Single-Column Modeling, General Circulation Model Parameterizations, and Atmospheric Radiation Measurement Data

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Introduction

We have developed a single-column model (SCM) to validate general circulation model (GCM) cloud-radiation parameterizations against Atmospheric Radiation Measurement (ARM) observational data. The SCM is a computationally efficient, one-dimensional representation of the atmospheric column overlying a single GCM grid cell. The SCM is integrated in time from observed initial states and is constrained with observational estimates of horizontal flux convergences. The surface latent and sensible heat fluxes were specified from ARM energy balance Bowen ratio (EBBR) observations. The model output is a complete atmospheric heat and water budget, including temperature and moisture profiles, clouds and their radiative properties, diabatic heating terms, surface energy balance components, and hydrologic cycle elements, all specified as functions of time.

In this paper, we examine model results found using forcing derived from two techniques. Relaxation techniques used to keep the model temperature and humidity profiles close to observations are discussed. The SCM is then used to evaluate how model cloud-radiation results respond to different cloud parameterizations, both with and without prognostic cloud liquid water. Finally, the effects of varying the SCM vertical resolution are analyzed with respect to the accuracy of model cloud heights.

Forcing Data

Objective Analysis Products

The time-dependent advection of heat, water, and momentum (i.e., forcing data) are specified from ARM observations taken during intensive observation periods (IOPs) at the ARM Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site. Forcing data from six IOPs have been used to operate the SCM and are produced from soundings of T, q, u, and v using objective analysis techniques. Unfortunately, we often found large differences between model temperature and humidity, and observations. Temperature errors at times exceed 20 K, while model humidities differed from observations by up to a factor of 2. These large errors have also been reported by other modeling groups, indicating there may be problems with the forcing data.

Constrained Variational Forcing Data

Prof. Minghua Zhang at State University of New York (SUNY) Stonybrook has produced a forcing data set for the Fall 1994 IOP using a constrained variational scheme. In addition to the objective analysis techniques used by the first data set, observed heat and moisture fluxes at the surface and the top of the atmosphere are used to constrain the data to conserve the column-integrated mass, moisture, static energy, and momentum (Zhang and Lin 1997).

We have tested the constrained variational forcing data in our SCM. The SCM temperature errors are reduced by more than half. Errors in model humidity are also reduced, but the reduction is not as large as for temperature.

Relaxation Techniques

Simple Relaxation of T(z) and q(z)

To prevent large model errors from developing, the SCM temperature and humidity profiles can be relaxed towards observed values using a specified relaxation time scale. When this "simple" relaxation is included with a time scale of 24 hours, the model temperature and humidity errors are drastically reduced. Temperature errors are typically less than 5° C, and model humidities are usually within 25% of the observed values.

The SCM was run using the forcing data from the six IOPs and with a simple 24-hour relaxation of model T and q to observed values. The model precipitation results from each of these six runs are shown Figure 1. The SCM precipitation compares very well with surface measurements from the Oklahoma Mesonet in five of the six IOPs.

Analysis of the temporal mean SCM temperature correction for each of the six IOPs tested (Figure 2) reveals some interesting patterns. Namely, below about 800 mb, the SCM produces temperatures higher than observed in all six IOPs. Between 800 and 300 mb, there seems to be no trend, while above 300 mb, the SCM again produces temperatures that were too high compared with observations. These areas where the SCM is consistently producing excessively warm temperatures may indicate either a deficiency in the model physics or problems in the production of the forcing terms. We suggest that an intermodel comparison between the SCM groups be conducted to help determine the source of these errors.

Relaxation Forcing

A new relaxation procedure (relaxation forcing) has recently been proposed. In this technique, the relaxation is applied in the specification of the horizontal advection terms. The horizontal advection ($V \bullet \nabla T$ and $V \bullet \nabla q$) has typically been calculated as a centered difference across the column using observed values of T and q along the perimeter of the array. In relaxation forcing, upstream differencing is used to specify ∇T and ∇q. The upstream value of T or q is specified from observations, while the value of T or q at the column midpoint is obtained from the model.

Preliminary SCM runs using relaxation forcing produce temperature and humidities that are very close to observed values. The horizontal advection of temperature and humidity computed using the relaxation forcing were compared with these same fields calculated solely from observations (not shown). The overall pattern is similar, but there are important differences between the two plots that are responsible for the much improved model performance.

The model precipitation from runs using relaxation forcing is consistently below observed values. However, precipitation from model runs using simple 24-hour relaxation compares very well with observations (see Figure 1). The relaxation forcing technique may constrain the SCM too closely to observations, which could inhibit feedbacks and instabilities from developing in the model atmosphere, thereby affecting the convective precipitation. Further work is needed to determine if this is true.

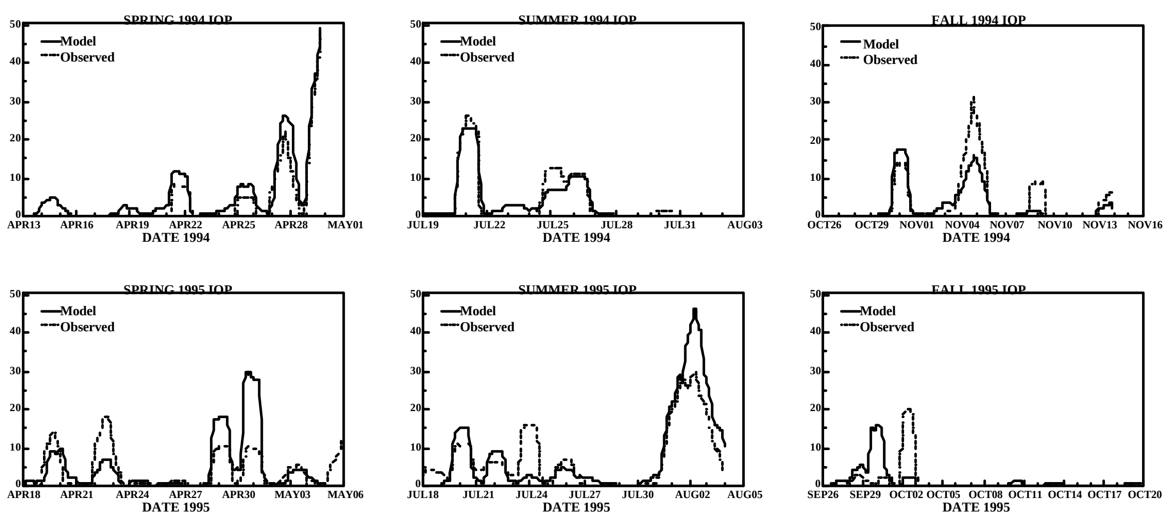

Figure 1. Model Precipitation Results from Six Intensive Observation Periods.

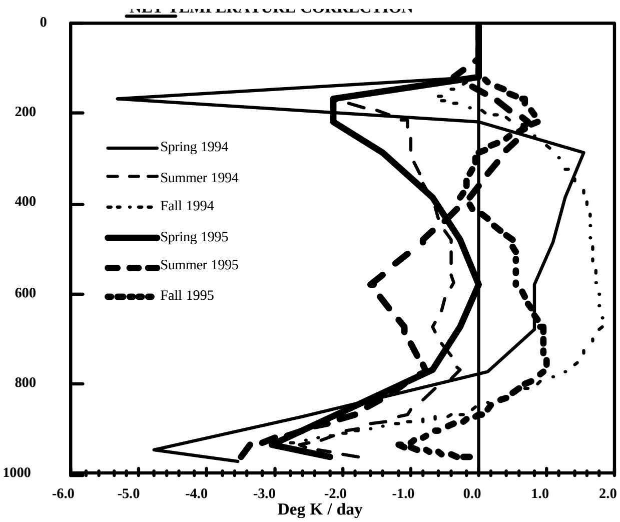

Figure 2. Analysis of Temporal Mean SCM Temperature Correction for Six IOPs.

Table 1. Model Configurations Tested.

Model	Cloud Liquid Water	Cloud Optical Thickness	Effective Droplet Radius
CCM2	None	Specified	Not Applicable
CW	Explicit	Specified	Not Applicable
CWRF	Explicit	Calculated	Fixed (10 μm)
CWRV	Explicit	Calculated	Varying (warm clouds)
CWRI	Explicit	Calculated	Varying (all clouds)

CCM2	Community climate model
CW	Interactive cloud water scheme; no radiative coupling with cloud water
CWRF	Interactive cloud water; interactive cloud radiative properties; varying effective droplet radius for water cloud only
CWRW	Interactive cloud water; interactive cloud radiative properties; varying effective droplet radius for warm cloud only
CWRI	Interactive cloud water; interactive cloud radiative properties; varying effective droplet radius including ice cloud

Validation of Cloud Schemes

The encouraging SCM precipitation results shown in Figure 1 suggest that model heat and moisture budgets are realistically balanced when simple 24-hour relaxation is applied. This allowed us to begin a preliminary investigation of whether the inclusion of cloud liquid water as a prognostic variable improves the model cloud-radiative results when compared with ARM measurements. We tested five different model configurations (see Table 1) which differed only in the specification of cloud liquid water, cloud optical thickness, and effective droplet radius.

The SCM cloud fraction, downwelling shortwave radiation, and outgoing longwave radiation were averaged over the length of each model run and then compared with the corresponding observed means.

We present the results from the Spring 1994 and Fall 1994 IOP in Figures 3 and 4, respectively. These results show that total cloud fraction, downwelling surface shortwave, and outgoing longwave are much better estimated (compared with surface and satellite measurements) using model configurations that include cloud liquid water as a prognostic variable.

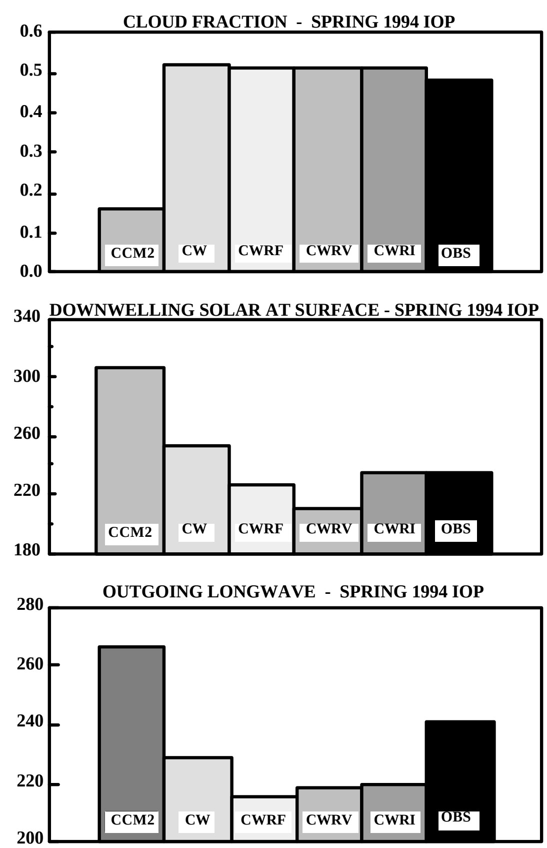

Figure 3. SCM Cloud-Radiative Results from Spring 1994 IOP.

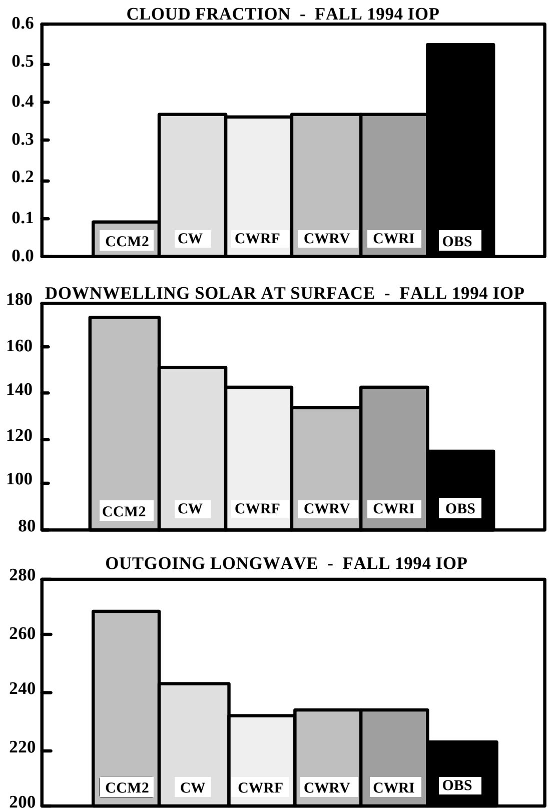

Figure 4. SCM Cloud-Radiative Results from Fall 1994 IOP.

Effects of SCM Vertical Resolution

Figure 5 shows the total cloud fraction, low cloud fraction, high cloud fraction, and downwelling solar from the CCM2 and CWRF model runs during the Spring 1994 IOP. While the CWRF model configuration produced total cloud amount close to observations, the SCM underestimates the amount of low clouds (surface to 700 mb) and overestimates the amount of high clouds (above 400 mb). The observed low cloud amount reaches a maximum on April 22 and is concurrent with a reduction in the observed surface downwelling solar radiation. However, the observed reduction in downwelling solar on April 22 is relatively modest, suggesting that the low clouds may be optically and geometrically thin.

Rerunning the CWRF model configuration with a much finer vertical resolution (53 layers vs. 16 layers) resulted in model cloud fields closer to the satellite estimates (Figure 6). The model downwelling solar from the high-resolution run is also closer to surface observations. These results indicate that the forcing data should be supplied on a vertical grid fine enough to support these "high" resolution SCM runs.

Conclusions

- Constrained variational forcing data products reduce model temperature and humidity errors. An intermodel comparison between the SCM groups would help separate errors that are due to model physics and errors that are due to inaccuracies in the forcing data.

- The preliminary SCM results obtained using relaxation forcing are encouraging. Additional study is needed to ensure that this relaxation method does not "over-constrain" the SCM, inhibiting convection.

- Inclusion of cloud liquid water as a prognostic variable improves the realism of model cloud and radiative results.

- SCM experiments indicate that it may be important to maintain high vertical resolution (~10-20 mb) for accurate cloud modeling.

Publications

Recent publications from this project are listed below.

Byrne, R. N., R. C. J. Somerville, and B. Subasilar, 1996: Broken-cloud enhancement of solar radiation absorption. *J. Atmos. Sci.*, **53**, 878-886.

Lee, W.-H., S. F. Iacobellis, and R. C. J. Somerville, 1997: Cloud-radiation forcings and feedbacks: General circulation model tests and observational validation. *J. Clim.*, in press.

Lee, W.-H., and R. C. J. Somerville, 1996: Effects of alternative cloud radiation parameterizations in a general circulation model. *Ann. Geophyci*, **14**, 107-114.

Randall, D. A., K.-M. Xu, R. C. J. Somerville, and S. Iacobellis, 1996: Single-column models and cloud ensemble models as links between observations and climate models. *J. Clim.*, **9**, 1683-1697.

Somerville, R. C. J., S. F. Iacobellis, and W.-H. Lee, 1996: Effects of cloud-radiation schemes on climate model results. *World Resource Review*, **8**, 321-333.

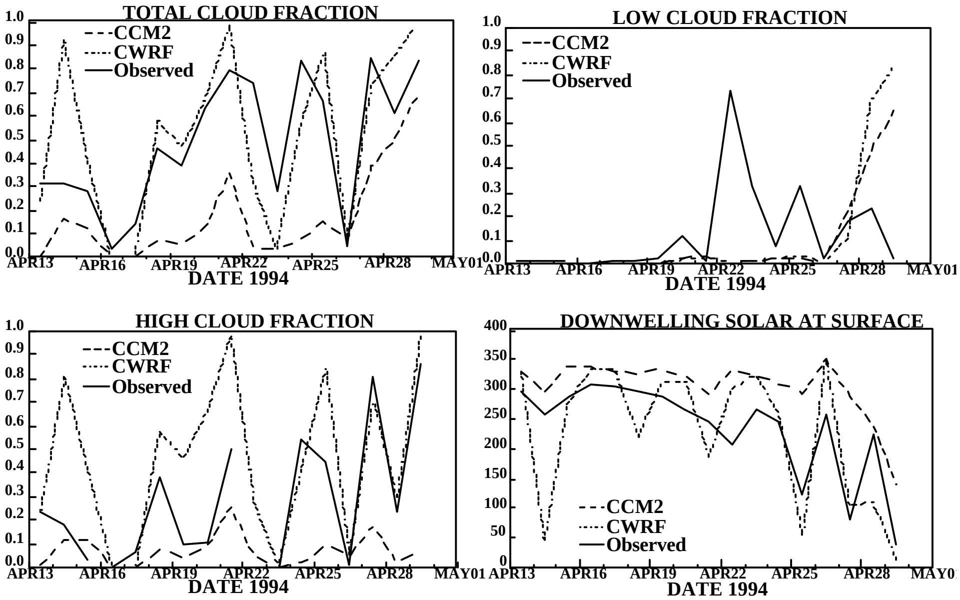

Figure 5. Total Cloud Fraction, Low and High Cloud Fractions, and Downwelling Solar from the CCM2 and CWRF Model Runs During the Spring 1994 IOP.

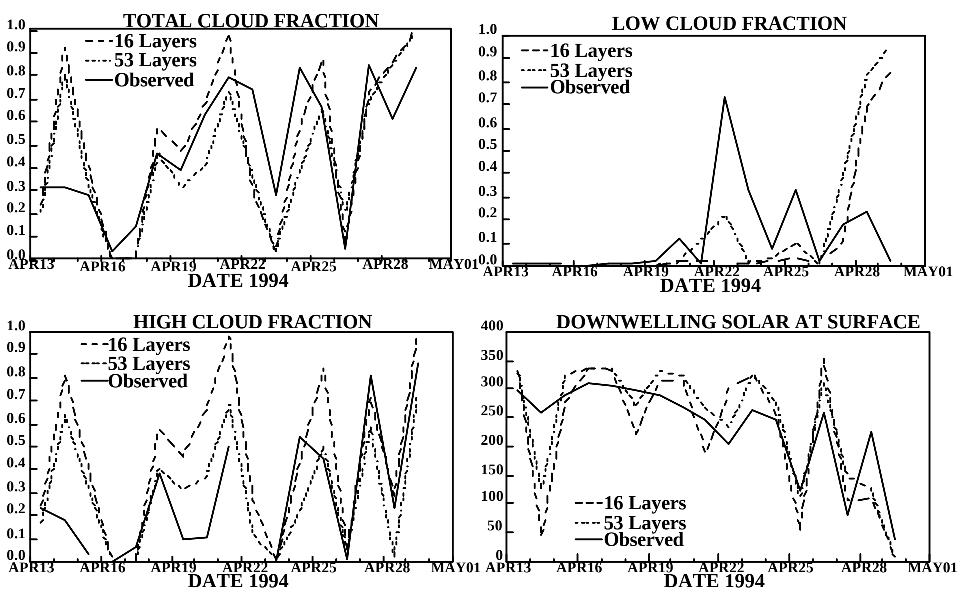

Figure 6. CWRF Model Configuration Rerun with a 53-Layer Vertical Resolution.

References

Zhang, M. H., and J. L. Lin, 1997: Constrained variational analysis of sounding data based on column-integrated budgets of mass, heat, moisture, and momentum: Approach and application to ARM measurements. *J. Atmos. Sci*., **54**, 1503-1524.