Sensitivity of Radiative Fluxes and Heating Rates to Cloud Microphysics

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Introduction

A single-column model (SCM) is used to examine the sensitivity of basic quantities such as atmospheric radiative heating rates and surface and top of atmosphere (TOA) radiative fluxes to various parameterizations of clouds and cloud microphysics. The SCM was run at the Atmospheric Radiation Measurement (ARM) Program's Southern Great Plains (SGP), Tropical Western Pacific (TWP), and North Slope of Alaska (NSA) sites using forcing data derived from forecast products. The forecast products were produced by a version of the U.S. National Center for Environmental Prediction's (NCEP) global spectral model (GSM). Several sensitivity experiments were performed at the SGP site during the periods of June 2000 to August 2000 and December 2000 to February 2001. Our results indicate that atmospheric radiative fluxes are sensitive to the scheme used to specify the ice particle effective radius (re) by up to 30 W m^{-2} on a daily time scale and up to 4 W m^{-2} on a seasonal time scale. We also found the inclusion of ice particle fallout can have an impact on the amount and location of high cirrus clouds. Unexpectedly, the variance of the modeled ice particle re at a given level is considerably smaller than that suggested by ARM cloud radar measurements. Our results indicate this theoretical underestimate of the ice particle re variance can have significant effects on modeled radiative fluxes of up to 25 W m^{-2} on the daily time scale and up to 5 W m^{-2} on the seasonal time scale.

Forcing Data for SCM

The forcing data for the SCM was produced using the 0- to 24-hour fields from each daily forecast made by the NCEP GSM. These forcing data fields are archived to allow long-term SCM runs currently extending back to May 2000. Besides the horizontal advective fluxes of heat, moisture, and momentum, the surface temperature and surface heat fluxes were also specified from the GSM forecast products.

SCM Control Version

The control version of the SCM used a prognostic cloud parameterization (Tiedtke 1993) with interactive cloud optical properties for liquid (Slingo 1989) and ice (McFarquhar 2002) clouds. The re is also calculated interactively using the schemes of Bower et al. (1994) for liquid droplets and McFarquhar (2001) for ice particles. The SCM uses 53 vertical layers and a timestep of 7.5 minutes. Relaxation advection (Randall and Cripe 1999) was used to keep the modeled temperatures and humidities from drifting towards unrealistic values. (See Table 1.)

Table 1. Characteristics of the various SCM experiments.

SCM RUN	CHARACTERISTICS
CONTROL	Prognostic Clouds (Tiedtke 1993) Ice Particle Sedimentation (Ivanova 2001) Ice Particle Radius (McFarquhar 2001) Ice Cloud Optical Properties (McFarquhar et al. 2002)
NOFALL	No Ice Particle Sedimentation
ICEREWY	Ice Particle Radius (Wyser 1998)
ICERESU	Ice Particle Radius (Suzuki et al. 1993)
ICEOPEC	Ice Cloud Optical Properties (Ebert and Curry 1992)
ICEMITC	Ice Particle Radius (Ivanova 2001) Ice Cloud Optical Properties (Mitchell 1996)

Evaluation of SCM Control Version: Long-Term Analysis

Figure 1 shows the monthly mean downwelling surface shortwave radiation (DSSR) from the SCM, GSM, and ARM surface observations at the three ARM sites between May 2000 and December 2001. At all three sites, the SCM results compare favorably with the ARM surface observations. Interestingly, the SCM results compare much better with the observations than the results from the three-dimensional GSM. Monthly mean values of outgoing longwave radiation (OLR) and cloud fraction from the SCM and GSM at the SGP site are shown in Figure 2 along with ARM surface and satellite observations. The results are consistent with those shown in Figure 1 at the SGP site. The GSM is systematically underestimating the cloud fraction hence, overestimating the value of OLR and DSSR. This version of the GSM uses diagnostic cloud-radiation parameterizations that appear to be inferior to the prognostic cloud scheme with interactive cloud radiative properties used in the SCM.

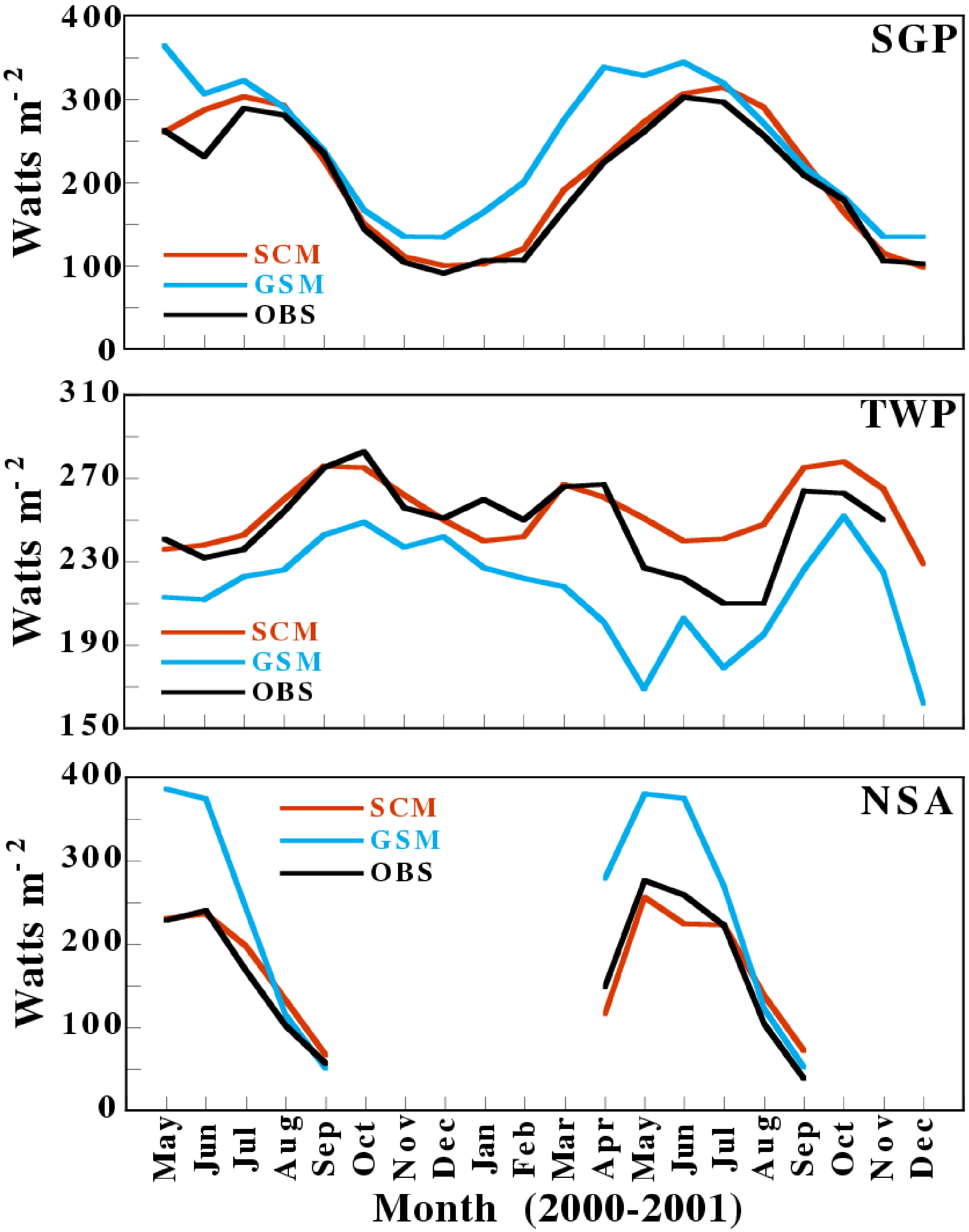

Figure 1. Monthly mean DSSR from the SCM, GSM, and ARM observations at the SGP (top panel), TWP, and NSA sites between May 2000 and December 2001.

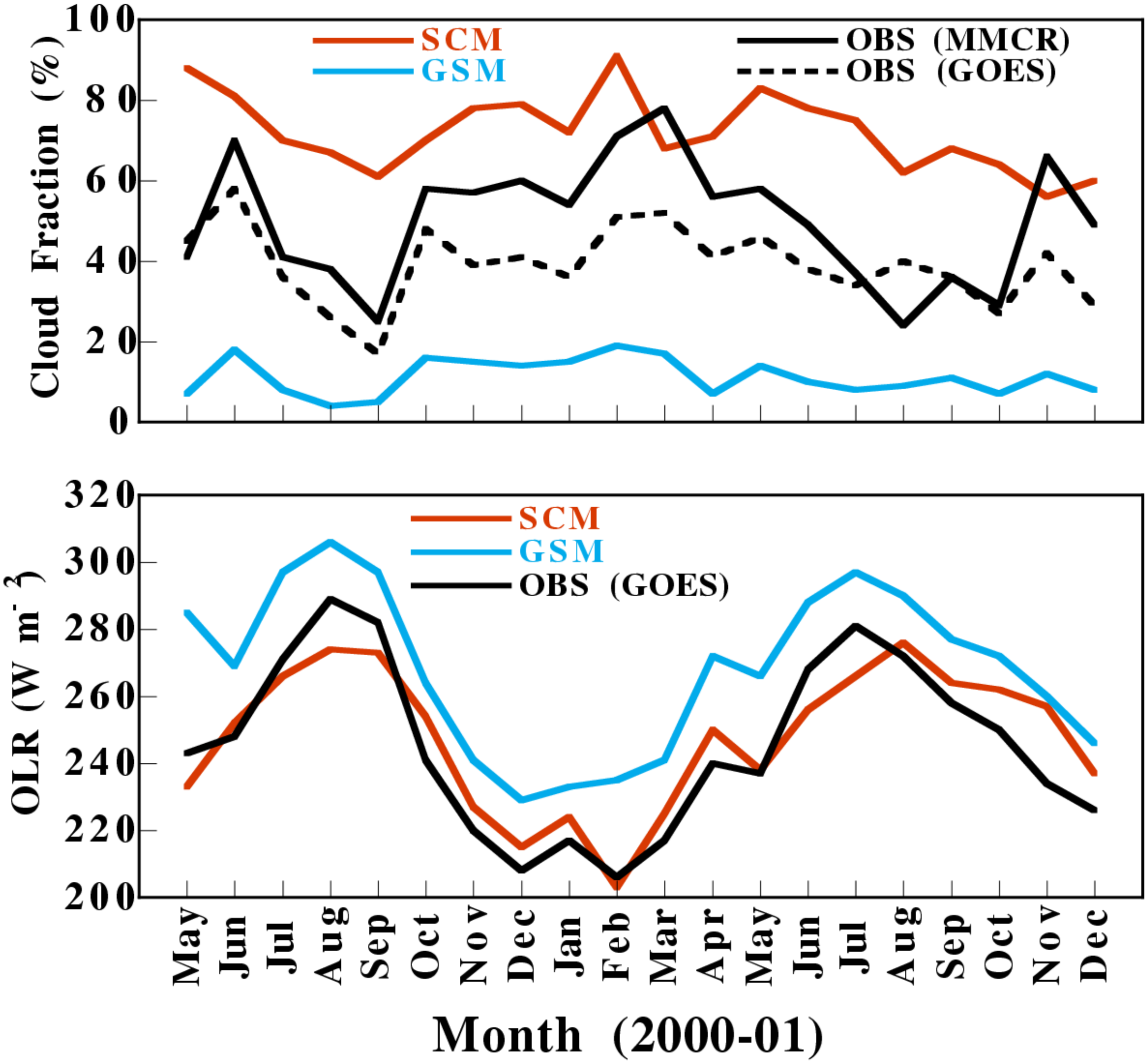

Figure 2. Monthly mean cloud fraction (top panel) and OLR (bottom panel) from the SCM, GSM, and ARM observations at the SGP site between May 2000 and December 2001.

Evaluation of SCM Control Version: Seasonal Analysis

Figure 3 shows results at the SGP site from the control version of the SCM for the 3-month periods June 2000 to August 2000 and December 2000 to February 2001. Overall, the SCM results reproduce much of the observed temporal variability, and the modeled 3-month mean radiative flux values are within 10% of ARM surface and satellite observations. The SCM is more successful at capturing the observed trends on the time scales of 3 to 4 weeks rather than at the shorter time scales of days to a week. Nonetheless, correlation coefficients between 5-day means from the SCM and ARM observations remained generally high, varying from 0.71 to 0.76 as shown in Table 2.

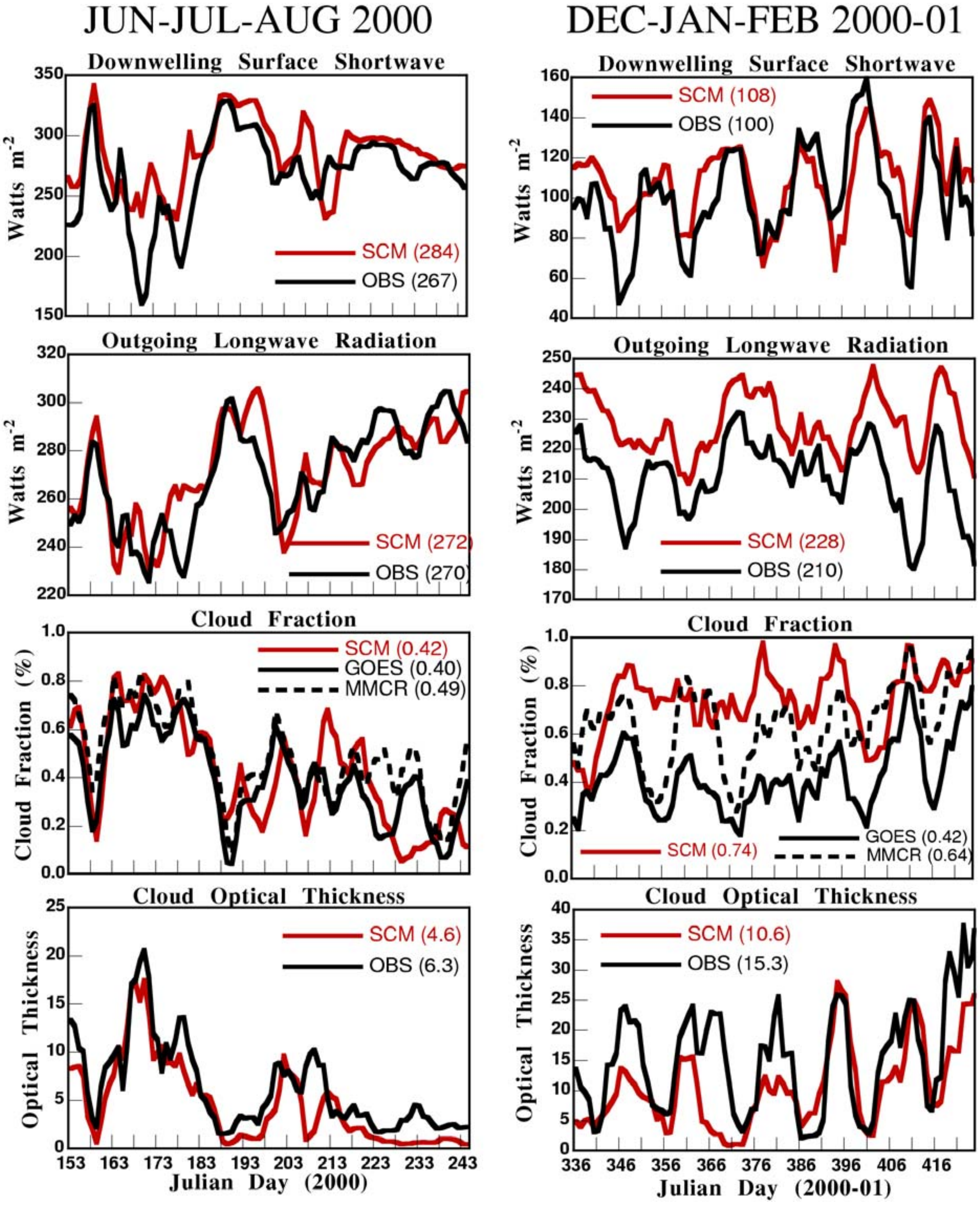

Figure 3. Results from the control version of the SCM at the SGP site for the periods June 2000 to August 2000 (left column) and the December 2000 to February 2001 (right column) along with ARM surface and satellite observations. The numbers in the parentheses are the 3-month mean values.

Table 2. Correlation coefficients between SCM control run and ARM observations for 3-month summer and winter runs.

	DSSR	**OLR**	**Cloud Fraction**	**Optical Thickness**
SUMMER:				
Correlation between daily means	0.56	0.70	0.61	0.69
Correlation between 5-day means	0.75	0.76	0.71	0.80
WINTER:				
Correlation between daily means	0.64	0.73	0.55	0.64
Correlation between 5-day means	0.79	0.82	0.76	0.60

Sensitivity to Ice Particle Fallout

The elimination of ice particle fallout in model run NOFALL increased the amount of high clouds, as shown in Figure 4. Without the removal of ice particles from these layers, the clouds that formed existed for longer time periods. The inclusion of ice particle fallout can also affect the diurnal cycle of cloudiness.

Figure 5 shows the peak cloudiness occurs earlier in the day in SCM runs, including ice particle fallout. This “shifting” of the diurnal peak of cloudiness could have a significant impact on the shortwave (SW) fluxes depending on the timing of the diurnal cycle. When ice particle fallout is omitted, the increased amount of high clouds results in lower values of seasonally averaged OLR of 6-8 W m^{-2}. Daily mean values of OLR varied by up to 50 W m^{-2}.

Sensitivity to Ice Particle Radius

SCM runs, CONTROL, ICEREWY, ICERESU, and ICEMITC, each used a different scheme to calculate the ice particle effective radius (R_{eff}). These runs produced very similar fractional cloud amounts; however, each run produced a different mean vertical profile of R_{eff}, as shown in Figure 6. Also shown in Figure 6 are the mean profiles of R_{eff} measured using MMCR measurements and the algorithm of Mace et al. (1998). While the mean R_{eff} from all four model runs decreases with increasing height, each profile is different. It is difficult to determine which compares most favorably with the observational data.

The same parameterization of SW cloud optical properties was used in CONTROL, ICEREWY, and ICERESU. The mean profile of ice cloud extinction from these runs is shown in Figure 7. Each parameterization of R_{eff} produces a different mean profile of ice cloud extinction leading to differences in the longwave (LW) cooling rates as shown in Figure 8. The dashed curves in Figure 8 are from model runs that used the same clouds (fractional amounts and heights) and cloud water/ice contents as the control run (non-interactive runs). The largest differences are on the order of 0.5°K day^{-1} (JJA) and 0.3°K day^{-1} (DJF) and occur at approximately the location of the maximum mean cloud amount. The differences between the solid and dashed lines are small indicating that the vast majority of the differences in the LW cooling rates are due to the alternate parameterizations of R_{eff} rather than to

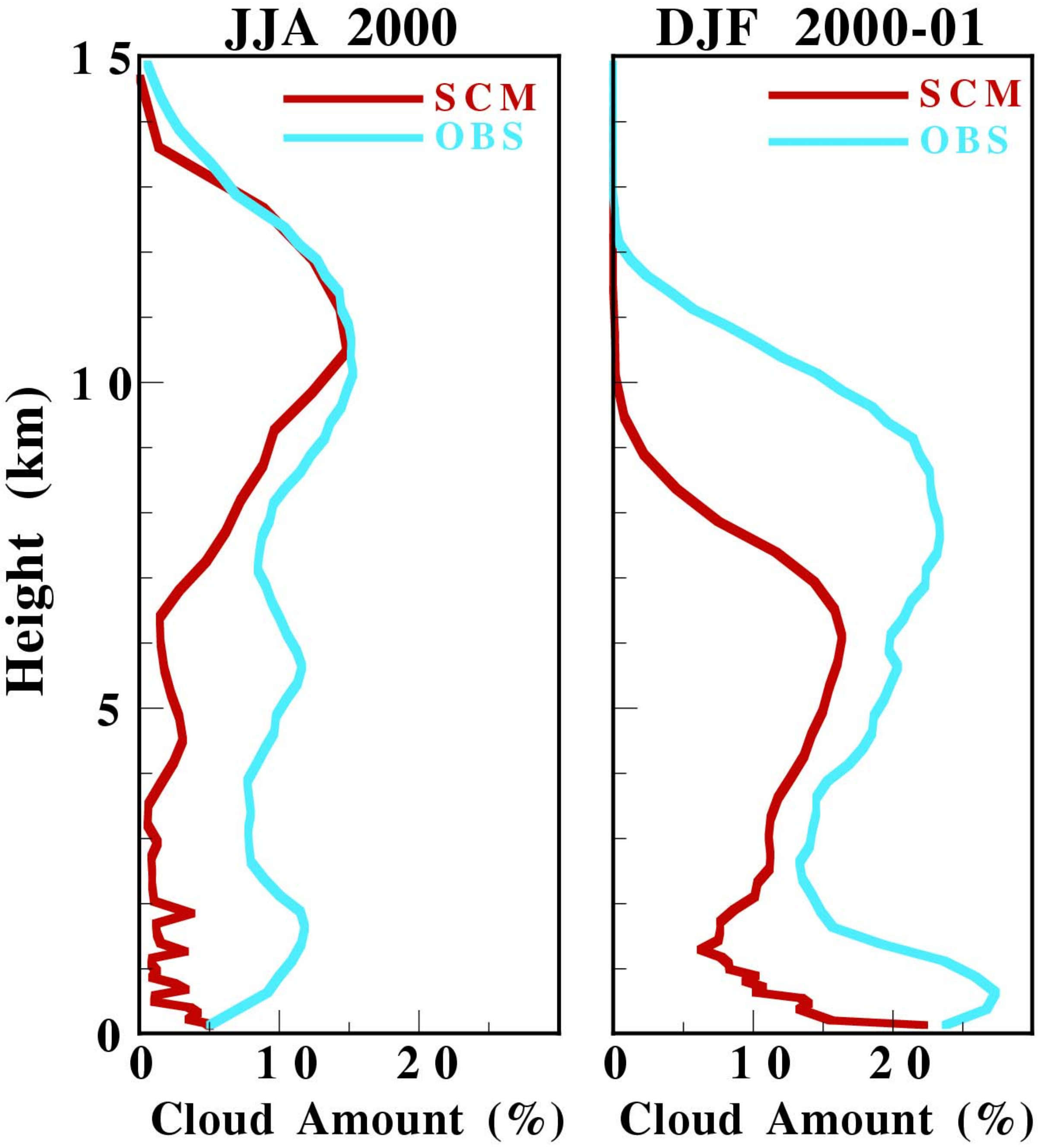

Figure 4. Vertical profiles of cloud fraction from the SCM and from ARM millimeter wave cloud radar (MMCR) observations at the SGP site.

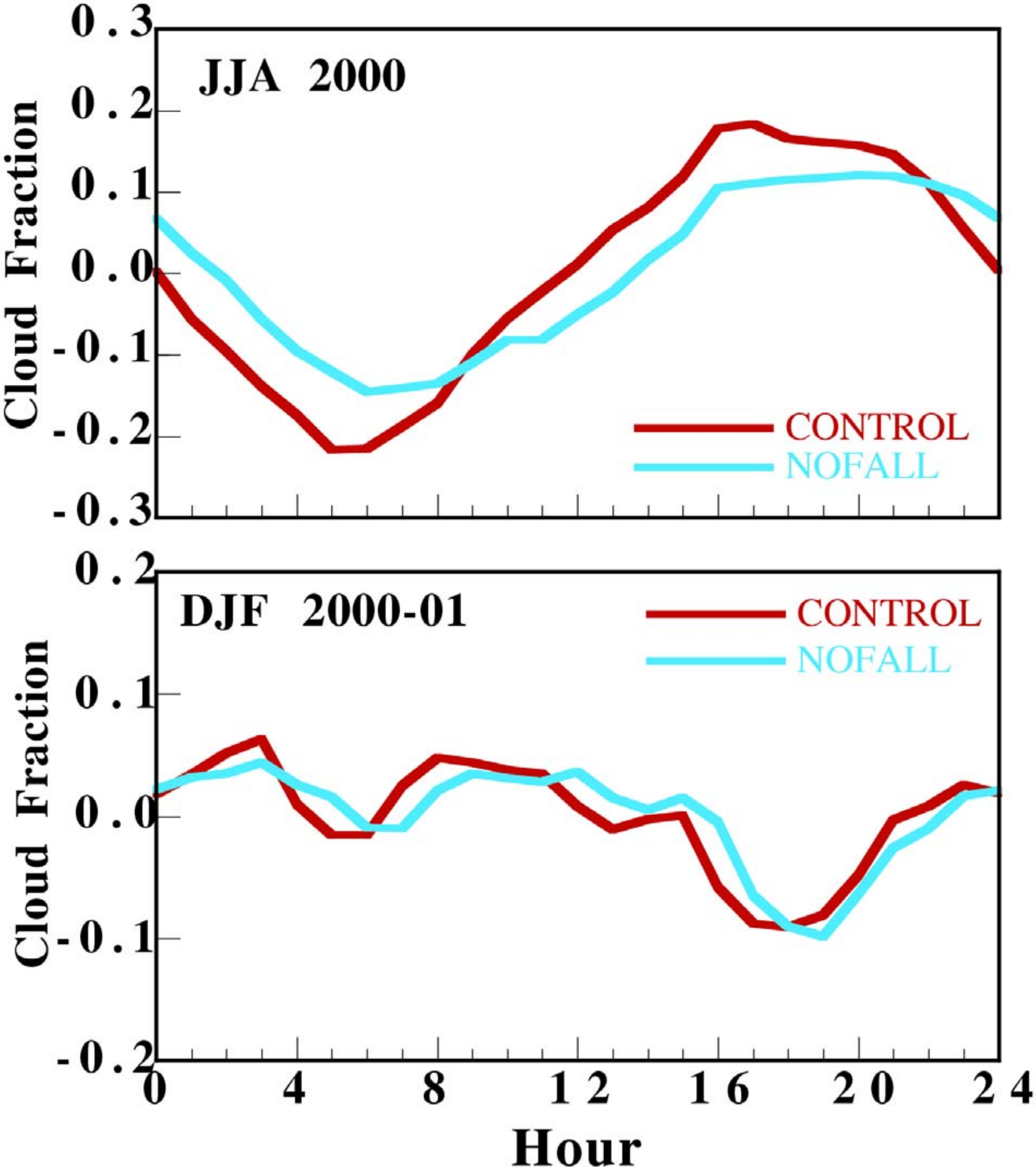

Figure 5. Mean diurnal cycle of cloud fraction from SCM runs CONTROL and NOFALL.

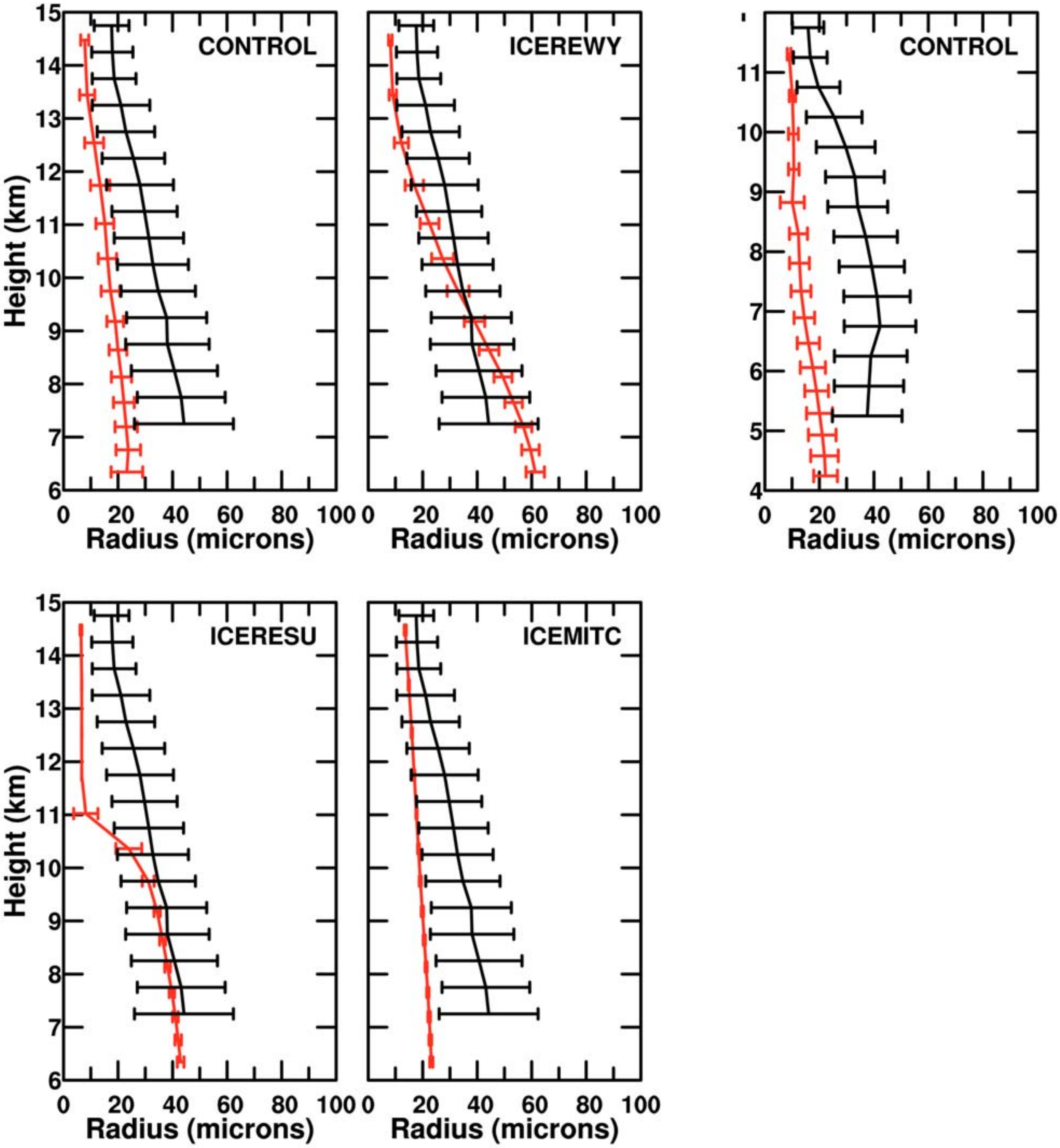

Figure 6. Vertical profile of ice particle re from various SCM runs (red) and MMCR measurements (black). The width of the horizontal bar is 2σ.

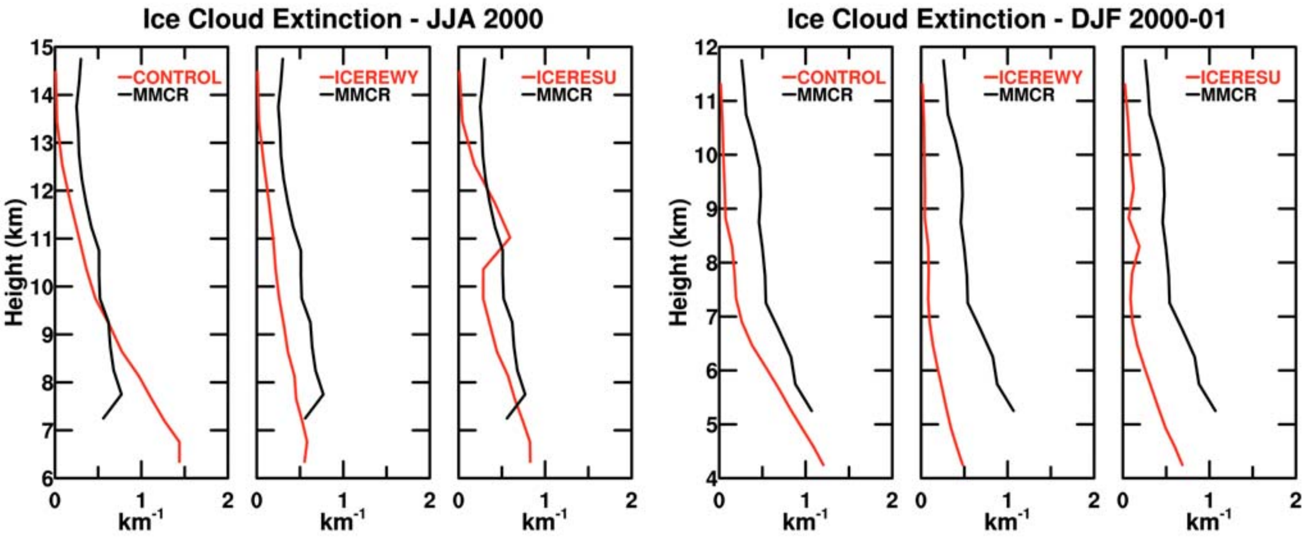

Figure 7. Vertical profile of ice cloud extinction from various SCM runs (red) and MMCR measurements (black).

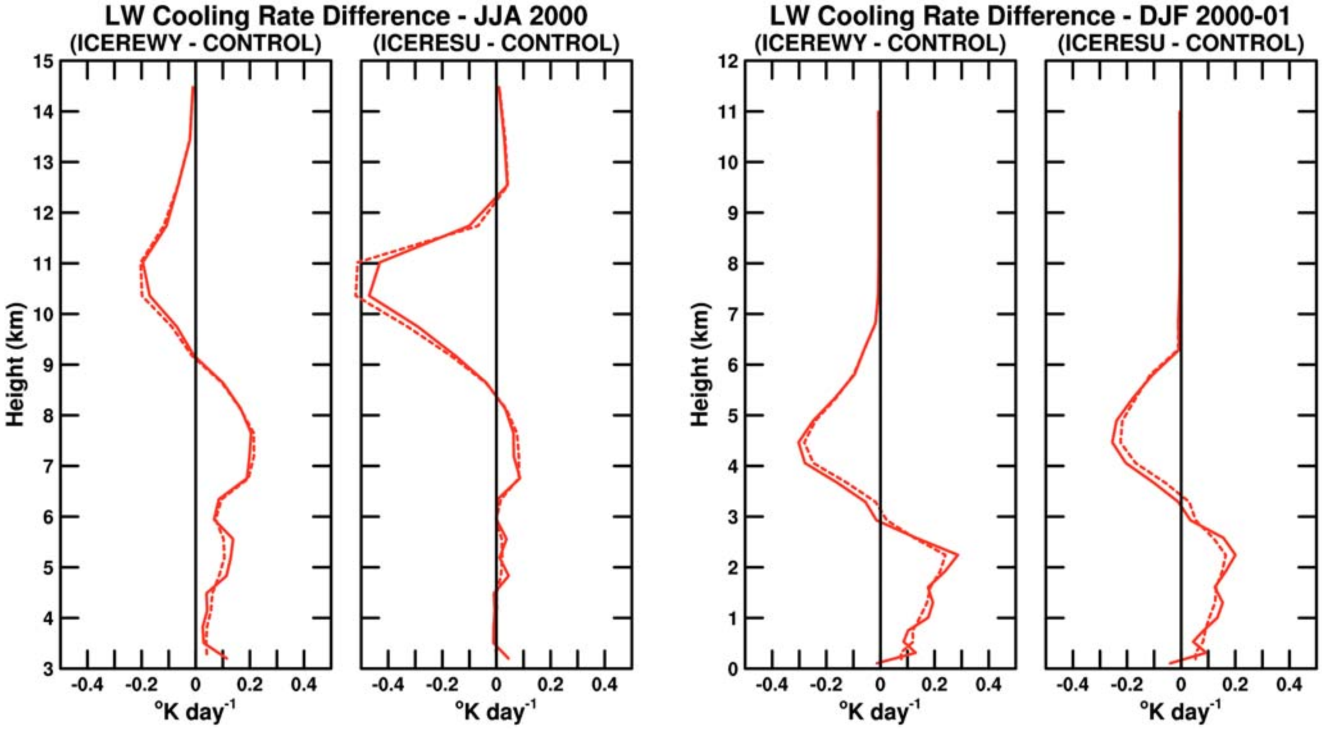

Figure 8. Mean vertical profile of LW radiative cooling rate differences (relative to control run). The solid line is from interactive run and dashed line is from non-interactive run.

changes in cloud amount, location, or water/ice content. The different parameterizations of R_{eff} yield surface and TOA radiative fluxes that vary by up to 32 W m^{-2} on daily time scales and 4 W m^{-2} on seasonal time scales.

The variability of R_{eff} at any given level is underestimated by all parameterizations examined. To help quantify the effect that the narrow range of R_{eff} 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} resulting in a probability distribution that more closely matches the distribution from the MMCR dataset. The results from this experiment indicate that the change in the distribution of R_{eff} can alter the solar and LW radiative fluxes at the surface and TOA by up 26 W m^{-2} on daily time scales and 5 W m^{-2} on seasonal time scales. 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 heat budget for the earth-atmosphere system.

Sensitivity to Ice Cloud Optical Properties

Figure 9 shows the mean profile of ice cloud extinction from runs CONTROL, ICEOPEC, and ICEMITC. Each of these runs used a different scheme to calculate the ice cloud optical properties, yet each produced very similar profiles of cloud extinction. Runs CONTROL and ICEOPEC used the same parameterization of R_{eff} and even though ICEMITC calculated R_{eff} with a different scheme, the mean profile of R_{eff} is similar to the other two runs (see Figure 6). As noted earlier, each SCM run produced nearly identical fractional cloud amounts and ice water contents. Thus, it appears that given similar values of R_{eff} and IWC, the three ice cloud optical property parameterizations examined here produce seasonally averaged profiles of cloud extinction with only small differences. Seasonally averaged

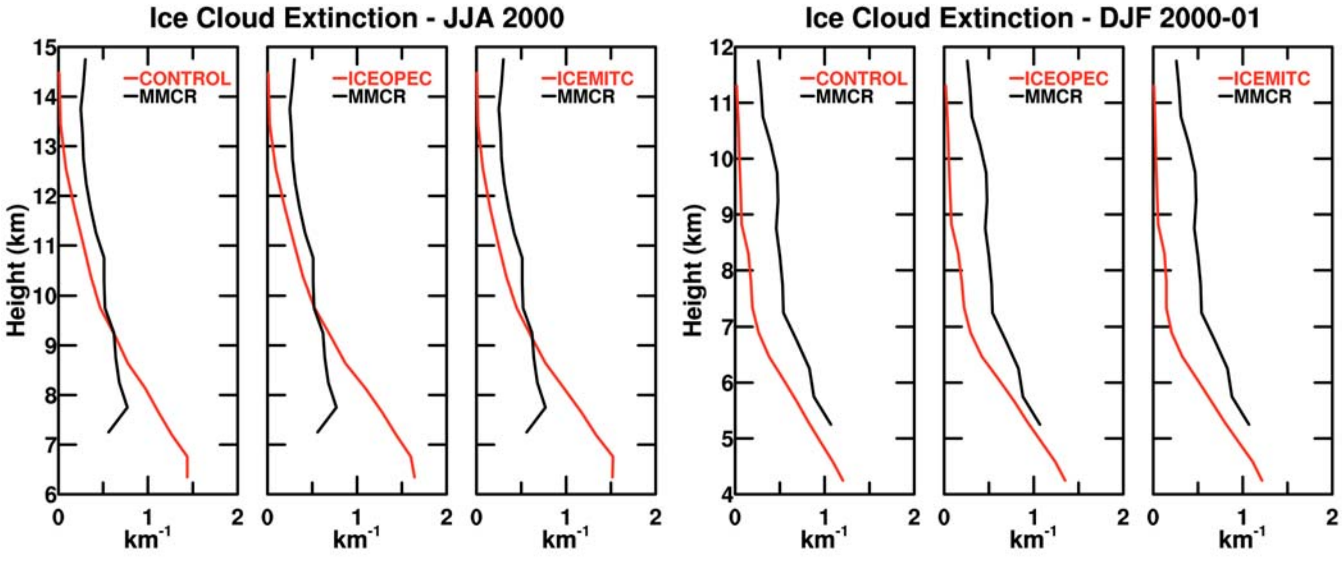

Figure 9. Vertical profile of ice cloud extinction from various SCM runs (red) and MMCR measurements (black).

surface and TOA radiative fluxes varied by less than 1 W m^{-2} in these experiments. However, daily mean fluxes varied by up to 29 W m^{-2} during the summer experiment indicating that there are times when the differences between these schemes can become important.

Figure 10 shows the seasonally averaged LW-cooling rate for these experiments. The differences are generally less than 0.05°K day-1 and are about an order of magnitude less than the maximum differences obtained from the different parameterizations of R_{eff} (Figure 8).

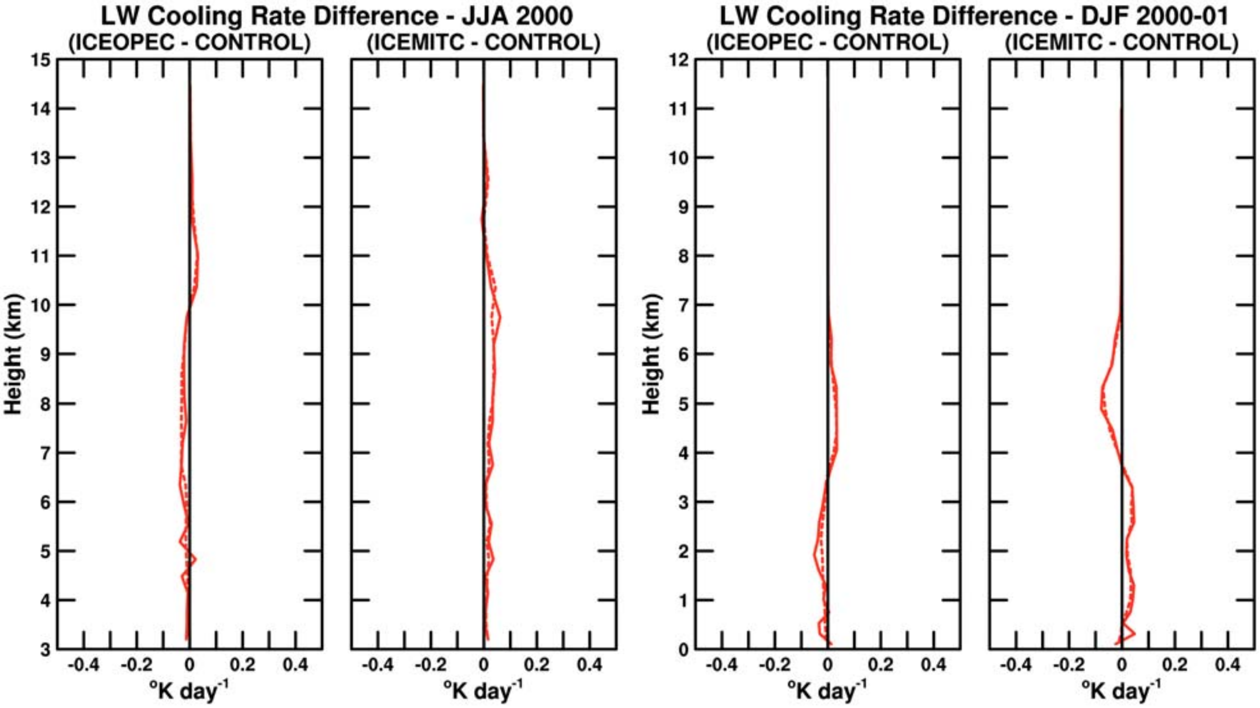

Figure 10. Mean vertical profile of LW radiative cooling rate differences (relative to control run). Solid line is from interactive run and dashed line is from non-interactive run.

Table 3. Summary of the sensitivity of individual cloud forcing terms.		
3-MONTH MEAN	JJA 2000	DJF 2000-01
Parameterization of Ice Particle Radius	1-4 W m^{-2}	1-3 W m^{-2}
Parameterization of Ice Cloud Optical Properties	0-1 W m^{-2}	0-1 W m^{-2}
Variability of Ice Particle Radius	4-5 W m^{-2}	2-3 W m^{-2}
Ice Particle Sedimentation	0-8 W m^{-2}	2-6 W m^{-2}
DAILY MEANS	JJA 2000	DJF 2000-01
Parameterization of Ice Particle Radius	0-32 W m^{-2}	0-14 W m^{-2}
Parameterization of Ice Cloud Optical Properties	0-29 W m^{-2}	0-4 W m^{-2}
Variability of Ice Particle Radius	0-26 W m^{-2}	0-17 W m^{-2}
Ice Particle Sedimentation	0-50 W m^{-2}	0-45 W m^{-2}

Conclusions

- SCM results from control run compare well with observations at daily to monthly time scales.

- Inclusion of ice particle fallout reduces high cloud amount and results in higher values of OLR by up to 6 W m^{-2} to 8 W m^{-2} on a seasonal time scale and 50 W m^{-2} on daily timescales.

- The four parameterizations of ice particle radius examined produce significantly different mean profiles of R_{eff}.

- The range of modeled R_{eff} is responsible for differences in radiative fluxes of up to 4 W m^{-2} on a seasonal time scale and 30 W m^{-2} on daily time scales.

- All parameterizations of R_{eff} underestimate variability compared to ARM measurements.

- Underestimated variability may be responsible for differences in radiative fluxes of up to 5 W m^{-2} on seasonal time scales and 25 W m^{-2} on daily time scales.

- Sensitivity to the parameterization of ice cloud optical properties is low. Given similar profiles of R_{eff} and IWC, all the three schemes tested produce similar values of ice cloud extinction.

- Sensitivities of radiative fluxes are generally lower in winter season.

Future Work

- Further examine sensitivities of ice-cloud microphysical parameterizations at SGP site.

- Apply similar analysis at other ARM Program sites (TWP and NSA).

- Continue to develop and test parameterizations to eliminate shortcomings found in this work.

- Perform additional analysis to determine statistical significance of the flux sensitivities found here.

- Investigate assimilation of radiosonde RH data into NCEP GSM forcing data.

- Incorporate prognostic cloud and cloud microphysics developed in SCM into the 3-dimensional GSM.

- Test parameterizations in short-range forecast experiments for impact on precipitation and cloudiness.

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