JAMES | Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE
10.1029/2018MS001578

**Special Section:**
Community Earth System Model version 2 (CESM2) Special Collection

**Key Points:**
- Single Column Models are useful tools for model analysis
- The SCM in CESM is flexible for development and science analysis
- Simulated clouds are sensitive to the settings in the turbulence parameterization

**Correspondence to:**
A. Gettelman,
andrew@ucar.edu

**Citation:**
Gettelman, A., Truesdale, J. E., Bacmeister, J. T., Caldwell, P. M., Neale, R. B., Bogenschutz, P. A., & Simpson, I. R. (2019). The Single Column Atmosphere Model version 6 (SCAM6): Not a scam but a tool for model evaluation and development. *Journal of Advances in Modeling Earth Systems*, *11*. https://doi.org/10.1029/2018MS001578

Received 29 NOV 2018
Accepted 23 FEB 2019
Accepted article online 22 FEB 2019



# The Single Column Atmosphere Model Version 6 (SCAM6): Not a Scam but a Tool for Model Evaluation and Development

**A. Gettelman[1], J. E. Truesdale[1], J. T. Bacmeister[1], P. M. Caldwell[2], R. B. Neale[1], P. A. Bogenschutz[2], and I. R. Simpson[1]**

[1]National Center for Atmospheric Research, Boulder, CO, USA, [2]Lawrence Livermore National Laboratory, Livermore, CA, USA

**Abstract** The Single Column Atmosphere Model (SCAM) is a single column model version of the Community Atmosphere Model (CAM). Here we describe the functionality and features of SCAM6, available as part of CAM6 in the Community Earth System Model, version 2 (CESM2). SCAM6 features a wide selection of standard cases, as well as the ability to easily configure a case specified by the user based on a particular point in a CAM 3-D simulation. This work illustrates how SCAM6 reproduces CAM6 results for physical parameterizations, mostly of moisture and clouds. We demonstrate how SCAM6 can be used for model development through different physics selections, as well as with parameter sweep experiments to highlight the sensitivity of cloud properties to the specification of the vapor deposition process in the cloud microphysics. Furthermore, we use SCAM6 to illustrate the sensitivity of CAM6 cloud radiative properties and precipitation to variable drop number (cloud microphysics properties). Finally, we illustrate how SCAM6 can be used to explore critical emergent processes such as cloud feedbacks and show that CAM6 cloud responses to surface warming in stratus and stratocumulus regimes are similar to those in CAM5. CAM6 has a larger response in the shallow cumulus regime than CAM5. CAM6 cloud feedbacks in the shallow cumulus regime are sensitive to turbulence parameters. SCAM6 is thus a valuable tool for model development, evaluation, and scientific analy sis and an important part of the model hierarchy in Community Earth System Model, version 2.

**Plain Language Summary** This paper describes and documents a simplified version of a global climate model, which contains only a single column of the atmosphere. This Single Column Atmosphere Model is a very effective tool for developing, evaluating, and understanding the complex interactions and processes that are represented by physical parameterizations in the full model. The paper describes how the single column is constructed and presents detailed comparisons of the single column model to the full three-dimensional model. Example methods and techniques for using Single Column Atmosphere Model to understand the full 3-D model are presented, from simple to complex analyses.

## 1. Introduction

Comprehensive General Circulation Models (GCMs), now Earth System Models (ESMs), are tools for understanding and simulating the climate system. But development and understanding of processes in such complex models is daunting. Often, increased realism comes at the expense of increased complexity in ESMs, making evaluation and targeted model improvement difficult. There are many ways to reduce those degrees of freedom to isolate specific processes and interactions. A useful tool to understand atmospheric parameterizations is the Single Column Model (SCM). SCMs simulate the unresolved subgrid-scale processes in a column of the atmosphere using parameterized physics, including clouds, turbulence, and radiation. SCMs evolved from energy balance models (e.g., Manabe & Strickler, 1964). SCMs typically specify the dynamical state and tendencies, removing dynamics-physics interactions. M. Zhang et al. (2016) provides a nice history on the use of SCMs (as well as details of how forcing is produced; see Table 1). Throughout this introduction, sample references are not exhaustive (this is not a review) but focused on relevant examples from recent work with the Community ESM (CESM).

SCMs generally contain identical physical parameterizations to full ESMs but simplify the dynamic forcing and reduce the spatial dimension to a single column of an ESM (Hack & Pedretti, 2000). SCMs are valuable

**Table 1**
*List of Single Column Atmosphere Model Intensive Observation Period Cases*

| Name | Long name | Lat | Lon | Date | Length | Reference | Type |
|---|---|---|---|---|---|---|---|
| arm95 | ARM Southern Great Plains | 36 | 263 | Jul 1995 | 18 | M. Zhang et al. (2016) | Land convection |
| arm97 | ARM Southern Great Plains | 36 | 263 | Jun 1997 | 30 | M. Zhang et al. (2016) | Land convection |
| atex | Atlantic Trade Wind Exp | 15 | 345 | Feb 1969 | 2 | Augstein et al. (1973) | Shallow cumulus |
| bomex | Barbados Ocean and Met Exp | 15 | 300 | Jun 1969 | 5 | Holland and Rasmusson (1973) | Shallow cumulus |
| cgilsS12 | CFMIP-GASS SCM/LES Intercomp | 35 | 235 | Jul 1997 | 30 | M. Zhang et al. (2013) | Stratus |
| cgilsS11 | CFMIP-GASS SCM/LES Intercomp | 32 | 231 | Jul 1997 | 30 | M. Zhang et al. (2013) | Stratocumulus |
| cgilsS6 | CFMIP-GASS SCM/LES Intercomp | 17 | 211 | Jul 1997 | 30 | M. Zhang et al. (2013) | Shallow cumulus |
| dycomsRF02 | Dynamics of Marine StratoCu | 32 | 239 | Jul 11 2001 | 2 | Stevens et al. (2003) | Stratocumulus |
| dycomsRF01 | Dynamics of Marine StratoCu | 32 | 239 | Jul 15 2001 | 2 | Stevens et al. (2003) | Stratocumulus |
| gateIII | GATE Phase III | 9 | 336 | Aug 1974 | 20 | Thompson et al. (1979) | Tropical convection |
| mpace | Mixed Phase Arctic Clouds Exp | 71 | 206 | Oct 2004 | 17 | Verlinde et al. (2007) | Arctic |
| rico | Rain and Cumulus over Oceans | 18 | 299 | Dec 2004 | 3 | Rauber et al. (2007) | Shallow cumulus |
| sparticus | Small Particles in Cirrus | 37 | 263 | Apr 2010 | 30 | Mace et al. (2009) | Cirrus, convection |
| twp06 | Tropical W. Pacific Convection | -12 | 131 | Jan 2006 | 26 | May et al. (2008) | Tropical convection |
| togaII | Tropical Ocean Global Atmosphere | -2 | 154 | Dec 1992 | 21 | Webster and Lukas (1992) | Tropical convection |

*Note.* Length is given in days. ARM = Atmospheric Radiation Measurement; GASS = Global Atmospheric System Studies; SCM = Single Column Model; LES = Large Eddy Simulation

tools for model evaluation and development, showing how changes to model physical parameterizations impact model solutions (e.g., Bogenschutz et al., 2012; Jess et al., 2011). SCMs are invaluable in developing complex code because they typically run all the physical parameterizations in the atmosphere identically to the full GCM model configuration and perform all necessary checks for energy and mass balance due to the atmospheric physics. Most errors can be rapidly detected and also rapidly diagnosed with debugging tools which work on single processors. An SCM provides rapid feedback on model and code changes in minutes using modest computer resources, compared to running the full GCM, but is representative of GCM results (Neggers, 2015).

Several intercomparisons of SCMs and evaluation against observations and Large Eddy Simulation have been performed within the Global Cloud System Studies project, now called Global Atmospheric System Studies. Among many examples, Derbyshire et al. (2004) used SCMs and Cloud Resolving Models to test the sensitivity of moist atmospheric convection to future climates. Guichard et al. (2004) used similar models (SCMs and Cloud Resolving Models) to evaluate the diurnal cycle. Neggers et al. (2017) looked at SCM performance of boundary layer schemes in the subtropical marine low-level cloud transition.

SCMs can be used as a tool to understand critical model processes (e.g., Brient & Bony, 2012; M. Zhang & Bretherton, 2008) as well as to compare different parameterization suites or parameter settings with the same dynamic forcing. For example, M. Zhang et al. (2013) used SCMs to understand the mechanisms behind low cloud feedbacks in GCMs. Sensitivity studies with parameter sweep experiments can also elucidate model sensitivity to parameters, such as recently done with Single Column Atmosphere Model, version 5 (SCAM5) by Guo et al. (2014) to analyze parameterizations for Community Atmosphere Model, version 6 (CAM6). Model evaluation is enabled with direct comparisons to observations, such as an intercomparison of cloud microphysics by Klein et al. (2009) where 17 SCMs are compared to observations, including several versions of SCAM. Evaluation for development of new model parameterizations is also commonly performed (e.g., Gettelman et al., 2008; Hourdin et al., 2013).

The advantages of an SCM go beyond reducing complexity as a computationally efficient way to understand many atmospheric physical processes noted in many studies above. SCM's are commonly used to specify a particular dynamical state to enable better comparisons to observations at specific locations and times (e.g., Bogenschutz et al., 2012; Gettelman et al., 2008). Because SCMs do not require large computing resources, they can be run quickly on smaller platforms and provide an ideal framework for model exploration and early stage development of atmospheric parameterizations, as well as sensitivity experiments to sample a large parameter space, especially for multiple different uncertain parameters. SCMs are limited however in elucidating remote impacts and coupling between atmospheric regimes, since such interactions between columns need to be modeled with multiple SCMs or specified interactions. SCMs are also limited in understanding physical-dynamical interactions and where 3-D transport effects and feedbacks come into play. These benefits and limitations will be highlighted in what follows.

The SCM provided as part of CESM is a configuration of the full atmospheric component model, the CAM, and is called the SCAM. SCAM has a long history of being used for parameterization development in CAM (e.g., Bogenschutz et al., 2012; Gettelman et al., 2008; Song & Zhang, 2011), parameter sensitivity tests (e.g., Guo et al., 2014), and analysis of perturbations in idealized tests (e.g., Hack & Pedretti, 2000; M. Zhang & Bretherton, 2008). SCAM has also participated in comparisons across SCMs, for example, to diagnose Cloud Feedbacks (M. Zhang et al., 2013).

Here we describe SCAM version 6 (SCAM6 or just SCAM). Section 2 describes the SCAM formulation, construction, and the different configurations of SCAM. Section 3 provides selected results showing how SCAM6 is used for model development and scientific analysis, and section 4 is a summary with some prospects for future work.

## 2. Model Description

SCAM6 is a version of CAM6 that includes the entire physics parameterization suite and a reduced dynamics component that handles vertical advection within the column. Any configuration of the physical parameterizations available in the full CAM model is also available with SCAM. This includes, for example, the standard CAM6 physics suite but also options for different convective parameterizations (e.g. UNICON, Park et al., 2014) or different cloud microphysics in convection (Song & Zhang, 2011). SCAM can also be run with the CAM5 physical parameterization suite (Neale et al., 2010). SCAM6 runs with the full interactive column radiation code and radiation interfaces for clouds and aerosols.

SCAM6 predicts temperature, humidity, and momentum within a column using large-scale tendencies that are provided as forcing terms along with local tendencies produced by the parameterized physics. Vertical advection is computed by the Eulerian dynamical core. The forcing fields are usually derived from an Intensive Observation Period (IOP), often a field project. For purposes of this work, "IOP" refers to the forcing file and initial conditions used to drive the dynamics for the SCM.

When SCAM was first developed, the Eulerian dynamical core was the default for CAM. It was designed to produce a 3-D forecast using separate routines for vertical and horizontal transports (Hack & Pedretti, 2000). Since the horizontal forcing and vertical pressure fields were already provided by the IOP, SCAM only needed the vertical transport subroutine in the Eulerian core, which can be used without modification in SCAM. The large-scale forcing from a CAM run using the Eulerian dynamical core (including the pressure field), fed into SCAM, can reproduce the CAM solution for a single column identically (bit-for-bit precision). This bit-for-bit test is still used today to ensure SCAM is configured correctly.

The Eulerian dynamical core differs from the default Finite Volume (FV) dynamical core used in CAM6. As a result, the large-scale forcing from a CAM run with the FV core does not reproduce bit for bit an FV CAM6 simulation. There are numerical and time step differences between the Eulerian and FV dynamical cores. The continued use of the Eulerian dycore is seen as sufficient for the purposes of vertical transport in SCAM. However, in the future, it is desirable to make SCAM more dynamical core agnostic and make sure the vertical advection does not rely on the dynamical core.

### 2.1. Forcing

SCAM predicts the evolution of temperature (T), moisture (Q), and momentum (U,V) in a single column using a combination of dynamics and physical parameterization forcings. The dynamic forcing is split into two pieces, the large-scale horizontal advection of the prognostic variables (U,V, T, and Q) is prescribed from an IOP data set, and the vertical advection tendencies are calculated by the Eulerian and/or Lagrangian cores using a vertical pressure field also provided by the IOP. By default, SCAM uses the Lagrangian core to calculate the vertical advection of Q and the Eulerian core to handle the vertical advection of U,V and T. Alternatively, SCAM can be configured to use specified vertical advection tendencies if they are available from the IOP. The physics parameterization suite provides the subgrid-scale tendencies which SCAM then uses to predict the evolution of temperature (T), moisture (Q), and momentum (U,V) in a single column. SCAM does not predict any advective tendencies on prognostic species other than specific humidity. These other prognostic species include cloud mass and number concentrations, aerosol mass and number concentrations, and chemical constituents. As will be discussed below, the only species that strongly affect solutions that are not constrained by the physics are the aerosol species.

The single column functionality was designed to be flexible and gives the user additional control over the complexity available for the model configuration. For instance, there are run time options that allow substitution of additional external forcings (e.g., surface fluxes) from the IOP file in place of model calculated ones. Additionally, SCAM has the ability to further constrain the solution by relaxing back to or substituting prescribed values of state variables (U,V,T,Q) in place of the prognosed ones.

In the default configuration, to account for missing or incorrect dynamical forcing, SCAM6 temperature fields are relaxed to temperatures in the IOP file with an *e*-folding time of 10 days at the surface to 2 days at the top of the model. The longer relaxation time scale near the surface allows the physics to dominate the tendencies, while the shorter time scale in the upper troposphere and stratosphere keeps temperatures close to observed in the absence of correct dynamical forcing. Because of long time scales for radiative relaxation and tracer transport in this region, slight errors in the dynamical forcing can result in large solution errors. This can happen if the IOP forcing was derived from a different dynamical core or radiation scheme in CAM or even from another model or analysis system.

Most SCM cases are run for environments where the dynamical forcing is described and invariant or for short timescales where slow dynamical effects do not matter. For longer SCM simulations and in environments where dynamical forcing is not well described, such as the upper troposphere and lower stratosphere, unless the forcing is nearly exactly consistent with model radiation and vertical advection fields, there will be imbalances. This is what we have found in practice in SCAM. Variational analysis in another model system used often to balance the forcing does not seem to be sufficient to accurately prevent drift of upper tropospheric temperatures in SCAM.

Specific humidity (Q) is generally allowed to be fully prognostic in SCAM6, though it can be prescribed. In fact, the infrastructure exists in SCAM to fix or relax any prognostic variable using the same mechanism that is used for temperature. See the SCAM section of the CAM6 users guide (http://www.cesm.ucar.edu/models/cesm2/atmosphere/) for more details on the specific namelist parameters.

In summary, SCAM uses advective forcings for momentum (U,V) and vertical advection from the Eulerian dynamical core. This is slightly different than the forcing methods investigated by Randall and Cripe (1999), being a hybrid of "revealed forcing" for the horizontal, with calculated vertical motion. Randall and Cripe (1999) found revealed forcing to yield good results with the simplest method. In the default mode, temperatures are relaxed to the input temperatures, and the physical parameterization tendencies for T,Q, other water substances (clouds), and trace constituents applied. Q can be relaxed as well to the input if desired.

In section 3.1, we illustrate how the construction of the forcing is used to reproduce temperatures and clouds in a free-running model simulation.

### 2.2. Aerosols

SCAM6 uses the full Modal Aerosol Model (MAM) aerosol model from CAM6 (Liu et al., 2012). As such, it needs a distribution of aerosols that is realistic, otherwise, stratiform cloud simulations will deviate significantly from a simulation with fully interactive aerosols (Lebassi-Habtezion & Caldwell, 2015). Aerosols are initialized based on climatological profiles. The standard cases (see below) use a monthly average aerosol profile for the relevant month at each location derived from a present day CAM6 simulation. The surface emissions for SCAM are taken from standard CAM6 aerosol emissions data sets for a particular point, typically an aerosol climatology, so the monthly mean for a given location is used.

The default treatment is to relax the aerosol species (mass and number) to the initial conditions with the same relaxation profile as for temperature, that is, with an *e*-folding time of 10 days at the surface to 2 days at the top of the model. The longer relaxation time scale near the surface allows aerosol emissions and the prognostic aerosol microphysics, sources, and sinks (wet and dry deposition) to evolve with the atmospheric physical parameterizations and humidity. Conversely, relaxing to climatology in the upper troposphere where aerosol advection is not resolved by SCAM is more important for the time mean distribution of aerosols. Note that in the future, it may be desirable for SCAM to include advective tendencies for aerosols to provide closer correspondence with 3-D cases or for situations with strong aerosol advection.

In section 3.1, we illustrate how the construction of the forcing is used to reproduce aerosols in a free-running model simulation.

SCAM can be run without aerosols in the full physics model (i.e., zero aerosols) or no aerosols just in the radiation code. In the former case (no aerosols), the cloud microphysics should be set to have fixed droplet and crystal numbers to ensure a reasonable simulation.

### 2.3. IOP Forcing

SCAM6 is enabled with precomputed forcing files from a number of IOP cases, drawn from field experiments (Table 1) designed to simulate a particular regime in the climate system. These experiments and the resultant IOP forcing files span multiple climate regimes from tropical convection and cirrus cases (TWP06 and TOGA) to Arctic mixed phase cloud cases (MPACE). Several are idealized experiments only 2 days long (ATEX and DYCOMS), while others span a month (ARM97 and SPARTICUS).

### 2.4. User-Generated Forcing

In addition to these precomputed cases, it is possible to create additional user cases. Details are contained in Appendix A or in the CAM6 user guide. A user would typically generate an IOP case for two reasons: first, to add a new case for comparison to field observations or, second, to debug or analyze the behavior of a single specific column in a global model simulation.

To reproduce a CAM simulation, the full GCM is run with specified outputs needed for SCAM (see Appendix A). Because of the different dynamical core used with SCAM, a script needs to be run to modify the CAM output file to be appropriate as a SCAM IOP forcing (input) file. In addition, aerosol forcing for SCAM should be generated with another script that takes mean aerosol outputs from CAM and reformats them into an initial condition file appropriate to the Eulerian dynamical core for SCAM. Both these scripts are available in the CESM2.1 code (see Appendix A).

In the case of reproducing a specific model simulation, the SCAM6 sample scripts allow a user to capture the appropriate forcing fields from a global model run and reformat them to be read in as a SCAM forcing file. SCAM6 will not reproduce answers bit for bit because of inconsistencies in the formulation of time stepping and vertical advection between the FV and Eulerian dynamical cores. The Eulerian core uses a leapfrog time scheme, so that the physics time step is always 2× the dynamics time step. The large-scale vertical advection calculation is also different between the Eulerian and FV cores. Another reason SCAM6 cannot reproduce CAM6 results bit-by-bit is that in the GCM, there is horizontal diffusion not present in SCAM. Although SCAM6 cannot reproduce a column of CAM6 in a bit-for-bit manner, it should come very close to reproducing the climate and high frequency variability of the original simulation, as illustrated in section 3.1.

In the case of observations of a specific place and time for comparison to field observations at a particular location, the simplest way to create a case that reproduces observed meteorological states (T and U,V) is to run CAM in a “nudged” or “specified dynamics” mode. This generates the forcing and initial conditions corresponding to a particular meteorological state at a particular location. The advanced user can also create an observed case by directly modifying/creating the IOP file.

## 3. SCAM Results

Here we show sample results and applications of SCAM6. Along the way, we demonstrate features of CAM6. We start with the reproduction of a particular CAM simulation and demonstrate the creation of a IOP case (section 3.1). We then illustrate how SCAM6 provides a platform for testing parameterizations (section 3.2), with changing parameters and even changing entire parameterizations. We also show how SCAM6 can quantify sensitivities of critical processes, such as aerosol cloud interactions (Twomey, 1977) in section 3.3, and even provide useful information on critical climate processes, such as cloud feedbacks (section 3.4).

### 3.1. Reproducing CAM Simulations With Relaxation

First, we demonstrate how SCAM6 with the standard configuration and default relaxation of temperature, specific humidity, and aerosols reproduces a CAM6 simulation. The example also illustrates how a user-generated IOP can be used to reproduce a particular model simulation. For this case, CAM6 was run in a nudged configuration using the National Aeronautics and Space Administration (NASA) Modern Era Retrospective ReAnalysis version 2 winds (Molod et al., 2015; Rienecker et al., 2011) interpolated to the 32

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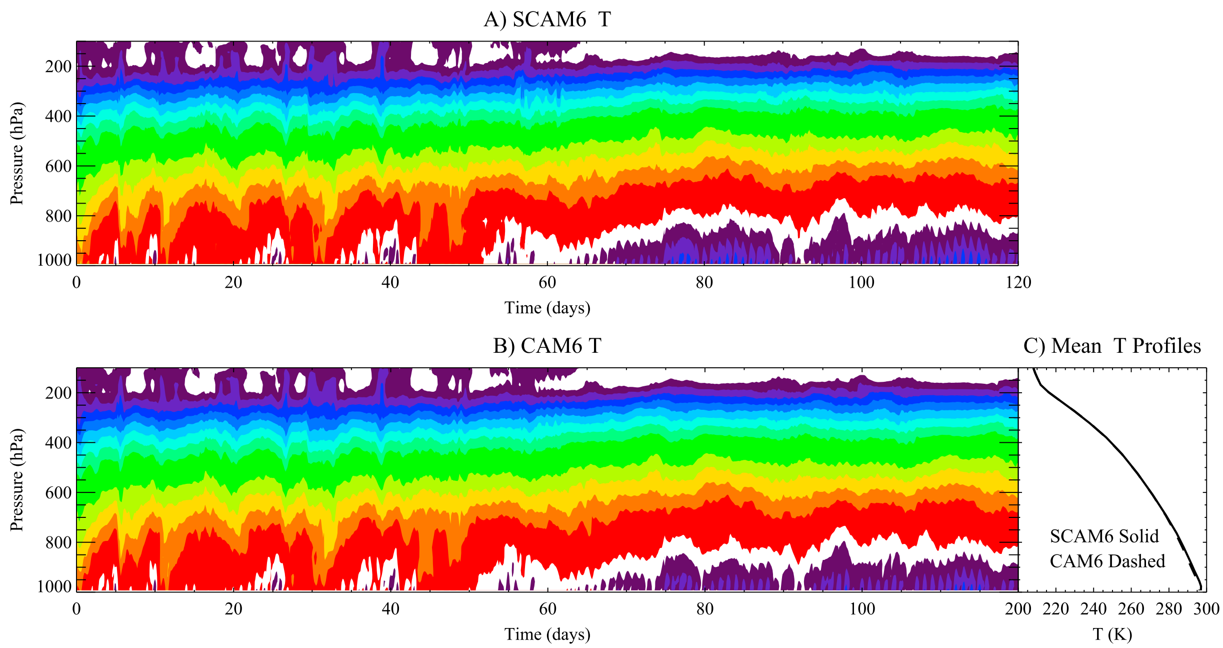


**Figure 1.** A test of the SCAM6 simulation of Temperature (T) evolution against CAM6. (a) SCAM6 T, (b) CAM6 T from the CAM6 simulation used as the forcing of SCAM6, and (c) mean profiles. CAM = Community Atmosphere Model; SCAM = Single Column Atmosphere Model.

CAM6 vertical levels with 48-hr relaxation. This CAM6 configuration reproduces the reanalysis meteorology with winds (U,V) and temperature (T) relaxed to the reanalysis. SCAM6 is run starting 1 April 2016, and data output every 3 hr for 5 months (153 days) simulating the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) program Southern Great Plains (SGP) site in Oklahoma (36° N, 263° E), the same location as the ARM95 and ARM97 IOP cases (Table 1). These data are processed and used to force SCAM6. Horizontal advective tendencies are prescribed directly in SCAM, while T and Q are relaxed to the CAM values, with a 2-day relaxation at the top of the model and 10-day relaxation at the bottom (with a constant linear ramp between bottom and top). This is necessary to keep upper tropospheric and stratospheric temperatures from drifting due to noninteractive and unresolved slow radiative forcing. Three-dimensional advective tendencies are used. Note that the standard configuration is to relax temperature to the initial condition but allow specific humidity to evolve freely. The initial condition is the June-averaged aerosols of the CAM6 simulation, with the aerosols relaxed to the June-averaged aerosol profile over the SGP site. Coupled Model Intercomparison Project, round 6 (CMIP6)-derived aerosol emissions are used in addition to the relaxation.

Figure 1 illustrates the results of this method. Relaxing temperature in SCAM6 to a CAM6 simulation reproduces nearly exactly the details of the CAM6 simulation. The mean temperature profiles are barely distinguishable (Figure 1c), where SCAM6 with relaxation is 0.6 K warmer than the base CAM6 simulation from 1,000–800 hPa, due to slight differences in the initialization and evolution of the land surface.

The simulation of cloud fraction (CLOUD) is illustrated in Figure 2. Clouds are derived in SCAM6 using the CAM6 microphysics (Gettelman & Morrison, 2015), turbulence (Bogenschutz et al., 2013), and deep convective (G. J. Zhang & McFarlane, 1995) parameterizations acting on the prognostic water vapor mixing ratio ($Q_v$) with advective tendencies calculated from the CAM6 simulation. The resulting SCAM6 simulation reproduces the mean cloud fraction profile over 120 days (Figure 2c). Individual cloud events and the day-to-day distribution of cloud are also well represented (Figures 2a and 2b). There are slight individual cloud differences, but most events (convective in this case) are reproduced. Clouds (particularly convection) are very nonlinear to small perturbations, but on the average, over the IOP period of 120 days, the clouds are very well reproduced. Higher-order diagnostics of the clouds, such as the individual and averaged convective mass flux (not shown) or the cloud drop number concentration (see below), also well simulated.

Fundamental to the complex atmospheric parameterizations in CAM6 and SCAM6 are the linkage among the prognostic aerosol model, MAM, and the double-moment moist turbulence schemes. These Aerosol

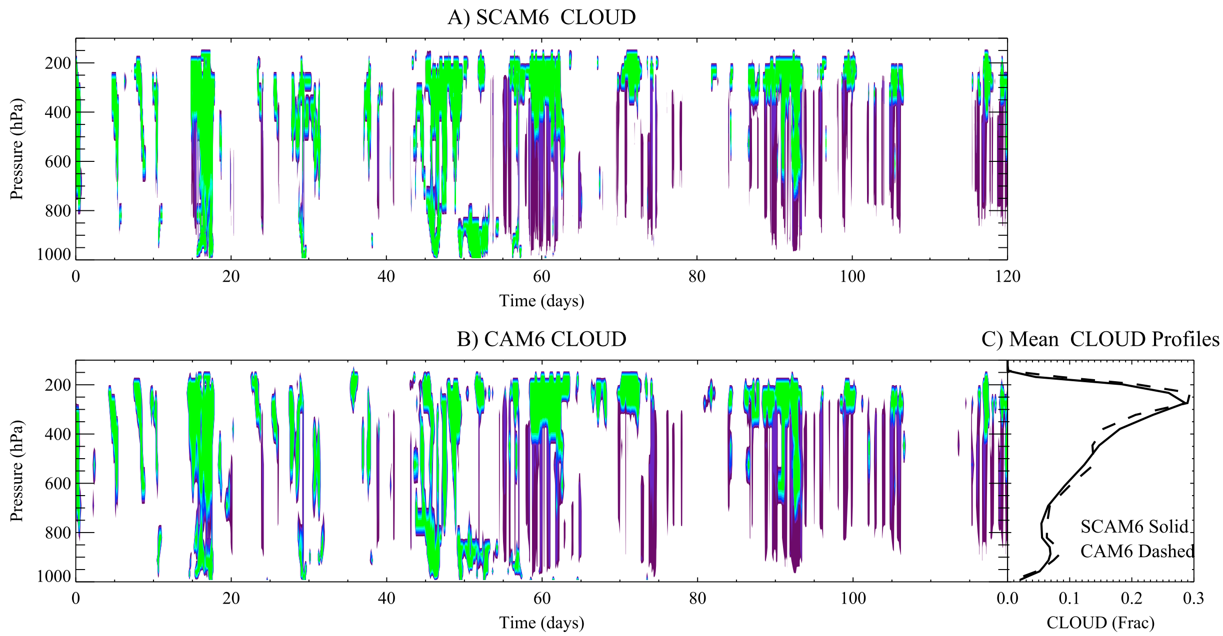


**Figure 2.** A test of the SCAM6 simulation of Cloud Fraction (CLOUD) evolution against CAM6. (a) SCAM6 CLOUD, (b) CAM6 CLOUD from the CAM6 simulation used as the forcing of SCAM6, and (c) mean profiles. CAM = Community Atmosphere Model; SCAM = Single Column Atmosphere Model.

Cloud Interactions, whereby aerosols affect cloud drop number, subsequently feed back on cloud microphysical processes, ultimately impacting the radiative fluxes (Gettelman, 2015). To represent these processes in SCAM6, it is necessary to reproduce the evolution of aerosols in CAM6. Figure 3 illustrates the evolution of Accumulation aerosol mode number concentration (*num_a*1) in SCAM6 (Figure 3a) and CAM6 (Figure 3b) using relaxation toward a monthly mean aerosol profile taken from the CAM6 simulation. Relaxation is performed on the mass of each aerosol constituent and the number concentration in each of the four modes. SCAM does use a full representation of aerosol emissions, as well as wet and dry aerosol scavenging processes. While the character of the individual events is different, since horizontal advection is not reproduced, SCAM6 reproduces the mean aerosol profiles (Figure 3c) in CAM6 at all levels. Furthermore, despite this being a convective cloud case, without extensive stratiform clouds affected by aerosols, cloud drop number concentrations are also well simulated to within 30%. In addition, the increase in aerosols over time from spring into summer in the CAM6 simulation (Figure 3b) is reproduced in SCAM6 (Figure 3a). SCAM6 uses emissions from the surface and vertical transport but does not represent advective transport. Variability in time is not completely reproduced, but the emissions of aerosols and the periods of transport into the free troposphere are broadly reproduced. It was not feasible to add horizontal advection of all constituents to SCAM6. Aerosol differences between CAM and SCAM may be a factor in simulation differences. In regions where there is strong advection of aerosols, SCAM may not be the best tool for analysis.

The results above describe simulations where the temperature field is relaxed to the observational estimate from the IOP. SCAM can also be run with temperatures fixed to the IOP or with "free-running" temperatures, forced by radiation, surface fluxes, etc. Figure 4 illustrates a number of properties of the cases when temperatures are taken directly from the IOP file (ObsT), relaxed (Rlx T), or left to be freely evolving (Free T). In all simulations, specific humidity is left to freely evolve. For cases that are in near-radiative convective equilibrium (e.g., with strong convection), SCAM maintains temperatures that are quite close to the IOP input temperature, even when temperatures are freely evolving, as in the SGP test case (Figure 4a) and GATEIII Tropical case (Figure 4g). However, where advective or other forcings (such as the large-scale stratospheric or tropospheric circulation) can dominate (i.e., in nonconvective regimes), temperatures may drift from the reference IOP case if allowed to evolve. This occurs in the MPACE Arctic case (Figure 4d) if temperatures are freely evolving or (to a lesser extent) relaxed to the IOP values. The result is that the simulation properties will deviate more from the fixed T reference case. Even for the SGP test case shown in Figure 1, free-running temperatures yield increases in cloud fraction (Figure 4b) and cloud liquid water (Figure 4c) which deviate from SCAM results fixed to input fields (ObsT). This is illustrated against the 3-D

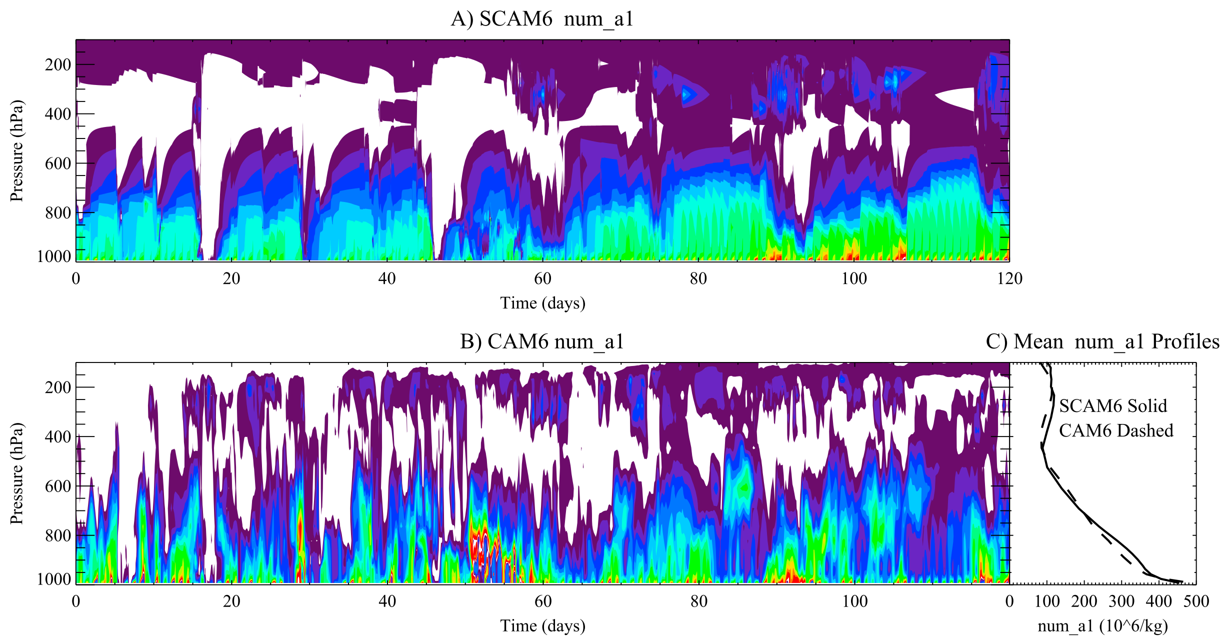


**Figure 3.** A test of the SCAM6 simulation of Accumulation mode aerosol number concentration (num_a1) evolution against CAM6. (a) SCAM6 num_a1, (b) CAM6 num_a1 from CAM6 simulation used as forcing, and (c) mean profiles. CAM = Community Atmosphere Model; SCAM = Single Column Atmosphere Model.

CAM results for the SGP case (Figures 4a–4c) where the temperature, cloud, and cloud liquid in the Rlx T case are the closest to the CAM simulation (red). This can occur simply because of bifurcations in the solutions (Hack & Pedretti, 2000) or because of small differences between IOP forcing derived from a different model version (or different configuration) and the SCAM simulation.

The differences in Figure 4 are not due to aerosol concentration, as the SGP and GATE cases are deep convective cases largely insensitive to aerosols. Rather, there are differences in specific humidity that drive differences in cloud fraction (CLOUD) and cloud liquid water content (CLDLIQ). In the SGP case, low-level differences in humidity feed higher altitude changes in CLOUD due to convective transport. In the MPACE case, differences in temperature cause humidity changes at upper levels (relative humidity does not change much, but temperatures change by 3–10 K, with 30–50% changes in specific humidity) and lower level temperature differences drive cloud changes. For the GATE case, there are some midtropospheric temperature differences that impact the convective instability and hence the vapor transport.

The user needs to be careful with the purpose of the SCAM experiment they wish to perform. If the case is close to radiative-convective equilibrium, then free-running temperatures will usually work. However, if the case is far from such equilibrium, and this may include shallow cloud cases where large-scale subsidence is important but not fully represented, then temperatures should be relaxed to the IOP. It also depends on the desired science: For some experiments, free-running temperature responses are necessary (see section 3.4 below), while for others, fixed temperatures or relaxation is more appropriate. In general, aerosol relaxation should be used. For analysis of cloud physics, specific humidity should generally not be relaxed, but for other applications (e.g., analysis of radiative fluxes), fixing humidity may be appropriate.

The above method of simulating a 1-D column from the 3-D model is very useful for case study analysis. Problems in specific regimes can be rapidly identified, starting with energy and mass conservation and extending to details of process rates. Flags for energy checking can be turned on with a CAM namelist variable (*print_energy_errors*). Full physics budgets are also available to be output with a namelist switch (*history_budget*). Such a method is suited for manual debugging or integrated debugging environments without need of large computing resources. In addition, CAM could be nudged to specific observations to reproduce a particular set of field observations.

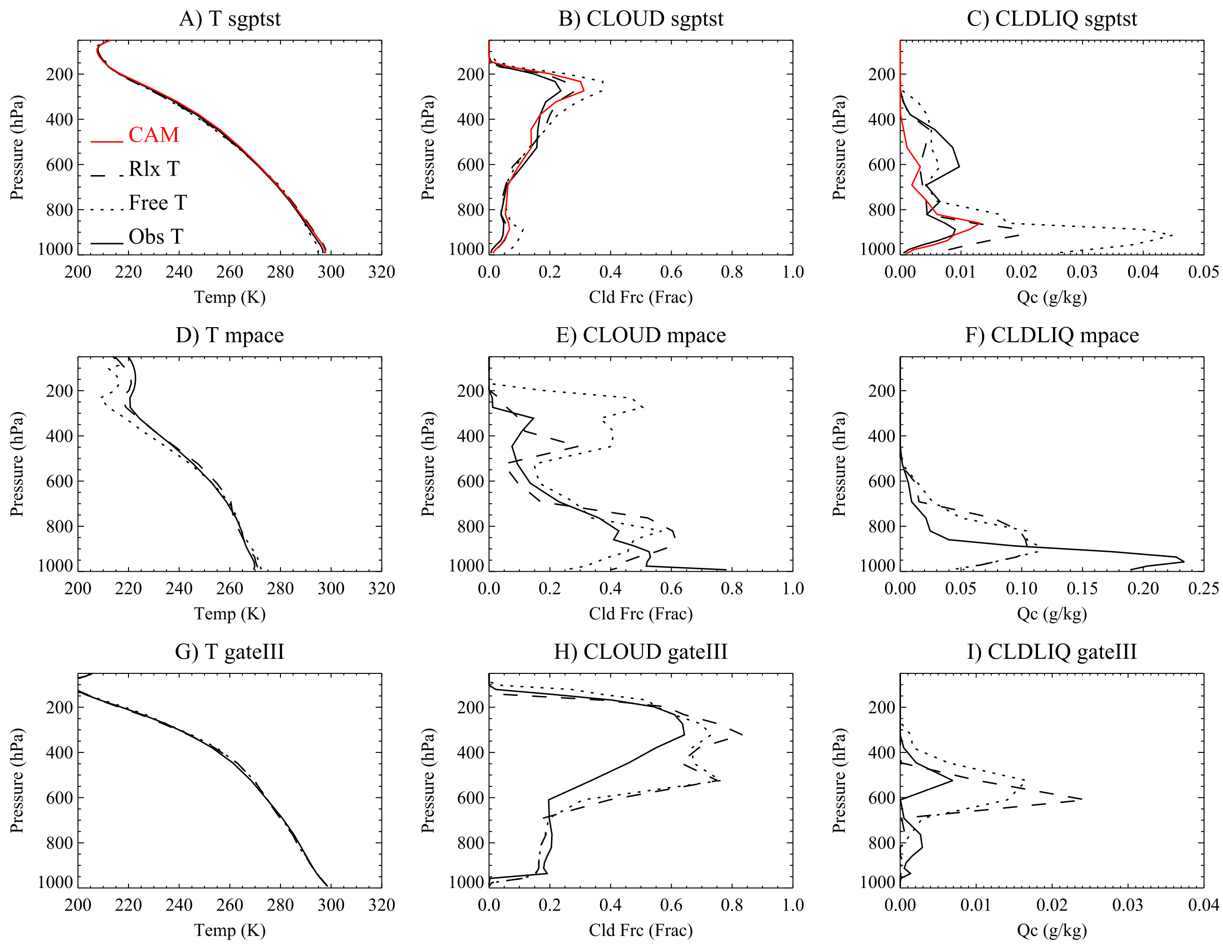


**Figure 4.** Time-averaged profiles from Single Column Atmosphere Model simulations for different Intensive Observation Period cases, different temperature relaxation, and different variables. Intensive Observation Periods are the Southern Great Plains test case (a–c), MPACE Arctic case (d–f), and the GATEIII tropical convection case (g–i). Different simulations use fixed temperature (Obs T: Solid), freely evolving temperature (Free T: Dotted), and temperature relaxation (Rlx T: Dashed). Variables are Temperature (T: a, d, and g), Cloud Fraction (CLOUD: b, e, and h) and Cloud Liquid (CLDLIQ: c, f, and i). Full 3-D CAM results (red) shown for the Southern Great Plains case (a–c). CAM = Community Atmosphere Model.

### 3.2. Parameterization Analysis and Development

Since SCAM runs the full CAM physics suite, one of its major uses is for the rapid development and testing of physical parameterizations, across multiple climate regimes. Furthermore, SCAM is a good tool for checking conservation of energy, cloud, aerosol, and chemistry species in parameterizations, as well as comparing to in situ observations. Here we illustrate an example of evaluating different physical parameterizations. In this case we are performing two experiments to compare to the standard SCAM case ("Base"): one with the deep convective parameterization (G. J. Zhang & McFarlane, 1995) turned off ("No Deep") and one where the deep convective scheme uses a detailed cloud microphysical parameterization (Song & Zhang, 2011; "ZM Microp"). Simulations are run for the ARM95 continental and TWP06 maritime convective cases, with freely evolving temperatures.

Figure 5 illustrates that in general, the addition of the Song and Zhang (2011) deep convective microphysics produces similar values of cloud fraction, cloud liquid, and cloud ice as the base case but a larger convective mass flux in the ARM95 case. Cloud drop number concentration is not fully prognostic with the deep convective microphysics, so we have not shown cloud drop or ice crystal number. There is more cloud liquid at midlevels in the GATEIII case (Figure 5g), but otherwise, solutions are similar. In the ARM95 case, there is 10% more precipitation, which may be associated with the increased mass flux. The no deep convection case has more cloud, less ice and liquid, and also 25% less precipitation than the base case with deep convection. The advantage of SCAM for parameterization development is direct comparison of physical parameterizations, with minimal feedbacks to dynamics (even with freely evolving temperatures, as in

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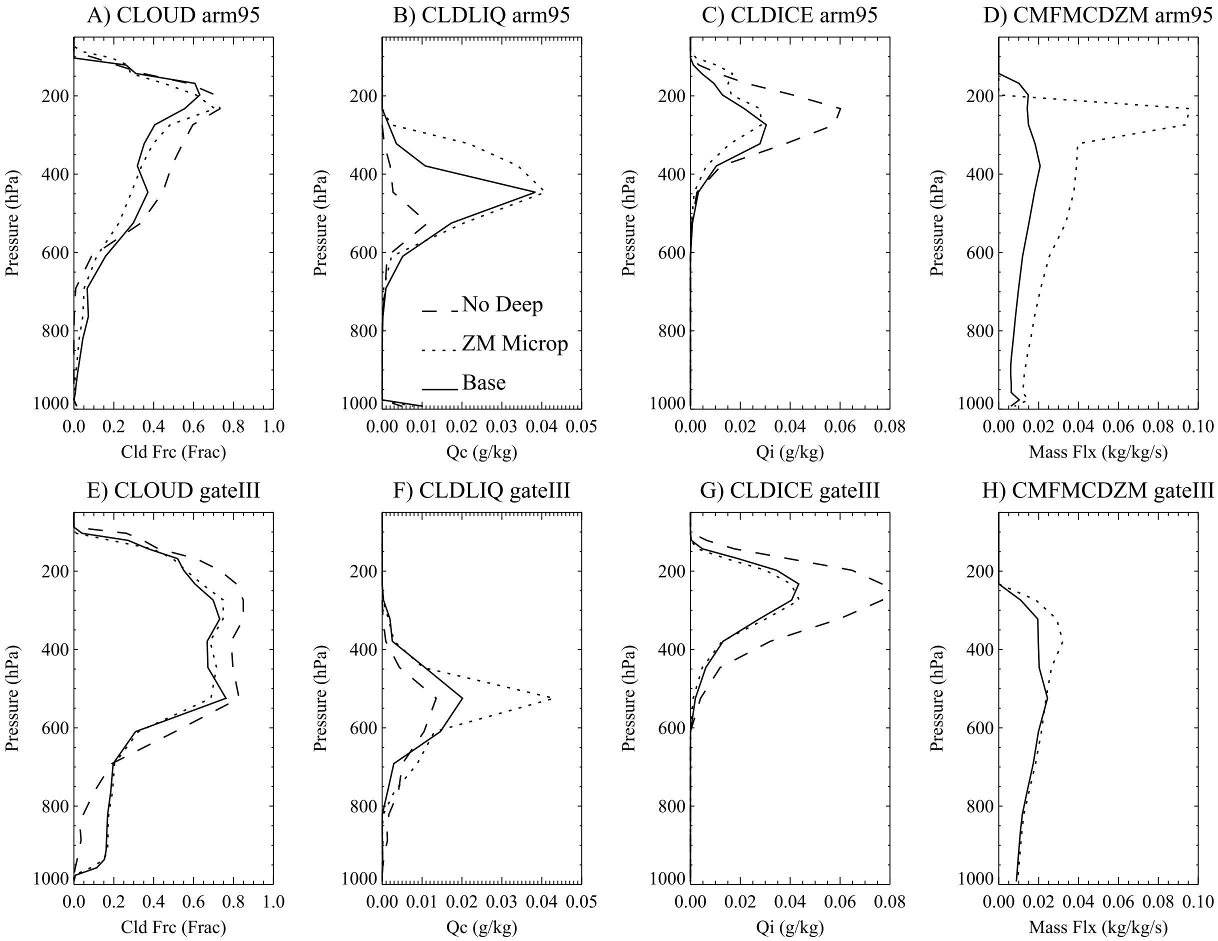


**Figure 5.** Time-averaged profiles from Single Column Atmosphere Model simulations for Atmospheric Radiation Measurement 95 (a–d) and TWP06 (e–h) Intensive Observation Periods. Shown are Base (Solid), Song and Zhang convective microphysics (ZM Microp: Dotted), and no deep convection (Dashed). Variables are Temperature (T: a and e), Cloud Fraction (CLOUD: a and e), Cloud Liquid (CLDLIQ: b and f), Cloud ICE (CLDICE: c and g), and Deep Convective Mass Flux (CMFMCDZM: d and h).

these cases). Furthermore, SCAM is a useful environment for energy conservation checking and debugging, as it uses the same energy checkers as the full model simulation. With quick turnaround, it is easy to explore pathologies and bugs during model development. It can also be used with the user IOP function to output a particular column from a CAM simulation for analysis and debugging purposes.

### 3.3. Sensitivity Tests

SCAM can also be used to investigate the sensitivity of the CAM physics suite to single or multiple parameters through efficient parameter sweep experiments. SCAM scripts can be set up to run multiple cases of a single compiled code base. The compiled model is "cloned," and then CAM namelist parameters can be easily modified to rapidly run different perturbations. As an example, we illustrate adjustments to the sensitivity of the vapor deposition process in the Gettelman and Morrison (2015) microphysics code. Korolev et al. (2016) noted that the vapor deposition process onto ice and depletion of liquid (the Wegener-Bergeron-Findeisen process) is rarely equal to its theoretical efficiency due to (a) inhomogeneity in humidity and updrafts and (b) the generation of supersaturation by updrafts which can allow both ice and liquid to grow. As a result, CAM6 contains an efficiency factor for the vapor deposition (*micro_mg_berg_eff_factor*). The efficiency factor set to 1 (perfect efficiency) is the default in CAM6. However, here we use SCAM cases with temperature relaxation to investigate the impact of this factor on a high latitude (MPACE) and a tropical convection (TWP06) case.

Figure 6 illustrates the impact of varying the efficiency of the vapor deposition from 0 (no vapor deposition onto ice: solid) to 1 (default: triple dot dash). With no vapor deposition onto ice, there is more liquid (Figure 6b) and more supercooled liquid ($Q_c < -5$°C; Figure 6c) than the default simulation (efficiency =

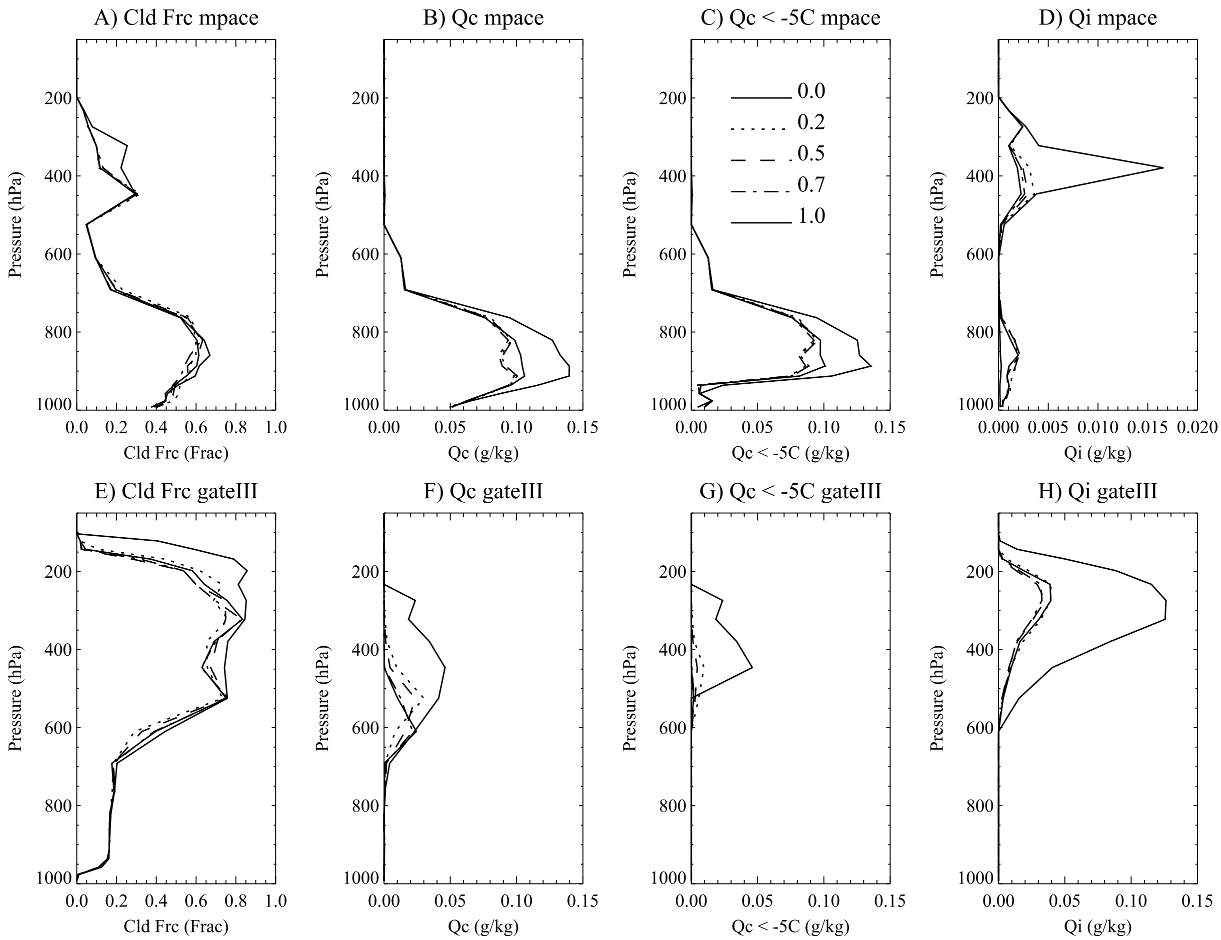


**Figure 6.** Time-averaged profiles from Single Column Atmosphere Model simulations for MPACE (a–d) and GATEIII (e–h) Intensive Observation Periods. Shown are different values of the Bergeron efficiency factor from 0–1. Variables are Cloud Fraction (a and e), Cloud Liquid (Qc: b and f), Supercooled Cloud Liquid (Qc less than −5 °C: c and g), and Cloud Ice (Qi: d and h).

1) for the MPACE case. There is also more ice at higher levels in MPACE (Figure 6d). The logic is that ice tends to fall out faster, and less ice and more supercooled liquid results in more condensate remaining in the atmosphere to freeze at higher levels. Note however that there is a difference between 0 and 0.2, but there is not strong sensitivity for any value of the Bergeron efficiency > 0.2, indicating that the process is highly nonlinear.

A similar story emerges in the case of tropical deep convection for the GATEIII (tropical) case (Figures 6e–6h). Here, for efficiency = 0, there is more high cloud cover (Figure 6e), liquid, and supercooled liquid at 200–600 hPa (Figures 6f and 6g) and more ice in cirrus anvils at 200 hPa (Figure 6h). The implication is that less ice formation in the supercooled region allows an increase in ice aloft. These changes then have strong radiative consequences. Interestingly, the vapor deposition process seems to be more important for tropical convective cases (GATEIII) than for a mixed phase Arctic cloud case (MPACE).

To explore whether this behavior is present in the 3-D model, we ran fixed Sea Surface Temperature (SST) experiments at standard (0.9° lat and 1.25° lon) horizontal resolution for 6 months and evaluated the monthly average results at the locations of the MPACE and GATEIII IOP cases in Figure 6 for October and August, respectively. Five cases were run with the Bergeron efficiency set to the same values as SCAM (0, 0.2, 0.5, 0.7, and 1). For the MPACE Arctic case, where supercooled liquid in the cloud microphysics is important, the same sensitivity is evident in the 3-D as in SCAM: highest water contents and ice content for the 0 efficiency (no vapor deposition onto ice) and nonlinear behavior where the perfect efficiency has more water and supercooled water than the intermediate cases. For the convective case, the 3-D model behavior is different, with higher cloud fraction in the cases with less vapor deposition efficiency (but also lower cloud

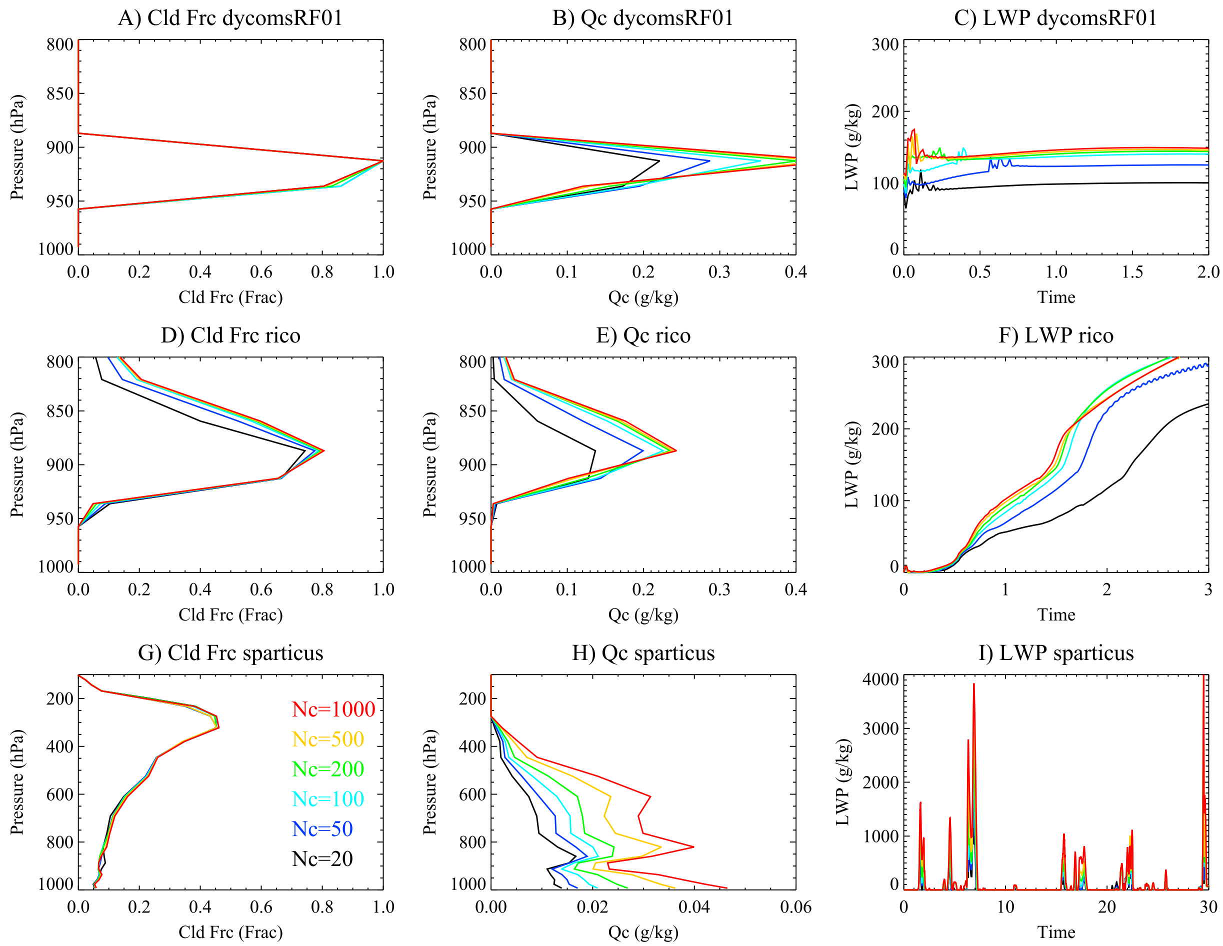


**Figure 7.** Time-averaged profiles from Single Column Atmosphere Model simulations for DYCOMS-RF01 (a–c), RICO (d–f), and SPARTICUS (g–i) Intensive Observation Periods. Different colors indicate different cases with fixed drop number in the stratiform cloud microphysics from 20 (black) to 1,000 $cm^{-3}$ (red). Variables are Cloud Fraction (a, d, and g), Cloud Liquid (Qc: b, e, and h), and vertically averaged Liquid Water Path (LWP: c, f, and i).

fraction overall). The differences between CAM and SCAM could be related to fixing temperature, in that tropical upper tropospheric temperatures are more dependent on cloud and ice interactions with radiation. Such a conclusion from SCAM deserves more analysis in the full model, but this is an example of using SCAM to illustrate and reproduce important sensitivities of the model.

SCAM also enables testing of the sensitivity of cloud schemes with further simplifications to the physics. Several types of aerosol particles are efficient Cloud Condensation Nuclei (CCN). Thus, adding aerosols to the atmosphere may increase cloud drop number, brightening clouds (Twomey, 1977). There are numerous observations of the positive correlation of aerosols and CCN (e.g., Rosenfeld et al., 2008) and negative correlation with cloud drop size (Yuan et al., 2011). In CAM, the MAM with four modes (MAM4; Liu et al., 2012; Mills et al., 2016) determines the evolution of aerosols. The aerosols are activated to CCN following Abdul-Razzak and Ghan (2000), and the activated number is passed to the cloud microphysics where it determines a minimum cloud drop number. These parameterizations are active in SCAM6 as in CAM6, using the aerosol fields but relaxed back to the initial condition.

Sensitivity to aerosols in SCAM could be tested by altering aerosol emissions and/or the aerosol initial condition used for relaxation. Another way to test the cloud microphysical response to changes in aerosols (called Aerosol Cloud Interactions) is simply to specify the drop number directly in the microphysics and examine the cloud response. Figure 7 shows the impact of fixing the droplet number at various values between 20 and 1,000 $cm^{-3}$ for several different IOPs, using temperature relaxation. In general, increasing drop number does not change cloud fraction very much (Figures 7a, 7d, and 7g), a result also found in the full CAM5

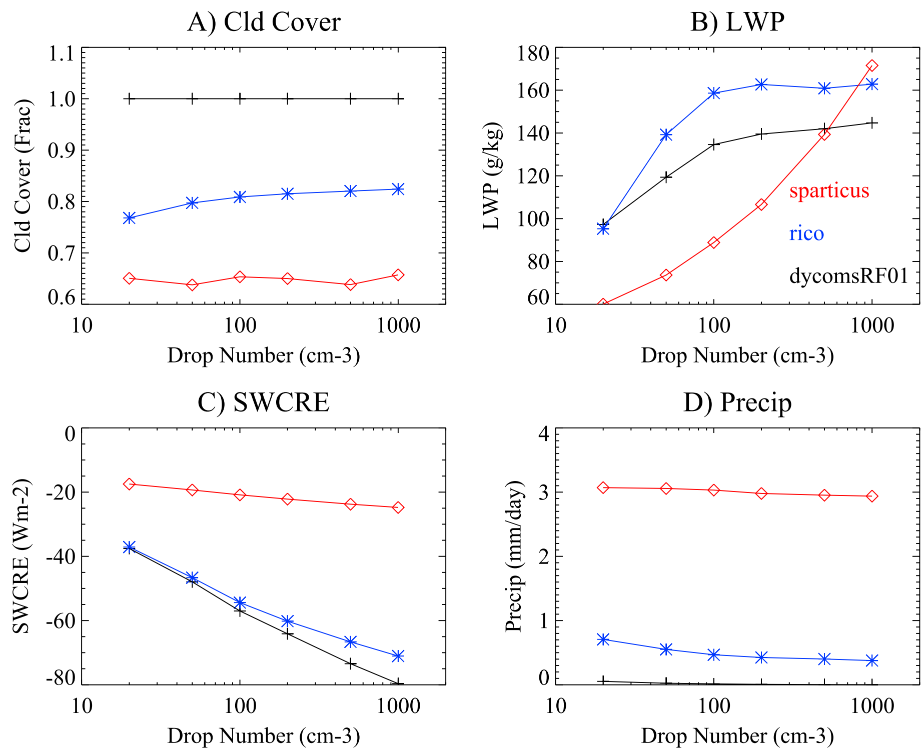


**Figure 8.** Time averages from Single Column Atmosphere Model simulations for DYCOMS-RF01 (Black), RICO (Blue), and SPARTICUS (Red) Intensive Observation Periods. Simulations performed with different drop numbers. Shown are time average Cloud Cover (a), Liquid Water Path (b: LWP), Shortwave Cloud Radiative Effect (c: SWCRE), and Precipitation Rate (d: Precip).

(e.g., Gettelman et al., 2010) and CAM6. However, in all experiments, the increase in drop number leads to an increase in cloud water mixing ratio (Figures 7b, 7e, and 7h) and thus total Liquid Water Path (LWP; Figures 7c, 7f, and 7i). The increase is true for low stratus cloud cases (DycomsRF01), stratocumulus cases (RICO), or convective cases (SPARTICUS).

Figure 8 illustrates the impact of the changes as the average across an IOP. Cloud cover increases in the RICO case (Figure 8a) with drop number but remains nearly constant for the other two cases. LWP (Figure 8b) increases in all cases, quite dramatically in the SPARTICUS case. As a result, the shortwave cloud radiative effect (CRE) has a larger magnitude (more negative; Figure 8c). The negative shortwave CRE values indicate stronger cloud reflection and a large cooling effect of the drop number changes. Precipitation decreases in all cases, fairly significantly for the lower precipitation shallow cloud cases or RICO and DYCOMS (Figure 8d). The SCAM results confirm a high sensitivity (or susceptibility) of CAM6 clouds to changes in drop number. Note that despite the large increase in LWP for SPARTICUS (Figure 8b), the radiative impact is lower than for shallower clouds (Figure 8c), likely due to the masking effect of cirrus clouds that are not impacted as much (ice number is not fixed in these cases but is affected by liquid number). The SCAM results form an interesting baseline from which different processes can be tested to explore the sensitivity of cloud responses to drop number changes.

To verify that the SCAM sensitivity of CREs to drop number is the same as for 3-D CAM, two 3-D CAM simulations were run with fixed drop numbers (Nc = 20 $cm^{-3}$ and Nc = 1,000$^{-3}$). Figure 9 shows the slope of shortwave CRE versus averaged column drop number in the different SCAM cases from Figure 8 (solid lines) and in the 3-D CAM cases (dotted lines). SCAM values are IOP averaged. CAM values are monthly means for each IOP month spatially averaged ±15° latitude and longitude around the IOP location for RICO, DYCOMS, and SPARTICUS cases. The results indicate that the CAM simulation sensitivity of radiation to drop number is reproduced in SCAM. While the values for some of the cases are different, the slopes in Figure 9 for each IOP (each color) between CAM (dotted) and SCAM (solid) are virtually the same and vary

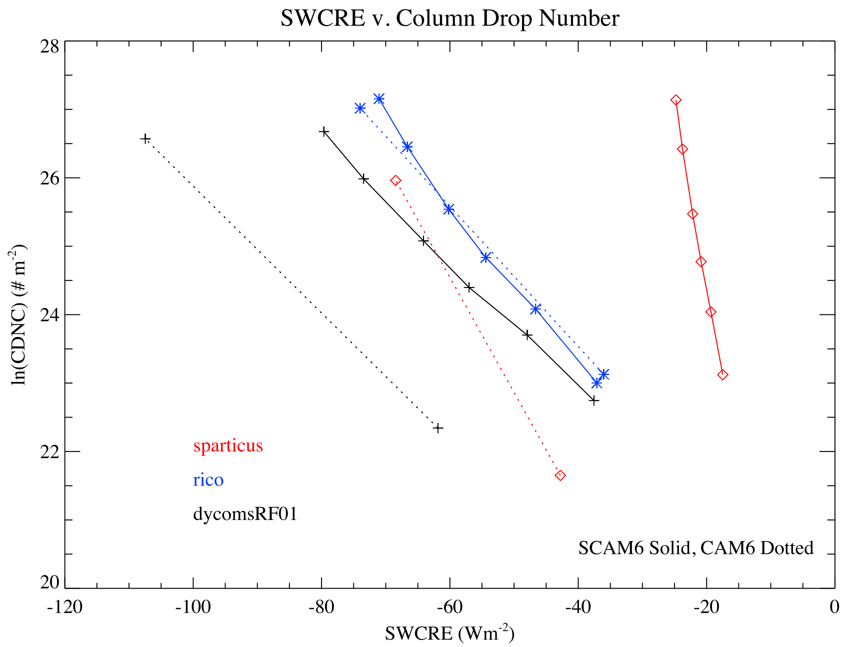


**Figure 9.** Shortwave Cloud Radiative Effect (SWCRE) from SCAM (solid lines) and 3-D CAM (dotted lines) simulations at the Intensive Observation Period locations for DYCOMS-RF01 (Black), RICO (Blue), and SPARTICUS (Red). SCAM = Single Column Atmosphere Model; CAM = Community Atmosphere Model.

in the same way between IOPs, indicating that SCAM is reproducing the 3-D CAM sensitivity of CREs to drop number.

### 3.4. Feedbacks

Finally, we illustrate how SCAM can be used to understand complex perturbations to the model. Cloud feedbacks, the cloud response to surface warming, are the largest uncertainty in projections of climate change (Boucher et al., 2013). The processes responsible for cloud feedbacks are complex (Gettelman & Sherwood, 2016), and cloud feedbacks differ in different regimes. Here we focus on low cloud feedbacks in the subtropics, across a range of regimes, and show how SCAM can provide basic insights into model cloud feedback processes. Vial et al. (2017) recently reviewed low-cloud feedback mechanisms. This work follows M. Zhang et al. (2013), who used the CGILS cases to investigate low-cloud responses to greenhouse gas-induced warming using Large Eddy Simulation model and SCM. This included versions of the CAM4 and CAM5 versions of SCAM. Here we explore similar perturbations with SCAM6.

We use the three CGILS cases, representing locations along an East Pacific transect from the California coast southwest toward the tropical Central Pacific. S12 (35° N,125° W) features a solid low stratus deck (e.g., Figure 10a), S11 (32° N,129° W) a broken stratocumulus deck with a cloud fraction around 0.5 (Figure 10c), and location S6 (7° N,149° W) hash shallow cumulus clouds (Figure 10e). These are good locations for examining low cloud feedbacks as clouds change in response to a surface perturbation. Following M. Zhang et al. (2013), we perform SCAM6 simulations at the three CGILS points. We do this with CAM6 physical parameterizations, and we do a base case and a case where the SSTs are increased by 4 K (SST + 4 K). Temperatures in these cases are allowed to evolve freely. The free-running temperatures do not evolve away from the IOP cases but stay close to the initial temperatures. We also perform SCAM simulations using the CAM5 physical parameterization suite (Neale et al., 2010). However, for consistency of boundary conditions, we use the CAM6 32 levels, instead of the CAM5 30 levels. The extra levels for CAM6 are in the upper troposphere, so the vertical resolution in the region of interest is the same as the standard CAM5.

Figures 10 and 11 illustrate the effect of increasing surface temperatures on clouds for CAM6 and CAM5. Note that surface fluxes are determined by a the low-level wind, which in these cases is specified in the advective forcing, and might evolve differently in a full 3-D simulation. Figure 10 illustrates the vertical profile of time average cloud fraction (Figures 10a, 10c, and 10e) and cloud water mixing ratio (Qc; Figures 10b, 10d, and 10f), while Figure 11 illustrates time averages of single level fields of cloud cover (Figure 11a), LWP

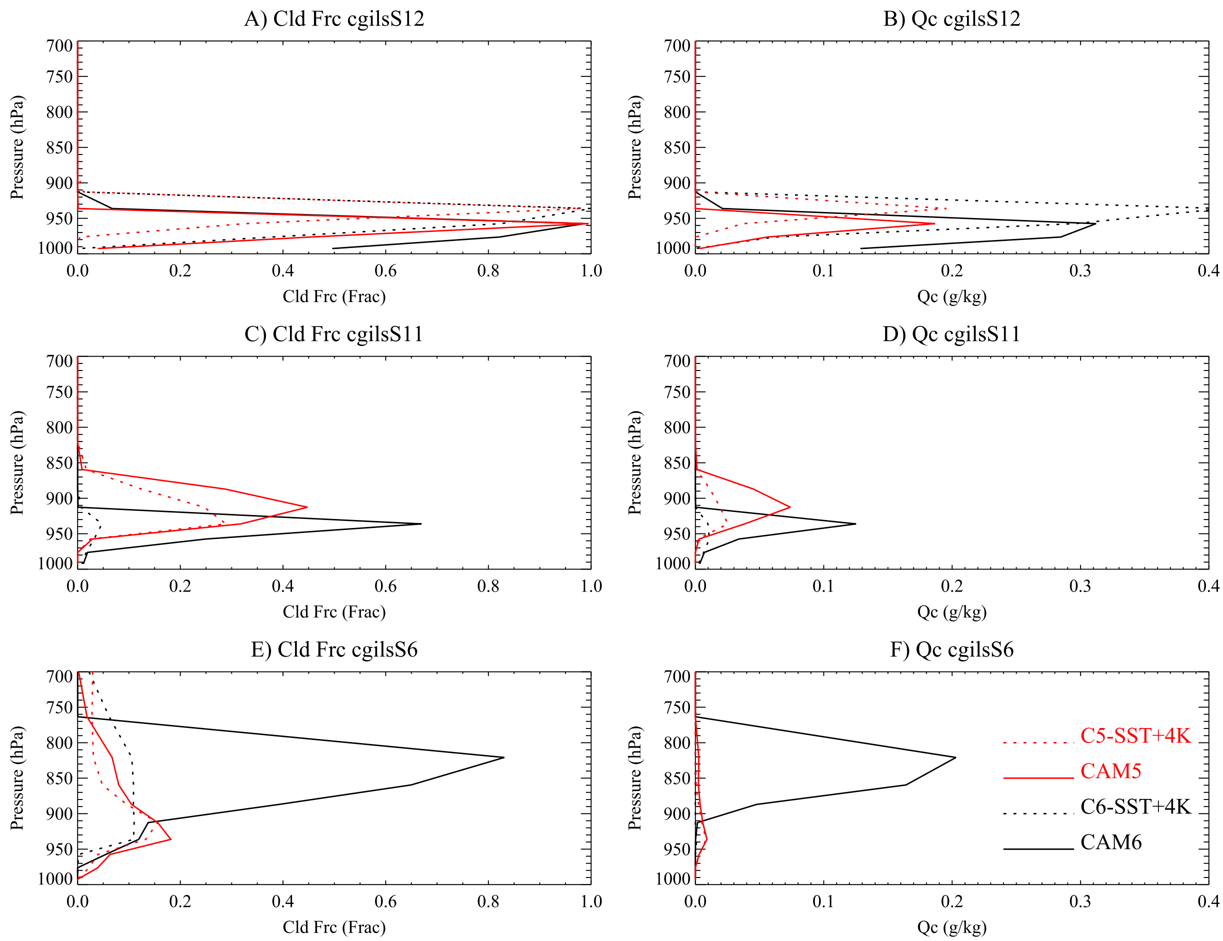


**Figure 10.** Time-averaged profiles from Single Column Atmosphere Model simulations for CGILS S12 (a and b), S11 (c and d), and S6 (e and f) Intensive Observation Periods. CAM6 in Black and CAM5 in red. Base = solid, SST + 4 K = dotted. Cloud Fraction (a, c, and e) and Cloud Liquid (Qc: b, d, and f). CAM = Community Atmosphere Model; SST = Sea Surface Temperature.

(Figure 11b), net (longwave + shortwave) CRE (Figure 11c), precipitation (Figure 11d), surface latent heat flux (Figure 11e), and precipitable water (Figure 11f).

Results vary by location and regime. CAM6 and CAM5 perform similarly for S11 (big increases decreases in cloud cover but very differently at S12 (stratus) and S6 (shallow convection). In the S12 case, cloud cover remains at near 100% in CAM6 and CAM5 with an increase in LWP but from a different mean state between CAM6 and CAM5 (higher LWP in CAM6). The result is a decrease in CRE (negative, increasing magnitude). CAM6 and CAM5 have increases in latent heat flux and precipitable water at S12. In the S11 case (stratocumulus), CAM5 and CAM6 have decreases in cloud fraction and LWP, leading to increasing CRE (less cooling). Latent heat fluxes, precipitation, and precipitable water see increases in both CAM6 and CAM5 at S11. However at S6 (shallow cumulus), there are large decreases in cloud cover and LWP in CAM6 but modest increases from a much lower level in CAM5, leading to large increases in CRE in CAM6, but small decreases in CAM5. This is a positive shallow cumulus feedback in the S6 region in CAM6 but a modest negative shallow cumulus feedback in CAM5.

The contrasting behavior indicates an opposite sign of behavior in cloud responses in the shallow convective regime in response to surface warming. To check these results, we have performed 10-year, global 3-D simulations at standard (0.9° lat and 1.25° lon) horizontal resolution with these same configurations (fixed SSTs and fixed SSTs + 4 K) with CAM5 and CAM6. We evaluated the climatological July monthly mean changes in clouds at each CGILS point. At S12 (stratus), clouds on average are thinner in CAM than SCAM, but the cloud height also rises in the 3-D simulations (as in Figure 10a), though LWP decreases in the 3-D model at S12. The 3-D simulations do indicate that cloud water (Qc) drops in SST + 4 K, and at S6, clouds

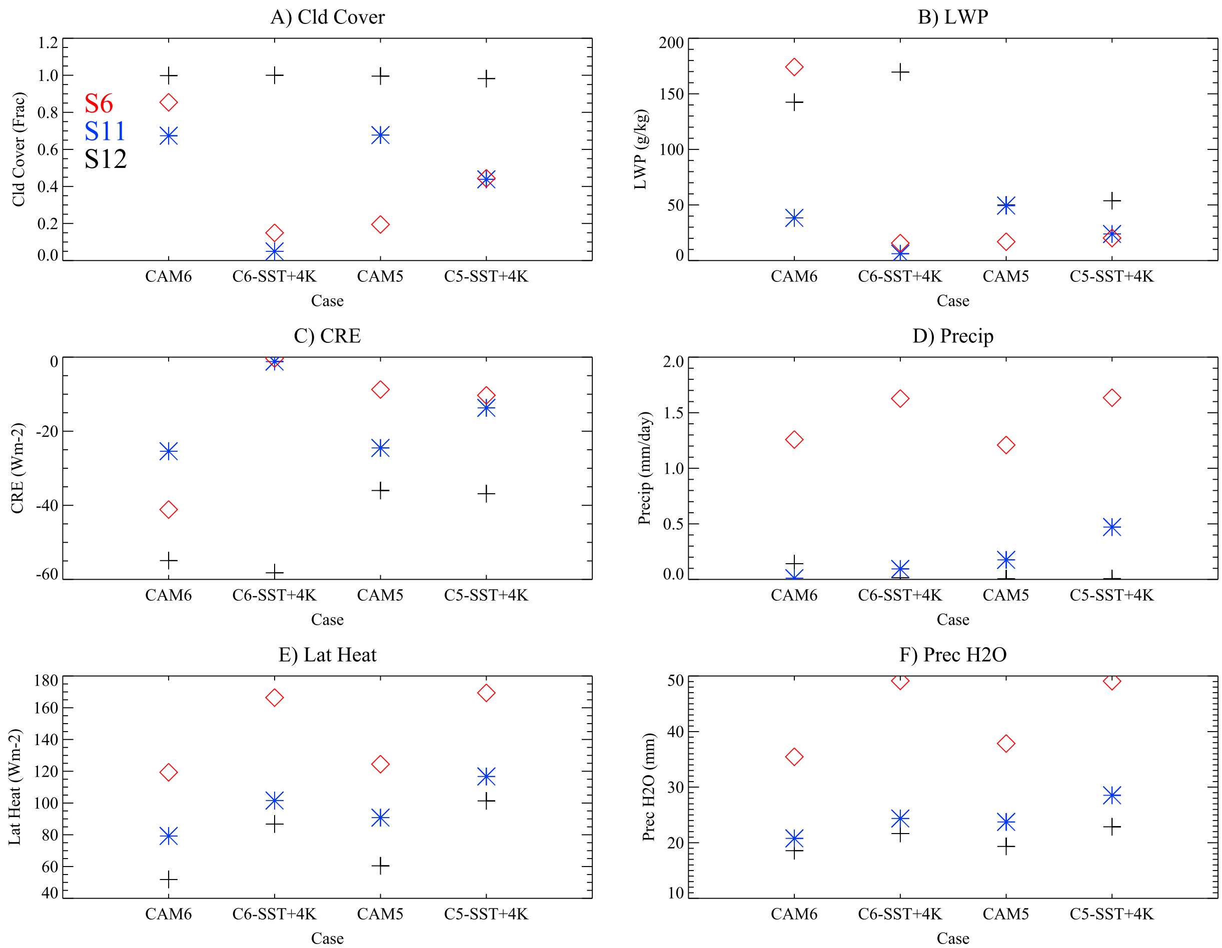


**Figure 11.** Time averages from SCAM simulations for CGILS S12 (Black), S11 (Blue), and S6 (Red) Intensive Observation Periods. Simulations performed with free-running temperatures for the base case, as well as SST + 4 K for CAM5 and CAM6. Shown are time average Cloud Cover (a), Liquid Water Path (b: LWP), Net (LW + SW) Cloud Radiative Effect (c: CRE), Precipitation Rate (d: Precip), Surface Latent Heat Flux (e: Lat Heat), and total Precipitable Water (f: Prec $H_2O$). CAM = Community Atmosphere Model; SCAM = Single Column Atmosphere Model; SST = Sea Surface Temperature.

are thinner descend in the 3-D model similar to SCAM (Figure 10e). As in Figure 11c, CREs also get less negative at S11 in the 3-D model but not at S12 in the 3-D model. Latent heat (Figure 11e) and precipitable water (Figure 11f) responses are also similar in 3-D to SCAM. Note that this comparison is the response of a free-running CAM simulation against imposed forcing from the CGILS IOP cases: So there are some differences to be expected in the base state between SCAM and CAM in this comparison.

A broad regional look at the cloud response in these full three-dimensional GCM simulations with CAM6 and CAM5 for similar SST + 4 K perturbations, to be described more fully elsewhere, confirms this different behavior in the full GCM in the Pacific and generally in the tropics: CAM5 has an opposite signed response at S6 (shallow convective regime), and the changes in cloud forcing are more moderate at S11 (transition regime). Thus, SCAM can be a useful tool in diagnosing different behavior between model versions and for more complex emergent features such as the response of clouds to SST perturbations. Note the limitation here that the large-scale dynamics impact (e.g., subsidence) is fixed in SCAM. In CAM, the large-scale dynamics evolves with increasing SSTs (e.g., Sherwood et al., 2014), which is not captured by SCAM simulations, and the SCAM forcing may be different from the full 3-D simulation. A more detailed comparison to examine feedbacks could be constructed with forcing from the 3-D CAM simulation at these points.

### 3.5. Parameter Sweep Experiments

In order to investigate this behavior further, we explore the sensitivity of the cloud response to SST perturbations, focusing on a key parameter of interest in the shallow cloud parameterization in CAM6. CAM6 features a unified turbulence scheme, Cloud Layers Unified By Binormals (CLUBB; Golaz et al., 2002) as

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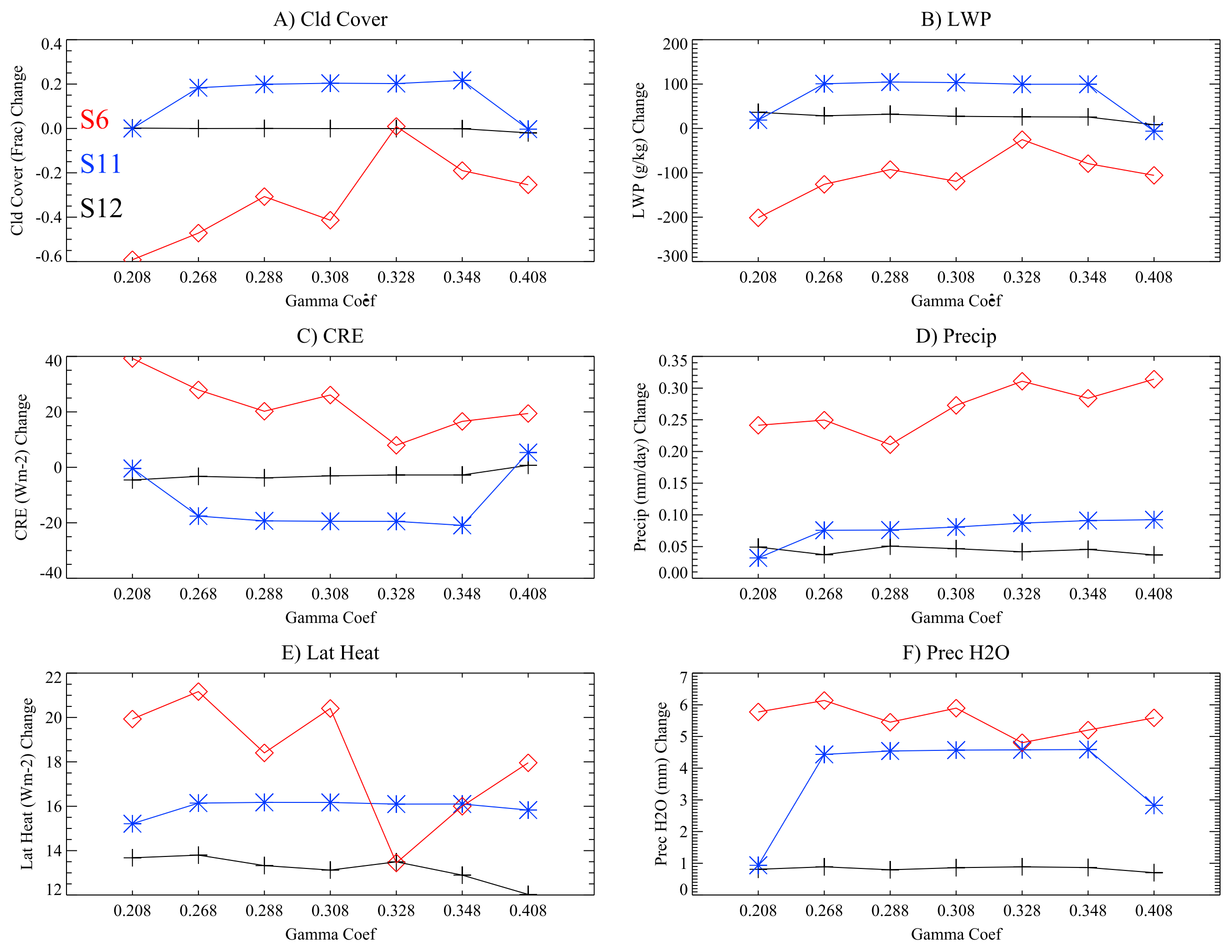


**Figure 12.** Time averages from Single Column Atmosphere Model simulations for CGILS S12 (Black), S11 (Blue), and S6 (Red) Intensive Observation Periods. Simulations performed with free-running temperatures for different values of the Cloud Layers Unified By Binormals gamma coefficient. Shown are time average changes in variables when 2 K perturbations to SST are applied (SST + 2 K = Base). Cloud Cover (a), Liquid Water Path (b: LWP), Net (LW + SW) Cloud Radiative Effect (c: CRE), Precipitation Rate (d: Precip), Surface Latent Heat Flux (e: Lat Heat), and total Precipitable Water (f: Prec $H_2O$).

described by Bogenschutz et al. (2013, 2010). In CLUBB, width of the overall Probability Distribution Function (PDF) of vertical velocity (gamma coefficient) is a key term for regulating vertical turbulent transport of the higher-order moments in shallow clouds. Decreased width suppresses upward mixing, which tends to increase low-cloud cover. Conversely, increasing the vertical velocity PDF width (higher gamma coefficient) tends to decrease low-cloud cover. The changes affect total water content and radiative effect of clouds. This parameter is commonly used as a tuning parameter for the top-of-atmosphere radiation balance and the extent of low clouds. The PDF width (gamma coefficient) has also been identified as a critical parameter for low-cloud feedback responses to climate change (H. Zhang et al., 2018).

Here we use SCAM6 to perform experiments to understand the sensitivity of the change in cloud properties as SST increases to the choice of gamma coefficient. We vary the gamma coefficient over the range from 0.208 to 0.408, with the default CAM6 setting at 0.308. Figure 12 illustrates the change in cloud properties with an SST + 2 K simulation for different settings of the gamma coefficient. We choose SST + 2 K in this case since it is closer to the tropical response of increased $CO_2$ scenarios than the higher SST + 4 K cases above. In addition, when SST + 4 K is used, almost all clouds disappear at S6 (Figure 11a). A higher gamma coefficient leads to globally decreased low cloud cover. In the case of S12 (100% cloud cover), there is no change in cloud cover (Figure 11a). At S11, cloud cover (65% in the base case) increases with SST + 2 K for most values of gamma, except the extremes (Figure 11a). However, at S6 (85% cloud cover in the base case), there is a strong dependence of cloud cover (Figure 11a) or CRE (Figure 11c) change across gamma coefficient values in the base case. This corresponds to the change in LWP (Figure 11b). The change means in this shallow convective regime, the low-cloud feedback (CRE Change) is dependent on the value of the CLUBB gamma coefficient (vertical turbulent transport).

## 4. Summary/Conclusions

SCAM is a tool that can be used for developing and understanding complex atmospheric physical parameterizations and helping improve our understanding of complex model simulations. We have illustrated how SCAM6 is run from standard IOP cases developed from field experiments and also how a user can extract boundary conditions and forcing from another CAM simulation. If the desired CAM simulation is nudged to observed meteorology, then any case can be simulated.

Using this framework, SCAM6 is able to reproduce results from full CAM6 simulations at single points, when appropriate boundary conditions and relaxation are applied. SCAM6 is not bit-for-bit with the full 3-D simulation because the vertical advection calculation is different in the Eulerian core from the default CAM6 FV dynamical core, but it produces nearly identical IOP average results and reproduces most cloud variability. A future project for SCAM is to be flexible with respect to dynamical core for more exact reproduction of column physics tendencies from a CAM simulation. Relaxation of aerosols to initial conditions can aid in the reproduction of full model simulations. Temperatures can be fixed to the time-evolving IOP temperatures, relaxed, or allowed to freely evolve. Freely evolving temperatures will deviate from full 3-D solutions when unrepresented dynamical forcing is important, often in the middle to high latitude upper troposphere and above.

SCAM is also a critical part of the model development process. In CESM2 and CAM6 development, SCAM6 was used to test sensitivity to different parameters, such as the vapor deposition efficiency explored here. In addition, SCAM6 was used to evaluate convective microphysics schemes.

Finally, some examples of critical uses of SCAM6 to understand CAM6 simulations are presented here. SCAM can be used to understand aerosol cloud interactions and the precipitation and cloud response to changes in drop number. SCAM can also be used as an idealized tool with forced dynamics to understand cloud responses to localized warming and diagnose some of the important details of cloud feedback responses and the parameter sensitivity of cloud feedback. Even though large-scale dynamics are not fully represented, these cloud responses mirror changes seen in full 3-D simulations by H. Zhang et al. (2018). Note that SCAM could represent large-scale dynamics in an idealized way, for example, using a Weak Temperature Gradient approximation.

Note that the methods described here, including switching parameterizations (section 3.2), parameter sweep experiments (section 3.5), and perturbing boundary conditions like SST (section 3.4), could be combined to understand in detail the differences in shallow cloud feedback response to forcing between CAM5 and CAM6 or to understand the contribution of aerosol and cloud processes to changes in aerosol-cloud interactions. This can be done with existing IOP forcing or with custom IOP forcing from a 3-D CAM simulation, both of which have been shown here.

This flexibility and the ability to configure SCAM6 with model-derived boundary and initial conditions make it a valuable tool for development of parameterizations and for understanding complex parameterizations. For these reasons, SCAM is an important part of a hierarchy of models available within CESM2. Future developments will make additional IOP test cases available, as well as the extension of SCAM to radiative-convective equilibrium cases.

## Appendix A: SCAM Forcing From a CAM Simulation

SCAM can be run with specified files generated from a CAM simulation. This is useful for detailed development of physical parameterizations. If CAM is "nudged" to actual meteorology, it can be used as a step to generate an arbitrary IOP forcing for any location and time. The basic method is to run CAM in any configuration with set output fields. There are then two scripts to (A) convert the detailed output to a SCAM IOP file and (B) generate an appropriate initial condition file for the relaxation of aerosols (and temperature fields if desired) to initial conditions. This information is also contained in the SCAM users' guide section of the CAM6 users guide (https://ncar.github.io/CAM/doc/build/html/users_guide/). Instructions for downloading the SCAM6 code as part of CESM2 are posted online (http://www.cesm.ucar.edu/models/cesm2/release_download.html).

### A1. Generation of IOP Forcing

First, any configuration of CAM should be run with the following namelist fields, to specify point output. Here the example is for 305° E, 62° N, a point in the Labrador Sea.

Add the following to the CAM namelist (atm_in):

```
fincl2='U','V','T','Q','OMEGA','TTEND_TOT','PTTEND, 'TAQ','TS','PS','PSL'

fincl2lonlat = 305e_62n

nhtfrq = 0,-3

avgflag_pertape = 'A','I'
```

Note that the averaging can be either 'I'nstantaneous or 'A'verage

Then run the `fv2iop_multi2_release.ncl` script (in the `./components/cam/bld/scripts` directory of the CAM source code) on the resulting h1 files.

This script uses NCAR Command Language (NCL) and NetCDF Operators (NCO) to create a SCAM IOP file. This file can be used with the 'iop' script to force SCAM.

### A2. Generating Initial Conditions

To generate initial conditions for SCAM, they need to be interpolated from the FV grid of standard CAM6 to the Eulerian Grid through which SCAM currently runs. There is an NCL script for this: `remapfv2eul.ncl` in the `./components/cam/bld/scripts` directory of the CAM source code.

These steps rely on the NCL and the NCO. Here `{case}` is the case name of a CAM simulation.

1. Run the `remapfv2eul.ncl` script with the source file set to the initial condition file (`SRC = {case}.cam.i.{month}` file) that is output from the CAM simulation.
2. Rerun the `remapfv2eul.ncl` script with the source file set to one of the monthly (h0) files (`SRC = {case}.cam.h0.{month}` file). This allows the monthly averaged aerosols to be used for the relaxation.
3. Next copy the regridded initial condition file to make a new one. For example, `cp {case}.cam.i.{date}.regrid.Gaus_64x128.nc {case}.cam.i.regrid.Gaus_64x128.nc`
4. Use the ncks NCO command to move averaged aerosols from the regridded monthly file to the regridded initial condition file: `ncks -A -v "bc_a1", "dst_a1", "dst_a3", "ncl_a1", "ncl_a2", "ncl_a3", "num_a1", "num_a2", "num_a3", "pom_a1", "so4_a1", "so4_a2", "so4_a3", "soa_a1", "soa_a2", "bc_a4" ,"num_a4", "pom_a4" {case}.cam.h0.{month}.regrid.Gaus_64x128.nc{case}.cam.i.regrid.Gaus_64x128.nc`
5. Finally, one last step is to 'fix' the attributes for aerosol number. The initial condition file needs a mixing ratio, whereas number units in the h0 files used to make the initial condition file are actually 1/kg. Again, using NCO: `ncatted -O -a units,num_a1,o,c,"kg/kg" -a units,num_a2,o,c,"kg/kg" -a units,num_a3,o,c,"kg/kg" -a units,num_a4,o,c,"kg/kg" {case}.cam.i.regrid.Gaus_64x128.nc`

### A3. Running the SCAM Case

In order to run the case, one can make a new directory in the `usrmods_dirs` section of the CESM tag (`./components/cam/cime_config/usermods_dirs`) with `scam_<IOPNAME>`, by following an existing case as a template to set shell commands for the location, start date, and length of run and modifying the user namelist for cam (`usr_nl_cam`) to point to the new IOP file and the initial conditions file generated above.

## Appendix B: Configuring SCAM

SCAM runs under the framework of the CESM. The first step to building and running SCAM is to install CESM on a given computer system.

The basic configuration procedure follows CESM conventions. It consists of a series of scripts to (1) create a new case (`create_newcase`), (2) set up the case (`case.setup`), (3) build the executable (`case.build`), and (4) run the case (`case.submit` or just execute). The system is a bit more complex because the model now is a single column ESM, but this provides more flexibility and ease of use. A sample SCAM script is provided in the `./components/cam/bld/scripts/directory` (`create_scam6_iop`). The CESM architecture adds minimally to the build and compile time.

In addition, the CESM architecture allows for the ability to configure build and compile a case and to 'clone' it. This feature enables multiple IOPs to be run from a single compile or any combination of namelist parameters to be changed for cloning. On a system with a job submission queue and multiple processors or nodes, this would enable parallel SCAM simulations to be rapidly executed. A script for doing this using the CESM `create_clone` utility is at `./components/cam/bld/scripts/create_scam6_iop_multi`.

The CESM architecture runs SCAM simulations with surface models. Over ocean, it is a fixed SST. Over land, SCAM runs with the CLM5 land model as an active component.

**Acknowledgments**
The National Center for Atmospheric Research is funded by the U. S. National Science Foundation (NSF). We acknowledge funding for idealized models from the Climate and Large Scale Dynamics program at NSF. Source code and scripts, as well as data files described in the text, are open source and part of the CESM2 code and input data release via github. Instructions are posted online (http://www.cesm.ucar.edu/models/cesm2/release_download.html). Specific instructions for running SCAM are also in the SCAM users' guide section of the CAM6 users guide (https://ncar.github.io/CAM/doc/build/html/users_guide/).

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