SCM Sensitivity to Microphysics, Radiation, and Convection Algorithms

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Introduction

In this paper, we briefly describe several ongoing sensitivity studies using our single-column model (SCM) and Atmospheric Radiation Measurement (ARM) observations. These studies investigate the sensitivity of model results to 1) the parameterization of cumulus convection, 2) the parameterization of longwave radiation, and 3) the initial profiles of temperature and humidity.

Our SCM results indicate:

- SCM with the Relaxed Arakawa-Schubert (RAS) convection scheme produces a significantly more realistic vertical distribution of cloud amount compared to model results using the Community Climate Model, Version 3 (CCM3) convection package.

- Surface and top of the atmosphere (TOA) mean radiative fluxes may vary up to 13 W/m^{-2} depending on the longwave radiation parameterization. Additionally, the two parameterizations tested show distinct differences in longwave cooling rates depending on the location in the atmosphere.

- Our SCM is sensitive to mild perturbations of the initial temperature and humidity profiles. Our results indicate that ensembles of up to 20 model runs may be necessary for a reliable representation of SCM results.

Model

The SCM is a diagnostic model resembling a single vertical column of a three-dimensional general circulation model. The one-dimensional SCM is forced with horizontal advection terms derived from either observations or numerical weather prediction analyses. In this paper, the horizontal advective terms were derived from observations taken during the Summer 1997 and Winter 1999 Intensive Operational Periods (IOPs) at the ARM Southern Great Plains (SGP) site. Unless otherwise noted, the SCM contains 53 vertical layers and a time step of 7.5 minutes. The control version of the SCM includes the shortwave radiation scheme of Fouquart and Bonnel (1980), the rapid radiative transfer model (RRTM) longwave radiation parameterization of Mlawer et al. (1997), the cumulus convection scheme from CCM3 (Zhang and McFarlane 1995) and the prognostic cloud scheme of Tiedtke (1993). Cloud optical properties are calculated as a function of cloud water/ice path and cloud particle radius using Slingo (1989) for liquid water clouds and Ebert and Curry (1992) for ice clouds. The effective cloud particle radius is parameterized following Bower et al. (1994) for liquid water and Wyser (1998) for ice.

Sensitivity of Clouds and Radiative Fluxes to Convection Scheme

In these experiments, the SCM was forced with observational data from the Summer 1997 IOP (June 19 through July 17) at the ARM SGP site. The SCM was operated in a “relaxation mode,” where the temperature and humidity profiles were relaxed to the observed profiles using a specified time constant, $\tau_a=D/2(u^2+v^2)^{0.5}$, where D is the distance across the SCM domain (370 km), and u and v are the observed horizontal wind components.

The time evolution of cloud cover, precipitation, downwelling surface shortwave radiation (DWSR), and outgoing longwave radiation (OLR) from the SCM control run compare fairly well with ARM observations. The SCM results capture much of the temporal variability displayed by the observations; however, there are some model biases, particularly an overestimation of the mean cloud cover (+23%) and DWSR (+33 W/m^{-2}) and an underestimation of the OLR (-23 W/m^{-2}).

Millimeter cloud radar (MMCR) data from the SGP Central Facility was used to obtain an approximate mean vertical cloud frequency profile during the Summer 1997 IOP. This vertical cloud frequency profile was produced by assuming a cloud was present if the radar reflectivity was above certain critical values. A value of -30 dB was chosen for altitudes above 4 km and -20 dB for altitudes between 1 km and 3 km. Between 3 km and 4 km the critical reflectivity varied linearly from -20 dB to -30 dB, and we assumed no clouds below 1 km. It should be noted that these values are very subjective.

The SCM control version overestimates the amount of high cloud cover and underestimates the amount of low cloud cover compared to the MMCR-derived data and is consistent with the biases in the DWSR and OLR discussed above.

Two experiment runs were performed. The first experiment run employed the RAS convection scheme in place of the Zhang-McFarlane parameterization used in the control run. The second experiment run used the CCM3 diagnostic cloud parameterization instead of the prognostic Tiedtke cloud parameterization used in the control run. The mean cloud frequency profile results from the control run and these two experiment runs, together with the MMCR-derived data are shown in Figure 1. Clearly, the best comparison to the MMCR mean cloud frequency profile is produced by the combination of the RAS convection scheme and the Tiedtke cloud parameterization. Additionally, the mean and correlation of cloud fraction, precipitation, DWSR, and OLR compared to observations are significantly improved when the RAS convection scheme is included.

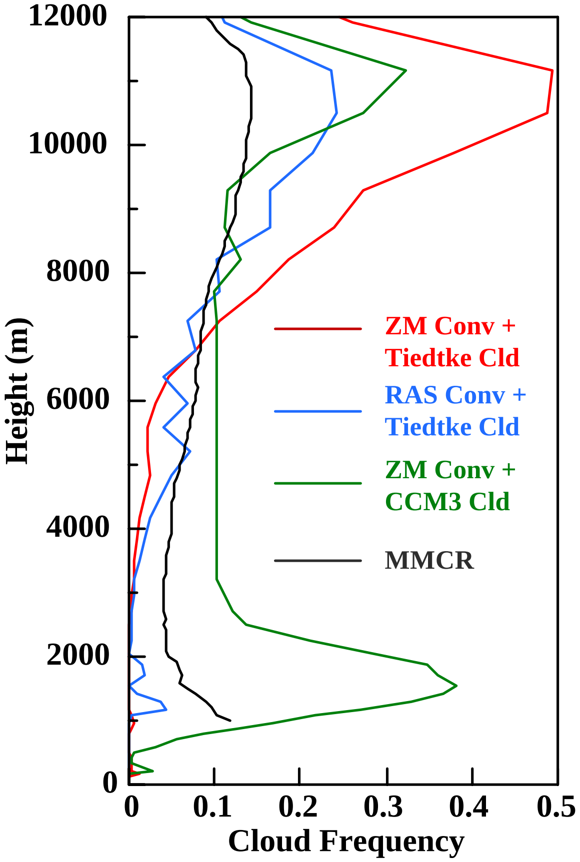

Figure 1. Mean vertical cloud frequency profiles from the SCM and MMCR-derived measurements during the Summer 1997 IOP.

Sensitivity to Longwave Radiation Parameterization

In this section, we investigate the sensitivity of model results to the specification of the longwave radiation parameterization. Two longwave radiation schemes are examined: 1) Morcrette (1990) (MOR90); and 2) Mlawer et al (1997) (RRTM). These sensitivities are calculated using four model configurations that differ with respect to the vertical resolution, cloud overlap assumption, and the parameterization of the longwave cloud emissivity. SCM runs were performed using ARM forcing data from the Summer 1997 IOP.

The longwave cooling rate differences (RRTM-MOR90) are very similar for each model configuration. The main difference between the two parameterizations is that RRTM tends to have smaller cooling rates in the lower atmosphere (surface - 650 mb) and larger cooling rates in the upper troposphere (650 - 150 mb) compared to MOR90. This is evident for both all-sky and clear-sky conditions. The differences between the mean longwave cooling rates from each parameterization are on the order of 0.5°K day^{-1}.

In all four configurations, RRTM produces smaller values of OLR and larger values of downwelling surface longwave flux relative to MOR90. The magnitude of these differences (~5 W/m^{-2}) does not appear to vary significantly with respect to the cloud overlap assumption or vertical resolution. The sensitivity of the mean OLR to the parameterization of the infrared cloud emissivity is somewhat higher (~13 W/m^{-2}).

Sensitivity to Initial Conditions

A study by Hack and Pedretti (2000) found that their SCM was sensitive to perturbations in the initial profiles of temperature (T) and humidity (q). Since nearly every SCM is comprised of a unique combination of physical parameterizations, it is not known if this sensitivity will be found in all SCMs. The sensitivity of our SCM was tested using ARM data collected during the Summer 1997 and Winter 1999 IOPs. A total of 50 model runs were performed for each IOP. Each model run utilized a slightly different set of initial conditions by including a random perturbation of ±1.0°C (T) and ±5% (q) in each model layer. No relaxation was used in these model runs.

The standard deviations of T and q were calculated to assess the sensitivity of the SCM. To facilitate the graphical presentation, a normalized humidity was used, where $q_{norm}(z) = q(z)/<q(z)>$. The temperature and humidity (normalized) standard deviations (σ_T and σ_q) are plotted in Figure 2 as a function of pressure and time.

The values of σ_T and σ_q are generally larger during the Summer 1997 case; however, the values of σ_q during the Winter 1999 case do not appear to be insignificant. During the Summer 1997 IOP, the maximum values of σ_T and σ_q occur in the upper troposphere, while in the Winter 1999 IOP, the maximum values are in the lower troposphere near 650 mb. The larger values of σ_T and σ_q in the summer case may be due to the presence of convection, which may act to increase the sensitivity of the SCM to the initial conditions. Ensemble runs with the RAS convection scheme yielded similar results (not shown). Thus, it appears that the sensitivity is not due to a particular parameterization of convection.

Since SCMs are often used for the testing and development of cloud and radiation parameterizations, the sensitivity of cloud amount and radiative fluxes to the initial conditions is also very important. Figure 3 shows the root mean square (rms) difference of cloud fraction, downwelling surface shortwave radiation (DWSR), and OLR for both the Summer 1997 and Winter 1999 IOPs. During the Summer 1997 IOP, the DWSR rms reach values as high as 100 W/m^{-2} and are well correlated with the maximum values of cloud fraction rms. These rms values represent large uncertainties between individual runs differing only in a slight modification of the initial conditions.

These results suggest that any parameterization testing/validation should be performed using an ensemble of SCM runs rather than a single run. Our results indicate that there is essentially no change in the ensemble means after 20 model runs. While these results are preliminary, they suggest that any testing or validating of cloud-radiation parameterizations should be evaluated with ensembles of at least 20 runs.

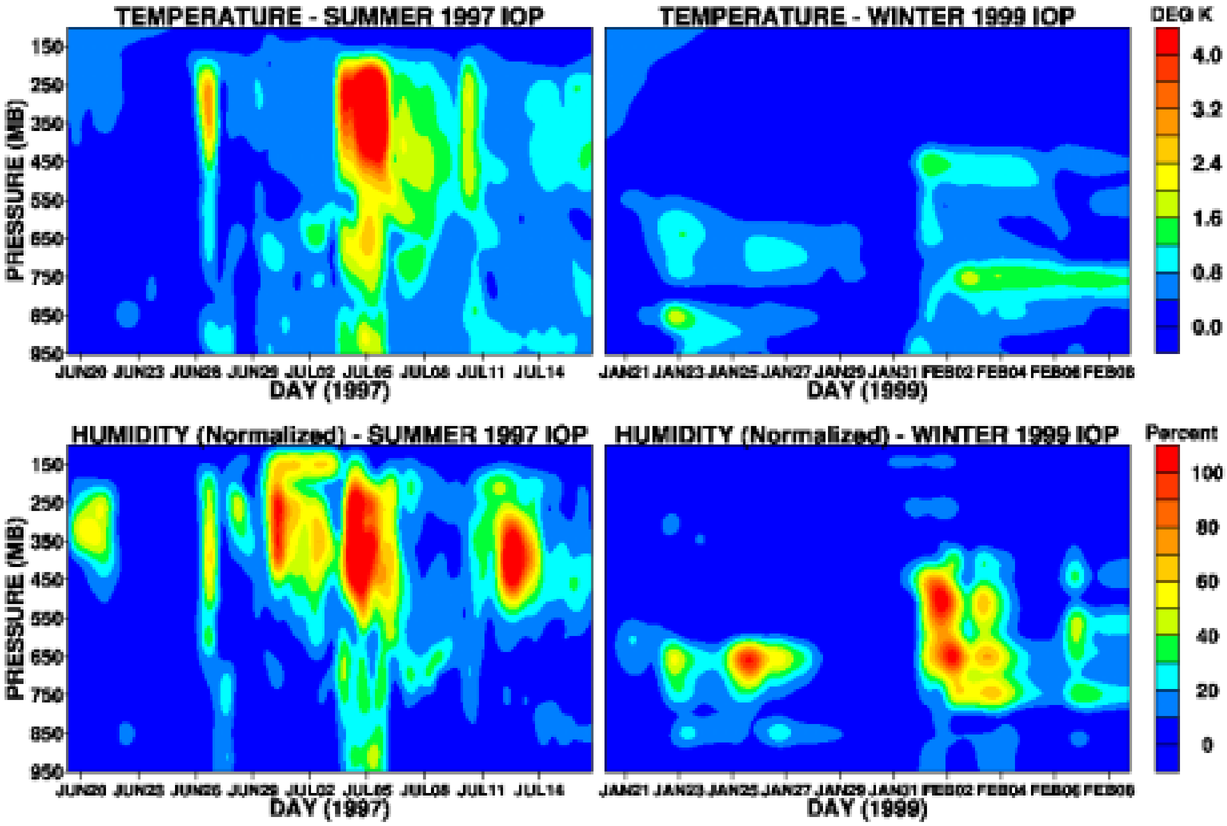

Figure 2. The standard deviation of temperature and humidity (normalized) from the 50 runs performed using the Summer 1997 and Winter 1999 data sets.

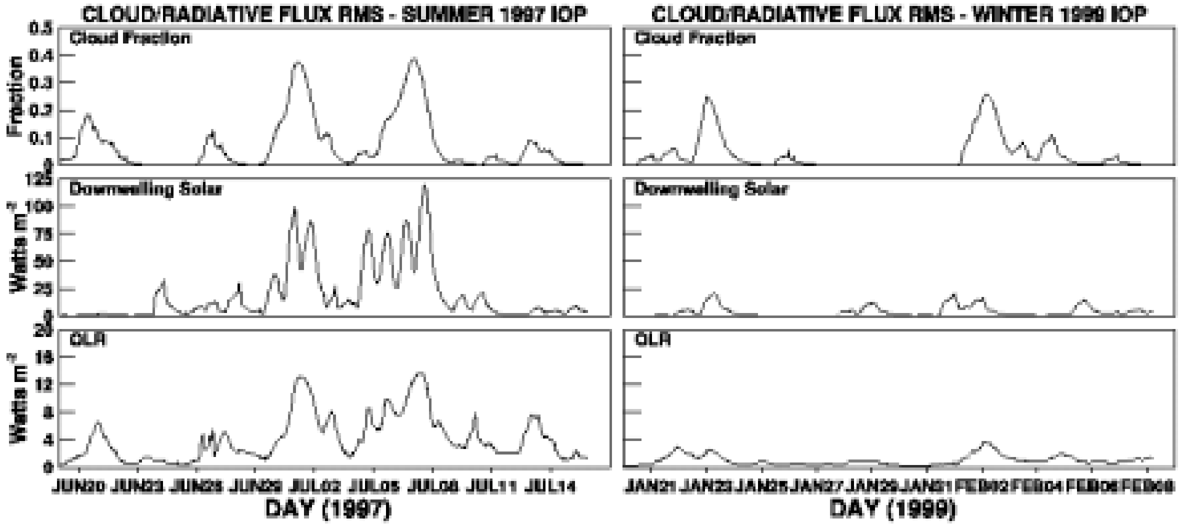

Figure 3. The rms differences of cloud fraction, downwelling surface shortwave radiation, and OLR from the 50 runs performed using the Summer 1997 and Winter 1999 data sets.

Conclusions

- SCM control run reproduces successfully most of the observed temporal variability found in radiative fluxes, precipitation, and total cloud cover during the Summer 1997 IOP.

- However, SCM control run with CCM3 convection underestimates the low-cloud amount and overestimates the high-cloud amount during the Summer 1997 IOP.

- SCM with the RAS convection scheme produces a significantly more realistic vertical distribution of cloud amount that leads to improved correlation and lower biases of modeled radiative fluxes when compared to ARM observations.

- Modeled mean surface and TOA longwave fluxes during the Summer 1997 IOP were somewhat sensitive (~10 W/m^{-2}) to the specification of the longwave radiation scheme. Within the atmospheric column there were variations in the mean longwave cooling rate of up to 0.5°K day^{-1}.

- SCM results are sensitive to perturbations in the initial profiles of T and q representative of typical instrument and measurement errors. The standard deviation of downwelling surface solar radiation at times approaches 80 W/m^{-2} to 100 W/m^{-2}.

- A preliminary analysis indicates that ensembles of up 20 model runs may be necessary for a reliable representation of SCM results.

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