JP2.13 SENSITIVITY OF RADIATIVE FLUXES AND HEATING RATES TO CLOUD MICROPHYSICS USING A SINGLE-COLUMN MODEL AND ARM DATA

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1. INTRODUCTION

For the last several years it has been recognized that much of the uncertainty in numerical simulations of potential climate scenarios (i.e., doubling CO_2) is due to incomplete and overly simplistic parameterizations of clouds and cloud microphysical properties. In response, many modeling centers have developed prognostic cloud and cloud microphysical parameterizations and incorporated them into their climate simulation models. Cloud parameterizations continue to be developed today, becoming increasing complex with the addition of more detailed cloud microphysics.

In this study we examine the latter issue using a single-column model (SCM) to address the question of how sensitive are basic quantities such as atmospheric radiative heating rates and surface and top-of-atmosphere (TOA) radiative fluxes are to the various parameterizations of clouds and cloud microphysics. The SCM is run at the ARM program sites in the U.S. Southern Great Plains (SGP), the Tropical West Pacific (TWP), and the North Slope of Alaska (NSA). The ARM program sites are providing a wealth of observational data that can be used to constrain and evaluate the SCM results and thus are ideal testing locations for examining these parameterizations. This study concentrates primarily on the SGP site, however the methodology can be easily applied to the other ARM sites.

2. MODEL DESCRIPTION

The SCM represents an isolated column of atmosphere extending upwards from, and including, the underlying surface. Unlike a three-dimensional general circulation model (GCM), the isolated atmospheric column within the SCM does not have any horizontally adjacent columns. As a result, time-dependent horizontal advective fluxes of heat, moisture and momentum (used to derive vertical velocity) must be supplied to SCM.

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 forcing data fields are archived to allow long-term SCM runs. The archived GSM forcing data currently extends back to May, 2000. Most of the SCM results presented in this paper were obtained from a 3-month long run extending from June through August, 2000. The necessary forcing data for this run was produced by concatenating the individual 24-hour forecasts. 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.

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3. RESULTS

3.1 *Long-term Analysis of SCM Control Version*

The control SCM run utilized a prognostic cloud parameterization (Tiedtke, 1993) together with interactive cloud optical properties for both liquid (Slingo, 1989) and ice (McFarquhar, 2002a) clouds. The effective radius is also calculated interactively using the schemes of Bower et al (1994) for liquid droplets and McFarquhar (2001) for ice particles. The SCM utilizes 53 layers (Lane et al, 2000) and thus has a relatively high vertical resolution. The SCM incorporates relaxation advection (Randall and Cripe, 1999) to keep the modeled temperatures and humidities from drifting towards unrealistic values.

Figure 1 shows the monthly mean downwelling surface shortwave radiation (DSSR) from the SCM, the GSM and ARM surface observations at each of the three ARM sites for the period May 2000 to September 2001. At all three sites, the SCM results compare very favorably with the ARM surface observations. Interestingly, the SCM results compare much better with the observations than 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 inferior to the prognostic cloud scheme with interactive cloud radiative properties used in the SCM.

3.2 *Three-month Control Run at SGP site*

The control version (CON) of the SCM was run at the SGP site for the 3-month period extending from June through August 2000. Time series of surface and TOA radiative fluxes, cloud fraction and precipitation from this SCM control run were compared to ARM observations. Overall, the model results reproduce much of the observed temporal variability and the 3-month mean radiative flux values from the SCM are within 10% of ARM surface and satellite observations.

The SCM is more successful at capturing the observed trends on the timescales of 3-4 weeks than at the shorter timescales 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 1.

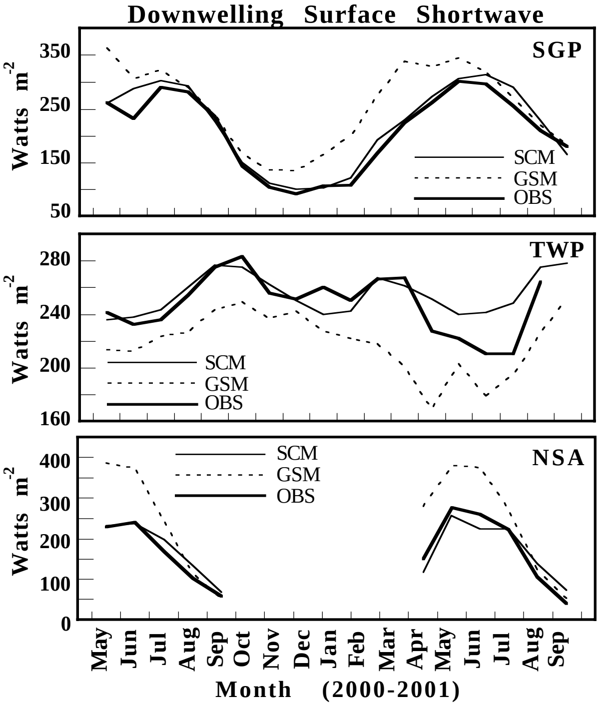

Figure 1. Monthly mean downwelling surface shortwave radiation from the SCM, GSM and observations at each of the three ARM Program sites.

	Surface Shortwave	OLR	Cloud Fraction
SCM 3-month mean	284 W m^{-2}	272 W m^{-2}	0.42
OBS 3-month mean	267 W m^{-2}	270 W m^{-2}	0.40
Correlation between daily means	0.56	0.70	0.61
Correlation between 5-day means	0.75	0.76	0.71

Table 1. Summary of SCM Control run results for the period June - August 2000 at the ARM SGP site.

3.3 *Prognostic vs. Diagnostic Clouds*

An experiment run (EXP-DC) of the SCM was performed in which the prognostic cloud scheme of the control run was replaced with the diagnostic parameterization from CCM3 (Slingo, 1987). In run EXP-DC, cloud water/ice amount is no longer an interactive variable and cloud optical properties are specified based on climatology using the scheme of McFarlane et al. (1992). The results from EXP-DC produced a mean vertical profile of cloud fraction markedly different from the control run (Figure 2). Compared to Millimeter Cloud Radar (MMCR) measurements, EXP-DC produced an overabundance of low clouds with a peak at approximately 2km, whereas the control SCM run underestimated cloud frequency throughout the lower troposphere. While EXP-DC produced a relative maximum of cloud frequency near 12 km, it generally underestimated the amount of high (ice) clouds. The results from CON produced more realistic values of high clouds with a maximum at 10-11 km similar to the MMCR measurements in both magnitude and height.

The mean values of ice cloud extinction from these two runs are also shown in Figure 2. In general, the values of ice cloud extinction from EXP-DC exceed those from CON, the difference being close to an order of magnitude between 6 and 10 km. Also displayed in Figure 2 is the mean ice cloud extinction during the model integration period derived from MMCR measurements using the algorithm of Mace et al (1998) (hereafter, M98). The M98 data only examines ice clouds that are optically thin and occur with no underlying low clouds. The model data shown includes all ice clouds regardless of optical thickness or underlying cloud amount, thus any conclusions drawn from this comparison should be regarded as preliminary.

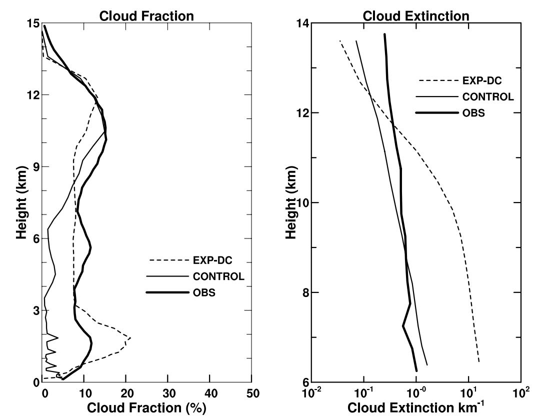

Figure 2. Vertical profiles of model cloud fraction and cloud extinction from runs CON and EXP-DC together with ARM observations.

As one might expect these differences in cloud properties between CON and EXP-DC have important effects on the modeled radiative fluxes at the surface. The mean DSSR from EXP-DC is 221 W m^{-2} compared to 284 W m^{-2} from CON (observed mean = 267 W m^{-2}).

3.4 *Effect of Ice Particle Radius Parameterization*

Two experiment runs were performed in which the ice particle effective radius parameterization used in the control run was replaced with the schemes of Wyser (1998) (EXP-ICE1) and Suzuki et al (1993) (EXP-ICE2).

The fractional cloud amounts produced by these two new model runs did not vary significantly from CON. However, each run produced quite different mean vertical profiles of ice particle effective radius R_{eff} and consequently different ice cloud optical properties. Figure 3 shows the mean vertical profiles of ice particle effective radius from these model runs and from the M98 data set. The width of the horizontal bars is equivalent to +/- $\sigma(z)$, where σ is the standard deviation. The various definitions of effective particle radius encountered in this study are converted to a generalized effective radius (Fu, 1996) for comparison purposes following McFarquhar et al (2002b). While the mean R_{eff} from all three model runs decreases with increasing height, each profile is notably different and it is difficult to determine which compares most favorably with the observational data.

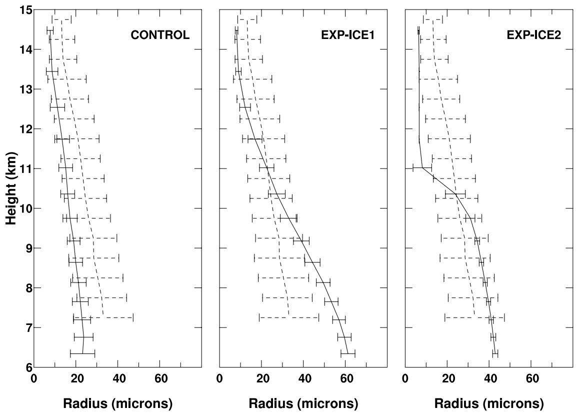

Figure 3. Vertical profile of ice particle effective radius from SCM runs CON, EXP-ICE1 and EXP-ICE2. Observations from the M98 data set are shown by the dashed lines. The width of the horizontal bars is 2σ.

The same parameterization of shortwave cloud optical properties was used in these runs and comparing results can illustrate the sensitivity of modeled radiative fluxes to the parameterization of R_{eff}. The cloud fields produced in EXP-ICE1 and EXP-ICE2 differ slightly from the control run due to feedbacks associated with the new parameterizations of R_{eff}. To distinguish between changes due to different clouds and due to different parameterizations of R_{eff}, additional "non-interactive" runs were performed using the clouds (fractional amounts and heights) and cloud water/ice contents from the control run. The amount of change due to the changing clouds can be determined by comparing the results from the "interactive" and "non-interactive" runs. Figure 4 shows the difference (relative to CON) in the mean longwave cooling rate from EXP-ICE1 and EXP-ICE2. The solid line represents the results from the interactive run while the results from the non-interactive run are shown by the dashed line. The largest differences are on the order of 0.5 °K day^{-1} occurring at approximately 10-11 km which is 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 longwave cooling rates are due to the alternate parameterizations of R_{eff} rather than to changes in cloud amount, location or water/ice content.

The mean value of OLR varied (relative to CON) by 4 W m^{-2} (EXP-ICE1) and 3 W m^{-2} (EXP-ICE2), while the mean value of DSSR varied by 3 W m^{-2} (EXP-ICE1) and 1 W m^{-2} (EXP-ICE2). These differences were the same for both the interactive and non-interactive experiment runs. These variations due to alternate parameterizations of effective ice particle radius are of a similar order of magnitude as those found in Kristjansson et al (2000) for mid-latitude conditions but generally less than those found in the tropical cloud modeling study of Iacobellis and Somerville (2000). The lower flux differences in the present study compared to Iacobellis and Somerville (2000) may be due to the generally lower amount of convective cirrus anvil cloud cover found in the mid-latitudes relative to that found in the tropics.

The variations in OLR and DSSR discussed above were averaged over the entire 3-month model integration period. As one might expect, the variations in daily mean values of OLR and DSSR between CON and EXP-ICE1 or EXP-ICE2 exhibited much larger magnitudes that the 3-month means. The largest variation in daily mean OLR was 14 W m^{-2} (EXP-ICE1) and 27 W m^{-2} (EXP-ICE2), while the largest difference in daily mean DSSR was 32 W m^{-2} (EXP-ICE1) and 31 W m^{-2} (EXP-ICE2). This maximum daily mean variability is calculated using the results from the non-interactive SCM runs and hence is entirely due to differences in the parameterization of R_{eff} and not to any changes in cloud fraction and/or cloud water/ice content.

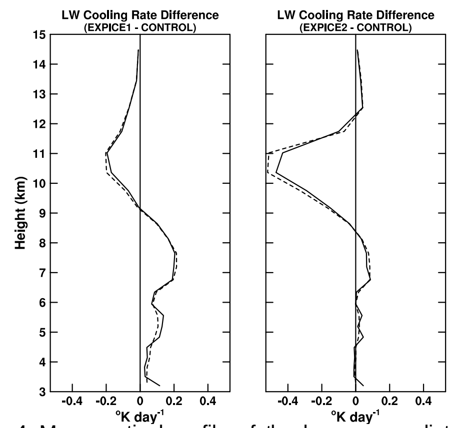

Figure 4. Mean vertical profile of the longwave radiative cooling rate differences (relative to control run). Solid line is from interactive run and dashed line is from non-interactive run.

The variability of R_{eff} at any given level, as measured by the standard deviation, is underestimated by all three parameterizations examined. The IWC variability is approximately equal in magnitude to the mean values for both the model and measured values. The radiative flux parameterizations, both longwave and shortwave, are highly non-linear and 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 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} (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. Figure 5 shows the probability distribution of effective particle radius from run EXP-WIDE for clouds occurring from 8-9 km and 12-13 km. The width of the distribution from EXP-WIDE more closely matches, albeit not perfectly, the distribution from the M98 data set.

The results from model run EXP-WIDE indicate that the change in the distribution of R_{eff} can alter the solar and longwave radiative fluxes at the surface and 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 longwave flux resulting in little change in the 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) that 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 decreasing the outgoing longwave radiation.

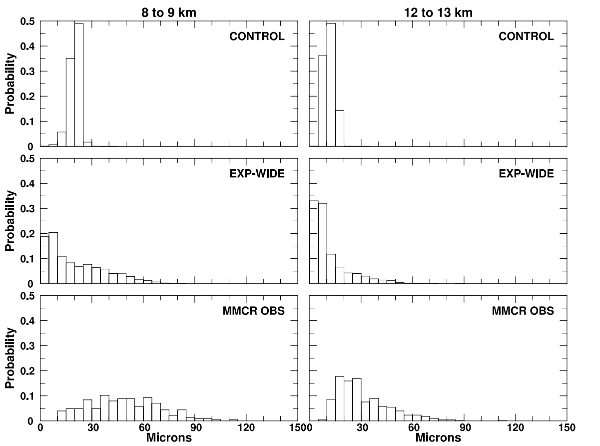

Figure 5. Probability distribution of effective ice particle radius from SCM runs CON and EXP-WIDE. and from ARM MMCR measurements.

4. SUMMARY AND FUTURE WORK

• Diagnostic cloud scheme produces much less realistic cloud properties compared to interactive prognostic cloud parameterization.
• The different parameterizations of ice particle effective radius produced a wide range of results. Daily mean values of DSSR and OLR varied by up to 30 W m^{-2}. Additionally, each scheme underestimated variability of ice particle radius compared to observations.
• Underestimation of R_{eff} variability may affect individual surface or TOA flux by up to 5 W m^{-2}. However, differences largely offset resulting in little change in the earth-atmosphere heat budget.
• Further examine sensitivities of ice-cloud microphysical parameterizations at SGP site.
• Apply methodology developed here at other ARM sites in tropical west Pacific and north slope of Alaska.

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