FINAL REPORT (DE-FG02-97ER62338): Single-column modeling, GCM parameterizations, and ARM data

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DOE Atmospheric Radiation Measurement (ARM) Program (Period of Support 2002 - 2007)

Introduction

This project has specialized in the development and use of single-column models (SCMs) for evaluating and improving cloud-radiation parameterizations using ARM observations.

Several Ph. D. dissertations have resulted from Somerville's ARM-supported research. During the most recent period of support (2002 - 2007), two more Ph.D. dissertations (by K. M. Shell and J. Berque) were completed and successfully defended in 2004 at Scripps under Somerville's supervision with ARM support.

Major publications from ARM-supported research by Richard C. J. Somerville since 2002:

Xie, S., K-M. Xu, R. T. Cederwall, P. Bechtold, A. D. Del Genio, S. A. Klein, D. G. Cripe, S. J. Ghan, D. Gregory, S. F. Iacobellis, S. K. Krueger, U. Lohmann, J. C. Petch, D. A. Randall, L. D. Rotstayn, R. C. J. Somerville, Y. C. Sud, K. von Salzen, G. K. Walker, A. Wolf, J. J. Yio, G-J. Zhang, M. Zhang, 2002: Intercomparison and evaluation of cumulus parameterizations under summertime midlatitude continental conditions. *Quarterly Journal of the Royal Meteorological Society*, **128**, pp. 1095-1136.

Lane, D. E., K. Goris, and R. C. J. Somerville, 2002: Radiative transfer through broken clouds: Observations and model validation. *Journal of Climate*, **15**, pp. 2921-2933.

McFarquhar, G. M., S. Iacobellis, and R. C. J. Somerville, 2003: SCM simulations of tropical ice clouds using observationally based parameterizations of microphysics. *Journal of Climate*, **16**, pp. 1643-1664.

Iacobellis, S. F., G. M. McFarquhar, D. L. Mitchell, and R. C. J. Somerville, 2003: The sensitivity of radiative fluxes to parameterized cloud microphysics. *Journal of Climate*, **16**, pp. 2979-2996.

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Berque, J., D. Lubin, and R. C. J. Somerville, 2004: Infrared radiative properties of the Antarctic Plateau from AVHRR Data. Part I: Effect of the snow surface. *Journal of Applied Meteorology*, **43**, pp. 350-362.

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Xie, S., M. Zhang, M. Branson, R. T. Cederwall, A. D. Del Genio, Z. A. Eitzen, S. J. Ghan, S. F. Iacobellis, K. J. Johnson, M. Khairoutdinov, S. A. Klein, S. K. Krueger, W. Lin, U. Lohmann, M. A. Miller, D. A. Randall, R. C. J. Somerville, Y. C. Sud, G. K. Walker, A. Wolf, X. Wu, K.-M. Xu, J. J.

Yio, G. Zhang, and J. Zhang, 2005: Simulations of midlatitude frontal clouds by SCMs and CRMs during the ARM March 2000 Cloud IOP. *Journal of Geophysical Research*, **110,** D15S03, doi:10.1029/2004JD005119, 2005.

Xu, K.-M., M. Zhang, Z. A. Eitzen, S. J. Ghan, S. A. Klein, X. Wu, M. Branson, A. D. DelGenio, S. F. Iacobellis, M. Khairoutdinov, W. Lin, U. Lohmann, D. A. Randall, R. C. J. Somerville, Y. C. Sud, G. K. Walker, A. Wolf, S. Xie, J. J. Yio, and J. Zhang, 2005: Modeling springtime shallow frontal clouds with cloud-resolving and single-column models. *Journal of Geophysical Research*, **110**, D15S04, doi:10.1029/2004JD005153.

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Shell, K. M., and R. C. J. Somerville, 2007: Direct radiative effect of mineral dust and volcanic aerosols in a simple aerosol climate model, *Journal of Geophysical Research*, **112**, D03205, doi:10.1029/2006JD007197.

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Summary of recent work

Our overall goal is 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 models. To test recently developed prognostic parameterizations based on detailed cloud microphysics, we have compared SCM (single-column model) (Randall et al., 1996) output with ARM observations at the SGP, NSA and 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 three-dimensional 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 present in this section some brief results of these tests, demonstrating the sensitivity of model performance to changes in parameterizations. 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. A prognostic parameterization of both cloud amount and cloud water together with fully interactive cloud radiative properties based on predicted cloud microphysics is tested in the SCM and incorporated into CAM3. Additionally the parameterization of the autoconversion (AC) process is also examined using the SCM.

Specifications of SCM runs

A series of SCM runs are performed extending from 2000-2001. Each run is 36 hours in length with the first 12 hours used as spin-up (spin-up not included in results) and the start time of each run offset by 6 hours. The forcing data for the SCM is obtained from the ECMWF analysis supplied to the ARM program. These runs were performed at the ARM SGP site with future runs planned for the other ARM sites.

The SCM has a vertical resolution of about 25 hPa (53 vertical layers) and uses a time step of 7.5 minutes. The SCM includes the prognostic cloud parameterization of Tiedtke (1993) with interactive cloud optical properties based on the treatments of Slingo (1989) for water clouds and McFarquhar et al. (2002) for ice clouds. Effective particle radius is parameterized using Bower et al. (1994) for liquid water droplets and McFarquhar (2001) for ice crystals. A series of runs designated SCM-S used the autoconversion parameterization of Sundqvist et al. (1989) to specify the precipitation conversion rate (G_p):

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

where l_c = cloud water content, l_{crit} = critical cloud water content (constant), and c_o^{-1} = characteristic time scale (constant). Another series of runs designated SCM-MC used the autoconversion scheme of Manton and Cotton (1977):

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

where f_c = mean collision frequency (depending on N_c), H = Heaviside step function, l_{cm} = threshold cloud water content (depending on N_c), and N_c = cloud droplet concentration. For further details, see Iacobellis and Somerville (2006).

Specifications of CAM3 runs

A series of three one-year runs using T31 resolution (48 x 96) of CAM3 is examined. The first run used the standard CAM3 configuration (CONTROL). In the second run (EXP01), the ice particle effective radius parameterization was replaced with McFarquhar (2001) scheme and the ice cloud optical properties parameterization replaced with the McFarquhar et al. (2002) scheme. These parameterizations have been tested and validated against ARM data (Iacobellis et al., 2003). The third run (EXP02) was the same as EXP01, but now incorporated the Tiedtke (1993) prognostic cloud and cloud water parameterization.

SCM results

The recent work 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 dominated by shallow frontal clouds. Our SCM results indicate that a Manton-Cotton AC scheme does produce more realistic LWC values for shallow frontal clouds during this period (Figure 1). However, the Sundqvist AC scheme performs better over longer time periods with a variety of cloud conditions (Figure 2).

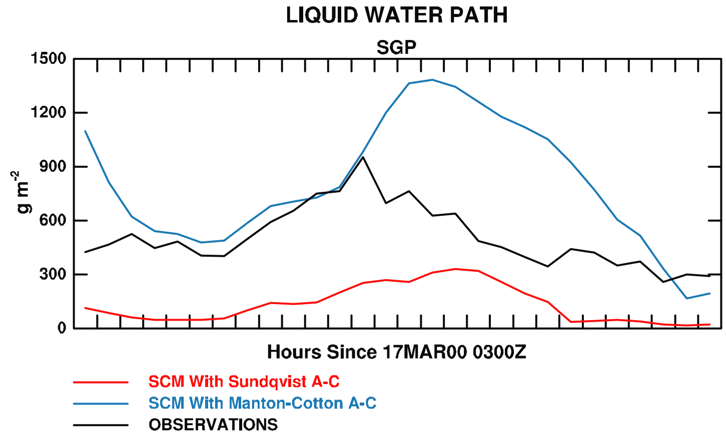

Figure 1. Time evolution of LWP from SCM-S, SCM-MC, and ARM MWR measurements during the 27-hour period.

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 LWC 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 3).

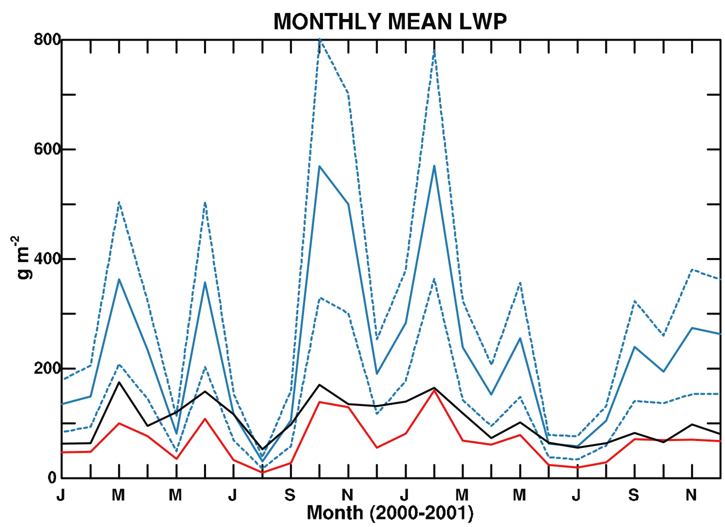

Figure 2. Monthly mean LWP from SCM-S (red), SCM-MC (blue) and ARM MWR measurements (black). The dashed curves are from runs of SCM-MC using values of N_c=100 cm^{-3} (lower curve) and N_c=300 cm^{-3} (upper curve)

The Manton-Cotton AC parameterization is very sensitive to the specification of the cloud droplet concentration, N_c (Figure 4). 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 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 algorithm.

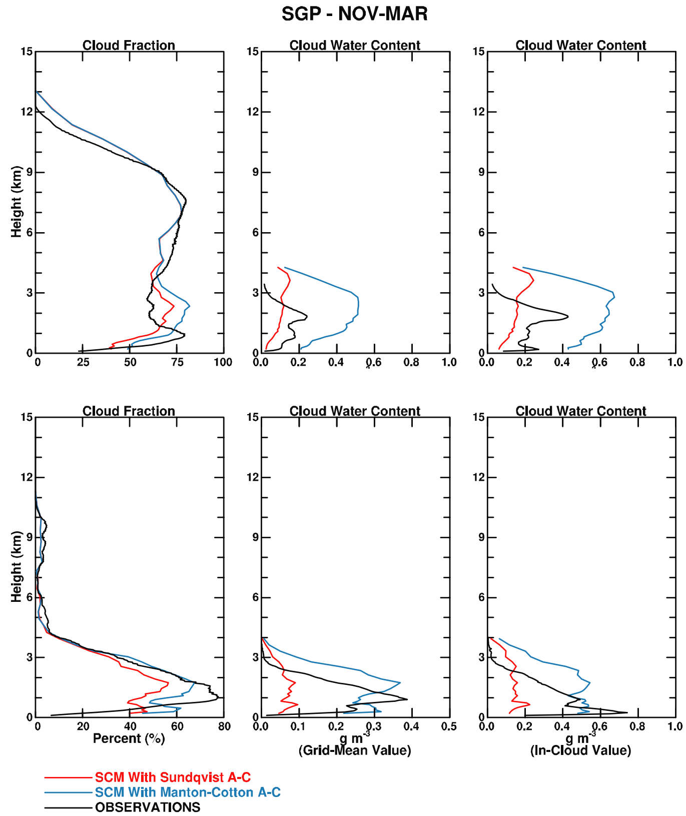

Figure 3. Seasonal mean vertical profiles of cloud fraction, grid-mean LWC, and in-cloud LWC during the months of November-March. The top row contains only those times when shallow clouds were present with no overlying clouds while the bottom row contains only times when shallow clouds were present with overlying clouds also present. Observational data shown in black is derived from ARM MMCR and MWR measurements.

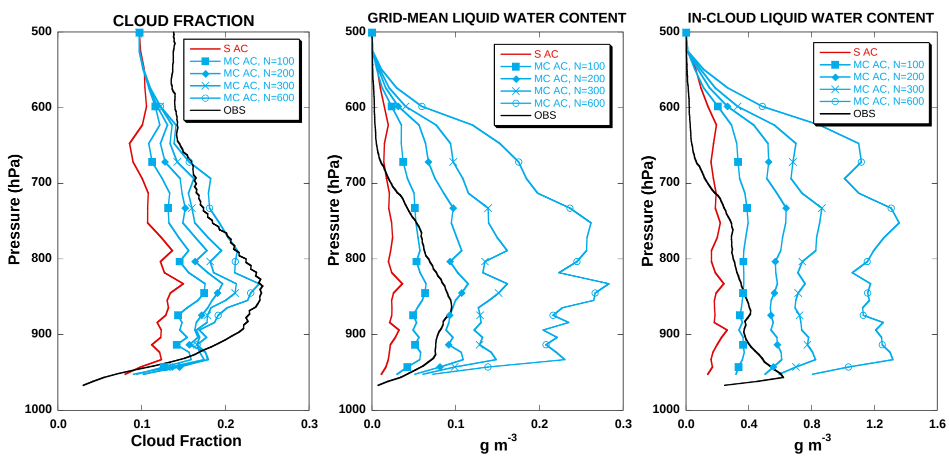

Figure 4. Mean vertical profiles of cloud fraction, in-cloud LWC, and grid-mean LWC during March 2000 for run SCM-S and several runs of SCM-MC using different values of droplet concentration N_c. Values derived from ARM MMCR and MWR measurements are shown in black.

CAM3 results: sensitivity to ice particle radius and ice cloud optical properties

Our CAM3 results indicate that the model results are sensitive to the parameterization of the ice particle radius. Significant differences in ice particle effective radius (R_{eff}) are seen between CONTROL and EXP01 in both the SGP and TWP regions (Figure 5). The cloud forcing values in the TWP region are more realistic from run EXP01 (Figure 6) which used the parameterizations of McFarquhar.

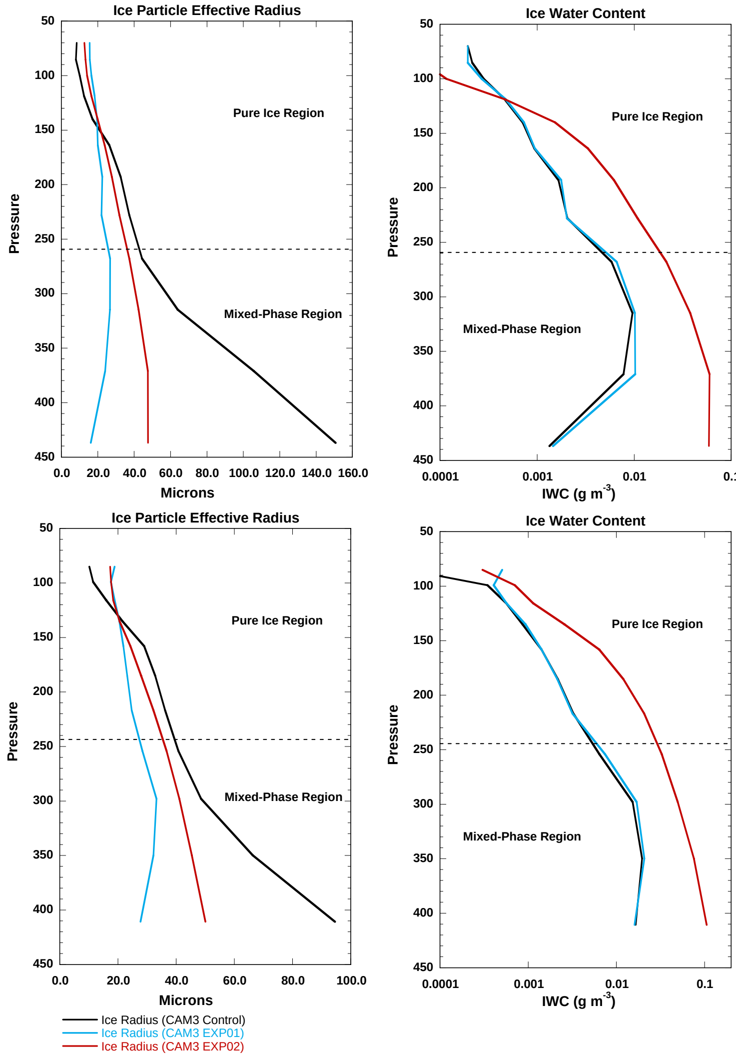

Figure 5. Mean vertical profiles of ice particle radius and ice water content from CAM3 runs CONTROL (black), EXP01 (blue), and EXP02 (red) during July. The top row is averaged over the region representing the Tropical Western Pacific and the bottom row is over the region representing the Midwestern U.S. The horizontal dashed line denotes the top of the mixed-phase region.

These runs of CAM3 were only for 1 year duration and are preliminary. Longer runs on the order of 20 years are needed to confirm these results. Future work will include using ARM observations to validate model ice particle size and cloud liquid/ice water content. Additionally we will also address the parameterization of the ice particle radius in the mixed-phase region (the McFarquhar parameterization is based on cirrus anvil studies and may not be appropriate for the mixed-phase region).

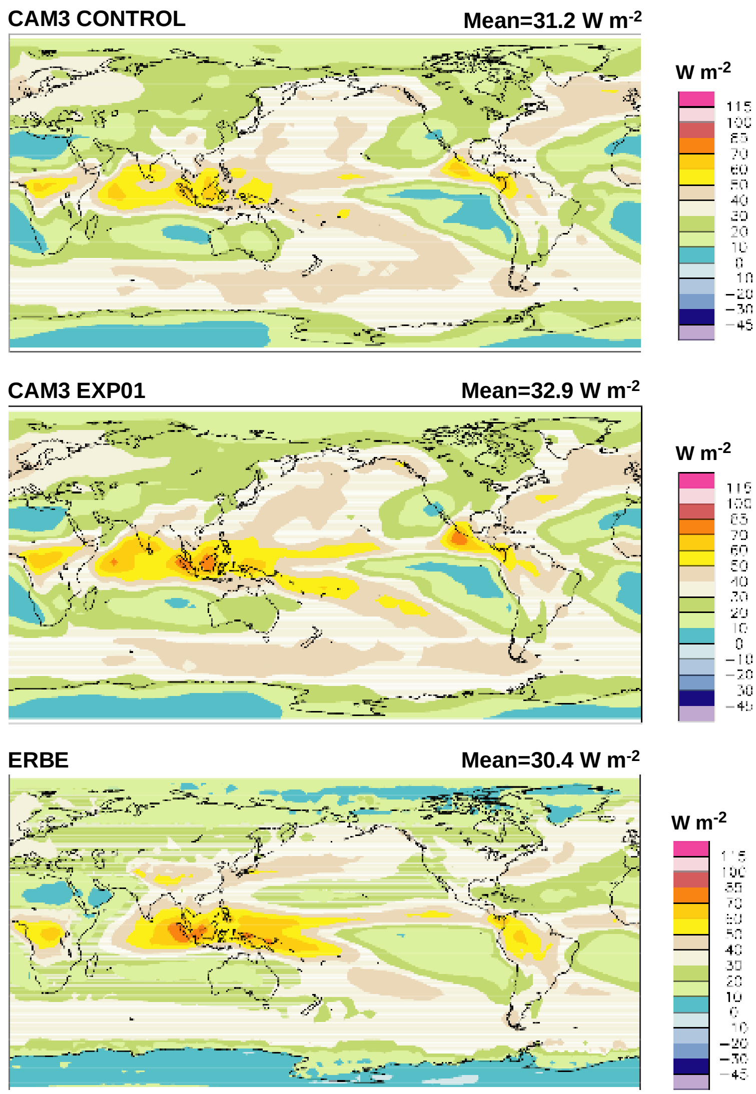

Figure 6. Annual mean longwave cloud forcing from run CONTROL (top panel), EXP01 (middle panel) and ERBE data (bottom panel). Run EXP01 using the McFarquhar ice cloud parameterizations (particle radius and cloud optical properties) produces more realistic values of longwave cloud forcing in the Tropical West Pacific region

CAM3 results: incorporation of Tiedtke prognostic clouds and cloud water

The incorporation of the Tiedtke prognostic cloud/cloud water parameterization into CAM3 (EXP02) produced results with more clouds and larger individual cloud forcing terms than CAM3 CONTROL and observations (ISCCP and ERBE) (Figure 7). Run EXP02 produces a significant increase in the cloud ice content (see Figure 5). 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. Additionally, EXP02 produces more realistic values of precipitable water (Figure 8) and cloud liquid water path (Figure 9) compared to CAM3 CONTROL.

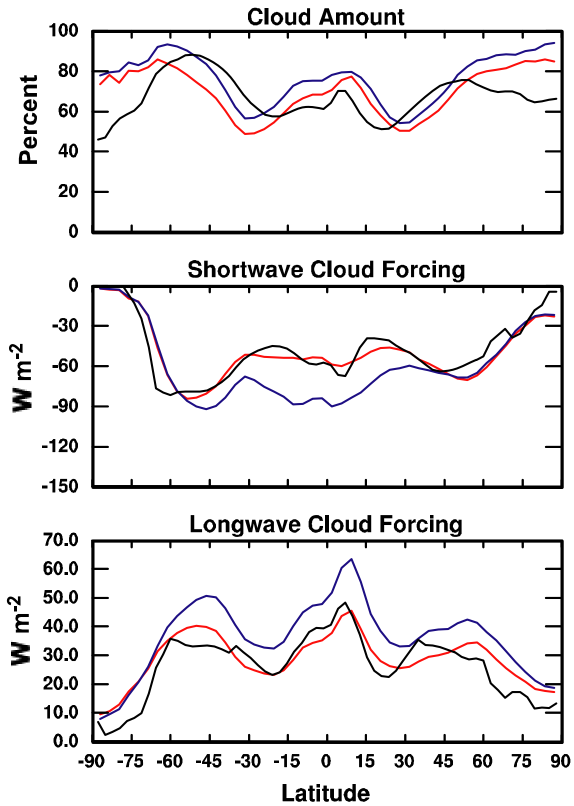

Figure 7. Zonal annual means of cloud amount, shortwave cloud forcing and longwave cloud forcing from CAM Control (red), EXP02 (blue) and observations (black). The cloud amount observations are from ISCCP and the cloud forcing observations are from ERBE.

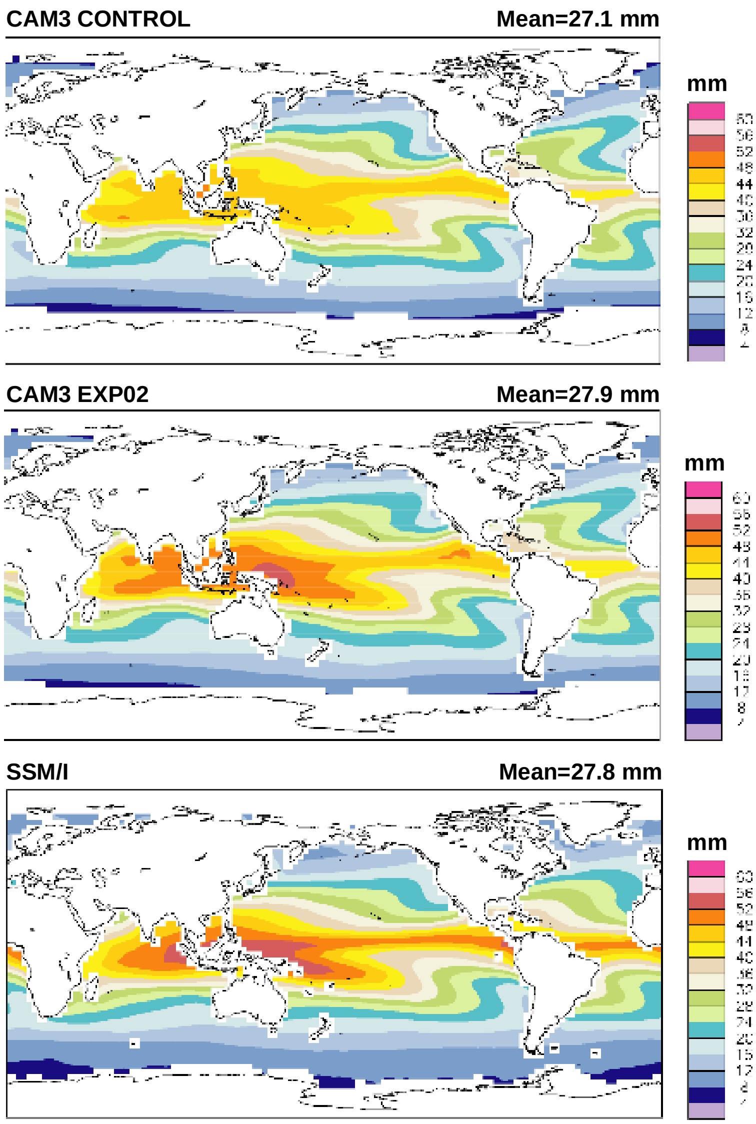

Figure 8. Annual mean precipitable water from run CONTROL (top panel), EXP02 (middle panel) and SSM/I data (bottom panel). Run EXP02 using the Tiedtke prognostic cloud/cloud water parameterization produces more realistic values of precipitable water, particularly in the tropical Pacific and Indian Ocean regions.

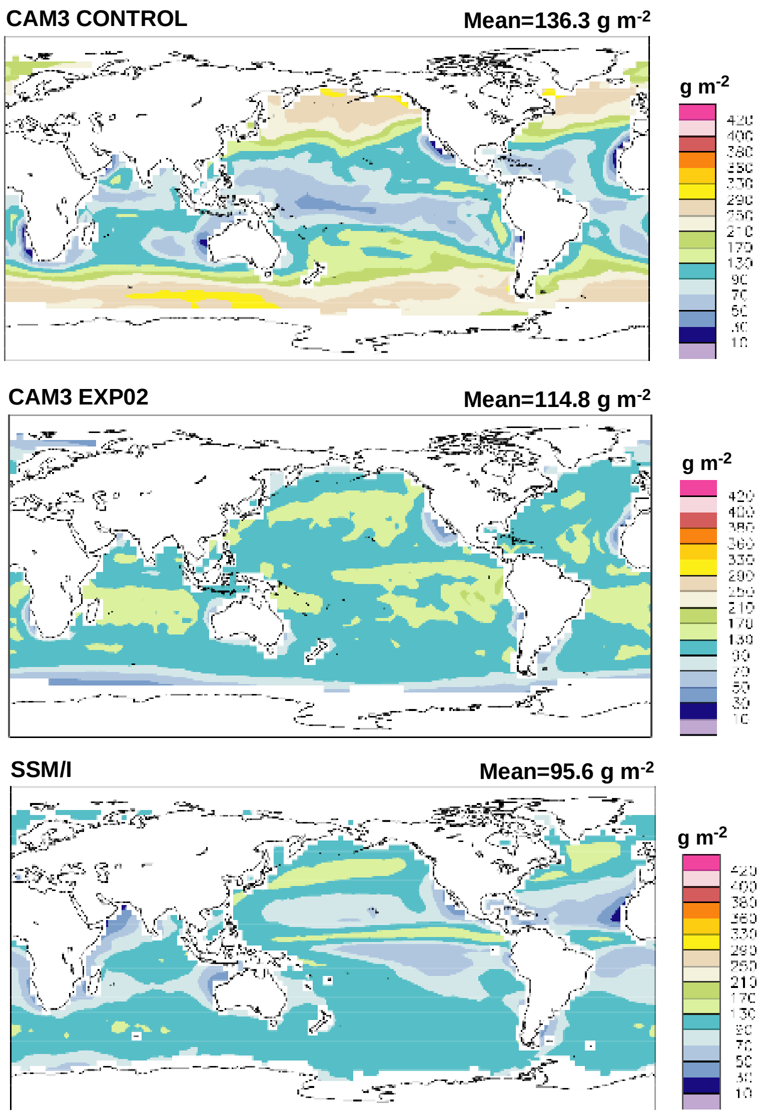

Figure 9. Annual mean cloud liquid water from run CONTROL (top panel), EXP02 (middle panel) and SSM/I data (bottom panel). Run EXP02 using the Tiedtke prognostic cloud/cloud water parameterization produces more realistic values of cloud liquid water, particularly in the mid-latitude storm tracks of both the northern and southern hemispheres.

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