.4	276.6	286.6	31.1	-52.6	-21.5

North American continent. The modifications to the cloud optical properties introduced in the RCCM2/BATS simulation caused this boundary to retreat to near its climatological position (Figure 2.2d). The same changed pattern can be seen over northern Asia.

**Table 2.3: Comparison of Regionally Averaged Surface Air Temperatures (K)
for the July Ensemble Averages**

	N. America ^a	S. America ^b	Asia ^c	Australia ^d
Observed	292.8	294.3	294.6	290.3
CCM2	297.1	291.9	297.7	287.7
CCM2/BATS	299.2	294.6	299.8	289.1
RCCM2/BATS	295.9	294.3	295.2	288.6

^a Averages between 32.1–60.0°N

^b Averages between 9.8°N and 29.3°S

^c Averages between 32.1–60.0°N and east of 36.6°E

^d Continental Australia, plus tropical islands of the Maritime Continent

Table 2.3 compares area-averaged surface temperatures over latitude ranges where the largest temperature biases were noted during the month of July. North America and Asia are examined between the latitudes of 30°N and 60°N. Regional averages over northern South America and Australia have also been added to show the changes in surface temperatures over tropical land due to modification to the optical properties of clouds. The interannual variability of these regional averages is small compared to the differences shown. CCM2 simulated temperatures are 4.3 and 3.1°C warmer than the Legates and Willmott climatology for North America and Asia, respectively, and the model with BATS1e is warmer by an additional 2.1°C.

The modifications to the cloud optical properties introduced in the RCCM2/BATS simulation substantially reduced the surface temperatures of the Northern Hemisphere summer continents, such that temperatures are now only 3.1°C warmer over North America and only

Legates & Willmott

Stand. CCM2

Figure 2.2: Geographical distribution of July surface air temperatures (K): a) Legates and Willmott (1990) climatology, b) CCM2, c) CCM2/BATS, and d) RCM2/BATS simulations. Contour interval of 10 K.

CCM2/BATS

RCCM2/BATS

Figure 2.2: continued

0.6°C warmer over Asia compared to the Legates and Willmott climatology. Over tropical regions, model surface temperatures are close to those observed and vary little with cloud changes. January temperature changes, not shown, are generally smaller, but overall also show improved agreement with observed temperatures in the Southern (summer) Hemisphere.

2.4 Conclusions

Two simple modifications to the computation of cloud optical properties were introduced in the model radiation parameterization: an increase in the optical thickness of summer clouds, and a more realistic representation of the equivalent radius of the cloud drop size distribution which accounts for the differences between land and oceanic regions. These changes act to: a) bring the global annually averaged absorbed solar radiation into very good agreement with ERBE data and net radiation nearly into balance (net heating of 0.5 Wm^{-2}); b) substantially reduce the large disagreement between model and ERBE top of the atmosphere fluxes and SRB surface solar fluxes in the Northern Hemisphere in summer; and c) likewise bring summer surface air temperatures for this region into much closer agreement with observations.

Part of the reason for excess surface solar radiation in the model is apparently an inadequate amount of low clouds relative to ISCCP. This process is at least somewhat affected by coupling to the land surface, such that the problem gets slightly worse with coupling to BATS. With a more realistic land-surface scheme, a feedback mechanism is established so that low clouds increase a bit with smaller land-surface incident fluxes. Thus, achieving better radiative balance through changing the cloud optical properties is at least in part simple tuning to compensate for the shortage of low clouds, and may have to be modified with improved cloud parameterizations. The currently improved radiative balances make the model more useful for climate sensitivity studies with an interactive ocean. A successful interactive parameterization for cloud liquid water, droplet sizes, and ice phase would further improve the model credibility for such climate studies.

3. Validation and Adjustment of Precipitation Simulated by CCM2/BATS over the Continental United States (M. Chen)

3.1 Introduction

This research concerns two major areas: a) validation of the temporal variability of the precipitation simulated by CCM2/BATS against observational data; and b) investigation of the spatial heterogeneity of precipitation in a CCM2 T42 grid cell and development of a new disaggregation method for precipitation.

The observed data used in this study are the hourly precipitation data from rain gauge records gathered from the United States, Pacific islands, Puerto Rico, and the Virgin Islands. The quality of this data set and the selection criteria for the stations are detailed in Chen (1994). Typically, precipitation data of 30-40 years at each station are used. Area labels and the locations of these stations are given in Figure 3.1a.

The simulated precipitation data are obtained from NCAR CCM2 at resolution T42 coupled with BATS version 1e, where sea surface temperature and ozone data are prescribed from climatological data with seasonal changes. The CCM2 grids over the continental United States are given in Figure 3.1b. One year of simulated data with daily sampling and a single month (August 6 to September 4) of hourly sampled data is available. For the first ten days of the month, there are also data sampled at 20-minute intervals. Simulated data used in our study are surface variables such as convective and non-convective precipitation and upper air variables such as air temperature, vertical velocity, effective cloud cover and total convective water flux.

Observed precipitation data are measured by rain gauges as a point value, while simulated precipitation is volume average in a CCM2 grid cell. In order to compare model simulations with observations, the Cressmen interpolation of observational data is used. A more detailed discussion of the interpolation process can be found in Chen (1994).

Figure 3.1: a) Location of gauge stations; b) T42 Grid cells and locations of Regions A, B and C.

3.2 Model Validation

The analyzed quantities include frequency, intensity, and amount of precipitation. The hourly (daily) intensity in this study is defined as a ratio of the total amount of precipitation to the total number of hours (days) with precipitation during a certain month. Hourly (daily) frequency is defined as a ratio of hours (days) with precipitation to total number of hours (days) counted.

3.2.1 Seasonal variation of daily precipitation

Our computations show that CCM2 simulates the precipitation patterns reasonably well in winter, spring and autumn, but it does not provide a good simulation for summer. Figure 3.1b defines three regions over the United States: Region A (west of 115°W), region B (between 100°W – 115°W) and region C (east of 100°W). Table 3.1 shows a detailed comparison between the observed and simulated intensity, frequency and amount of precipitation for these three regions. In general, for seasonal averages, CCM2 overestimates both the frequency and amount of precipitation but underestimates the intensity in these regions. The model simulates the seasonal variation of intensity and amount of precipitation well, but the simulation of frequency is good only in region A. For both the spatial pattern and the regional average, CCM2 simulates the seasonal variation of daily intensity well; the simulation of daily intensity is in better agreement with observations than that of frequency. These results are in agreement with the comparisons done by Morrill (1994) in her work with observed monthly precipitation amounts compared to CCM2/BATS simulated ones.

3.2.2 Diurnal variation of precipitation in August

Figure 3.2 shows the spatial distribution of the amplitude of diurnal variations of frequency, intensity and amount of precipitation. Amplitude is defined as the range of variables within 24 hours. It is found from Figure 3.2 that the observed amplitude of precipitation is controlled by the pattern of frequency, but the simulated amplitude of precipitation is controlled by the pattern of intensity. Observational data show high amplitudes in the southern United States

Table 3.1: Comparison of Daily Precipitation

	Obs. Intensity (mm/d)			CCM2 Intensity (mm/d)		
	Reg. A	Reg. B	Reg. C	Reg. A	Reg. B	Reg. C
Mean	7.9	6.0	10.3	2.7	3.1	3.8
Range	4.7-10.7	4.2-7.7	7.5-12.3	0.8-5.2	1.7-6.4	2.8-5.9
Max	Jan	Sep	Sep	Dec	Aug	Sep
Min	Jun	Jan	Jan	Sep	Jan	Feb

	Obs. Frequency (%)			CCM2 Frequency (%)		
	Reg. A	Reg. B	Reg. C	Reg. A	Reg. B	Reg. C
Mean	17.8	14.7	25.2	69.5	75.2	81.9
Range	7.2-26.5	11.0-19.5	21.0-28.6	45.2-90.5	60.0-86.0	65.0-91.8
Max	Dec	Jul	Jun	Oct	Nov	Nov/Jan
Min	Jul	Nov	Oct	Jul	Oct	Oct

	Obs. Rainfall (mm/d)			CCM2 Rainfall (mm/d)		
	Reg. A	Reg. B	Reg. C	Reg. A	Reg. B	Reg. C
Mean	1.5	0.9	2.6	2.4	2.6	3.2
Range	0.4-3.0	0.5-1.4	1.8-3.5	0.5-5.1	1.3-5.7	2.4-4.9
Max	Dec/Jan	Aug	Aug	Dec	Aug	Sep
Min	Jul	Jan	Jan	Aug	Jan	Feb

AMPLITUDE of CCM2 DIURNAL CYCLE RAINFALL mm/h AUG

CONTOUR FROM .1 TO .6 BY .1

AMPLITUDE of CCM2 DIURNAL CYCLE INTENSITY mm/h AUG

CONTOUR FROM .1 TO .9 BY .1

AMPLITUDE of CCM2 DIURNAL CYCLE FREQUENCY % AUG

CONTOUR FROM 5 TO 60 BY 5

Figure 3.2: continued

(Arizona and New Mexico), whereas high-amplitude areas from the simulated data are found in southeastern Texas, the Great Basin and the Rocky Mountains. Florida presents a small amplitude in the simulated data, which is opposite to that of the observed. Overall, CCM2 underestimates the amplitude of intensity and overestimates the amplitude of frequency in the diurnal variation of precipitation. As discussed in Chen (1994), one possible explanation for the poor performance of CCM2 in simulating phases of daily variation of precipitation the Great Plains is that the thermodynamic processes play a dominant role in generating precipitation in CCM2, whereas, in reality, for summer convective rainfall, dynamic processes should play a main role and thermodynamic processes play only a secondary role.

3.2.3 Extreme Events

Maximum hourly precipitation and the maximum length of wet and dry periods are chosen to represent extreme events. These parameters are calculated for both observations and CCM2 simulations for August.

Figures 3.3a–3.3b show the maximum of observed and simulated hourly precipitation, while Figure 3.3c shows their differences (CCM2 – observation). The maximum observed hourly precipitation was derived by averaging over ten years the maximum hourly rainfall for each August. The simulated maximum hourly precipitation has almost the same range as the observed. However, its spatial distribution is very different from that observed. In the Rocky Mountains area and the southeast (Georgia and Alabama) CCM2-simulated maximum hourly precipitation is larger than that observed. The difference, however, is less than 1 mm h^{-1} . In the rest of the continental United States, CCM2-simulated maximum hourly precipitation is less than the observed. Over the central states (Nebraska, Iowa, Kansas, Missouri), the difference can be more than 3 mm h^{-1} .

Comparisons of the maximum length of the wet (or dry) periods also show that CCM2 fails to simulate the overall observational pattern. CCM2's failure to simulate extreme events may be related to errors in the simulation of important patterns of the atmospheric circulation. Some of these details are summer subtropic ridges over the Pacific that are too strong, pressures over the continental United States that are too low (Hurrell *et al.*, 1993),

and summer surface temperatures over the central United States that are too warm (Bonan, 1994; Hahmann *et al.*, 1994).

3.2.4 Hourly precipitation

For the frequency of hourly precipitation, the positions of the simulated high and low centers are primarily the same as those observed. However, the magnitude of the frequency of simulated precipitation is much larger than that variability than the observed frequency. In contrast, simulated intensities have a much smaller variability than those observed.

Observed frequency of precipitation is 0.5%, 2.4% and 3.9% in Regions A, B and C, respectively. In contrast, the simulated value is 24%, 56% and 52%, respectively, in these same regions. Therefore CCM2 overestimates frequency by a factor of 48, 23 and 13 in Regions A, B and C, respectively. Observed intensity in Regions A, B and C is 2.24 mm h^{-1} , 3.20 mm h^{-1} , and 4.27 mm h^{-1} , while the simulated intensities are 0.06 mm h^{-1} , 0.35 mm h^{-1} , and 0.25 mm h^{-1} , respectively. Therefore, CCM2 underestimates intensity, which is only 3%, 11% and 6% of corresponding observations in Regions A, B and C, respectively. Although CCM2 has two opposite error tendencies, underestimating intensity and overestimating frequency, these two tendencies compensate for each other, producing overall less errors in precipitation amount. In Region A, observed and simulated precipitations are approximately the same. In region B, simulated amounts are approximately twice that of the observed. In region C, simulated amounts are about 80% of the observed amounts.

3.3 Adjustment of intensity on grid scale

To assess a possible method for adjusting the intensity of simulated precipitation, a regression analysis was conducted. In our analysis, the predictand is observed intensity of hourly precipitation; predictors are model simulated variables (not limited to precipitation itself) in a corresponding grid cell. For the observed intensity, a natural logarithmic transformation is used; for simulated intensity and convective total water flux, a square root transformation is used; and for the ratio of convective to total precipitation, a square transformation is used.

After the transformation, the variables become approximately normally distributed.

Table 3.2 lists predictand and predictors. The first step is to calculate correlation coefficients between predictand and each potential predictor, then the factor with the highest correlation coefficient is chosen as the first predictor. In each additional step, a new factor was added to the regression equation, which is chosen based on the test of significance of improvement resulting from adding the variable. Finally, the obtained regression equation is as follows:

$$\ln I_{hs} = a_0 + b_1\sqrt{i_{hs}} + b_2t_{bs} + b_3\sqrt{q_{as}} + b_4sq_8 + b_5r_{hs}^2 + b_6dt_8 + b_7w_{as} \quad (9)$$

where a_0 , and $b_1, \dots, b_7$ are constants whose values are $-0.8376, 0.125, 0.039, 0.075, -0.0028, -0.272, -0.0385$ and 1.19 , respectively. Predictors include precipitation (intensity and the ratio of convective to total precipitation), atmospheric thermal stability (temperature at a middle atmospheric level and its difference between a lower and a middle level of the troposphere), and vertical motion and water flux, which are related to the formation of rainfall and the nature of precipitation.

Figure 3.4 shows the correlation coefficients between fitted and observed intensity as a function of the number of fitting factors. The correlation coefficient between simulated and observed intensity is 35%, without fitting. Using only the first 2 predictors for fitting, the coefficient rises to 62%; when using all seven factors, the coefficient increases to 73%. This indicates that the first two predictors, simulated intensity and temperature at $\sigma = 0.598$, are more important than the other predictors. Figure 3.5 shows that these two predictors control the main features while the other predictors focus on the detailed features of intensity field. This suggests that to obtain a more robust relationship, only the first two predictors should be used. Equation (9) may then be simplified to

$$\ln I_{hs} = d_0 + e_1\sqrt{i_{hs}} + e_2t_{bs}, \quad (10)$$

where the value of the constants d_0, e_1, e_2 is $-14.21, 0.186$ and 0.0445 , respectively.

Table 3.2: Regression variables

Predictand / Predictor	Symbol	Units
Intensity of hourly precipitation, August	I_{hs}	Inches/hour
Intensity of daily precipitation, August	I_{ds}	Inches/day
Intensity of daily precipitation, January	I_{d1}	Inches/day
Intensity of hourly precipitation, simulated, August	i_{hs}	mm/hour
Intensity of daily precipitation, simulated, August	i_{ds}	mm/day
Intensity of daily precipitation, simulated, January	i_{d1}	mm/day
$I_{d1} - i_{d1}$	dI_{d1}	mm/day
Temperature at $\sigma=0.786$, simulated, August	t_{as}	K
Temperature at $\sigma=0.598$, simulated, August	t_{bs}	K
Temperature at $\sigma=0.786$, simulated, January	t_{a1}	K
Temperature at $\sigma=0.598$, simulated, January	t_{b1}	K
Difference of temperature ($t_{as} - t_{bs}$), August	dt_s	K
Difference of temperature ($t_{a1} - t_{b1}$), January	dt_1	K
Effective cloud fraction at $\sigma=0.786$	c_{as}	fraction
Effective cloud fraction at $\sigma=0.598$	c_{bs}	fraction
Convective total water flux at $\sigma=0.786$	q_{as}	Wm^{-2}
Convective total water flux at $\sigma=0.598$	q_{bs}	Wm^{-2}
Sum of convective total water flux ($q_{as} + q_{bs}$)	sq_s	Wm^{-2}
Ratio of convective to total hourly precipitation	r_{hs}	fraction
Vertical velocity at $\sigma=0.786$	w_{as}	Pa s^{-1}
Vertical velocity at $\sigma=0.598$	w_{bs}	Pa s^{-1}

* σ is the model's vertical coordinate.

Figure 3.4: Correlation coefficients as a function of number of predictors for hourly intensity in August.

Intensity of hourly precipitation

Figure 3.5: Comparison among observed, simulated and fitted hourly intensity in August for region A, B and C.

Robustness is an important criterion for evaluating a statistical method. Since another hourly simulated data set is not available at the moment, indirect estimation is adopted by means of similarity between hourly and daily intensity of precipitation. Not only is the daily intensity field similar to the hourly field, but also the observed daily field can be fitted by simulated fields with almost the same correlation coefficients. Using the same method, a regression equation for daily intensity is obtained:

$$\ln I_{d8} = f_0 + g_1 \sqrt{i_{d8}} + g_2 t_{a8} + g_3 c_{a8}, \quad (11)$$

where $f_0 = -12.06$, $g_1 = 0.0183$, $g_2 = 0.0378$, and $g_3 = 5.220$. Equation (11) has been applied to another August simulation (Day 1428–Day 1458). The correlation coefficient between observed and fitted daily intensities is 52%, which is lower by 13% than the one derived from dependent data.

In order to examine the sensitivity of this method to seasonal change, a winter case (January) is also studied. The equation for January is

$$\ln I_{d1} = l_0 + m_1 t_{b1} + m_2 i_{d1}, \quad (12)$$

where $l_0 = -47.63$, $m_1 = 0.209$ and $m_2 = -0.599$. This equation has also been applied to another January. The correlation coefficient between observed and fitted daily intensity is 75% for the January data, which is 1% higher than the one derived from dependent data.

3.4 Disaggregation

For convenience, seven CCM2 grid cells with different climates and various topographic features are selected in this study. The locations are listed in Table 3.3 and also marked in Figure 3.1b. For each cell, approximately 30 to 50 stations located in its vicinity were used.

Table 3.3: Positions and Averages of Intensity

Box	Latitude (°N)	Longitude (°W)	Station number	Averaged Intensity inches/hour
1	45.0–47.8	98.4–101.3	40	0.1153
2	33.8–36.6	84.4–87.2	33	0.1538
3	36.6–39.4	104.1–106.9	37	0.0823
4	45.0–47.8	121.0–123.8	38	0.0687
5	28.1–30.9	81.7–84.4	28	0.1752
6	39.7–42.2	81.7–84.4	50	0.1340
7	31.3–33.8	109.7–112.5	32	0.1276

Variability of precipitation depends heavily on the horizontal scale. For our purpose, precipitation is interpolated to 36 sub grids, so that each sub-cell is about $0.5^\circ \times 0.5^\circ$. Figure 3.6 shows the probability density functions of fractional coverage in Cells 2 in January. The probability decreases rapidly with increasing fractional coverage. Our computations also show that the probability decreases more rapidly in summer than in winter.

Based on our observational data analysis, different methods are proposed for the disaggregation of precipitation of different time scales.

3.4.1 Disaggregation method for hourly variable distribution

A disaggregation method is developed for hourly variable distribution, which is detailed in Chen (1994). In this method, hourly precipitation is considered a random variable, and its statistical average has a certain distribution (*i.e.*, its climatic distribution). The probability of fractional coverage, the probability of rain at a station for each fractional coverage, and the ratio of each station's precipitation to total cell precipitation under each rain pattern are considered. In this method, the characteristics of both the random and the spatial coherency (*i.e.*, correlation between stations' rainfall) of the precipitation field are considered. Figure

Region 2 (Jan) R

Rank 6 Eqn 103 $y^2=a+blnx/x^2$

$r^2=0.968613266$ DF Adj $r^2=0.965474593$ FitStdErr=0.0129449257 Fstat=648.072483

$a=3.5487781e-50$

$b=-6.4214193e-05$

Figure 3.6: Probability density function of fractional coverage in Cell 2 in January.

Figure 3.7: a) Observed and b) simulated distribution of hourly precipitation in Cell 4 in January.

3.7 shows that the average distribution simulated by this method matches the observed distribution quite well in both their patterns and magnitudes. Figure 3.8 illustrates the procedure used for this method.

3.4.2 Disaggregation method for monthly stationary distribution

A simple method to obtain the distribution of intensity (or any variable) in a GCM grid is developed by using the departure function $D(k)$, which is defined as

$$D(k) = (I(k) - I_m)/I_m \quad (13)$$

where k is the index of the sub-cell, I_m is the mean of intensity in the cell, and $I(k)$ is the intensity in the sub-cell k . $D(k)$ represents the departure of a sub-cell from the mean of the cell. The above equation can be rewritten as

$$I(k) = I_m(1 + D(k)) \quad (14)$$

and since $I_g = I_m$, we obtain

$$I(k) = I_g(1 + D(k)) \quad (15)$$

where I_g is the grid's mean value of intensity. Therefore, using the values provided by the GCM, the distribution of the variable in a grid cell can be calculated from the above equation. As long as observational data with sufficient density are available, $D(k)$ is easy to obtain. It is noted that $D(k)$ is a prescribed function without temporal change. Although it is only suitable for stationary cases, it is much simpler than other methods with a stationarity assumption.

Figure 3.8: Sketch to illustrate the procedure of our disaggregation method for hourly variable distribution. R is precipitation simulated by GCM at a grid cell. r is precipitation distributed at a fine mesh (1 grid cell includes m sub-grid cells). G is a random number generator. I is an interpolator which interpolates precipitation at stations into sub-grids. P_s , D and A are prescribed functions from observed precipitation. P_s is probability density function of the number of raining stations. K is the raining station number. P_k is probability density function of raining pattern under k stations with rain. L is a raining pattern under k stations with rain. D is raining locations in pattern L . A represents ratios of each station's precipitation to that of cell precipitation in pattern L .

3.5 Summary

Our analysis indicates that:

- The model simulates the seasonal variation of daily intensity reasonably well, while seasonal variation of frequency is poorly reproduced.
- The model underestimates the amplitude of intensity, overestimates the amplitude of frequency in diurnal variations, and simulates a much larger area of maximum nocturnal rain than observed south of 35°N.
- The simulated maximum hourly precipitation has almost the same range as does the observed. However, its distribution is very different from the observed. Also, the model fails to simulate the overall pattern of maximum wet or dry periods.
- The model overestimates frequency of hourly precipitation by a factor of 13 to 48, and its simulated intensity is equal to or less than one tenth of that observed. The model distorts not only the spatial distribution of precipitation, but also the temporal distribution of precipitation.

These results show that it is necessary to adjust the simulated precipitation for a realistic land surface simulation. After this adjustment, the intensity of precipitation is in much closer agreement to the observed value.

We have proposed new methods for the disaggregation of precipitation of different time scales. In the disaggregation method for hourly variable distributions, the characteristics of both random and coherent properties of the precipitation field are considered. The average subgrid distribution simulated by this method matches the observed quite well both in pattern and magnitude. The disaggregation method for monthly stationary distribution is easy to use.

4. Development of a Fine-Mesh Model

4.1 Fine-Mesh Land Data Sets (J. Vaughan)

The BATS model currently utilizes four data sets of global surface boundary conditions: line-break orography (ocean/land/sea-ice distribution), vegetation types (18 classes), soil textures (12 classes, from sand to clay), and soil color (8 classes, from light to dark). New data sets were developed for use with the fine-mesh version of CCM2/BATS.

The land vegetation types at 0.5° resolution were derived from the Olson *et al.* (1983) data at the same resolution. A "look-up" table was used to convert from the Olson land-type classification (63 classes) to BATS land types (18 classes). The orography flag data set was determined from the land-type categories according to the ocean/land distribution. Sea-ice distribution is not now available. At present, porosity has not been independently determined. We have developed an approach to inferring porosity from soil water capacity.

Based on a table for eight simple vegetation classes, vegetation cover was converted to root depth. This depth can be used to derive the root zone soil water capacity. To derive soil water capacity overall, Zobler's version of the Food and Agricultural Organization (FAO) soils database over a 1° grid was used in combination with rules developed at the Goddard Institute for Space Studies (GISS) for relating soil classifications to soil physical properties. These techniques require converting Zobler's soil types in terms of their proportions of sand, silt and clay to a "texture" index. This index, in turn, was used to calculate soil water capacity, using empirical studies relating the former with the latter. Results were compared carefully with similar plots from GIS until all discrepancies between the two analyses had been eliminated or explained satisfactorily. The data were then converted to equivalent porosities for BATS. A final step before input was to regrid the data to 0.5° resolution. The Geographic Resources Analysis Support System (GRASS) Geographical Information System (GIS) software was implemented on local workstations for visualization of these data.

The BATS land types and orography flags (including sea-ice derived from the coarse mesh) are presently being used in the fine-mesh version of CCM2/BATS. Soil data sets have not yet been implemented.

4.2 Prototype integration of the fine-mesh model (A. Hahmann)

The fine-mesh pointwise land process treatment through BATS remains the same as for the standard global mesh. What is new in the fine-mesh treatment is additional code to: i) transfer global mesh CCM2 information into inputs to BATS on the fine-mesh (disaggregation), and ii) average surface fluxes calculated by BATS on the fine-mesh over CCM2 grid squares to provide input to CCM2 atmospheric calculations (aggregation). For this purpose, we define the fine-mesh points as occurring over all land points at every half degree in latitude and longitude, located on the whole- and half-degree points. Grid squares of the global model are defined by lines intersecting the midpoints between mesh points. There are between 25 and 36 fine-mesh points for each such completely land grid square at T42.

Because of the size and complexity of the code to be modified, the above additions to CCM2 require considerable programming effort. In order to identify and eliminate programming errors, it has been necessary to proceed in small incremental steps. Initial phases involved putting in the fine-mesh treatment to do identical computations at each point and establishing that answers were unchanged from the original coarse-mesh version. We have identified the subsequent step as a major prototype in this process, that is, integration of the fine-mesh code, where the only use of the fine-mesh logic is the inclusion of fine-mesh data of the BATS land-surface classification. We have initially simplified the geography by assuming that T42 mesh squares are either all or no land. As an example, we show in Figure 4.1 for South America: a) the T42, b) the 0.5° land-cover type, and c) a summary of the differences between these. This integration was carried out for 40 days and compared with the conventional CCM2/BATS integrated from the same initial conditions. Figure 4.2 shows the changes over South America between fine-mesh (averaged over the coarse mesh) and the control simulation of: skin temperature, surface air temperature, root zone soil

GCM Vegetation Types

Fine-Mesh Vegetation Types

Figure 4.1: For South America, we show: a) the T42, b) the 0.5° land cover type, and c) a summary of the difference between these.

- Trop. Forest → Tall Grass
- Short Grass → Mix. Woodland
- Trop. Forest → Short Grass
- Tall Grass → Trop. Forest
- Shrubs → Short Grass
- Short Grass → Trop. Forest
- All Other Land Type Changes

Figure 4.1: continued

Figure 4.2: Changes over South America between fine mesh and control simulation averaged over the coarse mesh for: a) skin temperature, b) surface air temperature, c) root zone moisture, and d) runoff. The contour interval is 0.5°C for a) and b), 2 cm for c), and 2 mmday^{-1} for d).

moisture, and runoff. These differences correspond to an average over the last 30 days of the simulation.

Three features are noted: i) mean changes in surface variables, such as temperature and soil moisture parameters, can generally be associated with changes of the land classification over the fine mesh from the dominant class used at T42. In particular, substantial changes are noted where a significant fraction of a T42 grid square occurs on the fine mesh as a wetland, whereas it was dry on the coarse mesh (Figure 4.2c); ii) the computational time on a CRAY YMP has tripled from that of the standard model, implying a need to substantially improve code efficiency; and iii) some transient wavelike atmospheric anomalies are noted, which need further study to ascertain that they are not symptoms of a coding error.

5. Future Research Plans

5.1 Completion of linkages between fine-mesh and CCM2

A top priority is the completion of the development of fine-mesh data structures in the VBATS model and its link to CCM2. Several steps will be included in this process: i) revise sea-ice treatment in VBATS, ii) include realistic continental outlines and soil characteristics, iii) include options for fine-mesh output and restart capabilities, and iv) reduce the memory usage and CPU time.

As previously discussed, the prototype simulation displays some transient wavelike atmospheric anomalies over the high latitudes of both hemispheres. Differences in surface temperatures between this simulation and the control experiment are as large as 20°C by day 30. This problem appears to be related to the treatment of sea-ice in the current fine-mesh version of the VBATS model. Therefore, the sea-ice processes and their interaction with the atmosphere will have to be reviewed.

In order to prototype the linkage of the fine-mesh land scheme and CCM2, some simplifications were made in the specification of surface boundary conditions. First, it is assumed that the ocean/land/sea-ice specification of fine-mesh cells follows the T42 resolution; thus the 0.5° resolution of continental outlines and major continental lakes is lost. Second, soil textures and soil colors in the fine-mesh are specified only at the T42 resolution. The inclusion of better data sets, in particular the specification of major lakes, should result in a substantial improvement of the realism of the simulations. Data structures and computational methods will have to be developed to include these boundary conditions. This process will include the calculation of surface albedos, and therefore incident solar radiation, on the fine-mesh.

Another important task is to provide output for surface variables with 0.5° resolution. In the current fine-mesh CCM2/VBATS version, the output is available only in terms of the aggregated T42 variables. Without displays of the fine-mesh output, important details of the simulation in the fine-mesh cannot be examined. Also, the large computational cost

of the fine-mesh model simulations makes it important to include a restart option, that is the option of continuing a simulation after computer failure or when a longer integration is desired at a later time.

Finally, improvements in the efficiency of the fine-mesh VBATS FORTRAN code have become necessary. The current fine-mesh CCM2/VBATS version requires almost twice the memory and three times the execution time of the standard CCM2/VBATS at T42 resolution. A revision of the data structures and computational algorithms is necessary in both the standard BATS and the fine-mesh model to reduce memory usage and to speed computations.

5.2 Improvement of BATS model parameterizations

The BATS land model has been largely frozen for six years with the primary developments being the completion of a vectorized version as needed for our present study and code for coupling to CCM2. Such stability has made it practical to provide the code to many users and has allowed the community to gain familiarity with it. Most of the newer land codes have started with either the descriptions or, in quite a few cases, the source code and have then modified BATS in ways that the authors thought desirable. Unfortunately there has not been much information available to judge what "improvements" were justified. However, current and recently completed activities are helping to focus on where BATS parameterization might be improved. These are in particular, the First ISLSCP [International Satellite Land-Surface Climatology Project] Field Experiment (FIFE) and Boreal Ecosystem-Atmosphere Study (BOREAS) field programs to study land-atmosphere interaction, the PILPS international intercomparison of land models, and the focus through the NASA Earth Observing System (EOS) program on improving the global data sets available for land studies.

Particular data sets that suggest revisions of the BATS treatments are: more detailed soil descriptions derived from the FAO maps and efforts to improve upon these, more detailed descriptions of surface topography through digital elevations maps (DEMs), and land cover descriptions derived from global remote sensing, at present from the National Oceanic and At-

mospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) but in the future EOS.

Hydrological studies (*e.g.*, Band, 1993) show the importance of lateral movement of water over the landscape in maintaining a distribution of soil moisture, and land surface sensitivity studies (*e.g.*, Avissar and Pielke, 1989) indicate the importance of the land slope and orientation in determining local energy balances. The following features will be added to BATS to take advantage of these opportunities:

- an option for determining soil temperature by a multilayer calculation allowing for snow and frozen soil including permafrost;
- an improvement in the soil moisture parameterization to include multiple horizons, groundwater level, and redistribution between submesh points on the basis of slope and elevation information;
- a generalization of the surface radiative inputs from CCM2 information to allow for subgrid cloud effects on the underlying surface, the orientation of the surface with respect to the sun, and the shadows created by topographical features;
- an improved description of seasonal changes in land cover, including seasonally flooded areas (*e.g.*, Amazon and Pantanal regions over South America) to be inferred from the sub-mesh moisture redistribution and vegetation cover as constrained by satellite data and seasonal temperatures and soil moisture;
- modifications of the stomatal closure formulation to recognize advances in understanding the underlying leaf physiology (*e.g.*, Sellers *et al.*, 1992). These include, in particular, modification of the parameterization for dependence on humidity at the leaf surface, and dependence of maximum stomatal resistance on depth in the canopy.

5.3 Parameterizability of subgrid-scale processes (X. Zeng)

Traditionally, the predictability of a system is defined based on the sensitivity to initial conditions, and the parameterizability of subgrid-scale processes has seldom been addressed in the past. Recently, Xubin Zeng's research activities have included the question of the predictability and parameterizability of geophysical flows. First, he has developed a general description of chaos and predictability. He emphasized that the predictability of a system depends on its sensitivity not only to the initial conditions but also to the boundary conditions and model parameters. The predictability of geophysical flows has also been examined. In particular, we have demonstrated that strong boundary forcing can substantially extend the predictability from what would be expected based on the more traditional evaluation of the sensitivity to initial conditions. Finally, the parameterizability of the subgrid-scale processes in numerical models has been examined. He has suggested that parameterizability needs to be studied, and the results need to be documented before any parameterization scheme can be implemented in numerical models.

This work will be published as a part of the invited paper (Pielke *et al.*, 1994) in which various unresolved issues in numerical modeling of geophysical flows will be addressed.

5.4 Complete and refine fine-mesh atmospheric parameterizations

Development of physically based algorithms for distribution of precipitation over the fine mesh is a key element in the use of our approach to improve the realism of climate simulations over land. The research activities carried out so far, as described in the preceding section, will be continued until a satisfactory solution is achieved.

The process of computing the effects of physical processes on a fine-mesh, as done with the land-surface processes, will also be extended to other physical parameterizations. The CCM2 physical parameterizations that are being considered for this treatment are: shortwave (Briegleb, 1992) and longwave (Hack *et al.*, 1993) atmospheric radiation calculations; planetary boundary-layer processes (Holtslag and Boville, 1993); and moist convection (Hack, 1994). All these parameterizations, similar to the VBATS model, are ideal for massively

parallel systems since they do not involve any horizontal coupling.

Xubin Zeng is working towards coupling the (BATS) to the Colorado State University (CSU) Regional Atmospheric Modeling System (RAMS). Using this model, he will address the consistency of the parameterization of hydrological processes and the transportability of parameterization schemes. This study will focus on the seasonal to interannual climate prediction.

5.5 Sensitivity studies

Once the fine-mesh CCM2/VBATS model, with all the planned enhancements, becomes fully operational and has been extensively tested, two main groups of sensitivity studies are being considered. These sets of experiments, besides testing the advantages of a high-resolution land-surface model, will also focus on specific scientific problems of interest.

- Sensitivity to anthropogenic land-surface modification (tropical deforestation). At present, most published studies of the sensitivity of general circulation models to tropical deforestation (Nobre *et al.*, 1991; Dickinson and Kennedy, 1992; Henderson-Sellers *et al.*, 1993a) have considered the effects of a complete replacement of the Amazon forest by degraded grassland. However, as shown by a recent satellite study, the deforestation process in this region occurs in only particular areas and in a "patchy" manner (Skole and Tucker, 1993). The fine-mesh version of CCM2/VBATS, due to its high resolution, is ideal for examining the effects of this selected and "patchy" deforestation process. Several 90-day integrations are planned to assess the effects of location, amount, and spatial distribution of deforested areas.
- Sensitivity to inclusion of inland bodies of water. Results of simulations with the standard version of CCM2/VBATS display a large temperature bias over the central United States during the summer. As described previously, part of this bias can be attributed to unrealistic representation of cloud optical properties in the CCM2 radiation parameterization. However, the exclusion of the Great Lakes from the land surface type specification in this region may have contributed to this bias. We propose to include

the Great Lakes and other major lakes (at least of 1-degree horizontal extent) in the fine-mesh version of CCM2/VBATS and to couple this model to a lake model such as described in Hostetler *et al.* (1993). A year-long simulation will be performed to study the sensitivity of the model simulation to the presence of continental open water surfaces.

6. References

- Avissar, R., and R. A. Pielke, 1989: A parameterization of heterogeneous land surfaces for atmospheric numerical models and its impact on regional meteorology. *Mon. Wea. Rev.*, **117**, 2113 – 2136.
- Band, L. E., 1993: Effect of land surface representation on forest water and carbon budgets. *J. Hydrology*, **150**, 749 – 772.
- Bonan, G. B., 1994: Comparison of the land surface climatology of the National Center for Atmospheric Research community climate model 2 at R15 and T42 resolutions. *J. Geophys. Res.*, **99** (D5), 10,357 – 10,364.
- Briegleb, B. P., 1992: Delta-Eddington approximation for solar radiation in the NCAR Community Climate Model. *J. Geophys. Res.*, **97**, 7603 – 7612.
- Charlock, T. P., and V. Ramanathan, 1985: The albedo field and cloud radiative forcing produced by a general circulation model with internally generated cloud optics. *J. Atmos. Sci.*, **42**, 1408 – 1429.
- Chen, M., 1994: *Validation and Adjustment of Precipitation Simulated by CCM2/BATS over the Continental United States*. M.S. Thesis, University of Arizona, Tucson, AZ, 86pp.
- Dickinson, R. E. 1984: Modeling evapotranspiration for three-dimensional global climate models, in *Climate Processes and Climate Sensitivity*, Geophysical Monograph 29, Maurice Ewing Volume 5, American Geophysical Union.
- Dickinson, R. E., and P. J. Kennedy, 1992: Impacts on regional climate of Amazon deforestation. *Geophys. Res. Letters*, **19**, 1947 – 1950.
- Dickinson, R. E., P. J. Kennedy, and A. Henderson-Sellers, 1993: *Biosphere-Atmosphere Transfer Scheme (BATS) Version 1e as coupled to the NCAR Community Climate Model*.

- NCAR Technical Note, NCAR/TN-387, National Center for Atmospheric Research, Boulder, CO, 72 pp.
- Griffith, K. T., S. K. Cox, and R. G. Knollberg, 1980: Infrared radiative properties of tropical cirrus clouds inferred from aircraft measurements. *J. Atmos. Sci.*, **37**, 1077 – 1087.
- Hack, J. J., 1994: Parameterization of moist convection in the NCAR Community Climate Model. *J. Geophys. Res.*, **99**, 5551 – 5568.
- Hack, J. J., B. A. Boville, B. P. Briegleb, J. T. Kiehl, P. J. Rasch, and D. L. Williamson, 1993: *Description of the NCAR Community Climate Model*. NCAR Technical Note, TN-382+STR. National Center for Atmospheric Research, Boulder, CO, 108 pp.
- Hahmann, A. N. D. M. Ward, and R. E. Dickinson, 1994: Surface Land Temperature and Radiative Fluxes Response of the NCAR CCM2/BATS Land Scheme to Modifications in the Optical Properties of Clouds. Accepted for publication in *J. Geophys. Res.*.
- Henderson-Sellers, A., R. E. Dickinson, T. B. Durbidge, P. J. Kennedy, K. McGuffie, and A. J. Pitman, 1993a: Tropical deforestation: Modeling local- to regional-scale climate change. *J. Geophys. Res.*, **98**, 7289 – 7315.
- Henderson-Sellers, A. Z.-L. Yang, and R. E. Dickinson, 1993b: The Project for Intercomparison of Land-surface Parameterization Schemes (PILPS), *Bull. Amer. Meteor. Soc.*, **74**, 1335 – 1349.
- Heymsfield, A. J., 1993: Microphysical structures of stratiform and cirrus clouds, in *Aerosol-Cloud-Climate Interactions*, ed. P. V. Hobbs, N.Y., Academic Press.
- Holtslag, A. A. M., and B. A. Boville, 1993: Local versus nonlocal boundary-layer diffusion in a global climate model. *J. Climate*, **6**, 1825 – 1842.
- Hostetler, S. W., G. T. Bates, and F. Giorgi, 1993: Coupling of a lake model with a regional climate model. *J. Geophys. Res.*, **98**, 5045 – 5058.

- Hurrell, J. W., J. J. Hack, and D. P. Baumhefner, 1993: *Comparison of NCAR Community Climate Model (CCM) Climates*. NCAR Thec. Note, NCAR/TN-395+STR, National Center for Atmospheric Research, Boulder, CO, 335 pp.
- Kiehl, J. T., 1994: Sensitivity of a GCM climate simulation to differences in continental versus maritime cloud drop size. *J. Geophys. Res.*, in press.
- Kiehl, J. T., J. Wolski, B. P. Briegleb, and V. Ramanathan, 1987: *Documentation of Radiation and Cloud Routines in the NCAR Community Climate Model (CCM1)*. Tech. Note NCAR/TN-288+IA, National Center for Atmospheric Research, Boulder, CO.
- Kiehl, J. T., J. J. Hack, and P. B. Briegleb, 1994: The simulated earth radiation budget of the NCAR CCM2 and comparisons with the Earth Radiation Budget Experiment (ERBE). *J. Geophys. Res.*, 99, 20,815 – 20,827.
- Legates, D. R., and C. J. Willmott, 1990: Mean seasonal and spatial variability in global surface air temperatures. *Theor. Appl. Climatol.*, 41, 11 – 21.
- Morrill, J., 1994: *A Comparison of CCM2/BATS Simulated Precipitation and Runoff with Observed Values Over the Continental United States*. M.S. Thesis, University of Arizona, Tucson, AZ, 150 pp.
- Nobre, C. A., P. J. Sellers, and J. Shukla, 1991: Amazonian deforestation and regional climate change. *J. Climate*, 4, 957 – 988.
- Olson, J. S., J. A. Watts, and L. J. Allison, 1983: *Carbon in live vegetation of major world ecosystems*. U. S. Department of Energy, DOE/NBB-0037, No. TR004, U. S. Department of Energy, Washington, DC, 152 pp.
- Pielke R. A., M. E. Nicholls, T. A. Nygaard, and X. Zeng, 1994: Unresolved issues in numerical modeling of geophysical flows. To be published in a special publication of the Canadian Meteorological and Oceanographic Society. (Invited)

- Sellers, P. J., J. A. Berry, G. J. Collatz, C. B. Field, and F. G. Hall, 1992: Canopy reflectance, photosynthesis, and transpiration. III. A reanalysis using improved leaf models and a new canopy integration scheme. *Remote Sens. Environ.*, **42**, 187 – 216.
- Seth, A., F. Giorgi, and R. E. Dickinson, 1994: Simulating fluxes from heterogeneous land surfaces: Explicit subgrid method employing the biosphere atmosphere transfer scheme (BATS). *J. Geophys. Res.*, **99**, 18,651 – 18,667.
- Shuttleworth, W. J., and R. E. Dickinson, 1989: Comments on "Modeling tropical deforestation: A study of GCM land-surface parameterizations" by R. E. Dickinson and A. Henderson-Sellers. *Quart. J. Roy. Meteor. Soc.*, **115**, 1177 – 1179.
- Skole, D., and C. Tucker, 1993: Tropical deforestation and habitat fragmentation in the Amazon: Satellite data from 1979 to 1988. *Nature*, **260**, 1905 – 1910.
- Slingo, A., 1989: A GCM parameterization for the shortwave radiative properties of water clouds. *J. Atmos. Sci.*, **46**, 1419 – 1427.
- Whitlock, C. H., T. P. Charlock, W. F. Staylor, R. T. Pinker, I. Laszlo, R. C. DiPasquale, and N. A. Ritchey, 1993: *WCRP Surface Radiation Budget Shortwave Data Product Description Version 1.1*. NASA Technical Memorandum 107747, National Aeronautics and Space Administration, Langley Research Center, Hampton, VA.
- Williamson, G. S., 1993: *CCM2 Datasets and Circulation Statistics* NCAR Tech. Note, NCAR/TN-391+STR, National Center for Atmospheric Research, Boulder, CO, 85 pp.
- Williamson, D. L., and P. J. Rasch, 1994: Water vapor transport in the NCAR CCM2. *Tellus*, **46A**, 34 – 51.