The Sensitivity of Radiative Fluxes to Parameterized Cloud Microphysics

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Introduction

We have used a single-column model (SCM) to examine the sensitivity of fundamental quantities such as atmospheric radiative heating rates and surface and top of atmosphere (TOA) radiative fluxes to various parameterizations of clouds and cloud microphysics. When an SCM, which consists of one isolated column of a global atmospheric model, is forced with observational estimates of horizontal advection terms, the parameterizations within the SCM produce time-dependent fields which can be compared directly with measurements. In the case of cloud microphysical schemes, these fields include cloud altitude, cloud amount, liquid and ice content, particle size spectra, and radiative fluxes at the surface and the TOA. Comparisons with Atmospheric Radiation Measurement (ARM) data demonstrate conclusively that prognostic cloud algorithms with detailed microphysics are far more realistic than simpler diagnostic approaches. Long-term comparisons of quantities strongly modulated by clouds, such as monthly mean downwelling surface shortwave (SW) radiation, clearly demonstrate the superiority of parameterizations based on comprehensive treatments of cloud microphysics and radiative interactions. These results also demonstrate the critical need for more and better in situ observations of cloud microphysical variables.

The single-column model was run at the ARM Southern Great Plains (SGP), Tropical Western Pacific (TWP), and North Slope of Alaska (NSA) sites using forcing data derived from operational numerical weather prediction. Our results indicate that atmospheric radiative fluxes are sensitive to the scheme used to specify the ice particle effective radius (r_e)by up to 30 Wm^{-2} on a daily time scale and up to 5 W m^{-2} on a seasonal time scale. We also found that the inclusion of ice particle fallout can have a significant effect on the amount and location of high cirrus clouds. On a seasonal time scale, atmospheric fluxes were sensitive to the inclusion of ice particle fallout, typically by about 8 W m^{-2}. An unexpected finding was that the variance of the modeled ice particle r_e at a given level is considerably smaller than that suggested by ARM cloud radar measurements. Our results indicate that this theoretical underestimate of the ice particle r_e variance can have significant effects on modeled radiative fluxes.

Model Description

The necessary forcing data for the SCM was obtained from a version of the National Center for Experimental Predictions (NCEP) global spectral model (GSM) (Roads et al. 1999). The forcing data was produced using the 0 - 24 hour fields from each daily forecast made by the GSM. These individual 24-hour forecasts were concatenated to produce a continuous forcing dataset that extends back to May 2000. The SCM was run at the SGP, TWP, and NSA sites using this forcing data. Additionally, a 3-month subset (JJA 2000) of this forcing data was used to run the SCM at the SGP site to examine model sensitivities to the specification of cloud microphysics. In addition to the horizontal advective fluxes of heat, moisture and momentum, the surface temperature and surface heat fluxes were also specified from the GSM forecast products.

The SCM version employed for this study utilizes 53 layers (Iacobellis and Somerville 2000) and thus, has a relatively high vertical resolution (Lane et al. 2000). The horizontal extent represents a single column of a GCM centered on the each of the ARM sites. For the 3-month (JJA 2000) run, the SCM incorporates relaxation advection (Randall and Cripe 1999) to keep the modeled temperatures and humidities from drifting towards unrealistic values.

Results

Long-Term Analysis of SCM Control Version

The control SCM run (CONTROL) utilized a prognostic cloud parameterization (Tiedtke 1993) together with interactive cloud optical properties for both liquid (Slingo 1989) and ice (McFarquhar et al. 2002) clouds. The r_e is also calculated interactively using the schemes of Bower et al. (1994) for liquid droplets and McFarquhar (2001) for ice particles. Ice particle settling is included in the SCM with individual crystal fall speeds calculated from Mitchell (1996). Typical fall speeds range from 0.25 to 1.0 m sec^{-1}. Maximum cloud overlap has been assumed throughout this study.

Figure 1 shows the monthly mean downwelling surface SW radiation (DSSR) from the SCM, the GSM, and ARM surface observations at each of the three ARM sites. At all three sites, the SCM results generally compare very favorably with the ARM surface observations. An exception to this favorable comparison occurs during part of the record at the TWP site. Interestingly, the SCM results compare much better with the observations in most cases than do the results from the GSM. Analysis indicates that these flux differences are due to the cloud fields produced by each model. This version of the GSM utilizes diagnostic cloud-radiation parameterizations that appear to be generally inferior to the prognostic cloud scheme with interactive cloud radiative properties used in the SCM.

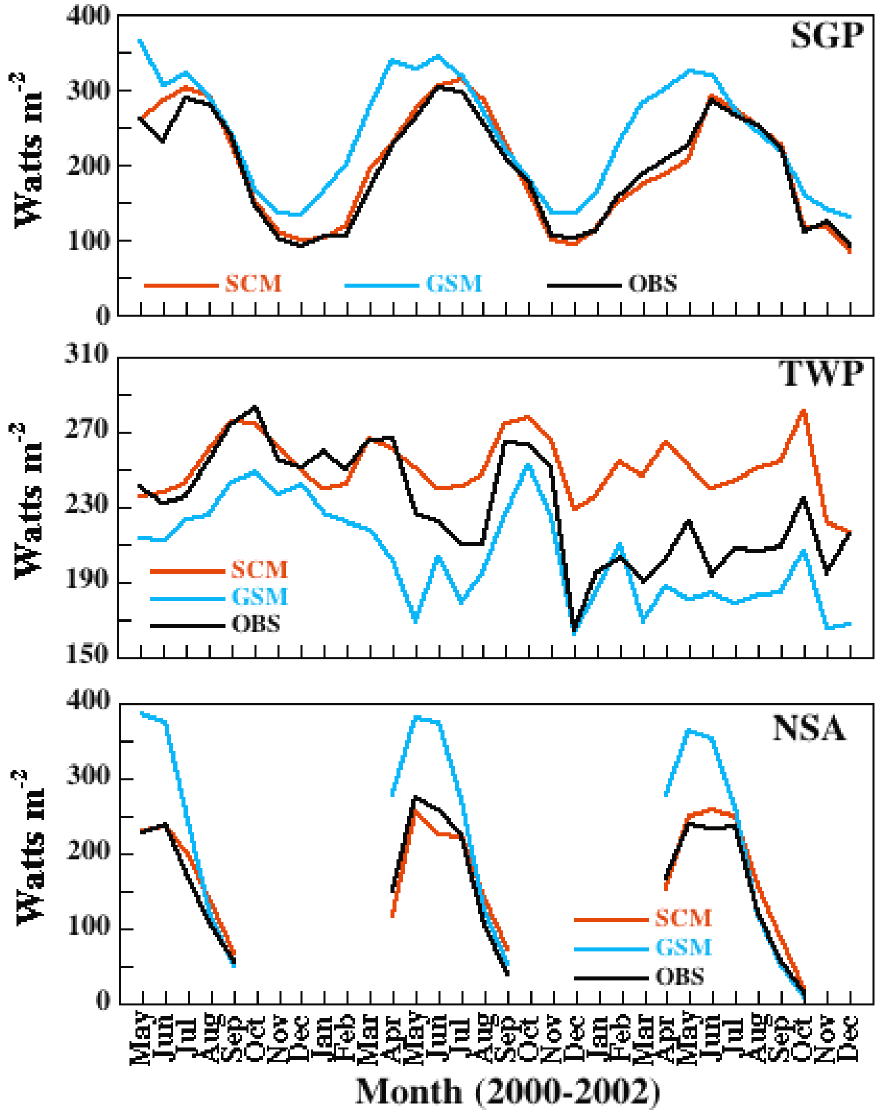

Figure 1. Monthly mean downwelling surface SW radiation from the SCM, GSM, and ARM observations at the SGP (top panel), TWP (middle panel), and NSA (bottom panel) for the period of May 2000 to December 2002.

3-Month Control Run at SGP Site

Most of the comparisons between model data and observations in this study are performed using averages over an entire 3-month model run. However, it is important to know whether the SCM produces a realistic evolution of model variables using the prescribed forcing dataset. The time series of downwelling surface SW radiation, TOA SW cloud forcing, outgoing longwave (LW) radiation (OLR), TOA LW cloud forcing, cloud fraction, cloud optical thickness, and precipitation from the SCM control run and from ARM and GOES satellite observations have all been compared. Overall, the model results appear to reproduce much of the observed temporal variability of these quantities. The model is notably more successful at capturing the observed trends on longer timescales of 3 to 4 weeks than at shorter timescales of a few days to a week. For cloud fraction, the differences between the SCM values and those of either the GOES or MMCR data are comparable to the difference between the two observational estimates.

Effect of Ice Particle Fallout

An experiment model run was performed in which the ice particle fallout mechanism of Mitchell (1996) was removed. As one would expect, the removal of ice particle fallout increased the amount of high clouds. Without the removal of ice particles from these layers, the clouds that formed existed for longer times.

The ice crystal fall speed calculation (Mitchell 1996) used in the control run assumed a planar-polycrystal ice crystal habit. Additional runs were performed that included ice particle fallout using hexagonal columns, bullet rosettes, and spheres as the assumed crystal habit. Not surprisingly, the mean cloud amount decreased as the mean ice crystal fall speed increased. The runs which included ice particle fallout produced higher values of ice water path (IWP) than model runs without fallout. One might have expected to see a decrease in the IWP when ice crystal fallout is activated. However, we found that feedbacks within the SCM act to increase the convective mass flux and ice water detrainment, and these processes together more than offset any loss of ice water due to settling. It is not clear whether this result is dependent on the particular SCM used in this study.

Interestingly, the changes in cloud amount in the SCM did not result in any significant changes in mean downwelling surface SW radiation (DSSR). In fact, values between runs differed by <1 W m^{-2}. There are two factors to explain the non-varying character of DSSR. First, the larger IWP resulted in higher cloud optical thicknesses, which partly compensated for the reduced cloud amount. Second, another contributing factor is related to the diurnal pattern of increased cloud fraction in the run without ice fallout. The increase in the mean cloudiness from eliminating ice fallout occurs mostly in the late evening and early morning hours when there is little or no solar radiation. In both runs, convection is dominant in the late afternoon with detraining cloud water/ice forming cirrus anvil clouds that reach a peak magnitude around 1600 local time. Soon after this time, the cloud amount begins to decrease in both runs. However, the cloud amount decreases faster in the control run, because of ice particle fallout.

The modeled outgoing longwave radiation (OLR) is more sensitive to the inclusion of ice particle fallout and the assumption of ice crystal habit than is the DSSR. This increased sensitivity arises partly because, unlike the case of DSSR, the diurnal pattern of cloudiness changes noted above will have little effect on the OLR. Furthermore, the mean OLR increased as the mean ice crystal fall speed increased. Most of this change is due to the reduction in cloud amount as ice particle fall speed increases. However, part of the change is due to the decrease in the mean cloud height as ice particle fall speeds increase. A lower mean cloud height results in a warmer effective cloud temperature, thereby increasing the emission of LW radiation by the clouds. Using the mean cloud height, lapse rate and cloud amount from the control run, we can estimate that the reduction in cloud height (relative to the run without ice fallout) increased the OLR about 2 W m^{-2} or about 22% of the total increase.

Effect of Ice Particle Radius Parameterization

The parameterization of the ice particle r_e used in the control run was replaced with alternate schemes in three additional model runs, which we denote by ICEREWY (Wyser 1998), ICERESU (Suzuki et al. 1993) and ICEMITC (Mitchell et al. 1996; Ivanova et al. 2001). The fractional cloud amounts produced by these three model runs did not vary significantly from CONTROL. However, these runs produced different mean vertical profiles of ice particle r_e and consequently different ice cloud optical properties. We compared the mean vertical profiles of ice particle r_e from these model runs and from the observationally-based ice cloud properties dataset of Mace et al. (1998, hereafter M98). The M98 dataset uses an algorithm that combines MMCR cloud reflectivity data with co-located infrared radiance data. The technique described in McFarquhar et al. (2003) was used to convert the various definitions of effective particle radius encountered in this study to Fu's (1996) definition of R_{eff} for comparison purposes. The mean R_{eff} from all four models runs decreases with increasing height as does the observational data. While the profiles from CONTROL and ICEMITC are similar, there are still notable differences between these two profiles and those from ICEREWY and ICERESU, and it is difficult to determine which compares most favorably with the observational data. The wide range of mean R_{eff} profiles is not entirely unexpected. Each of the R_{eff} schemes is based upon a different set of in situ measurements with varying assumptions about the ice crystal habits.

Some of the SCM runs in this study use schemes that parameterize R_{eff} as a function of temperature and ice water content. Obviously, these schemes cannot be expected to produce a realistic value of R_{eff} if the model ice water content values are unrealistic. The mean vertical profiles of temperature and ice water content from each of the four runs are in fact nearly identical. The modeled cloud ice water content compares reasonably well with the measured values in the middle troposphere below an altitude of approximately 9 km, but begins to underestimate the measured values significantly as one moves upward from 9 km toward the tropopause. As a result, errors in the SCM values of R_{eff} above 9 km may be due to the model underestimating the ice water content.

Nevertheless, some of this difference in IWC between our model results and observationally-based data may be due to errors in the predicted particle size distribution used by the algorithm of the M98 dataset. This algorithm is particularly insensitive to small particles, and in fact the small particle distribution is predicted based on the observed distribution of larger particles. This can lead to serious errors in the small particle distribution, as noted by the authors of the M98 study. If the M98 algorithm actually did underestimate the number of small particles, then a larger value of IWC would be predicted in order to produce a cloud emissivity to match the measured value. In addition, one would expect the number of small particles, and hence their relative influence on the cloud radiative properties, to increase as the altitude increases between 9 and about 15 km. This factor may help explain the differences between SCM and measured IWC above 9 km.

All four SCM runs underestimate R_{eff} above 9 km, which is what one would expect if low values of IWC are used. However, the Suzuki et al. (1993) parameterization calculates R_{eff} as a function of temperature only, suggesting that the discrepancies above 9 km may be due to more than simply low values of modeled IWC. Below 9 km, where the model produces reasonable estimates of ice water content, two of the four SCM runs, those with the Wyser (1998) and Suszuki et al. (1993) schemes, produced mean values of R_{eff} within one standard deviation of the observed data.

Hourly means values of model and measured data were examined in order to determine whether errors in the SCM IWC are responsible for the underestimates of R_{eff} noted above. In order to isolate those times when the SCM values of IWC and cloud temperature were in close agreement with measured values, the following criteria were used to select a subset of hourly means: (1) those hours when the SCM cloud fraction maximum occurred within the cloud base and cloud top limits indicated by the M98 data; and (2) hours when the SCM IWC was within 50% of the M98 value. Application of these criteria resulted in approximately 20-25 hourly means for each SCM experiment. Using this dataset, we found that even when the IWC and cloud temperature are close to the measured values, the SCM and the M98 values of R_{eff} still do not agree well. In other words, it does not appear that the differences between the SCM and M98 values of R_{eff} are due to erroneous values of model-calculated IWC. The R_{eff} parameterizations used in CONTROL (McFarquhar 2001) and ICEMITC (Ivanova et al. 2001) were both based on ice particle distributions determined from dedicated instrumentation to measure small ice particles. It is not surprising that these two experiments predict a larger contribution from small particles, as evidenced by the lower values of R_{eff}, than either ICEREWY (Wyser 1998) or ICERESU (Suzuki et al. 1993). These results are consistent with either the M98 data underestimating, or the McFarquhar (2001) and Ivanova et al. (2001) schemes overestimating, the contributions of small ice particles.

A feature of the Ivanova et al. (2001) scheme incorporated in the control version of the SCM is that one can specify the crystal habit and the distribution shape (monomodal vs. bimodal). The settings in the ICEMITC run specified planar polycrystals and a bimodal particle size distribution. Additional runs were performed using both hexagonal columns and a monomodal distribution. The best comparison to the M98 measurements is found with the Ivanova et al. (2001) scheme using hexagonal columns and a monomodal particle size distribution. However, this favorable comparison may be coincidental, if the M98 measurements underestimate the contribution from small particles, as is likely to occur if a bimodal distribution was encountered. Again, due to possible errors extrapolating the small particle distribution in the M98 measurements, it is difficult to say with any certainty that any one particular scheme compares best with observations.

The variability of R_{eff} at any given level, as measured by the standard deviation of this quantity, is notably underestimated by all four parameterizations examined. The radiative flux parameterizations, both LW and SW, are non-linear, so an underestimation of the variability of cloud microphysical properties such as R_{eff} could have important consequences on model calculated mean radiative fluxes. To help quantify the effect that the narrow range of model-generated R_{eff} values has on the modeled radiative fluxes, the control version of the SCM was rerun with a random ΔR_{eff} added to the model calculated value of R_{eff} (we call this model run EXP-WIDE). This was a conservative procedure such that the mean value of R_{eff} at each model level did not change from the control run. The width of the particle size distribution from EXP-WIDE more closely matches the distribution from the M98 dataset.

The results from model run EXP-WIDE indicate that the change in the width of the distribution of R_{eff} can alter the solar and LW radiative fluxes at both the surface and the TOA by up to 5 W m^{-2} relative to the control run. However, at the TOA level it appears that increases in the outgoing solar radiative flux are largely offset by decreases in the outgoing LW flux, resulting in little change in the net heat budget for the earth-atmosphere system. The wider distribution of R_{eff} in model run EXP-WIDE results in optically thicker ice clouds (on average), and so these clouds reflect more sunlight. The optically thicker ice clouds also have a higher mean emissivity compared to the control run, thus essentially increasing the effective radiative cloud height and thereby decreasing the outgoing LW radiation.

Further details of some aspects of both this study and other related work may be found in Iacobellis et al. (2003).

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