Single-Column Modeling, GCM Parameterizations and Atmospheric Radiation Measurement Data

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Introduction

Our overall goal is identical to that of the Atmospheric Radiation Measurement (ARM) Program: the development of new and improved parameterizations of cloud-radiation effects and related processes, using ARM data at all three ARM sites, and the implementation and testing of these parameterizations in global and regional models. To test recently developed prognostic parameterizations based on detailed cloud microphysics, we have first compared single-column model (SCM) output with ARM observations at the Southern Great Plains (SGP), North Slope of Alaska (NSA) and Topical Western Pacific (TWP) sites. We focus on the predicted cloud amounts and on a suite of radiative quantities strongly dependent on clouds, such as downwelling surface shortwave radiation. Our results demonstrate the superiority of parameterizations based on comprehensive treatments of cloud microphysics and cloud-radiative interactions. At the SGP and NSA sites, the SCM results simulate the ARM measurements well and are demonstrably more realistic than typical parameterizations found in conventional operational forecasting models. At the TWP site, the model performance depends strongly on details of the scheme, and the results of our diagnostic tests suggest ways to develop improved parameterizations better suited to simulating cloud-radiation interactions in the tropics generally. These advances have made it possible to take the next step and build on this progress, by incorporating our parameterization schemes in state-of-the-art 3D atmospheric models, and diagnosing and evaluating the results using independent data. Because the improved cloud-radiation results have been obtained largely via implementing detailed and physically comprehensive cloud microphysics, we anticipate that improved predictions of hydrologic cycle components, and hence of precipitation, may also be achievable. We are currently testing the performance of our ARM-based parameterizations in state-of-the-art global and regional models. One fruitful strategy for evaluating advances in parameterizations has turned out to be using short-range numerical weather prediction as a test-bed within which to implement and improve parameterizations for modeling and predicting climate variability. The global models we have used to date are the CAM atmospheric component of the National Center for Atmospheric Research (NCAR) CCSM climate model as well as the National Centers for Environmental Prediction (NCEP) numerical weather prediction model, thus allowing testing in both climate simulation and numerical weather prediction modes. We present detailed results of these tests, demonstrating the sensitivity of model performance to changes in parameterizations.

Overview

- A Single-column model and the NCAR CAM3 are used to examine the sensitivity of model results to the parameterization of cloud microphysics at the ARM Program sites.
- SCM results confirm that a Manton-Cotton autoconversion (AC) scheme produces more realistic liquid water content (LWC) values than Sundqvist scheme for shallow frontal clouds.
- However, SCM results indicate that Sundqvist AC performs better over longer time periods with a variety of cloud conditions.
- Results from a series of one-year runs of CAM3 show sensitivity of modeled cloud forcing to the parameterization of effective ice particle radius (R_{eff}). The McFarquhar (2001) R_{eff} scheme produces more realistic cloud forcing in the TWP.
- Experiment run of CAM3 using the Tiedtke cloud parameterization produces realistic cloud fields with improved precipitable water and cloud liquid water amounts relative to the CAM3 Control Case.

Single-Column Model Forcing Data

Forcing data for the SCM consists of horizontal advective fluxes of heat, moisture and momentum, surface temperature and surface heat fluxes. Forcing data in this study was obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis supplied to the ARM program.

Single-Column Model Runs

- Each run 36 hours in length.
- First 12 hours is spin-up (not included in results).
- Start time of each run offset by 6 hours.
- SCM runs extend from 2000-2001 (see Figure 1).

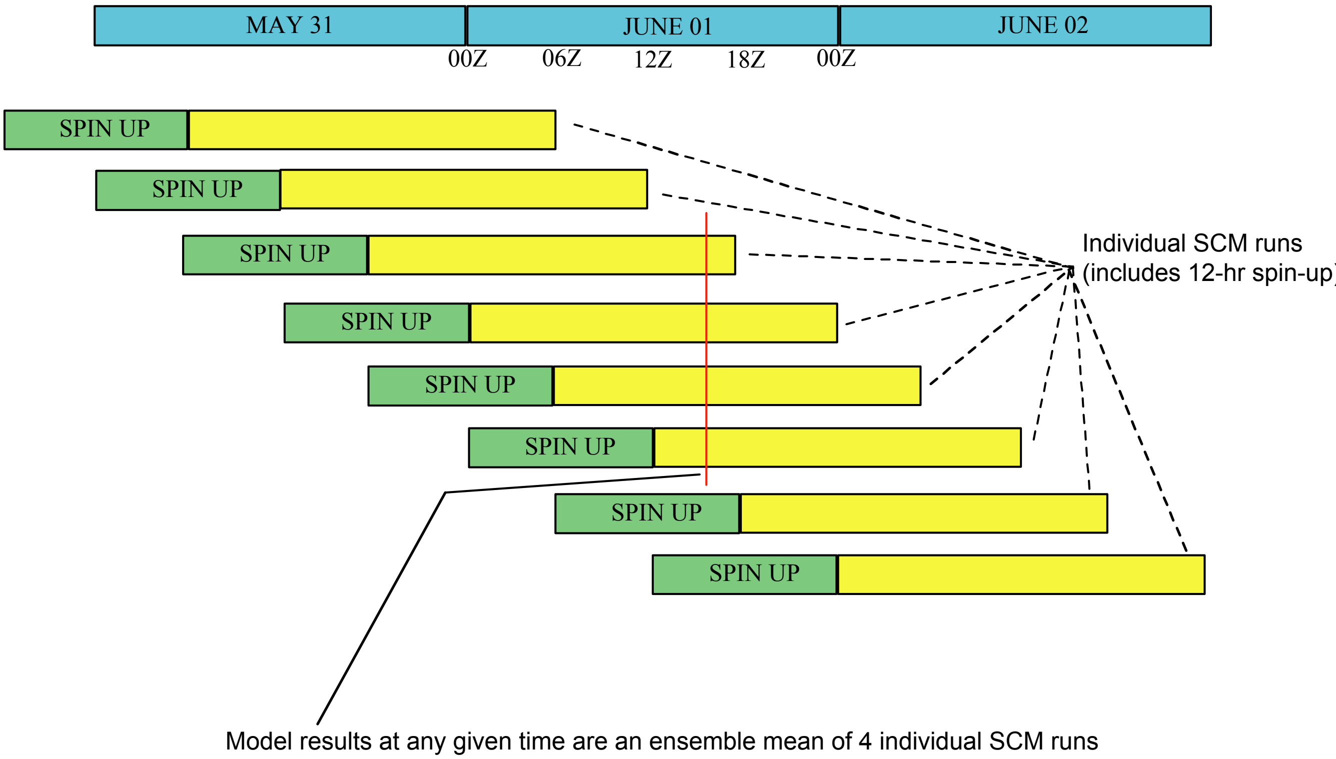

Figure 1. Schematic diagram of the SCM run production method.

Single-Column Model Configurations

- Vertical resolution ~ 25 mb (53 vertical layers).
- Time step = 7.5 minutes.
- Prognostic cloud parameterization (Tiedtke 1993).
- Interactive cloud optical properties:
  - liquid water (Slingo 1989); ice (McFarquhar et al. 2002).
- Particle effective radius:
  - liquid water droplets (Bower et al. 1994)
  - ice particles (McFarquhar 2001).
- Precipitation Autoconversion:
  - Sundqvist et al. (1989) (SCM-S) or
  - Manton and Cotton (1977) (SCM-MC).

CAM3

- Series of three one-year runs made with T31 version (48 x 96).
- Each run started on 01SEP00.

Run 1: (CONTROL) Standard CAM3 configuration

Run 2: (EXP01) Ice particle effective radius parameterization replaced with McFarquhar (2001) scheme. Ice cloud optical properties parameterization replaced with McFarquhar et al. (2002) scheme.

Run 3: (EXP02) Same as EXP01, but now with Tiedtke prognostic cloud and cloud water parameterization incorporated.

Single-Column Model Results

- Recent paper by Xu et al. (2005) suggests that a Manton-Cotton type autoconversion scheme produces more realistic results than the Sundqvist type scheme. However, Xu et al. (2005) only examine a 27-hr period at the ARM SGP site.
- SCM runs with the Sundqvist autoconversion (SCM-S) and with the Manton-Cotton autoconversion (SCM-MC) performed during period 2000-2001.
- SCM results confirm findings of Xu et al. (2005) than Manton-Cotton AC produces better results during 27-hr period dominated by shallow frontal clouds (Figures 2 and 3).
- However, SCM results averaged over longer time periods with a variety of cloud types indicates that the Sundqvist AC produces more realistic values of LWP (Figure 4).
- Compositing results between those times when shallow clouds occurred with and without overlying high clouds produces an interesting finding. The Manton-Cotton AC scheme produces much more realistic values of ice water content (IWC) during episodes of shallow clouds without overlying clouds. During periods of shallow clouds with overlying clouds, the SCM produces more realistic results when using the Sundqvist AC scheme (Figure 5).
- The Manton-Cotton AC parameterization is very sensitive to the specification of the cloud droplet concentration, N_c (Figure 6). A constant value of N_c=200 cm^{-3} was used in this study. This value was selected based on limited in-situ observations taken during the March 2000 SGP intensive operational period (IOP). However, it is very likely that the value of N_c varied considerably during the 2000-2001 period. Future work will be directed at incorporating a time-dependent value of N_c into the SCM.

Precipitation conversion rate (G_p):

- Sundqvist:

  $G_p = (\rho_a l_c / c_o) [1 - \exp -(l_c/l_{crit})^2]$

  l_c = cloud water content
  l_{crit} = critical cloud water content (constant)
  c_o^{-1} = characteristic time scale (constant).

- Manton-Cotton:

  $G_p = f_c l_c H (l_c - l_{cm})$

  f_c = mean collision frequency = func(N_c)
  H = Heaviside step function
  l_{cm} = threshold cloud water content = func(N_c)
  N_c = cloud droplet concentration.

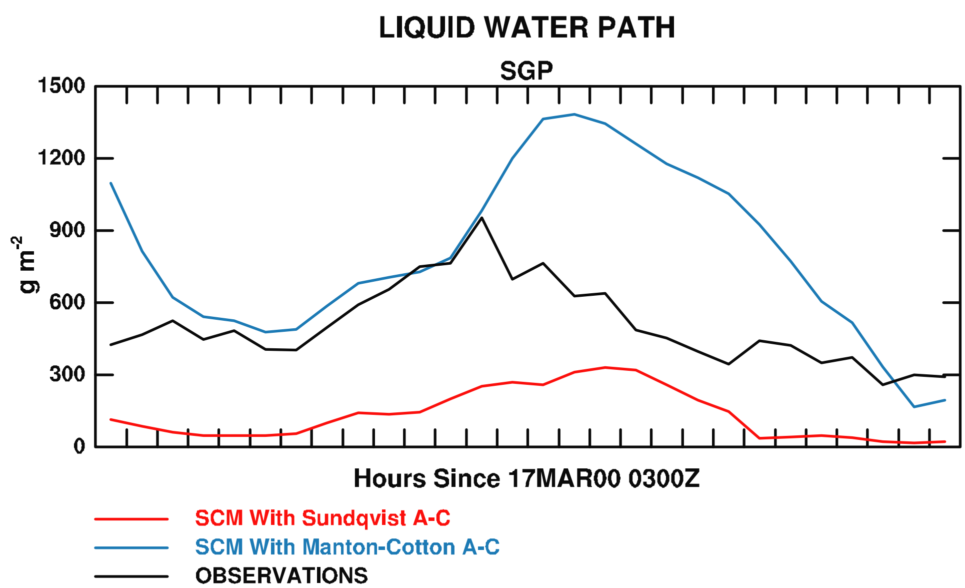

Figure 2. Time evolution of LWP from SCM-S, SCM-MC, and ARM microwave radiometer (MWR) measurements during the 27-hr period.

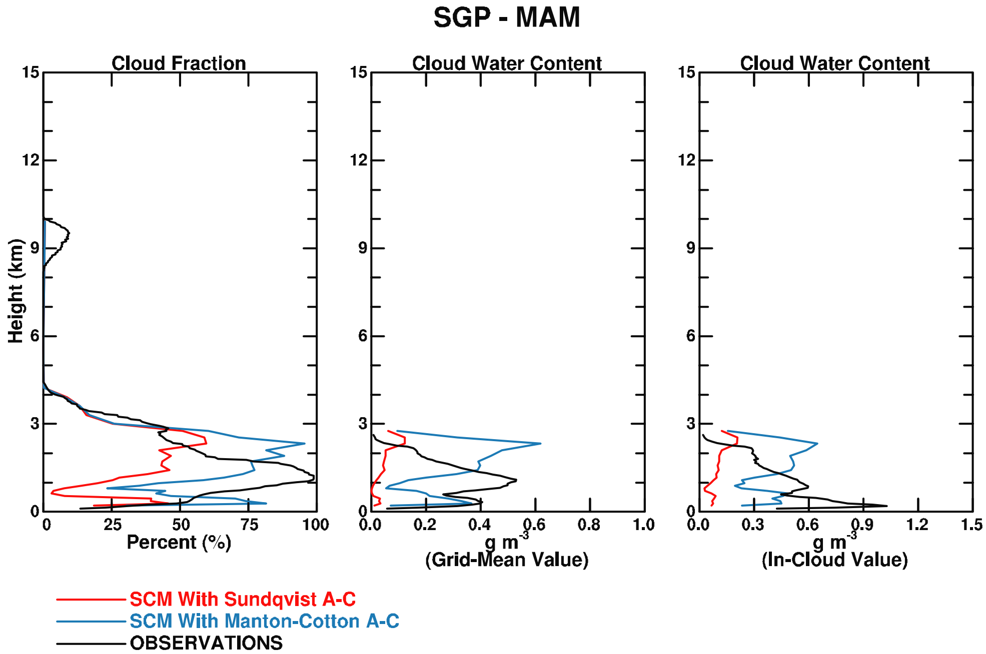

Figure 3. Mean vertical profiles of cloud fraction, grid-mean LWC and in-cloud LWC during the 27-hr period 0300Z March 17 to 0600Z March 18. Observational data shown in black is derived from ARM MMCR and MWR measurements.

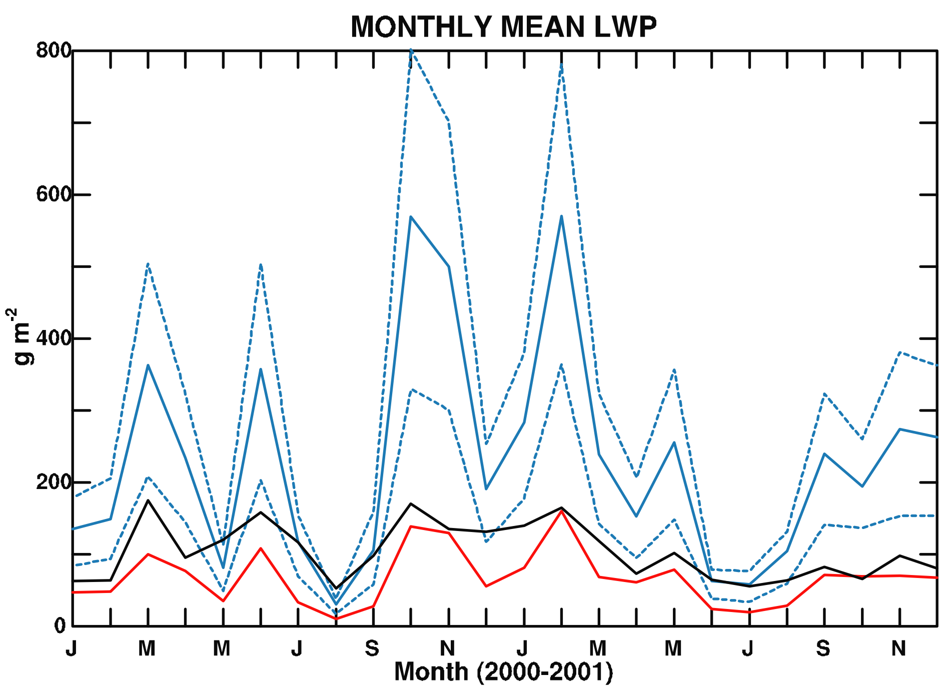

Figure 4. Monthly mean LWP from SCM-S (red), SCM-MC (blue) and ARM MWR measurements (black). The dashed curves are from runs of SCM-MC using values of N_c=100 cm^{-3} (lower curve) and N_c=300 cm^{-3} (upper curve).

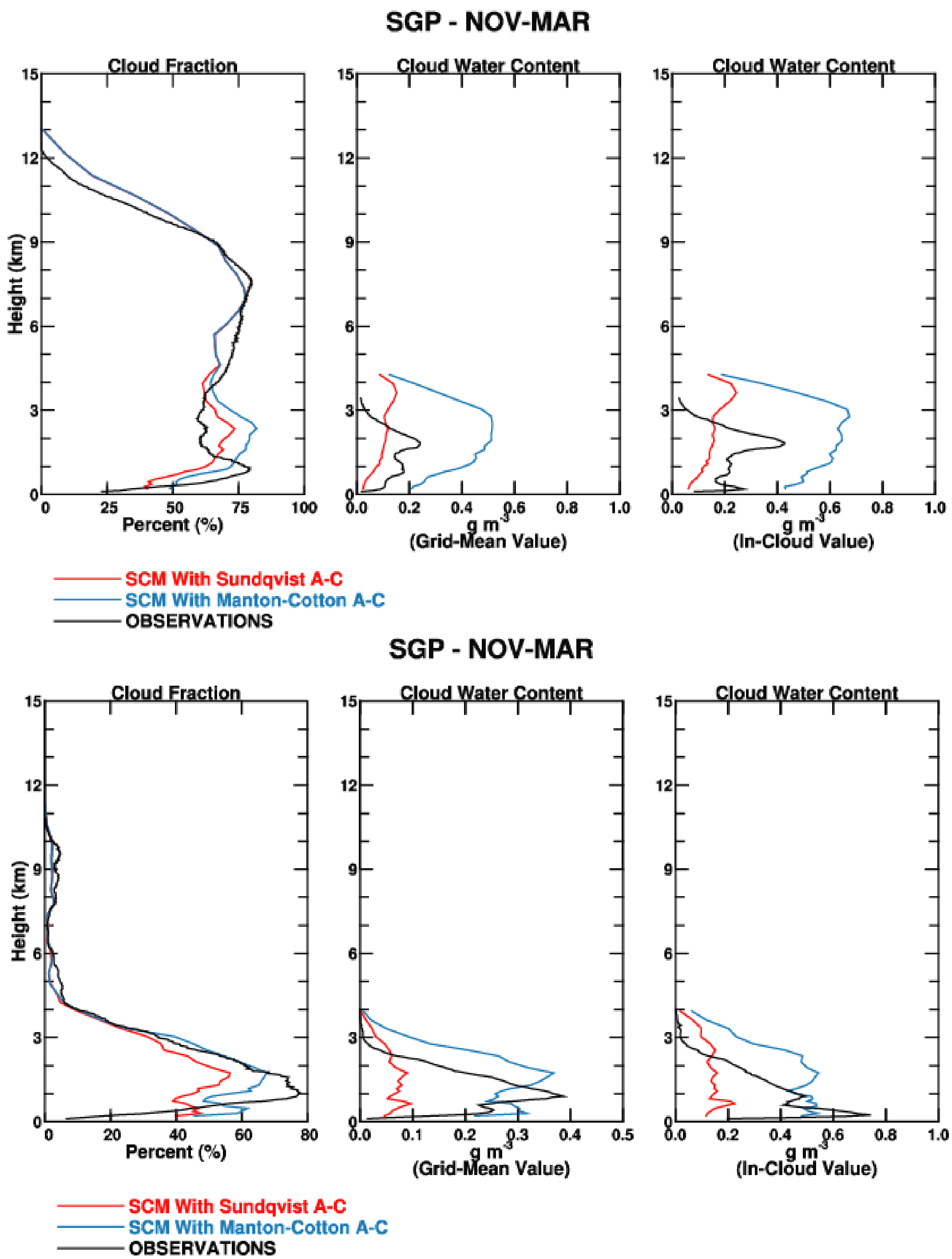

Figure 5. Seasonal mean vertical profiles of cloud fraction, grid-mean LWC, and in-cloud LWC during the months of November-March. The top row contains only those times when shallow clouds were present with no overlying clouds while the bottom row contains only times when shallow clouds were present with overlying clouds also present. Observational data shown in black is derived from ARM MMCR and MWR measurements.

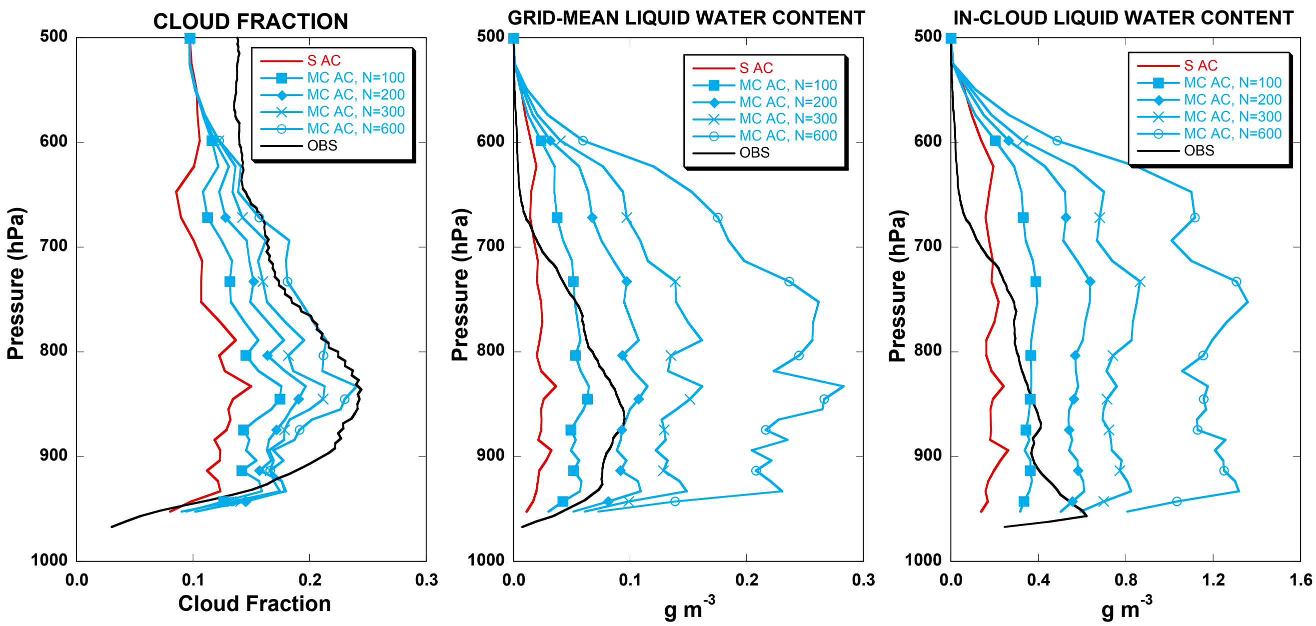

Figure 6. Mean vertical profiles of cloud fraction, in-cloud LWC, and grid-mean LWC during March 2000 for run SCM-S and several runs of SCM-MC using different values of droplet concentration N_c. Values derived from ARM MMCR and MWR measurements are shown in black.

CAM3 Results: Sensitivity to Ice Particle Radius and Ice Cloud Optical Properties

- Incorporated ice cloud microphysics of McFarquhar into CAM3 (CAM3 EXP01). These parameterizations have been tested and validated against ARM data (Iacobellis et al. 2003).
- Significant differences in ice particle effective radius (R_{eff}) are seen between CONTROL and EXP01 in both the SGP and TWP regions (Figures 7 and 8).
- Largest differences in R_{eff} are in the mixed-phase region. McFarquhar parameterization based on cirrus anvil studies and may not be appropriate for mixed-phase region.
- Run EXP01 produces more realistic cloud forcing values in TWP region (Figure 9).
- These preliminary runs of CAM3 were only for one year duration. Longer runs are needed to confirm these results.
- Future work to include using ARM observations to validate model ice particle size and ice water content.

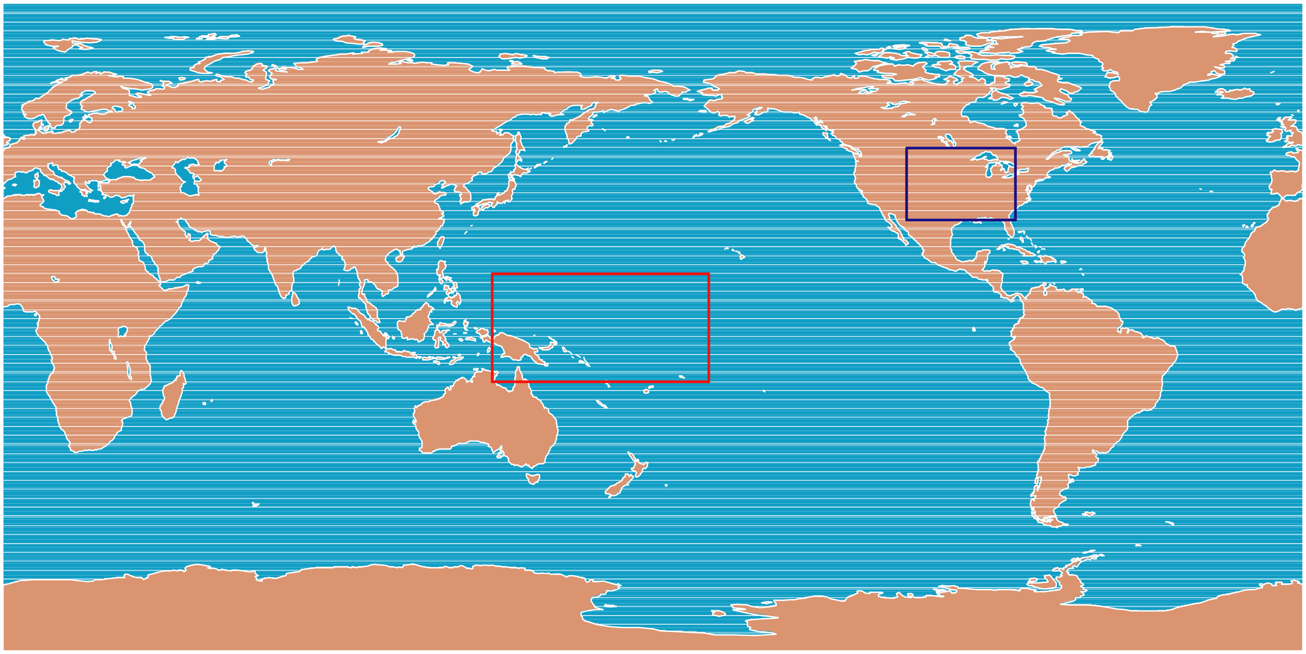

Figure 7. The regions representing the TWP and the Midwestern US/SGP.

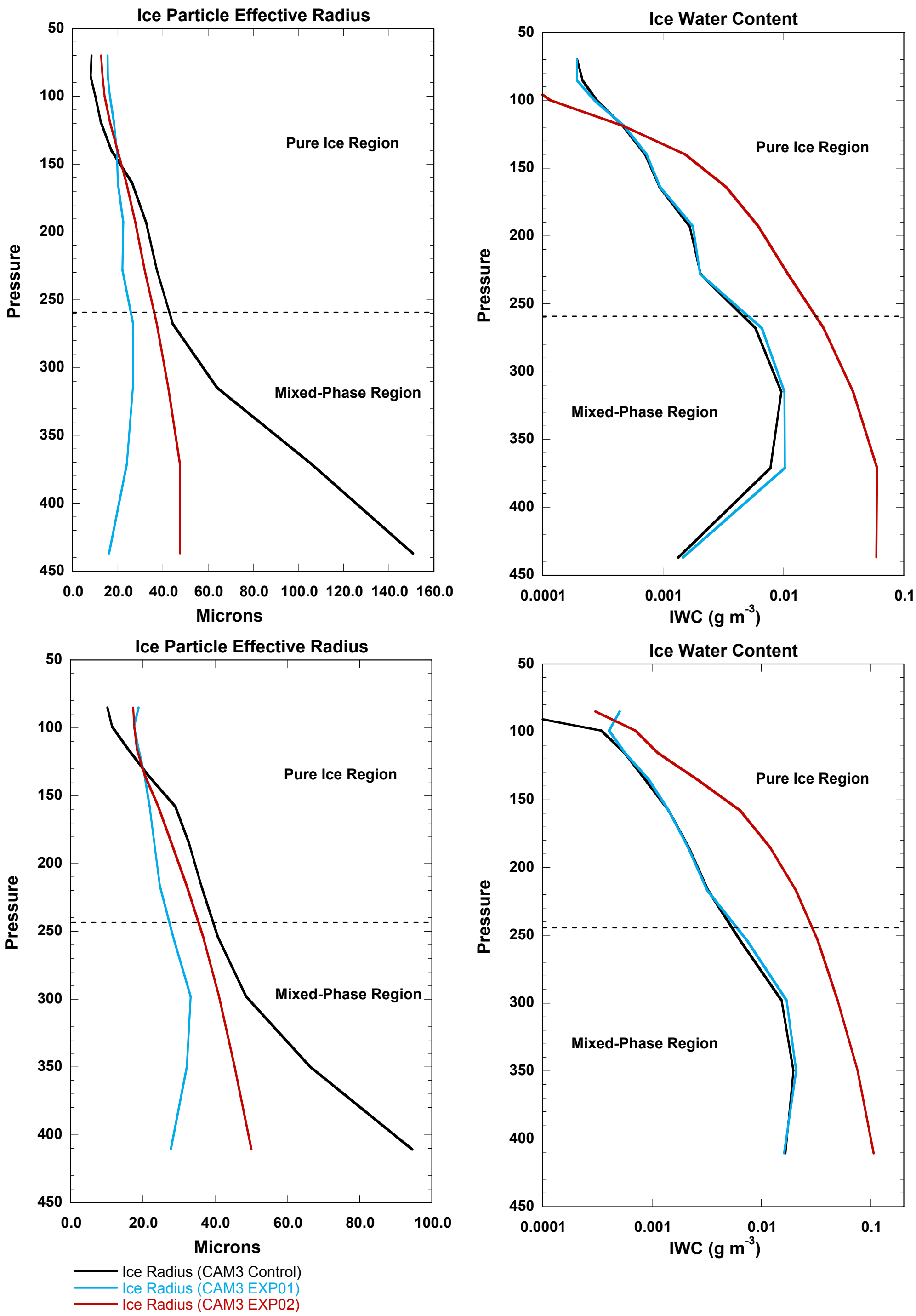

Figure 8. Mean vertical profiles of ice particle radius and ice water content from CAM3 runs CONTROL (black), EXP01 (blue), and EXP02 (red) during July. The top row is averaged over the region representing the TWP and the bottom row is over the region representing the Midwestern U.S. (See Figure 7 for region locations). The horizontal dashed line denotes the top of the mixed-phase region.

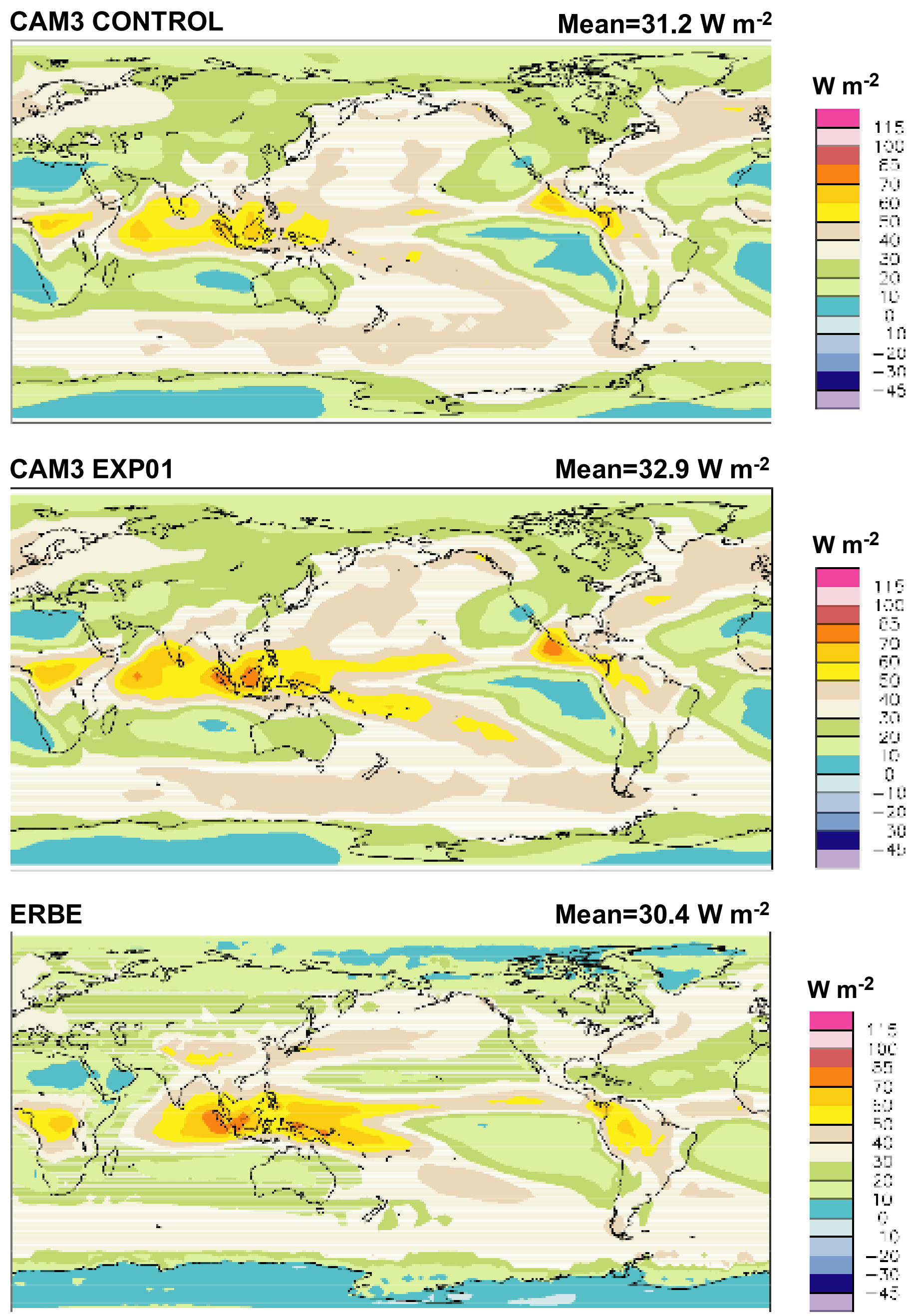

Figure 9. Annual mean longwave cloud forcing from run CONTROL (top panel), EXP01 (middle panel) and ERBE data (bottom panel). Run EXP01 using the McFarquhar ice cloud parameterizations (particle radius and cloud optical properties) produces more realistic values of longwave cloud forcing in the Tropical West Pacific region.

CAM3 Results: Incorporation of Tiedtke Prognostic Clouds and Cloud Water

- Incorporated Tiedtke prognostic cloud/cloud water parameterization into CAM3 (EXP02). This replaces diagnostic clouds and prognostic cloud water of CAM3 CONTROL.

- EXP02 generally produces more clouds and larger individual cloud forcing terms than CAM3 CONTROL and observations (International Climatology Program [ISCCP] and Earth Radiation Budget Experiment [ERBE]) (Figure 10).

- EXP02 produces a significant increase in the cloud ice content (see Figure 8). This is in part due to the production of ice clouds in the Tiedtke scheme from convective detrainment of cloud water. This convectively detrained cloud water was evaporated in CAM3 CONTROL.

- EXP02 produces more realistic values of precipitable water (Figure 11) and cloud liquid water path (Figure 12) compared to CAM3 CONTROL.

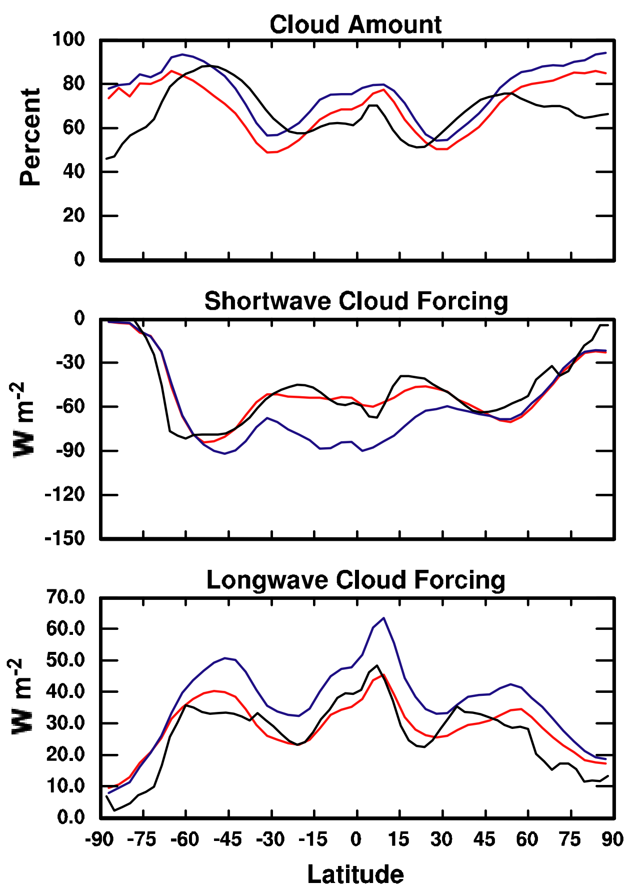

Figure 10. Zonal annual means of cloud amount, shortwave cloud forcing and longwave cloud forcing from CAM Control (red), EXP02 (blue) and observations (black). The cloud amount observations are from ISCCP and the cloud forcing observations are from ERBE.

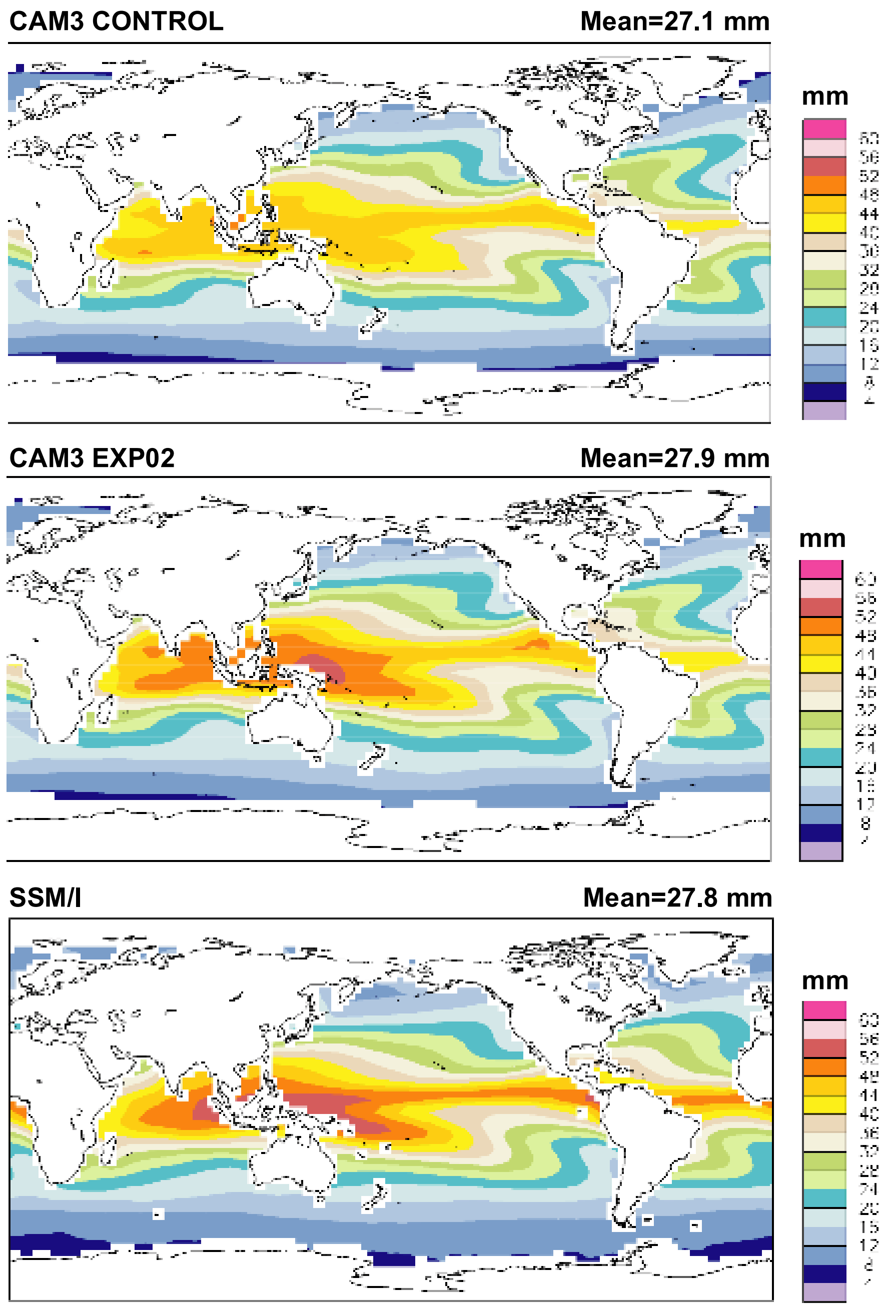

Figure 11. Annual mean precipitable water from run CONTROL (top panel), EXP02 (middle panel) and SSM/I data (bottom panel). Run EXP02 using the Tiedtke prognostic cloud/cloud water parameterization produces more realistic values of precipitable water, particularly in the tropical Pacific and Indian Ocean regions.

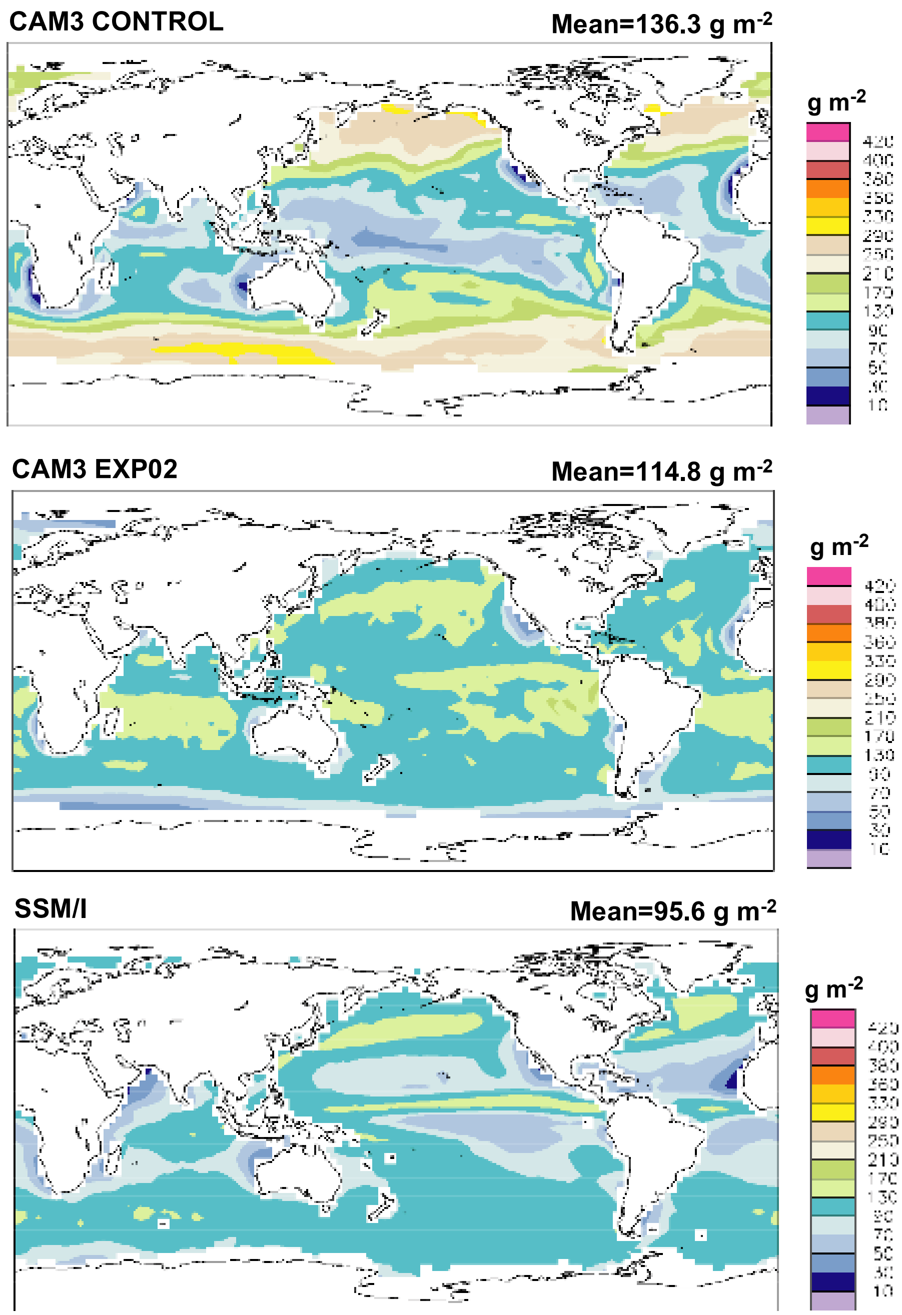

Figure 12. Annual mean cloud liquid water from run CONTROL (top panel), EXP02 (middle panel) and SSM/I data (bottom panel). Run EXP02 using the Tiedtke prognostic cloud/cloud water parameterization produces more realistic values of cloud liquid water, particularly in the mid-latitude storm tracks of both the northern and southern hemispheres.

Conclusions

- Manton-Cotton AC is sensitive to specification of cloud droplet concentration.

- SCM results indicate Manton-Cotton AC performs better during periods of shallow clouds but that Sundqvist AC is more realistic during other periods.

- Ice cloud microphysical parameterizations validated with ARM data result in improved cloud forcing in the tropics in CAM3.

- Incorporation of Tiedtke prognostic cloud/cloud water scheme in CAM3 yields improved representations of both cloud liquid water and precipitable water compared to the CAM3 Control case. Ice clouds produced from convectively detrained ice are now modeled in a more realistic manner which should improve IWC values. This needs to be verified using ARM data.

Future Work

- Investigate why Manton-Cotton AC scheme works well with shallow clouds but not with other cloud types. Possibility of missing microphysics in model.

- Incorporate and evaluate time-dependent cloud droplet concentration in SCM. Can it be parameterized as a function of a routinely measured ARM quantity?

- Produce 20-year runs of CAM3 to validate the results found in these 1-year runs.

- Use ARM measurements of cloud microphysical properties (R_{eff} and IWC) to evaluate CAM3 experiment results. Is the increase in IWC seen in EXP02 realistic.

- Test AC parameterizations in CAM3 and evaluate modeled cloud water results using ARM MMCR measurements.

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

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