10.9 TESTING CLOUD-RADIATION SCHEMES WITH SINGLE-COLUMN MODELS AND ARM OBSERVATIONS

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1. INTRODUCTION

We have developed a single-column model (SCM) to investigate the sensitivity of cloud-radiation interactions to various cloud parameterizations. The cloud parameterizations differ with regard to the inclusion of cloud liquid water, the specification of the effective cloud droplet radius, and the parameterization of the cloud optical properties (both solar and terrestrial). Results from a control version of the SCM are first evaluated for realism by comparing model produced clouds and radiative fluxes against surface and satellite observations taken at the Atmospheric Radiation Measurement (ARM) Program Southern Great Plains (SGP) site. The sensitivity of model radiative fluxes to the specification of the cloud parameterization is then analyzed. Finally, these sensitivities are compared to the changes in the radiative fluxes which result when different solar and longwave radiation parameterizations are employed.

2. MODEL DESCRIPTION

The SCM is a diagnostic model resembling a single vertical column of a 3-dimensional general circulation model (GCM).The SCM contains a full set of parameterizations of subgrid physical processes that are normally found in a modern GCM and is applied at a specific site having a horizontal extent typical of a GCM grid cell. Since the model is one-dimensional, the advective terms in the budget equations must be specified from observations or operational numerical weather prediction analyses. For a more complete discussion of SCMs, the reader is referred to Randall et al. (1996).

The configuration of the single column model used in this study has 19 vertical layers and a timestep of 7.5 minutes. A diurnally varying solar signal dependent on the latitude and time of year is applied at the top of the model atmosphere. The SCM is modular in design allowing for easy switching between alternative parameterizations. The SCM experiments in this study use the longwave radiation parameterization of Morcrette (1990) or Mlawer et al (1997) and the solar radiation parameterization of Fouquart and Bonnel (1980) or Lacis and Hansen (1974). Clouds are parameterized using either the formulation of Tiedtke (1993) or Slingo (1987). In the Slingo scheme, cloud fraction depends upon the large-scale model relative humidity, vertical velocity, static stability, and convective mass flux. The visible cloud optical depths are parameterized using model temperature, humidity and pressure following McFarlane et al (1992). The Tiedtke cloud scheme introduces two new prognostic equations for cloud liquid water/ice and cloud amount. Terms representing the formation of clouds and cloud water/ice due to convection, boundary layer turbulence and stratiform condensation processes are included in these equations. Cloud water/ice is removed through evaporation and conversion of cloud droplets and ice to precipitation. When the Tiedtke scheme is used, cloud liquid water/ice is a prognostic variable and the visible cloud optical depth is calculated using the parameterizations of Slingo (1989) for water clouds and Ebert and Curry (1992) for ice clouds. A necessary input to each of these schemes is the effective cloud droplet radius (R_e). This variable is a major focus of this study and can be parameterized by one of six different techniques outlined below in Table 1:

	WATER CLOUDS	ICE CLOUDS
IRE=0	$R_e=10\mu m$ (constant)	$R_e=10\mu m$ (constant)
IRE=1	R_e=f(LWC) Bower et al (1994)	$R_e=10\mu m$ (constant)
IRE=2	R_e=f(LWC) Bower et al (1994)	R_e=f(T) Suzuki et al (1993)
IRE=3	R_e=f(LWC) Bower et al (1994)	R_e=f(IWC) McFarlane et al (1992)
IRE=4	R_e=f(LWC) Bower et al (1994)	R_e=f(T) Ou and Liou (1995)
IRE=5	R_e=f(LWC) Bower et al (1994)	R_e=f(T,IWC) Wyser (1998)

Table 1. Various parameterizations of the effective cloud droplet radius used by the SCM. LWC = Liquid Water Content; IWC = Ice Water Content.

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The SCM employs the cumulus convection parameterization of Zhang and McFarlane (1995) and the scheme of Hack (1994) for shallow convection. This is the same cumulus convection parameterization package contained in the NCAR community climate model (CCM3). In this study, the land surface temperature and surface heat fluxes are specified from observations.

The SCM is operated in a 'relaxation mode' in which the temperature and humidity profiles are relaxed to the observed profiles using a specified time constant, $\beta = 24$ hrs is used. This value of β helps to insure that model errors in the temperature and humidity profiles remain small without seriously distorting the atmospheric profiles. The magnitudes of the correction terms are usually small compared to other budget components. Further, results from SCM runs which used no relaxation correction (i.e., $\beta = \infty$) have shown that the conclusions derived from the SCM results with relaxation are not dependent on the inclusion on the correction terms.

3. MODEL EXPERIMENTS

Numerical experiments were performed by applying the SCM in the atmospheric column directly over the ARM SGP site. The SCM was forced with horizontal advection tendencies and vertical velocities calculated using the constrained variational scheme of Zhang and Lin (1997). This forcing data was derived from measurements gathered by radiosondes and wind profilers at the ARM SGP site during the three week period Intensive Observing Period (IOP) in the Summer of 1995. We have assumed maximum overlap of clouds due to the strongly convective atmospheric environment at the ARM SGP site during summer.

3.1 *Control Run*

The control version of the SCM contained the following parameterizations: i) Clouds: Tiedtke; ii) Longwave: Morcrette; iii) Shortwave: Fouquart and Bonnel; iv) Effective cloud droplet radius: Bower (water) and Wyser (ice) (IRE=5). Model means of cloud fraction (CLD), downwelling surface shortwave radiation (SW↓), downwelling surface longwave radiation (LW↓), outgoing longwave radiation (OLR), shortwave cloud forcing (CF_{SW}) and longwave cloud forcing (CF_{LW}) from the SCM control run (SCM-CO) are shown together with observed values in Table 2.

The time-averaged results from the control run compare very well to observed values except for SW↓ and CF_{SW}. The magnitude and sign of the differences between model and observed SW↓ and CF_{SW} are consistent and indicate that the model clouds are not reflecting enough incoming solar radiation.

	CLD	SW↓	LW↓	OLR	CF_{SW}	CF_{LW}
SCM-CO	56	253	401	249	-48	47
OBS	52	238	405	252	-61	46

Table 2: Model (control) and observed mean values. (units = W m^{-2}; except for CLD which is in percent).

Comparison of the model results to Micropulse Lidar (MPL) cloud base height data from the ARM SGP site suggests that the SCM with the Tiedtke cloud scheme underestimates the amount of low optically thick clouds. This conclusion is consistent with the values of the variables shown in Table 2. If contiguous with overlying high clouds, an increase in low cloud amount would not increase the total cloud amount (due to the assumption of maximum overlap) or significantly affect the OLR and CF_{LW}, but may increase the LW↓. However, tests with the SCM indicate that artificially increasing the low cloud amount (800 mb) could lower SW↓ by as much as 50 W m^{-2} while only increasing the LW↓ by 7 W m^{-2}.

3.2 *Sensitivity to the Parameterization of Clouds*

The SCM was rerun using the Slingo cloud scheme in place of the Tiedtke cloud scheme (SCM-SL). The time-averaged model results from this run are shown in Table 3. A comparison between observations and the results from run SCM-SL indicate that the model with the Slingo cloud scheme produces far too many clouds, particularly at low levels (900 – 700 hPa). Based on this limited study period, the SCM results are more realistic when the Tiedtke cloud scheme is used. The underestimation of low clouds by the Tiedtke scheme noted earlier may be due to deficiencies in the convection scheme since low cloud production is strongly coupled to the convective mass detrainment.

	CLD	SW↓	LW↓	OLR	CF_{SW}	CF_{LW}
SCM-SL	73	160	421	227	-121	69
OBS	52	238	405	252	-61	46

Table 3: As in Table 2, but for model run SCM-SL.

3.3 *Sensitivity to the Parameterization of Cloud Droplet Radius*

The SCM control run utilized the effective cloud droplet scheme denoted by IRE=5 (see Table 1). The SCM was rerun using each of the other 5 techniques available for calculating R_e. Below 600 hPa, the parameterization of Bower et al (1994) produces an effective droplet radius of approximately 5 µm in liquid water clouds compared to the constant value of 10 µm used when IRE=0. The time-averaged vertical profile of R_e above 600 hPa from each of these experiments is shown in Figure 1. Above 600 hPa, the various parameterizations produce values of R_e for ice clouds which vary considerably. These widely varying values of R_e have significant effects on the parameterized values of cloud extinction and cloud emissivity (Figure 2) which influence both shortwave and longwave radiative fluxes at the surface and top-of-atmosphere (TOA)(Table 4).

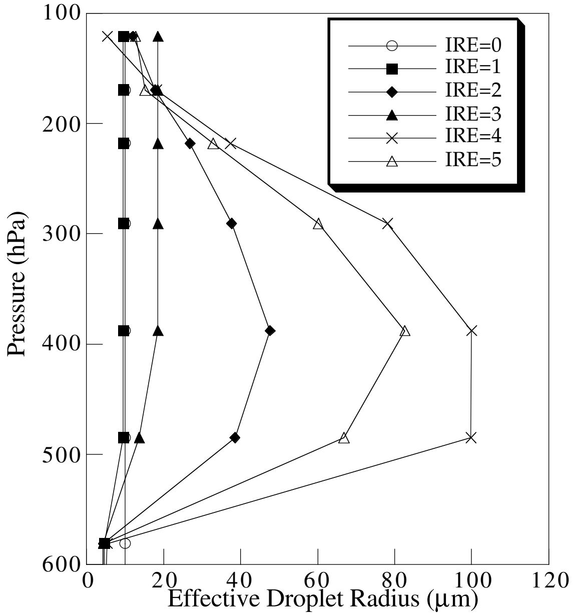

Figure 1: Time-averaged vertical profile of model produced effective droplet radius.

	CLD	SW↓	LW↓	OLR	CF_{SW}	CF_{LW}
IRE=0	56	220	403	233	-80	63
IRE=1	56	220	403	233	-80	62
IRE=2	55	246	402	245	-55	50
IRE=3	59	227	403	237	-73	59
IRE=4	57	255	401	251	-47	44
IRE=5	56	253	401	249	-48	47
OBS	52	238	405	252	-61	46

Table 4: Sensitivity to effective radius.

The different parameterizations of R_e produce a wide range of surface and TOA radiative fluxes: ΔSW↓ = 35 W m^{-2}; ΔOLR = 18 W m^{-2}; ΔCF_{SW} = 33 W m^{-2}; and ΔCF_{LW} = 19 W m^{-2}. The cloud amount and downwelling surface longwave flux do not show significant sensitivity to the parameterization of R_e.

Recent observations of cirrus clouds near the ARM SGP site during the SUCCESS program in April-May 1996 suggest that the mean values of R_e produced by the SCM with IRE=2, 4, and 5 are the most realistic (Gerber et al, 1998; Mace et al, 1998). However, it remains a difficult task to compare model produced values of R_e representative of an area with a length scale of 100-200 km to aircraft measurements of individual clouds. Techniques currently being developed to estimate droplet size from satellite retrieved radiances (e.g., Young et al, 1998) can produce mean values over large horizontal areas and will be a valuable tool to validate model results.