February 11, 2015

Richard Neale
Editor, Geophysical Model Development (GMD)
editorial@copernicus.org

Re: Responses to comments on "*Aerosol specification in single-column CAM5"* by B. Lebassi-Habtezion and P. Caldwell

Dear Dr. Neale:

We hope that our response letter and revised manuscript have answered all of the points raised by the two anonymous referees and yourself, which we believe has resulted in an improved paper.

Please contact me if you require additional information.

Thank you for your continued interest in this paper.

Sincerely yours,

Bereket Habtezion

B. Responses to comments to referee #1

Anonymous Referee #1 (Comments to Authors):

1.GENERAL COMMENTS

This study takes a close look at the role of aerosol in single column model experiments with CAM5. By default, the model initializes the aerosol fields to zero, which is interpreted as being incorrect. Three alternatives are explored: specifying climatological aerosol, specifying observed aerosol, and fixing the droplet and ice numbers. Several typical SCM cases are used: marine stratocumulus (DYCOMS), Arctic stratus (MPACE), shallow convection (RICO), and deep convection (ARMSGP). Several interesting points emerge through the study. The microphysics desiccates the atmosphere and has a very strong impact on the LWP. This effect is deleterious in mixed phase clouds and is controlled by the Myers formulation for ice nucleation. There is a physical inconsistency associated with the microphysics removing so much water because cloud fraction is determined before this process, so CAM5 does not completely get rid of the old "empty cloud" problem previously reported for CAM3/4. Convective cloud regimes are relatively insensitive to aerosol effects because of the simpler microphysics in the convection schemes, but near cloud-base activation still dominates the determination of droplet number so aerosol matters there while detrainment dominates the determination of droplet number at higher levels. Although I appreciate the general approach of the study, I believe there are several major issues that should be addressed before it is suitable for publication. One is the framing of the problem.

The whole study seems to hinge on the initialization of aerosol to zero in the default model being wrong. It is not a priori wrong to take this approach, and one could probably argue that it is as valid as any of the alternative approaches presented in this paper. The results show that there are probably ways to make the SCM better capture the observed cloud properties, perhaps supporting adoption of another aerosol specification. On the other hand, which of the approaches best matches the results from the full 3D model? The answer is not clear in this study, but probably should be considered as central in defining what the SCM should do. The first sentences of both the abstract and introduction indicate that SCMs are useful for model improvements, and therefore must (before all else) be representative of the full 3D model. Whether any of the aerosol specifications discussed here come closer to the full model is unclear.

We thank the reviewer for their thoughtful comments. We agree that the point of single column modeling is to improve the GCM and that our previous draft did not make a clear case for how our proposed fixes contributed to that goal. We now mention in the text that using aerosol specified from previous GCM runs (the PrescAero method) is the best way to match the *typical* behavior of the 3d model. In order to identify the source of *problems* in the GCM, however, it is best to perform sensitivity studies where quantities typically predicted by the model are prescribed instead. Idealized experiments of this sort are also extremely useful for optimizing a parameterization of interest without while avoiding compensating errors from other schemes. It is for this purpose that we propose the FixHydro and ObsAero methods.

We strongly disagree that initializing aerosol to zero is as valid as specifying aerosol or droplet and crystal number. Clouds respond very strongly to cloud number concentrations, so using a number concentration which is unrealistic (compared to observations and/or typical model values) will produce very unrealistic and unuseful output. In this sense using zero aerosol is like initializing temperature to zero Kelvin - the planet you are simulating is not Earth and the SCM results will bear little resemblance to a column from the 3d model. You are asking the physical parameterizations to act far outside of the conditions they were designed for and any results you get are unlikely to be relevant for guiding GCM development.

All of this was poorly explained in the previous version of the paper - we have revised the paper to make these points more clearly.

A second major issue is that there is a bit of a false dichotomy being presented in the comparison of the default model and the alternatives, and it comes down to the difference between the way the default model is initialized versus how aerosol is specified throughout the integration in the alternatives. The default model initializes the aerosol to zero and is subsequently driven by surface emissions, so the aerosol field (if I understand correctly) remains prognostic, but is erroneous because the only source is at the surface and vertical transport is the only way to populate the upper levels. In the alternative approaches, the initialization of the aerosol is likely to be inconsequent for the result. Instead it is the specification of aerosol fields through the column through the integration that matters. Connecting to my first point, it seems like the prognostic aerosol approach is most consistent with the 3D model, but the SCM would then require aerosol as part of the large-scale forcing, and how to construct an appropriate aerosol forcing may be ambiguous. This distinction between the initialization problem and the specification problem may seem nit-picky, but I think it is fundamental to the study, and the issues are confused throughout the text.

We agree that the default model is fundamentally different from our proposed fixes because it prognoses aerosol while the other fixes just specify aerosol or cloud number densities. This means that simulations using our proposed fixes have less opportunity to go wrong. As noted above, constraints of this type are acceptable or even preferable when the goal is to optimize some aspect of the GCM unrelated to aerosol. It is true that aerosol activation can't be studied when cloud number densities are prescribed, and that's why we developed the PrescAero and ObsAero methods. It is also true that none of our methods can be used to study cloud/aerosol interaction. We have tried to clarify the tradeoffs between our proposed approaches to aerosol treatment in the SCM in the revised paper.

Third, the text presents the results of the default and alternatives, but never makes any recommendation for what would be the best method. From my vantage point, this lack of a clear recommendation is rooted in the previous points regarding how to think about and frame the problem of aerosol in SCMs.

We agree that framing for our aerosol treatments was lacking. Hopefully with that in place it is clear that there is no single best approach. If one is interested in the impact of their changes to cloud physics, using observed droplet/crystal concentrations is optimal (if they are available). If one is interested in testing changes to the aerosol activation scheme, using observed aerosol is probably best. And if one wants to know how biases in modeled aerosol concentrations impact cloud and thermodynamic behavior, they should compare specAero against obsAero runs. If one is interested in interactions between cloud and aerosol, the 3d model is needed (or better initialization and specification of horizontal advective tendencies is needed). We have included this explanation in the new revision.

Finally, and related to the others, the text needs a substantial editing for grammatical errors, clarity, and concision.

We agree that the previous draft was sloppy and apologize for that. We've tried to clean up the new version.

SPECIFIC COMMENTS

1. The abstract is overly long and does not highlight the main results very well.

We agree and have completely rewritten the abstract to address your concerns.

2. The first paragraph (pg 3-4) is a little hard to parse. The points get lost in all the call outs to the SCM studies. I think the paragraph could be cleaned up substantially by focusing on the themes that have emerged from these studies, rather than the specific conclusions from each one. It seems unnecessary to establish these results except to introduce the cases to be used later.

Good point. We have moved discussion of previous GCSS/GASS results into the sections devoted to each case study and instead highlight the importance of these case studies and of idealizations as a means to improve model behavior.

3. pg 4, line 19-21: What does it mean for aerosol to be handled "appropriately" in an SCM. This is not established, but would be a useful discussion for this paper. It should also be explained (here or in Section 2) what the default model actually does (initialize to zero and then use surface emissions in MAM).

We have tried to explain this better.

4. The use of the word "fixes" for the alternative aerosol specifications seems informal on the one hand and misleading on the other. If these "fixes" actually fix the issue, then the study should determine what the default model behavior should be and make a recommendation. As mentioned above, there is also this issue about the difference between incorrect specification of the aerosol forcing (in the sense of the specified aerosol transport) versus initialization and actual physics. This comes back on page 5, lines 22-24: "As mentioned previously, this prognostic aerosol model in SCAM5 mode initializes the mass-mixing ratio of the different aerosol species to zero. Hence we test other fixes to solve this problem as described below." This statement must be interpreted as one of an initialization problem, but none of the "fixes" is focused on initialization (and in fact, if the aerosol are still initialized to zero, it probably would not make any difference after the first time step).

We see the 'problem' to be that aerosol and number concentration are so low that SCM runs are simulating an environment that would never happen in CAM or in the real world. In this sense our 'fixes' really are fixes in the sense that they solve the problem. We have tried to clarify this usage in the last sentence of the introduction and have replaced 'fixes' with 'solutions' to be less colloquial.

5. pg 7, line 2 overstates the breadth of the cases. These cases are appropriate for the study, but do not cover the "full range of cloud types."

Agreed. We have changed this text to read 'a range of climatologically-important cloud regimes'

6. Section 2 could probably be streamlined by constructing a table with all the forcings and then the text could focus on the big picture of each case and any caveats (which are already there, e.g., the change in w for the MPACE case).

We thank the referee for insightful comment. We have added a new table (table 1) and edited the text accordingly.

7. On pg 12, line 24, the 3D model result is referenced and is very different from the SCM result. What does this mean for interpreting the SCM as a cheap version of the full model? Could the difference in this case be due to sampling? Specifically, is the diurnal cycle in the long 3D run biasing the mean profile compared to the DYCOMS result?

This is a good point. Yes, including daylight hours is undoubtedly causing the BL depth to decrease in the GCM (which we now note in the text). The fact that the SCM runs are a short case study forced by observations and the GCM is a long-term climatology is undoubtedly also playing a role. As noted above, SCM case studies are typically used for testing how the model would respond if it was given realistic forcings rather than trying to replicate the bias of the full model.

8. Pg 13, line 10 blames the initialization of aerosol, but this is after hours of simulation. Is the problem that there isn't enough vertical transport of aerosol from the surface emissions?

This is an interesting point. Schubert et al (1979) identify the turbulent mixing timescale of the stratocumulus-topped boundary layer as being ~1 day. Since this is longer than our DYCOMS and MPACE case studies, it is reasonable to blame initialization for some underprediction of aerosol. We see this empirically as well - it tends to take a couple of days for aerosol to equilibrate.

9. Pg 15: "empty clouds" have been pointed out in previous versions of CAM. Are these empty clouds conceptually similar, or is the different microphysics responsible for a new kind of empty cloud error?

Good catch. Yes, these 'empty clouds' are similar to those that plagued CAM3. The occurrence of empty clouds in CAM5 have been greatly reduced by adding checks in the macrophysics scheme (=cloud fraction + condensation/evaporation) which zero out cloud fraction if condensate is zero (or vice versa). Thus we were surprised to see empty clouds in this study. As explained in the text, these clouds are emptied by microphysics acting after all the macrophysical checks have been performed. We've included a discussion of this in the most recent draft.

10. Pg 15-16: The three paragraphs ending this section should be combined and reduced. The third paragraph contains most of the useful information, so the other two should be turned into one or two supporting sentences in the third.

Agreed. We ended up totally rewriting this section to address the reviewer's concern. .

11. In the RICO case, how can the surface fluxes be so far off if the surface temperature and wind are prescribed?

This is a very good point. To a reasonable level of approximation, surface fluxes depend on SST, wind speed, air temperature, and near-surface humidity, As the reviewer notes, wind speed and SST are fixed in these simulations. The source of surface flux error seems to be a drift towards colder and dryer conditions in the atmosphere. We could have worked harder to improve these simulations (e.g. by nudging the free troposphere or calculating winds from geostrophic values) but our main point with RICO is that aerosol doesn't matter (so model skill is independent of aerosol treatment and thus outside the direct scope of the paper).

12. I was surprised there was no discussion of precipitation in the RICO case. The SCM results must be precipitating, right?

Response: Yes the RICO case is a precipitating case. However, since the case is convective we didn't see much precipitation difference for the different aerosol specification cases.

TECHNICAL CORRECTIONS

pg 3: First sentence of the paper is incomplete: insert "for" between tool and efficient. Also, it is the Community Atmosphere Model, not "Atmospheric." (http://www.cesm.ucar.edu/models/cesm1.2/cam/)

Fixed, thanks.

pg 3, sentence starting at line 13 is grammatically wrong. Perhaps it should just be "In another SCM intercomparison, simulations ... "

Completely rewrote this section.

pg 3, the next sentence (line 16) is also wrong. Perhaps "The SCM intercomparison of ... "

Completely rewrote this section.

pg 4, line 17: There is a problem with the tense. Maybe it should read: "As a result, developing aerosol parameterizations has become a high priority in the climate modeling community."

Corrected as suggested

pg 4, line 18: This sentence reads awkwardly. First because it sounds like it is in the wrong tense ("had"), and second because the use of "break-through" is a bit aggrandizing of the aerosol model. It is a major development and adds capability, but for most applications it isn't a game-changer.

Deleted this sentence

pg 4, line 20: The SCM is referred to as CAM5-SCM here, but as SCAM5 later. Choose one and be consistent throughout.

Corrected as suggested and consistency check made throughout text

pg 5, line 14: "Brethorton" -> Bretherton

Corrected as suggested

pg 5, line 25 versus pg 6 line 3, and also throughout the paper there is a lot of switching between tenses. It's distracting to the (or at least this) reader.

Agreed. We have tried to be more consistent.

pg 5, line 26: "This case is the setup in default" is confusing, perhaps change to "This case is identical to the default"

Agreed. This whole section was confusing and we have rewritten it to (hopefully) improve clarity.

pg 7, line 8 AND EVERY SUB-SECTION TITLE: the letter denoting the subsection is repeated (e.g., a. a. DYCOMS RF02 case)

This issue seems to be related to GMDD's automatic conversion of word documents. We have deleted our lettering in hopes of fixing this problem.

pg 8, line 21: delete "values"

We completely rewrote this section to improve clarity.

pg 10, line 21: "The ARM95 included because" should be "The ARM95 case is included because" (?)

We completely rewrote this section for improved clarity.

pg 11, lines 16-19: grammar fixes: "We also include cloud base, zb, which is computed by interpolating to the level at which cloud fraction first exceeds 0.5 and cloud-top height, zi, which is computed by interpolating to the highest level at which the total water mixing ratio drops below 8gkg-1." -I think that zi is probably the lowest level at which q is below 8 g/kg, right?

Actually we do use interpolation. First we identify the level just below the cldfrac=0.5 or qt=8 g/kg mark and then we do linear interpolation between this level and the level just above to get an interpolated height rather than a layer height. This approach avoids noise due to snapping to model levels and reduces sensitivity to the grid specification. We have tried to explain this better.

pg 14, line 10: "not" -> "no"

Corrected

pg 14, lines 22-24: This sentence reads very poorly, perhaps change to, "In PrescAero and ObsAero, the microphysics removes all the liquid water, but this feedback is removed in the FixHydro case by specifying constant droplet and ice numbers."

Agreed. We have rewritten this section to make more sense.

pg 14, line 28: "consistes" -> consists

Oops, thanks.

pg 15, line 4: "the 10 years October 2004" What is this supposed to mean?

We have corrected this section to be more clear.

pg 16, line 22: the first "LHF" should be "SHF"

Corrected

pg 16, line 24: "compared to LES, (0.19) and (19 g m2), respectively." -> "compared to LES (0.19 and 19 g m-2, respectively)."

We've removed these numbers from the text since they can be easily read from the table.

pg 17, line 4: has -> have

Corrected

pg 17, line 5: "was" probably is not correct tense

Corrected

pg 17, lines 27-28: incomplete sentence (maybe need "is" between overestimation and due?)

Corrected

pg 18, line 16: "every other day" what is meant by this?

Corrected

pg 18, line 21: "Generally, SCAM over estimated LWP at all periods." -> "Generally, SCAM5 overestimated LWP during all periods." (If the past tense is to be used.)

Corrected

pg 19, line 14-15: "formed when you have higher aerosol burden." -> "formed with a higher aerosol burden."

Rewrote this section.

Figure 1: the global run isn't labeled.

Good point. Fixed.

Figure 4 caption: " 3-D CAM values are 10 years July average global CAM extracted at the location of MPACE-B." -> "They cyan line shows the July average from a 10-year integration of the full 3D CAM at the MPACE-B location."

Thanks. Fixed

Figure 5: add legend for the observations

Great idea, done.

Figure 7: "No Aero" is the wrong color in the legend.

This figure seems irrelevant since N_d has no impact on the simulations, so we removed it entirely.

C. Responses to comments from referee #2

Review on "Aerosol specification in single-column CAM5" by B. Lebassi-Habtezion and P. Caldwell

Major comments:

Single-column model (SCM) is an important tool for the climate model developments. This study implements different approaches of aerosol specification for the SCM of the NCAR/DOE CAM5, and examines effects on SCM simulations under several cloud scenarios.

This study is a useful contribution to the global climate model (GCM) community regarding the importance of aerosols for simulation of clouds when GCMs have been implementing the aerosol effects on clouds.

I feel this manuscript in current version was prepared rash and there are many places through the text needing to improve the accuracy of wording. Some important references relevant to this study are missing.

I recommend the publication of this manuscript after my comments are sufficiently addressed.

Other comments:

1.P7694. Line 25-28. The current statement is a bit confusing and please change the wording here "This finding suggests…". Since ARM95 is a convective case, and CAM5 does not treat the aerosol activation and droplet nucleation for this type of clouds, the underestimation of predicted droplet concentrations suggests that CAM5 needs to include the sophisticated cloud microphysics and aerosol effects for this type of clouds.

We have rewritten this section to improve clarity. The idea that lack of convective aerosol treatment is the source of low aerosol in the SGP region is an interesting idea that should be tested. Our intuition is that convective microphysics would further *reduce* aerosol number due to rain out and combination of aerosol particles when droplets evaporate. Note that convective aerosol *transport* already exists in (in a crude form) in CAM5 so lofting should already be happening.

2.P7696. Line 19. Citation of Abdul-Razzak and Ghan, 2000 is not correct one. Cite Ghan et al. (2012) and put behind Liu et al. (2012).

Oops, thanks. Fixed.

3.P7697. Line 17. Remove "simplified". "Easter et al. 2014" is not a correct one, replaced by "Liu et al., 2012)".

Sorry, fixed.

4.P7702. Line 26. Please give a reference for the "State University of New York (SUNY) objective analysis method".

Done

5.P7703. Line 9. At which vertical level is Nd/Ni in Table 1?

Great question. These quantities are the average over the in-cloud portions of all cloudy levels of the column. We have tried to clarify this in the table captions.

6.P7704. Line 9. "4.45 kgkg-1 s-1" is 8 orders of magnitude higher than other numbers here. Is this a correct value?

Oops, corrected.

7.P7706. Line 10. Change "not" to "no".

Done.

8.P7706. Lines 22-24. This issue is not new and has been identified by earlier studies, e.g., Liu et al. 2011. Please cite this study.

It is true that Liu et al (2011) note low LWP caused by microphysics and suggest that the Meyers nucleation scheme is a cause - we should have (and now do) cite them for this. We find no mention of total depletion in their paper however, so don't cite them for this.

9.P7707. Line 5 and other places. The CAM5 model time step is 30 min not 20 min.

Good point, fixed.

10.P7707. Lines 22-28. Earlier studies have found the overestimation of ice number from Meyers et al. parameterization and also tested several new parameterizations. These studies (e.g., Liu et al. 2011, Xie et al. 2013; English et al. 2014) should be mentioned and discussed.

True. References added.

11.P7708. Line 17. "The Default, PrescAero, and ObsAero cases showed an average Nd value of 51 cm-3". However, it is not 51 cm-3 in Table 3. Please clarify.

This value was left over from an earlier round of model runs. We have deleted these numbers from the body of the text in the new draft because it was redundant - the reader can easily extract such information directly from the tables.

12.P7708. Line 24. Is there a reason why "All the models simulated CLC (0.18), and LWP (19.4 gm-2) very well as compared to LES, (0.19) and (19 gm-2), respectively".

Since the vertically-resolved cloud fraction (Fig. 8) is so different between the LES and CAM5-SCM, we have to conclude that good agreement in cloud cover is (unfortunately) coincidental. This behavior is, however, canonical for the UW ShCu scheme (as noted in Park and Bretherton, 2009).

13.P7709. Line 13. Why does the ObsAero give the lowest aerosol burdens compared to Default case?

This is a good question. There's no rule that Default needs to be the lowest - it builds up aerosol from surface emissions over the 24 hr RICO simulation period so there's no reason it couldn't reach higher N_d levels than ObsAero. What is strange is that N_d is only 14 cm^{-3} in ObsAero even though it uses aerosol specifications which produced reasonable droplet concentrations in LES. We have checked that we implemented the suggested aerosol numbers from VZ11 correctly but otherwise have no explanation.

14.P7709. Lines 23-25. Mass flux figure is shown in Fig.8b not 8a. How do you know "condensate is overpredicted"? Condensate is shown in Fig.8a not in Fig.8b.

The figure numbers are corrected and statement reworded.

15.P7710. Line 27-28. Why the Nd from prescAero is so different from that from the 10-years prescribed climatology (Figure 11)?

The 3d model includes horizontal advection so can feel aerosol emitted in other regions. Also, as mentioned with regard to DYCOMS RF02, N_d can be (and undoubtedly is) created by convective detrainment in these simulations. As a result, N_d wouldn't be the same between prescribed-aerosol GCM and SCM runs unless their convection timeseries were similar (and there's no reason to expect that is the case).

Aerosol Specification in Single-Column CAM5

Bereket Lebassi-Habtezion and Peter M. Caldwell

Lawrence Livermore National Laboratory~~, PCMDI, Cloud Processes Research Group~~

February 11, 2015

~~October 14, 2014~~

Corresponding author address: Peter Caldwell~~Bereket Lebassi-Habtezion~~, Lawrence Livermore National Lab, PO Box 808~~Laboratory, PCMDI, Cloud Processes Research (CPR) Group~~, Livermore~~,~~ CA 94551.
E-mail:caldwell19~~habtezion1~~@llnl.gov

Abstract

Single column model (SCM) capability is an important tool for general circulation model development. The SCM mode of version 5 of the Community Atmosphere Model (CAM5) is shown to handle aerosol initialization and advection improperly, resulting in aerosol, cloud droplet, and ice crystal concentrations which are typically much lower than observed or simulated by CAM5 in global mode. This deficiency has a major impact on stratiform cloud simulations. It has little impact on convective cases because aerosol is currently not used by CAM5 convective schemes and convective cases are typically longer in duration (so initialization is less important). By imposing fixed aerosol or cloud-droplet and crystal number concentrations, the aerosol issues described above can be avoided. Sensitivity studies using these idealizations suggest that the Meyers et al. (1992) ice nucleation scheme prevents mixed-phase cloud from existing by producing too many ice crystals. Microphysics is shown to strongly deplete cloud water in stratiform cases, indicating problems with sequential splitting in CAM5 and the need for careful interpretation of output from sequentially split models. Droplet concentration in the GCM version of CAM5 is also shown to be far too low (~25 cm^{-3}) at the Southern Great Plains Atmospheric Radiation Measurement site.

~~The ability to run a global climate model in single-column mode is very useful for testing model improvements because single-column models (SCMs) are inexpensive to run and easy to interpret. A major breakthrough in Version 5 of the Community Atmosphere Model (CAM5) is the inclusion of prognostic aerosol. Unfortunately, this improvement was not coordinated with the SCM version of CAM5 and as a result CAM5-SCM initializes aerosols to zero.~~

~~In this study we explore the impact of running CAM5-SCM with aerosol initialized to zero (hereafter named Default) and test three potential fixes. The first fix is to use CAM5's prescribed aerosol capability, which specifies aerosols at monthly climatological values. The second method is to prescribe aerosols at observed values. The third approach is to fix droplet and ice crystal numbers at prescribed values. We test our fixes in four different cloud regimes to ensure representativeness: subtropical drizzling stratocumulus (based on the DYCOMS RF02 case study), mixed-phase Arctic stratocumulus (using the MPACE-B case study), tropical shallow convection (using the RICO case study), and summertime mid-latitude continental convection (using the ARM95 case study).~~

~~Stratiform cloud cases (DYCOMS RF02 and MPACE-B) were found to have a strong dependence on aerosol concentration, while convective cases (RICO and ARM95) were relatively insensitive to aerosol specification. This is perhaps expected because convective schemes in CAM5 do not currently use aerosol information. Adequate liquid water content in the MPACE-B case was only maintained when ice crystal number concentration was specified because the Meyers et al. (1992) deposition/condensation ice nucleation scheme used by CAM5 greatly overpredicts ice nucleation rates, causing~~

~~clouds to rapidly glaciate. Surprisingly, predicted droplet concentrations for the ARM95 region in both SCM and global runs were around 25 cm~~ ~~$^{-3}$~~ ~~, which is much lower than observed. This finding suggests that CAM5 has problems capturing aerosol effects in this climate regime.~~

1. Introduction

The Single Column Model (SCM) version of the Community Atmosphere Model (CAM) is a very important tool for development of model numerics and physics. One advantage of the SCM is that it is much more computationally affordable, which allows developers to easily test a wide variety of model changes. Another advantage is that there exists a large number of standard SCM case studies exist which can be used to evaluate model behavior in a wide variety of important climate regimes. These case studies (typically organized by the Global Energy and Water Experiment Cloud System Study (GCSS) Boundary Layer Cloud Working Group and later by the Global Atmosphere System Studies (GASS) Panel) are typically based on observations from field campaigns which provide data for driving the SCM and for evaluating its output (Randall et al., 2003). Cases tend to focus on a single meteorological phenomenon, which makes them perfect testbeds for thinking deeply about the processes responsible for model behavior.

In the first GCSS intercomparison (Moeng et al., 1996), liquid water path (LWP) in nocturnal stratocumulus was found to vary by a factor of 5 across large-eddy simulation (LES) models. The source of this spread could not be identified because model parameterizations differed so widely. This experience sparked a long tradition of idealizing aspects of models performing these standard case studies in order to isolate the source of differences between simulations. In particular, variables normally predicted by general circulation models (GCMs) are often hard-coded to observed values in these SCM case studies in order to separate errors due to prediction of these variables from errors in other parts of the model. By idealizing or specifying aspects of a simulation, the processes responsible for model bias can be illuminated, providing a pathway towards model improvement.

~~The Single Column Model (SCM) version of Community Atmospheric Model (CAM) is a very important tool efficient development of model numerics and physics. Based on observed test cases, many SCM intercomparison studies of stratocumulus and cumulus cloud-top boundary layers have been undertaken with the goal of improving physical parameterizations of clouds and cloud-related processes and their interactions. A number of SCM intercomparison studies by the Global Energy and Water Experiment (GEWEX) Cloud Systems Study (GCSS) Boundary Layer Cloud Working Group (BLCWG) have been conducted to understand common biases in climate models. For example, one of the early SCM intercomparison studies (Moeng et al. 1996) simulated nocturnal non-precipitating stratocumulus clouds and showed that the LWP decreased substantially during the initial period of the simulation, which was explained by excessive dry air entrainment. Another SCM intercomparison simulations of the Second Dynamics and Chemistry of the Marine Stratocumulus field study (DYCOMS II) research flight RF01 (DYCOMSRF01) also showed low liquid water path (LWP) despite improvement of entrainment rates in the models (Zhu et al., 2005). SCM intercomparison of drizzling stratocumulus from the DYCOMS II research flight 02 (DYCOMSRF02) by vanZanten and Stevens (2005) tested the impact of drizzle in SCMs and found that drizzle decreased LWP substantially in most of the models. Another SCM study by Wyant et al. (2007) also carried out SCM intercomparison simulations for the DYCOMSRF02 case. They found that models need improvement in drizzle, sedimentation, and sub-cloud evaporation parameterizations. A recent SCM and cloud-~~

~~resolving model intercomparison study by Klein et al. (2009) simulated the mixed-phase stratocumulus cloud observed during the Atmospheric Radiation Measurement (ARM) program's Mixed-Phase Arctic Cloud Experiment (MPACE-B). They found that models generally showed ice water path (IWP) in good agreement with observations while LWP was severely under predicted. This was attributed to the interaction between liquid and ice-phase microphysics suggesting the need to improve the representation of mixed-phase microphysics. Previous SCM and LES intercomparison studies were also undertaken for deep (ARM southern Great Plain [ARM SGP] site) and shallow (Rain in Cumulus over the Ocean [RICO]) convective cases. Ghan et al., 2000 performed an SCM intercomparison study for ARM SGP using eleven SCMs and found that no individual models stood out as superior, and the model ensemble showed close agreement with observations. A recent study by VanZanten et al., 2011 used twelve LES simulations to study the interplay between micro and macro physics processes in the evolution of clouds and precipitation, with a wide range of microphysical representations, during the undisturbed period of the RICO field study. Many features of their LES simulations generally agreed with observations. Similar thermodynamic and energetic behavior was produced as compared to previous studies based on SCMs.~~

A significant fraction of the uncertainties in climate projections results from the representation of aerosol (~~Houghton et al., 1996;~~ Haywood and Boucher, 2000; Forster et al., 2007). Aerosols affect climate by directly absorbing and reflecting atmospheric radiation (known as the direct effect) and by changing cloud optical properties and lifetimes (known as aerosol indirect effects). As a result, developing~~development and~~

~~testing of~~ aerosol parameterizations has become~~have been~~ a high priority in the climate modeling community.

The inclusion of ~~the~~ prognostic aerosol ~~model~~ in version 5 of CAM (CAM5) has~~had~~ been a major milestone~~breakthrough~~ in its development (~~Abdul-Razzak and Ghan, 2000;~~ Liu et al., 2012; Ghan et al. 2012). Horizontal advective tendencies are required for ~~). However, CAM5-SCM has not been updated appropriately to handle the addition of~~ prognostic aerosol, however, and these cannot be calculated from a single column. The SCM case was not considered in the development of CAM5 aerosol, so horizontal advective tendencies for aerosol are hardcoded to zero (i.e. advection neither increases or decreases aerosol concentrations) in CAM5-SCM. It would be straightforward to edit the code to allow aerosol advection in SCM mode to be specified, but such functionality would be of limited use since observed aerosol advective tendencies are not typically available for SCM case studies. A bigger problem is that CAM5-SCM~~CAM. In particular, it~~ initializes all aerosol mass mixing ratios to zero. As a result, aerosol concentrations are unrealistically low (compared to observations or GCM ~~the default SCM release substantially underestimates IWP and LWP of the SCM~~ simulations) in SCM runs until surface emissions (specified from observed climatology) loft sufficient aerosol. Since this process can take several days (e.g. Schubert et al, 1979), SCM case studies (particularly stratiform ~~for a variety of~~ cloud studies, which tend to be short) are plagued by extremely low aerosol. The goal of~~regimes.~~

~~In~~ this study is to~~we~~ test the impact of CAM5-SCM's aerosol treatment~~the zero aerosol initialization problem, and we introduce fixes for this issue. To ensure representativeness, we test SCM simulations~~ for a variety of classic case studies and to evaluate the efficacy of several potential solutions to the problems induced by unrealistically low aerosol concentration. ~~cloud regimes. The SCM cases used for this study include summertime mid-latitude continental convection (ARM95), shallow convection (RICO), subtropical drizzling stratocumulus (DYCOMSRF02), and multi-level Arctic clouds (MPACE-B). Results are analyzed and compared to observations and previous LES results.~~

2. Methods

2.1 Model~~SCAM5~~ Setup

All simulations in ~~In~~ this paper were performed using~~study we employed the SCM version of~~ CAM5~~, (SCAM5),~~ which is described in detail in Neale et al (2012). Briefly,~~consists of physics parameterizations driven by prescribed advective tendencies (Hack and Pedretti, 2000).~~

~~There are two types of clouds in SCAM5: stratus clouds with symmetric~~ turbulent transport at all model levels in CAM5 is computed following Bretherton and Park (2009). Stratiform cloud fraction~~properties~~ and condensation/evaporation is computed following Park et al (2014) ~~cumulus clouds with vertically stretched shapes~~ and stratiform microphysics is handled according to ~~asymmetric turbulence properties. We use the~~ Morrison and Gettelman (~~stratiform cloud microphysics scheme (Morrison and Gettelman,~~ 2008) and Gettelman et al., (2010). Shallow~~the Park et al. (2014) macrophysics scheme. to model stratiform clouds. Deep~~ convection follows Park and Bretherton (2009), while deep~~is handled by the modified Zhang-McFarlane parameterization scheme (Zhang and McFarlane, 1995), and shallow~~ convection is parameterized according to Zhang and McFarlane (1995) as modified by Richter and

Rasch (2008~~by the University of Washington shallow convection parameterization scheme (Park and Bretherton, 2009). Turbulence is handled following Brethorton and Park (2009~~). Radiation is calculated using the Rapid Radiative Transfer Model (RRTMG) radiation scheme (Mlawer et al., 1997). Aerosol are handled by

~~CAM5 is~~ the ~~first version of CAM that was designed to simulate aerosol-cloud interactions. It has a~~ three mode simplified modal aerosol model (MAM3; Liu~~) (Easter~~ et al., 2012~~2004~~; Ghan et al. 2012) with accumulation~~Accumulation~~, Aitken, and coarse~~Coarse~~ modes. MAM3 is capable of treating complex aerosol physical, optical, and chemical processes and simulating aerosol size, mass and number distributions. The aerosol size distribution is lognormal, and internal and external mixing between aerosol components is assumed in the model. ~~As mentioned previously, this prognostic aerosol model in SCAM5 mode initializes the mass-mixing ratio of the different aerosol species to zero. Hence we test other fixes to solve this problem as described below.~~

In SCM mode, a column from the global model is extracted and driven by prescribed winds and horizontal advective tendencies (Hack and Pedretti, 2000). This results in an idealized version of the GCM where code related to fluid flow is replaced by externally-imposed data but the parameterized physics component of the model retains its full complexity. All SCM runs use a timestep of 1200 sec and 30 vertical grid levels (with ~20 levels in the free troposphere).

Most of the simulations described in this paper are SCM runs as described in Sect. 2.3, but we do conduct two 10 yr-long GCM run using the finite-volume dynamical core at $1.9x2.5^0$ resolution for comparison. One simulation was done using the default prognostic aerosol method and the other uses the prescribed aerosol functionality included in version 1.2 of the Community Earth System Model (CESM). Both GCM runs were driven by a repeating annual cycle of year 2000 SST, greenhouse gases, and aerosols. They use an 1800 sec timestep and the same 30 vertical levels used for the SCM runs.

2.2 Proposed Solutions

As noted in the introduction, a problem with CAM5-SCM is that aerosols are initialized to zero and horizontal advection of aerosol is not treated realistically. As a result, aerosol concentrations in SCM runs are much lower than observed or simulated in GCM runs. In this section we outline 3 possible solutions to the problem of low aerosol concentration in CAM5-SCM.

1. Our first approach (hereafter called FixHydro) is to fix cloud droplet (N_d) and ice crystal (N_i) number concentrations at observed values. Because N_d and N_i are the means through which aerosol affects cloud in CAM5, fixing these concentrations is a simple way to avoid cloud problems due to low aerosol in CAM5-SCM. The FixHydro approach is attractive because a). These number concentrations are available for most popular SCM case studies and b). Specifying N_d and N_i isolates biases in the microphysics from biases related to aerosol treatment. Ability to isolate the parameterization responsible for bad behavior is critical for avoiding a model held together by compensating errors. One downside to FixHydro is that it does not alleviate clear-sky impacts of low aerosol. This is not a critical problem since clear-sky effects tend to be small relative to the radiative impact of cloud changes, but it does motivate our other solutions.

~~1.~~ Our~~The first method we employed is to fix cloud droplet (N_d) and ice crystal (N_i) concentration (hereafter called FixHydro). This case is the setup in default SCAM5 with prognostic MAM3 but N_d and N_i values are prescribed before the microphysics call. We then set N_d and N_i tendencies inside the microphysics to zero, which keeps the value of N_d and N_i to their corresponding prescribed values.~~

2. ~~The~~ second method (hereafter called PrescAero) uses the new prescribed aerosol capability included in ~~Community Earth System Model (~~CESM~~)~~ version 1.2. PrescAero prescribes mass mixing ratios of aerosol species using mean climatological values for each month of the year ~~and~~ for each grid cell (based on results from a long prognostic aerosol run). By default, prescribed aerosol values are ~~actually~~ specified by daily random draws from a lognormal distribution based~~centered~~ on climatological average values. We turn this random sampling off for SCM~~SCAM5~~ because it would make SCM~~this sampling makes SCAM~~ runs irreproducible and ~~provides~~ occasionally provides very unusual values which would unnecessarily complicate interpretation of SCM results~~odd values~~. Random sampling is not needed in the tropics~~,~~ but may be required to reproduce CAM5 polar climate (Jin-Ho Yoon, personal communication 2014),~~,~~ in which case ensembles of CAM5-SCM~~SCAM5~~ runs are probably needed.

3. In our~~The~~ last method, ~~we employed is the observed aerosol case where~~ we apply~~use~~ observed mixing ratios and size distributions to~~of~~ the aerosols in MAM3. This method (hereafter named obsAero) makes use of~~modifies the~~ PrescAero code but imposes~~methodology to instead use~~ observed rather than modeled mass mixing ratios of the different aerosol species for all the modes. To use this approach~~mode~~, observed values are needed for the number concentrations of the aerosol mode~~parameters~~ N_j,

the geometric mean dry radius a_{mj}, and the geometric standard deviation σ_j of~~ for~~ the multimode lognormal aerosol size distribution given by the following equation (Abdul-Razzak and Ghan, 2000):

$$\frac{dn}{da} = \sum_{j=1}^{3} \frac{N_j}{\sqrt{2\pi}\sigma_j} \cancel{\sum_{j=1}^{I} \frac{N_J}{\sqrt{2\pi}\sigma_J}} exp\left\{-\frac{ln^2(\frac{a}{a_{mj}})}{2ln^2\sigma_j}\right\}, \qquad (1)$$

where the summation is over all 3 aerosol modes (accumulation, aitken~~N_j, a_{mj}~~, and coarse).

Each of our 3 solutions has advantages~~σ_j are the number concentrations of the aerosol mode, the geometric mean dry radius,~~ and disadvantages. Many case studies lack the information necessary for the ObsAero method and some lack N_d and N_i information needed for the FixHydro approach. For these cases, PrescAero is the only viable option. PrescAero is also the best choice if one's goal is to emulate the behavior~~geometric standard deviation~~ of the GCM as closely as possible (since it uses aerosol values from the full model). But aerosol from GCM simulations is often a poor proxy for observed values (both because values at the time of observation may differ greatly from climatology and because the model climatology may be biased), so fixes based on observed data are more appropriate for experiments which will be validated against observations at a particular time and place. ~~mode j, respectively.~~

The goal of the experiment also plays a critical role in determining which fix is best. For example, FixHydro is clearly inappropriate for studying aerosol effects but its simplicity makes it optimal for teasing out errors in the microphysics scheme. ObsAero and FixHydro methods are useful for testing aerosol activation but not 2-way cloud/aerosol interactions. Comparing FixHydro and ObsAero results may be the best way to identify whether biases come from aerosol activation or other processes. In short, there is no 'best' approach to obtaining realistic aerosol in CAM5-SCM. Our goal in this paper is to prove that all 3 methods yield acceptable solutions and are suitable for use as appropriate.

If one's goal is to study interaction between cloud and aerosol, none of our proposed methods are appropriate. It would be relatively straightforward to add another SCM option which initializes aerosol to observed or model-specified values and allows the model to ingest horizontal aerosol advective tendencies. We do not do this because we do not know of any SCM case studies where such information is available, our personal research plans don't require this functionality, and global simulations with specified meteorology (e.g. Rasch et al., 1997) already fill this role.

2.3 SCM Cases

In order~~*2.2 SCAM Cases*~~

~~In an attempt~~ to test aerosol effects over a~~the full~~ range of climatologically-importantcloud~~ types, we tested our fixes using case studies from four different cloud regimes. We set up four SCAM5 case simulations using the Default configuration and each of the three different fixes discussed in the previous section. The idealization and setup of each case is based on several SCM and LES intercomparison studies conducted for each of the four different~~ cloud regimes we analyze results from 4 case studies, each highlighting a different type of cloud. These cases include drizzling subtropical stratocumulus, mixed-phase Arctic stratocumulus, maritime shallow convection, and continental deep convection. The details of these~~the~~ experiments conducted are summarized below.

~~*a.*~~ *DYCOMS RF02 Case*

~~On July 11, 1999, DYCOMSRF02 sampled drizzling stratocumulus off the coast of California. Measurements from this flight formed the basis for large eddy simulation (LES) and SCM intercomparisons by Ackerman et al. (2009) and Wyant et al. (2007), respectively. For this paper we used an experimental configuration similar to Wyant et al. (2007).~~ Subtropical stratocumulus are important because of all cloud types they have the biggest impact on the planetary radiation budget (Hartmann et al., 1992), and difficulty in simulating them is a leading source of uncertainty in climate sensitivity (e.g. Bony and Dufresne, 2005). Because they are important yet hard to simulate, stratocumulus have been the focus of a large number of field campaigns. Research Flight 2 of the Second Dynamics and Chemistry of Marine Stratocumulus field campaign (hereafter DYCOMS RF02) sampled drizzling stratocumulus off the coast of California during the night of July 11, 1999. Data from this flight formed the basis for an SCM intercomparison by Wyant et al (2007; hereafter W07) and an LES intercomparison by Ackerman et al (2009). Like previous intercomparisons, the SCMs studied varied greatly in their ability to predict stratocumulus properties. Precipitation was found to play an important role in these simulations by reducing LWP and (to a lesser extent) reducing cloud-top entrainment.~~the leading source of uncertainty in climate sensitivity (Bony and Dufresne, 2005).~~

Our experimental configuration (outlined in Table 1) follows ~~Like Wyant et al. (2007), for maintaining an approximate balance between radiative cooling and subsidence warming above~~ the specifications of W07~~inversion, a constant divergence~~ with a few exceptions. One difference is that ~~value 3.75×10^{-6} s^{-1} was used to create an omega profile in the DYCOMSRF02 case, the RRMTG shortwave~~ radiation is calculated using RRTMG~~was turned off, and we ran our simulations for 6 hrs. Constant surface latent and sensible heat flux values of 93 w m^{-2} and 16 w m^{-2} (respectively) were imposed based on observed mean values from vanZanten and Stevens, (2005).~~

~~Unlike Wyant et al. (2007), the default RRMTG longwave radiation code was used~~ instead of the~~applying an~~ idealized ~~radiation~~ scheme used in W07. We also kept *u* and *v* for our simulations constant *instead of calculating winds from specified geostrophic wind profiles (which is reasonable since shear was not important in DYCOMS RF02).* While these changes make our simulations slightly less comparable to the runs in W07, they are simpler to implement and produce runs which are still realistic enough to be reasonably compared against observations. We also turn off cloud ~~. Cloud~~ processes ~~were turned off~~ above 700 hPa ~~in order~~ to prevent ice formation at the troposphere, which would otherwise occur~~occurs~~ due to interaction between the idealized SCM forcing specifications and ~~assumptions related to~~ subgrid ~~relative humidity~~ variability assumptions in CAM5. Observed aerosol information (for testing the ObsAero method) were taken from Ackerman et al. (2009), who assumed aerosol was comprised entirely of sulfate and chose parameters for the ~~For the FixHydro case, an observed N_d value of 55 cm^{-3} was used as recommended by Wyant et al. (2007). The~~ bimodal lognormal distribution (equation 1) in order to have N_d match~~was assumed to consist of sulfate aerosols with dry density 1.77 g cm^{-3}. The total number, mode radius, and geometric standard deviation for the aitken (125 cm^{-3}, 0.011 µm, 1.2) and accumulation (65 cm^{-3}, 0.06 µm, 1.7) modes, respectively were used. These values were chosen by Ackerman et al. (2009) to produce an in-cloud droplet~~

~~concentration in their LES, which matched~~ the observed droplet concentration value of 55 cm^{-3}.

~~*b.*~~ *MPACE-B Case*

Our second case comes from the Mixed-Phase Arctic Cloud Experiment (MPACE), which sampled clouds over open ocean near Barrow, AK. We focus particularly on the portion of this experiment between October 9, 1700 UTC to October 10, 0500 UTC, 2004 (known as MPACE-B), a period when mixed-phase stratocumulus was observed. This case was the subject of an intercomparison by Klein et al. (2009; hereafter K09). Most models participating in this intercomparison greatly underestimated the observed LWP because conversion to ice was too efficient. We choose this case because mixed-phase stratocumulus are very important to the polar surface budget, yet models (including CAM5) have a hard time simulating these clouds. MPACE-B is attractive because it includes both liquid and ice processes without being overly complicated. Our case setup (listed in Table 1) is similar to K09 with a few notable exceptions. We again specify winds at all levels while K09 advocates nudging winds below 700 hPa. We nudge thermodynamics variables to initial conditions above 700 hPa with a timescale of 1 hr while K09 specifications require all variables to be kept at their initial values above 700 hPa. These changes were again implemented for convenience and are not expected to have dramatic effects on our simulations.

~~The second case is MPACE-B, which consists of mixed-phase stratocumulus over open Ocean near Barrow, AK. The MPACE-B case is based on Arctic stratocumulus observed during the Mixed-Phase Arctic Cloud Experiment period B, which was the subject of an intercomparison by Klein et al. (2009). The case focused on the period~~

~~October 9, 1700 UTC to October 10, 0500 UTC, 2004. This case is useful because it is relatively simple yet includes both liquid and ice processes. The setup of this case was similar to that of Klein et al. (2009). Above 700 hPa, all variables were kept near to their initial values by nudging temperature and moisture with a time scale of 1 hr. While Klein et al. (2009) nudged *u* and *v* below 700 hPa, values *u* and *v* were kept constant at the observed values of -13 m s^{-1} and -3 m s^{-1} (respectively) in our study. Surface latent and sensible heat flux values of 107.7 W m^{-2} and 136.5 w m^{-2}, respectively, were used and were kept constant throughout the simulation period. Klein et al. (2009) specified a vertical velocity pressure (omega) value greater then zero at the top of the atmosphere (TOA), which causes huge advective heating from the top of the model, causing the model to crash in a few time steps. For this study we replaced the omega values from Klein et al. (2009) above 500 hPa with values that exponentially decrease to zero at TOA. The value used for advective temperature (moisture) tendency at the surface is -4.63e-5 K s^{-1} (-3.47 e-8 kg/kg/s); it increases linearly to a value of -0.174e-5 k s^{-1} (-0.19e-8 kg/kg/s) at 850 hPa, and stays constant above this level.~~

~~For the FixHydro case, an ice crystal concentration of 0.16 L^{-1} [were used as recommended by Klein et al. (2009)] and a N_d value of 50 cm^{-3}. For the ObsAero case, the aerosol mass mixing ratios of the three modes were diagnosed from the number mixing ratio and bimodal log-normal size distributions (equation 1) with aerosol partitioning of 70% SO_4 and 30% primary organic matter (POM) for the accumulation mode and 10% SO_4, 85% sea salt, and 5% dust for the coarse mode. We also used total number concentration, mode radius, and geometric standard deviation of the~~

~~accumulation (72.2 cm^{-3}, 0.054 μm, 2.04) and coarse (1.8 cm^{-3}, 1.3 μm, 2.5) modes, respectively (again following Klein et al., 2009).~~

~~c.~~ *RICO case*

Shallow Convection is another important cloud type with major impact on climate sensitivity (e.g. Medeiros et al., 2008). To sample this cloud type, we use data from the Rain in Cumulus over Ocean (RICO) experiment, which was ~~climatological regime . The RICO experiment was~~ conducted on the upwind side of the Islands of Antigua and Barbuda during the winter of 2004 ~~when trade winds cover the northwestern Atlantic Ocean~~ (Rauber et al., 2007). Unlike previous experiments such as~~, namely~~ the Atlantic Trade Wind Experiment (ATEX) and Barbados Oceanographic and Meteorological Experiment (BOMEX)~~),~~ which did little to measure clouds and precipitation, RICO has extensive cloud-related measurements, which make it useful~~an important study~~ for studying shallow cumulus clouds and their precipitation. Unfortunately, cloud data came at the expense of large-scale information, forcing modeling studies ~~For this case we tried to set up our case similar~~ to use idealized composite information which is not directly comparable to time-evolving observations. vanZanten et al. (2011), hereafter VZ11, describe the results of an LES intercomparison based on this composite data. An SCM intercomparison was planned (http://www.knmi.nl/samenw/rico/index.html) but never published. Our simulations are a blend between LES and SCM specifications as listed in Table 1 and described~~). The assumptions made for the RICO case are discussed~~ below.

One unique aspect of the RICO case is that radiation tendencies are included in the prescribed large-scale temperature ~~advection~~ tendency. As a result, we had to turn off the shortwave and longwave radiation schemes. The case was designed specifically~~There~~

~~was no nudging applied for this case since specifications were chosen~~ to be energetically and moisture balanced, and as a result we found we did not need to use nudging to obtain stable simulations. ~~. Like vanZanten et al. (2011), piecewise linear profiles of u, v, omega, and large-scale forcings of heat and moisture were used. The u value used was –1.9 m s^{-1} near the surface linearly increasing to -9.9 m s^{-1} at the top of the boundary layer. The v value was kept constant to -3.8 m s^{-1}. We used a subsidence rate (w_s), which linearly increased from 0 to -0.5 cm s^{-1} to about 2.2 km and was constant from this level to 4 km , then decreased linearly to zero at the TOA. The large-scale heat forcing was kept constant at a value of -2.5 K day^{-1}, and the moisture forcing profile increased from –1 g kg^{-1} day^{-1} close to the surface to 0.3456 g kg^{-1} day^{-1} at about 3km and was fixed at that value throughout the free troposphere. The driving conditions were created by averaging observations over December 16, 2004 to January 8, 2005.~~

~~For the FixHydro case, an observed N_d value of 70 cm^{-3} was used (vanZanten et al., 2011). For the ObsAero case, the aerosol mass mixing ratios of the three modes were diagnosed from the number mixing ratio and two log-normal size distributions (equation 1) assumed to consist of SO_4 with dry density of 1.77 g cm^{-3}. We also used a total number, mode radius, and geometric standard deviation 90 cm^{-3}, 0.03 μm, and 1.28 for the aitken mode; 150 cm^{-3}, 0.14 μm, and 1.75 for the accumulation mode. Coarse aerosol mass is assumed to be zero. This specification is recommended by vanZanten et al. (2011).~~

~~*d.*~~ *ARM95*

The last~~ARM95 included because it is the default~~ case we consider is an 18 day~~, which has~~ long simulation of summertime~~been included with CAM releases. It is~~

~~also an example of~~ continental convection spanning~~, which is an important climate regime. The ARM95 case tests the deep convection scheme and to some extent the mixed-phase cloud processes. The case spans~~ July 18 to Aug 3, 1995 at the Atmospheric Radiation Measurement (ARM) program's Southern Great Plains (SGP) site. We included this case because for a long time it was the only SCM case that was included in the released version of CAM. This case is useful because it tests the model's deep convective scheme (which plays a huge role in determining model climate), yet is extra-tropical so the imposed vertical velocity assumption of typical SCMs is less problematic (e.g. Sobel and Bretherton, 2000). This case was the subject of an intercomparison of 11 SCMs and one coarse LES. As reported by Ghan et al., (2000), temporal variability in the models exceeded observed values. This was interpreted as forcing error since all models behaved similarly. Large temperature and moisture biases were reported over the simulation unless nudging was used; we do not use nudging despite this warning because clouds form at all levels during the simulation and nudging areas with clouds makes it hard to tell whether model physics or nudging is causing the modeled behavior.~~, and we used the full shortwave and longwave radiation.~~ Advective forcing was generated by the State University of New York (SUNY) objective analysis method (Zhang et al. 2001) and ~~the~~ surface fluxes were specified with the ~~estimated using~~ Doran et al. (1998) surface analysis technique using~~by~~ the Simple Biosphere (SiB2) model (Ghan et al., 2000). Forcings for~~For~~ this case are not included in Table 1 because they vary in time (which makes them impossible to represent compactly in a table). Aerosol and cloud number densities are not available for this case, so~~we~~ only ~~simulated the~~ Default and PrescAero methods~~cases because N_d/N_i, and aerosol concentration are unknown.~~

~~All the cases~~ were tested~~run at the default time step of 1200 seconds and 30 vertical grid levels with 20 levels in the free troposphere. We carried out four simulations each for DYCOMSRF02, MPACE-B, and RICO and two simulations for ARM95. Results from each method and each case are discussed in the four sections below~~.

3. Results and Discussion

DYCOMS RF02

Table 2~~1~~ shows observed and modeled cloud-related variables averaged during the last two hours of the six hour DYCOMS RF02 simulations. In addition to N_d~~,~~ and surface precipitation (Pr), we include LWP~~the liquid water path~~ both before and after microphysics was called (LWP_{pre} and LWP_{post}, respectively). These values are different because CAM5 sequentially updates the model state after each parameterization is applied. As described in Gettelman et al. (2014), LWP_{pre} is often much bigger than LWP_{post} because microphysics tends to deplete cloud water and when it acts in isolation~~sequential updating leaves microphysical depletion acting~~ over the ~~an inappropriately~~ long model timestep a great deal of water can be lost.~~time step.~~ We also include cloud base~~,~~ z_b (computed by identifying the first layer from the bottom with cloud fraction exceeding 0.5, then linearly interpolating between this layer and the one below it to get the exact height~~the level~~ where cloud fraction =~~first rises about~~ 0.5) and cloud top height~~,~~ z_i (computed by identifying~~interpolation~~ the top-most layer with~~highest level where the~~ total water mixing ratio q_t>~~drops below~~ 8 g kg^{-1} and linearly interpolating between this layer and the one above it to find the exact height where q_t = 8 g kg^{-1}).~~.~~ Cloud top entrainment velocity $w_e = \delta z_i/\delta t - w_s$ was also computed.

The Default method~~case~~ underestimated the observed N_d (=~~(which was~~ 55 cm^{-3}), while ObsAero and particularly PrescAero overestimated N_d . As expected, runs with higher N_d tend to precipitate less and as a result have higher LWP. LWP computed before microphysics is too high except for the Default case. Values after microphysics show more variability, with the Default case being too low and the FixHydro and PrescAero being too high. Difference between pre- and post-microphysics values illustrate the difficulty of interpreting output from sequentially-split climate models.

Cloud base and cloud top were both slightly higher than observed yet entrainment was much smaller than observed. This suggests that the prescribed subsidence ~~we imposed~~ may be too weak in this case study. Surface precipitation is too weak when realistic N_d is used. This could be due to excessive re-evaporation of precipitation below the cloud base. This is consistent with the fact that the ObsAero and FixHydro models have the highest below-cloud base evaporation of precipitation (~~given by~~ 5.85×10^{-5} g~~85e-8~~ kg^{-1} ~~/kg/~~s^{-1} and 4.45$\times10^{-5}$ g kg^{-1} ~~/kg/~~s^{-1}, respectively)~~,~~ while the Default and PrescAero have lower values (3.62×10^{-5} g kg^{-1} s^{-1},~~62e-8,~~ and 1.33×10^{-5} g~~33e-8~~ kg^{-1} ~~/kg/~~s^{-1}, respectively).

Figure 1a shows N_d profiles of the different aerosol specification cases averaged over the last two hours of the simulation period. We have also included the 10 year July-average N_d profile of the corresponding 3D CAM5 run in which N_d values were extracted at the closest grid point to the DYCOMS RF02~~DYCOMSRF02~~ location. The specified aerosol ~~All~~ SCM cases show~~showed~~ higher N_d values at the cloud base and slightly lower values at the cloud top. This is inconsistent with observations, which tend to show constant values throughout the cloud (e.g. Martin et al, 1994). The Default run show the lowest N_d values and PrescAero showed the highest. Low N_d for the default scheme is expected because it initializes aerosol to zero (as noted above); aerosol in the default simulation increased over time due to surface emission (not shown). The 3D model N_d values are as high as the PrescAero case but the whole profile is shifted towards the surface. Collapsed boundary layers like this occur when stratocumulus becomes too thin to maintain the turbulence necessary to support a deep boundary layer. Differences in behavior between the SCM and GCM runs are unsurprising because the former were initialized to a well-mixed profile and driven by observed large-scale conditions for a short time period while the latter had 10 yrs to develop biases and were driven by large-scale conditions from the model itself. Additionally, SCM runs are nocturnal while GCM runs include both day and night. This is relevant since solar radiation damps turbulence, reducing boundary layer height (e.g. Caldwell et al., 2005). The fact that the GCM results look very different from the SCM results indicates that the source of GCM bias either takes a long time to spin up or is related to bad large-scale conditions rather than the quick-acting cloud physics parameterizations. This is useful information because it tells us that GCM biases in this case can't be solved solely by analyzing SCM runs.~~The Default model showed the lowest N_d values (an average of 33 cm^{-3}). This is probably due to the zero aerosol initialization; aerosol in the run increased as the simulation progressed due to emission sources. The PrescAero case showed highest N_d values (an average of 139 cm^{-3}) and the highest total aerosol burden, while the obseAero case showed slightly higher N_d values (an average of 74 cm^{-3}) as compared to the observations (an average of 55 cm^{-3}), even though it had lower aerosol burden. The 3D model N_d values are as high~~

~~as the PrescAero case; however, there is a shift of the whole profile towards the surface, suggesting a collapsed boundary layer.~~

Even though stratocumulus are typically thought to be nonconvective~~non-convective clouds~~, shallow convection is triggered occasionally in our DYCOMS RF02 simulations. This detrainment ~~, with higher frequency in the Default case than the other cases. Detrainment from this convection~~ is a major source of N_d in simulations with low aerosol. Convective detrainment can create droplets out of thin air~~some simulations. This occurs~~ because CAM5 convection schemes detrain cloud droplets at ~~detrains droplet numbers according to~~ a fixed droplet mean volume radius with no dependence on aerosol at all. Convection triggers more often in the Default run, perhaps because strong precipitation due to low N_d tends to cause more decoupled, convective conditions. In order to isolate the effect of ~~assumption rather than considering the actual droplet or aerosol availability. As a result, the~~ convective detrainment on N_d~~from cloud top increased the in-cloud N_d values. In order to separate the number of droplets generated by activation and convective detrainment~~ we conducted a~~another~~ set of sensitivity experiments where convection detrains vapor rather than condensate~~is detrained from convection~~. N_d profiles from these experiments are shown in Fig.~~figure~~ 1b. This figure reveals that almost all of the droplets in the Default case are created by convective detrainment. Detrainment plays a secondary but non-negligible role in~~due to zero aerosol initialization. In~~ the PrescAero and ObsAero cases~~activation dominates, though detrainment increases the total N_d in all cases~~, especially near the cloud top.

~~N_d of DYCOMSRF02 case correlates well with the total aerosol burden. The PrescAero case has the highest aerosol burden resulting in high values of N_d, while the~~

~~zero-aerosol initialized Default case has the lowest. The ObsAero case has higher aerosol burden in the accumulation and aitken modes resulting in N_d values slightly higher than observed.~~

Figure 2 shows the temporal evolution of ~~the~~ LWP_{pre} and LWP_{post} from~~of~~ the DYCOMS RF02~~DYCOMSRF02~~ case. There is large~~high~~ variability of LWP during the first few hours in all cases, with ~~the highest~~ variability lasting longest and having largest amplitude in the Default run. ObsAero shows~~in the Default case. During the last two hours this case performed worst and showed low LWP due to low N_d that caused clouds to precipitate out. The FixHydro and ObsAero cases showed~~ good agreement with observations, while~~as compared to the observational ranges. The~~ PrescAero and FixHydro~~case had higher~~ LWP was too high (consistent with its overpredicted~~due to higher~~ N_d values).~~.~~

In summary, the DYCOMS RF02~~DYCOMSRF02~~ case shows strong sensitivity to aerosol specification. In the Default case, detrainment from shallow convection is a major source of N_d, which artificially limits sensitivity to aerosol burden. Interpretation of model LWP is very sensitive~~In other cases, higher aerosol burden translates~~ to whether it is sampled before or after microphysics. ~~higher droplet concentration.~~

MPACE-B

Table 3~~2~~ shows ~~the~~ observed and modeled cloud-related variables averaged during the last four hours of the MPACE-B case. All runs except FixHydro substantially overestimate~~The variables are N_i, N_d, LWP, IWP, w_e, z_b, z_i, and surf Pr. The N_i values for the Default, PrescAero, and ObsAero cases are 0.4, 0.7, and 0.6 L^{-1}, respectively. All of these cases overestimated~~ the observed N_i value. Because the Bergeron process efficiently freezes ~~(0.16 L^{-1}). Aircraft and ground based remote sensors observed the existence of boundary layer mixed-phase clouds, which contained~~ liquid ~~and ice and were capped by a weak inversion with a cloud top temperature of about -15°C (Klein et al., 2009). However, except for the FixHydro case all simulations produced not liquid. This is because ice removes all supersaturated vapor (and liquid)~~ when N_i is plentiful, these runs have zero LWP~~crystal numbers are too high~~. The FixHydro case, on the other hand, has ~~showed~~ reasonable N_i and LWP, which illustrates the importance of cloud number densities for obtaining ~~(133 g m^{-2}) and w_e (12.37 mm/day) due to the~~ realistic simulations. The cloud layer for FixHydro is of approximately the right thickness but is slightly too high in the atmosphere. Its surface precipitation is a bit too high and its IWP is slightly too low.~~use of N_d and N_i; however, it underestimated the IWP (0.63 g m^{-2}) and overestimated z_b (1783 m) and surf Pr (0.5 mm/day).~~

Figure 3 shows height-normalized MPACE-B profiles of liquid water content (LWC) and ice water content (IWC) including and excluding snow mass as a function of scaled height, before and after micro-physics. This figure is useful for interpreting our earlier conclusion that LWP=0 for all runs ~~The dark-shaded region, light-shaded region, and black solid line depict the median value, the inner 50%, and the outer 50% envelope of the high frequency observed aircraft data respectively, from Klein et al. (2009). Before microphysics, a reasonable amount of liquid water is shown by the FixHydro case, while the other cases showed shallower cloud and smaller amounts of liquid water (Fig 3a). After the execution of microphysics,~~ except ~~for the~~ FixHydro. Fig. 3a shows that all runs have LWP>0 before microphysics, so the problem is that each microphysics step removes all LWC in these runs. LWC before microphysics is, however, underpredicted and cloud top is too shallow for these runs. This is unsurprising since in mixed-phase stratocumulus, radiative cooling of liquid at cloud top is the main source of boundary-layer turbulence (which is needed to supply the cloud layer with liquid and to maintain cloud top height in the face of subsidence) and radiative transfer in CAM5 is computed after microphysics (at which point LWP is zero in these runs). In contrast with LWC, all runs showed reasonable ~~case, the microphysics physics removed all the liquid water in the other three models, resulting in complete depletion of liquid water. All cases showed good~~ agreement with ~~of IWC as compared to aircraft~~ observations for IWC except FixHydro, which is a bit higher than the bulk of the observational data (Fig 3b and c). IWC consists, however, almost~~(Figs. 3b and 3c), with some overestimation of IWC by the FixHydro case. The microphysics slightly removed some IWC from the Default case but did not make any change to the three other cases (Figs. 3b and 3c). However, IWC consistes~~ entirely of snow for all cases ~~except for the FixHydro case, which showed some cloud ice before microphysics~~ (Fig. 3d). Underprediction of liquid and dominance of ice over cloud ice have been reported previously for CAM5 (e.g. Gettelman et al., 2010, Liu et al., 2011).

Figure 4 shows the N_i profiles for all runs~~of the different cases~~ averaged over the last four hours of the MPACE-B period along with the climatological October average N_i profile from our GCM run using data from the grid point closest to the MPACE-B location. All SCM runs except FixHydro have very similar N_i profiles. This is because ice ~~. We have also included the 10 years October 2004 average N_i profile values of the 20 min timestep, 30 levels, 3D CAM run, and values extracted at the closest grid point to the MPACE-B location. Except for the FixHydro case all the other cases overestimated N_i.~~

~~Despite the difference in the aerosol burden, the Default, PrescAero, and ObsAero cases showed no sensitivity to the aerosol specification except for slightly higher N_i values for the ObsAero case. Similarly, except for the FixHydro case, which had N_d value of 50 cm^{-3}, all the other cases showed N_d value of zero due to the complete depletion of liquid water by the microphysics discussed above. However, all the cases simulated cloud fraction well as compared to aircraft and remote sensing observation (Fig. 5). Reasonable cloud fraction yet zero cloud condensate is possible in CAM5 because cloud fraction is computed before microphysics and is unchanged by physical processes, while cloud mass is affected by subsequent processes.~~

~~There exist large uncertainties in the representation of the ice~~ nucleation at the temperatures sampled during MPACE-B occurs primarily through ~~processes in climate models. In CAM, homogeneous and heterogeneous (~~deposition/~~,~~ condensation freezing which is treated in CAM5 by a scheme (~~, contact freezing, and immersion freezing) ice nucleation processes in the mixed- phase regime (-40 < T < -3°C) are represented as follows. Deposition/condensation freezing ice nucleation process is represented by the~~ Meyers et al., ~~. (~~(1992) ~~empirical formulation,~~ which ~~only~~ depends only on temperature and saturation vapor pressure. Compared to the observed value used by FixHydro, all other SCM runs and the GCM overpredict N_i. This is a well-known model deficiency which is improved by newer nucleation parameterizations (e.g., Liu et al., 2011, Xie~~Similarly, immersion freezing is prescribed using the formulation of Bigg (1953) and contact freezing on dust is represented using the formulation of Young (1974). Detailed literature of ice nucleation formulation and parameterization for cirrus and mixed phase clouds can be found in Gettelman et al. (2012).~~

~~In our SCM simulation of MPACEB, N_i did not show any sensitivity to aerosol specification. This is due to the dominance of the Meyers~~ et al., 2013; English et al., 2014). N_d is not shown because its cloud-layer average is zero for all cases except FixHydro (where it is set to the observed value of 50 cm^{-3}; see Table 3).~~. (1992) deposition/condensation freezing ice nucleation, which does not use explicit aerosol information but only depends on an empirical formulation using temperature and saturation vapor pressure. The other ice nucleation processes did not produce any N_i. The Meyers deposition/condensational freezing depleted all the liquid to form overestimated N_i regardless of the aerosol specification. As a result, activation did not produce any liquid droplets due to the total liquid water depletion.~~

Profiles of cloud fraction are shown in Fig. 5. Interestingly, simulated cloud *fraction* compares well with aircraft and remote sensing observations for all SCM cases. Clouds with volume but no mass (commonly called 'empty clouds') were a problem with CAM3 and CAM4 (e.g. Hannay et al., 2009, Medeiros et al., 2012) because cloud fraction and condensation/evaporation schemes were disconnected. This disconnect was patched in CAM5 (Park et al, 2014) so finding empty clouds in this study was somewhat surprising. The empty clouds seen here for Default, PrescAero, and ObsAero come from cloud fraction being computed before microphysics and left unchanged even after microphysics removes all condensate. Closer coupling between cloud fraction, condensation/evaporation, and microphysics are needed to solve this problem.

RICO

Table 4~~3~~ shows ~~the averages of~~ N_d, surface sensible heat flux (SHF), surface latent heat flux (~~,~~LHF), cloud base mass flux ~~, Cloud Base Mass Flux~~ (CBMF), cloud cover (the fraction of the sky which appears to a surface observer to be obscured by clouds~~Cloud Cover (CLC~~), and LWP averaged over~~during~~ the last four hours of the 24 hour~~hours~~ simulation of the RICO case for the four SCM~~model~~ simulations. We include ~~and from vanZanten et al. (2011)~~ LES intercomparison data from VZ11~~results. We use LES~~ as a crude proxy for truth here because (as discussed in Sect. 2.3), the RICO ~~this~~ case study is created by compositing 2 months of observations ~~idealized~~ and thus is not comparable with~~to~~ observations from any particular time. SCM behavior is almost identical for all ~~All the model~~ runs even though aerosol and ~~from this study showed similar~~ N_d vary substantially. This is because clouds in RICO are generated by the shallow convection scheme and (as mentioned in Sect. 3a) CAM5 convection schemes have no dependence on aerosol.

All SCM configurations overestimate the ~~,~~SHF, LHF, and CBMF relative to LES ~~, CLC, and LWP~~ values but nonetheless capture cloud cover and LWP very well. Similar to DYCOMS RF02 results, LWP shows high temporal variability at the beginning of RICO SCM simulations~~when compared to one another. The Default, PrescAero, and ObsAero cases showed an average N_d value of 51 cm^{-3}, which slightly underestimated the LES value (70 cm^{-3}),~~ which settles out over time (Fig. 6). Consistent with overpredicted CBMF, cloud base condensate is overpredicted (Fig. 7a). As expected~~is a best estimate of an average value~~ from previous studies (e.g. Siebesma et al., 2003), both condensate and mass flux decrease with distance above z_b (Fig. 7). Fig. 8 breaks cloud cover into its vertical distribution (total cloud fraction) as well as cloud fraction contributions~~flight measurements using the Fast Forward Scattering Spectrometer Probe (FFSSP) during four flights, with measurements ranging~~ from shallow, deep, and large-scale contributions. Even though cloud *cover* is well predicted, cloud *fraction* is overpredicted by ~~50 to 100 cm^{-3} (vanZanten el al., 2011; Brenguir et al., 1998). On average all the runs overestimated the LHF (12.7 w m^{-2}), LHF (207.9 w m^{-2}), and CBMF (0.06 m s^{-1}) as compared to~~ the SCMs because~~LES value (8.5 w m^{-2}, 158 w m^{-2}, 0.026 m s^{-1}), respectively. All~~ the maximum-random cloud overlap assumption used by CAM5 is inconsistent with cloud tilt and life-cycle effects found in real shallow ~~models simulated CLC (0.18), and LWP (19.4 g m^{-2}) very well as compared to LES, (0.19) and (19 g m^{-2}), respectively. The time series of the LWP shown in figure 6 also depicts high variability during the spin-up period and good agreement with LES after 15 UTC for all models.~~

~~Figure 7 shows the N_d profiles of all the cases of this study averaged over the last 4 hours of the simulation period. We have also included the 10 years July average N_d profile values of the 20 min timestep and 30 levels 3D CAM extracted at the closest grid point to the RICO location. The PrescAero, the Default and 3D has similar values of N_d at the cloud base where the statiform cloud was present. However, the N_d value is underestimated as compared to observations (70 cm^{-3}). The ObsAero case showed the lowest N_d (about 14 cm^{-3}). At the cloud top, except for the FixHydro case, all the SCM cases showed N_d values approaching the no aerosol case (black line). The no aerosol case was run without aerosols to estimate the N_d values due to~~ convective conditions (Park and Bretherton, 2009). At ~~detrainment.~~

~~The N_d of the RICO case at the cloud base correlates well with the different aerosol burden values in the different modes. The PrescAero and Default cases have comparable N_d values due to high aerosol burden. The ObsAero case shows the lowest N_d values at the~~ cloud base~~, due to its low aerosol burden. Hence, the activation process is~~

~~dominant at the cloud base in creating the droplets. However, at the cloud top, despite the differences in the aerosol specifications, the N_d values did not change. Thus activation is the dominant process at the cloud base while detrainment dominates at the cloud top.~~

~~Vertical structure of the cloud mass flux and condensate is important for studying the parameterization of clouds and precipitation. Shallow convective mass flux maximizes near the cloud base and decreases with height, consistent with observations (Siebesma et al., 2003). However, the mass flux at the cloud base is overestimated in all the cases (Fig. 8a). Unsurprisingly, the condensate profile also shows overpredicted condensate at the cloud base and decreases with height (Fig. 8b).~~

~~The total cloud fraction is also overestimated as compared to LES (Fig. 9). At cloud base the~~ overestimation is due to both shallow convective and stratiform clouds. Modeled cloud extends further into the troposphere than observed ~~because deep convection is being triggered and the runs showed deeper clouds~~ due to the deep convection scheme~~convective cloud fraction (Fig. 9). Non of the runs show sensitivity of mass flux, condensate, and cloud fraction to aerosol specification~~.

~~In summary, the RICO runs did not show sensitivity to aerosol specification except at the cloud base where activation dominates and more droplets are formed as the aerosol burden increases. At the cloud top, detrainment is dominant and regardless of the aerosol burden the N_d profiles are similar.~~

ARM95

As noted above, ARM95 is much longer in duration than our other case studies. During the first 10 simulated days,~~The last case is based on ARM SGP site and spans 17 days starting July18 to 4 August, 1995. It was chosen because it is the default SCM case~~

~~distributed with CAM5. This case is the basis of the Ghan et al. (2000) SCM intercomparison. Only the Default and the PrescAero cases are simulated due to lack of observed N_d, N_i and aerosol data.~~

~~This case spans 3 different weather regimes. Due to the existence of~~ a large-scale stationary upper-level trough sat over the continental U.S., resulting in temporally-~~.~~ ~~during the first ten-day period, there existed~~ variable cloud cover and precipitation ~~every other day~~. There followed a 3 day period of high pressure and clear skies, and the final 7 days consisted of stormy weather with high cloud cover and intense precipitation. As noted above, only the Default and the PrescAero cases are simulated due to lack of observed N_d, N_i, and aerosol data.

Figure 9~~10~~ shows the time series of LWP and IWP for the Default and PrescAero cases. Observed ~~The time series of the~~ LWP ~~observations are also plotted~~ from Xu and Randall (2000) are also included. SCM runs capture the observed temporal trends but generally overestimate~~). Generally, SCAM over estimated~~ LWP. Default and PrescAero behave very similarly, which is consistent with our finding from RICO that aerosol is not important for convective cases.

Fig. 10 shows N_d profiles from our simulations. Surprisingly, N_d is fairly similar for both SCM simulations even though visible aerosol ~~at all periods. Both runs showed comparable LWP, IWP, and surface precipitation (Fig. 10) as well as N_d (Fig. 11). Aerosol~~ optical depth differs substantially between these runs (~~in the visible range was~~ 0.163 for PrescAero and ~~only~~ 0.081 for the Default case). Typical observed N_d values at SGP are around 200 cm^{-3} (Frisch et al, 2002; Iacobellis and Somerville, 2006), so modeled values have a large low bias. Is this a problem with the SCM setup? We test this by including climatological July data for the GCM grid cell closest to SGP. We include GCM data from runs using both prognostic and prescribed aerosol. Both GCM runs show similarly low N_d values~~, however~~, indicating that this bias is related to aerosol values predicted by MAM3 rather than ~~the ARM95 case is insensitive to aerosol specification. As noted above, this result is not surprising since CAM's convective schemes do not use aerosol information. More surprising, however, is~~ the specified values used ~~fact that~~ ~~N_d~~ for the prescribed aerosol mode. This bias has little impact on model behavior in the current version of CAM (because convection is independent~~SGP region from both SCM and GCM simulations is ~25 cm~~~~$^{-3}$~~~~, a factor~~ of aerosol) but may cause problems ~~8 smaller than typically observed~~ in future model versions with more sophisticated convective microphysics.~~this region (e.g. Iacobellis and Somerville, 2006). This is a major bias in cloud properties which likely has significant negative effects on climate simulations.~~

4. Summary and Conclusions

This~~In this~~ study points out that~~we identified a problem with SCAM5 in its default configuration and introduced fixes to the identified problem. We used three new~~ aerosol treatment~~specification methods~~ in CAM5 ~~our~~ SCM is unrealistic and causes problems for non-convective case studies~~simulations~~. The issue is that initial aerosol and horizontal~~cases considered are Default case (with prognostic~~ aerosol advective tendencies are hard-coded~~, initialized~~ to zero in SCM mode. Aerosol can still build up in the boundary layer from surface emissions, but the resulting aerosol loading is likely to be unrealistic because remote sources cannot be included. Additionally (and more important), SCMs are typically run for a shorter period than it takes to build up reasonable aerosol concentrations via surface emission and subsequent lofting into the cloud layer.. As a result, aerosol in SCM runs is typically much lower than observed or simulated by the GCM. This limits the usefulness of the SCM for model development.

To fix this problem, we propose 3 idealizations: prescribing aerosol from CAM5~~),~~ ~~PrescAero case (with monthly~~ climatological ~~aerosol~~ values (PrescAero), prescribing aerosol~~), ObsAerosol case (with aerosols~~ from observations (ObsAero), and prescribing cloud~~the FixHydro case (with fixed~~ droplet and ice crystal numbers (FixHydro~~concentrations~~). We test these configurations against the default~~use~~ SCM (Default)~~simulations~~ for 4 different~~a variety of~~ cloud regimes:~~. The sites used for these studies include~~ summertime mid-latitude continental convection (ARM95), shallow convection (RICO), subtropical drizzling stratocumulus (DYCOMS RF02~~DYCOMSRF02~~), and mixed-phase stratocumulus~~multi-level Arctic clouds~~ (MPACE-B).

These fixes were found to have a big impact on non-convective cases. Aerosol and cloud number density has almost no effect on convective cases, however, because CAM5 convection does not depend on aerosol or droplet number. Cloud droplet number at the site of the ARM95 case was found to be underpredicted in CAM5-GCM by a factor of 8 relative to observations. Even though this deficiency has no effect on CAM5 simulations, lack of dependence on aerosol or droplet number is unrealistic and will be fixed in future versions of CAM, which makes finding solutions to droplet number underprediction at SGP worth pursuing even if it doesn't affect the current model version.

Shallow convection is found to be unexpectedly triggering in DYCOMS RF02, where it artificially increases N_d because convectively-detrained condensate is partitioned into droplets according to an assumed volume-mean radius rather than a dependency on available cloud condensation nuclei. Another finding is that the Meyers deposition/nucleation freezing scheme in CAM5 is too active in the temperature and moisture conditions sampled during MPACE-B. As a result, ice crystal number concentration is too high in all of our SCM and GCM runs except FixHydro (which fixes N_i at observed values). When observed N_i is used, LWP matches observations. Otherwise microphysics depletes all liquid water whenever it is called. This results in 'empty clouds' which have volume but no mass. This trouble with the Meyers et al (1992) scheme has long been recognized and alternative parameterizations have been explored (e.g., Liu et al., 2011, Xie et al., 2013; English et al., 2014).

~~The DYCOMSRF02 case shows strong sensitivity to aerosol specification. Activation dominates over convective detrainment so a number of droplets are formed when you have higher aerosol burden. Convection does occur in all runs, however, and convective detrainment is source of~~ ~~N_d~~ ~~in all cases, regardless of the aerosol specification. Default aerosol treatment in DYCOMSRF02 produced greatly underestimated~~ ~~N_d~~ ~~and LWP. All proposed fixes substantially improve~~ ~~N_d~~ ~~and LWP.~~

~~In MPACE-B,~~ ~~N_i~~ ~~was too large and was insensitive to aerosol specification in all cases except FixHydro. This is due to the dominance of the Meyers et al. (1992) deposition/condensation freezing ice nucleation, which does not use aerosol information but only depends on empirical formulation using temperature and saturation vapor pressure. The other ice nucleation processes did not produce any~~ ~~N_i. The Meyers deposition/condensational freezing was also too strong, causing all supersaturated vapor~~

~~to freeze. This resulted in zero LWP for all cases except FixHydro, which had LWP value of 30 g m^{-2} (in agreement with observations).~~

~~The RICO case did not show sensitivity to aerosol specification except at the cloud base where activation dominates and more droplets are formed as the aerosol burden increases. At the cloud top, convective detrainment is the dominant source of droplets, and regardless of the aerosol burden the number of droplets is similar. Detrainment seems to be too strong near cloud base, resulting in profile with too much cloud near cloud base and too little above.~~

~~The deep-convection ARM95 case also did not show any sensitivity to aerosol specification. Droplet number for both SCM and GCM runs at ARM95 were consistently 25 cm^{-3}, which is much lower than expected over land. This indicates a problem with aerosol specification in this region.~~

~~In summary, stratiform cloud cases (DYCOMS RF02 and MPACE-B) were found to have a strong dependence on aerosol concentration, while convective cases (RICO and ARM95) were relatively insensitive to aerosol specification. This is perhaps expected because convective schemes in CAM5 do not currently use aerosol information. Adequate liquid water content in the MPACE-B case was only maintained when ice crystal number concentration was specified because the Meyers et al. (1992) deposition/condensation ice nucleation scheme used by CAM5 greatly overpredicts ice nucleation rates, causing clouds to rapidly glaciate. Surprisingly, predicted droplet concentrations for the ARM95 region in both SCM and global runs were around 25 cm^{-3}, which is much lower than observed. This finding suggests that CAM5 has problems capturing aerosol effects in this region.~~

5. Acknowledgements

We thank the Lawrence Livermore National Laboratory (LLNL) for providing funding through the Multiscale Scientific Discovery through Advanced Computing (SciDAC) project. ~~The SCM simulations were performed using computing resources provided by LLNL.~~ The research ~~reported here was supported by DOE award 33871/SCW1316-BER and~~ was performed under the auspices of the United States Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344.

6. References

Abdul-Razzak, H., and S. Ghan, 2000: A parameterization of aerosol activation: 2. Multiple aerosol types, J. Geophys. Res., **105(D5)**, 6837–6844.

Ackerman, A. S., et al., 2009: Large-eddy simulations of a drizzling, stratocumulus-topped marine boundary layer, *Mon. Weather Rev.*, **137(*3*)**, 1083–1110, *doi:*10.1175/2008MWR2582.1.

~~Bigg, E. K., 1953: The formation of atmospheric ice crystals by the freezing of droplets, *Q. J. R. Meteorol. Soc.*, **79**, 510–519.~~

Bony, S., *and* J.-L. Dufresne *(*2005*)*, Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models, *Geophys. Res. Lett.*, **32**, *L20806*, *doi:*10.1029/2005GL023851.

Brenguier, J. L., T. Bourrianne, A. de Araujo Coelho, R. J. Isbert, R. Peytavi, D. Trevarin, and P. Weschler, 1998: Improvements of droplet distribution size measurements with the fast-FSSP (forward scattering spectrometer probe). *J. Atmos. Oceanic Technol.*, **15,** 1077–1090.

Bretherton, C. S., and S. Park, 2009: A New Moist Turbulence Parameterization in the Community Atmosphere Model. *J. Climate*, **22**, 3422–3448.

Caldwell, P. M., C. S. Bretherton, and R. Wood, 2005: Mixed-Layer Budget Analysis of the Diurnal Cycle of Entrainment in Southeast Pacific Stratocumulus. *J. Atmos. Sci.*, **62**, 3775–3791.

Doran, J. C., J. M. Hubbe, J. C. Liljegren, W. J. Shaw, G. J. Collatz, D. R. Cook, and R. L. Hart, 1998: A technique for determining the spatial and temporal distributions of surface fluxes of heat and moisture over the Southern Great Plains Cloud and Radiation Testbed, *J. Geophys. Res.*, **103(D6)**, 6109–6121, *doi:*10.1029/97JD03427.

English, J. M., J. E. Kay, A. Gettelman, X. Liu, Y. Wang, Y. Zhang, and H. Chepfer, 2014: Contributions of clouds, surface albedos, and mixed-phase ice nucleation schemes to Arctic radiation biases in CAM5, *J. Climate*, **27**, 5174–5197. doi: http://dx.doi.org/10.1175/JCLI-D-13-00608.1.

~~Easter, R. C., S. J. Ghan, Y. Zhang, R. D. Saylor, E. G. Chapman, N. S. Laulainen, H. Abdul-Razzak, L. R. Leung, X Bian and R. A. Zaveri, 2004: MIRAGE: Model description and evaluation of aerosols and trace gases, *J. Geophys. Res.*, **109**, doi: 10.1029/2004JD004571.~~

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W., Haywood, J., Lean, J., Lowe, D. C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., and Dorland, R. V.: Changes in atmospheric constituents and in radiative forcing, in: Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge Univ. Press, UK and New York, 2007.

Frisch, S., M. Shupe, I. Djalalova, G. Feingold, and M. Poellot, 2002: The Retrieval of Stratus Cloud Droplet Effective Radius with Cloud Radars, *J. Atmos. and Oceanic Tech.* **19**, 835-842.

Gettelman, A., H. Morrison, and S. J. Ghan, 2008: A new two-moment bulk stratiform cloud microphysics scheme in the NCAR Community Atmosphere Model (CAM3), Part II: Single-column and global results, *J. Climate*, **21(15)**, 3660–3679.

Gettelman, A., X. Liu, S. J. Ghan, H. Morrison, S. Park, A. J. Conley, S. A. Klein, J. Boyle, D. L. Mitchell, and J.-L. F. Li (2010), Global simulations of ice nucleation and ice supersaturation with an improved cloud scheme in the Community Atmosphere Model, *J. Geophys. Res*., **115**, D18216, doi:10.1029/2009JD013797.

Gettelman, A., X. Liu, D. Barahona, U. Lohmann, and C. Chen, 2012: Climate impacts of ice nucleation, J. Geophys. Res., **117**, D20201, doi:10.1029/2012JD017950.

Gettelman, A., H. Morrison, S. Santos, P. Bogenschutz and P. M~~H~~. Caldwell, 2014: Advanced Two-Moment Microphysics for Global Models. Part II: Global model solutions and Aerosol-Cloud Interactions., *J. Climate*, in press, http://www.cgd.ucar.edu/staff/andrew/papers/gettelman_mg2_global_rev2.pdf

Ghan, S. J., et al., 2000, A comparison of single column model simulations of summertime midlatitude continental convection, *J. of Geophys. Res.*,**105**, 2091-2124.

Ghan, S. J. , X. Liu, R. C. Easter, R. Zaveri, P. J. Rasch, J.-H. Yoon, and B. Eaton, 2012: Toward a Minimal Representation of Aerosols in Climate Models: Comparative Decomposition of Aerosol Direct, Semidirect, and Indirect Radiative Forcing. *J. Climate*, **25**, 6461–6476. doi: http://dx.doi.org/10.1175/JCLI-D-11-00650.1

Hack, J. J., and J. A. Pedretti, 2000: Assessment of Solution Uncertainties in Single-Column Modeling Frameworks. *J. Climate*, **13**, 352–365. doi: http://dx.doi.org/10.1175/1520-0442(2000)013<0352:AOSUIS>2.0.CO;2

Hannay, C., D. L Williamson, J. J Hack, J. T. Kiehl, J. G. Olson, S. A. Klein, C. S. Bretherton, and M. Koehler, 2009: Evaluation of forecasted Southeast Pacific stratocumulus in the NCAR, GFDL and ECMWF models. *J. Climate*, **22**, 2871-2889.

Hartmann, D. L., M. E. Ockert-Bell, and M. L. Michelsen, 1992: The Effect of Cloud Type on Earth's Energy Balance: Global Analysis. *J. Climate*, **5**, 1281–1304.

Haywood, J. M., and Boucher, O., 2000: Estimates of the direct and indirect radiative forcing due to tropospheric aerosols, 2000: A review, *Rev. Geophys.*, **38**, 513–543, doi: 10.1029/1999RG000078.

~~Houghton, J. T., Filho, L. G. M., Callander, B. A., Harris, N., Kattenberg, A., and Maskell, K., eds.: Intergovernmental Panel on Climate Change, Climate Change 1995: The Science of Climate Change, The Contribution of Working Group I to the Second Assessment Report of the IPCC, Cambridge Univ. Press, New York, 1996.~~

Iacobellis, S. F., and R. C. J. Somerville, 2006: Evaluating parameterizations of the autoconversion process using a single-column model and Atmospheric Radiation Measurement Program measurements, *J. Geophys. Res.*, **111**, D02203, doi:10.1029/2005JD006296.

Klein, S.A., et al., 2009: Intercomparison of model simulations of mixed-phase clouds observed during the ARM Mixed-Phase Arctic Cloud Experiment. Part I: Single-layer cloud., *Q. J. R. Meteorol. Soc.*, **135**, no. 641, 979-1002, doi:10.1002/qj.416.

Liu, X., S. Xie, J. Boyle, S. A. Klein, X. Shi, Z. Wang, W. Lin, S. J. Ghan, M. Earle, P. S. K. Liu, Z. Wang and A. Zelenyuk, 2011: Testing cloud microphysics parameterizations in NCAR CAM5 with ISDAC and M-PACE observations, *J. Geophys. Res*, **116**, D00T11, doi:10.1029/2011JD015889.

Liu, X., et al., 2012: Towards a minimal representation of aerosol direct and indirect effects: Model description and evaluation, *Geosci. Model Dev.*, **5**, 709–735, doi:10.5194/gmd-4-709-2012.

Martin, G. M., D. W. Johnson, and A. Spice, 1994: The Measurement and Parameterization of Effective Radius of Droplets in Warm Stratocumulus Clouds, *J. Atmos. Sci.*, **51**, 1823–1842.

Medeiros B., B. Stevens, I. M. Held, M. Zhao, D. L. Williamson, J. G. Olson, and C. S. Bretherton, 2008: Aquaplanets, Climate Sensitivity, and Low Clouds. *J. Climate*, **21**, 4974–4991.

Meyers, M. P., P. J. DeMott, and W. R. Cotton, 1992: New primary ice-nucleation parameterizations in an explicit cloud model, *J. Appl. Meteorol.*, **3**, 708–721.

Mlawer, E. J., S. J. Taubman, P. D. Brown, M. J. Iacono, and S. A. Clough, 1997: Radiative transfer for inhomogeneous atmosphere: RRTM, a validated correlated-k model for the longwave, *J. Geophys. Res.*, **102 (D14)**, 16 663–16 682.

Moeng, C., H., W. R. Cotton, C. S. Bretherton, A. Chlond, M. Khairoutdinov, S. Krueger, W. S. Lewellen, M. K. MacVean, J. R. M. Pasquier, H. A. Rand, A. P. Siebesma, R. I Sykes, and B. Stevens, 1996: Simulation of a stratocumulus-topped PBL: Intercomparison among different numerical codes, *Bull. Amer. Meteorol. Soc.*, **77**, 261–27.

Morrison H, and Gettelman A., 2008: A new two-moment bulk stratiform cloud microphysics scheme in the Community Atmosphere Model, version 3 (CAM3). Part I: Description and numerical tests, *J. Climate*, **21**, 3642–3659.

Neale, R., and Coauthors, 2012: Description of the NCAR Community Atmosphere Model (CAM 5.0). NCAR Tech. Note NCAR-TN-486+STR, 274 pp.

Park, S., and C. S. Bretherton, 2009: The University of Washington Shallow Convection and Moist Turbulence Schemes and Their Impact on Climate Simulations with the Community Atmosphere Model, *J. Climate*, **22**, 3449–3469. doi:http://dx.doi.org/10.1175/2008JCLI2557.1

Park, S., C. S. Bretherton, and P. J. Rasch, 2014: Integrating Cloud Processes in the Community Atmosphere Model, Version 5, *J. Climate*, **27**, 6821–6856.

doi: http://dx.doi.org/10.1175/JCLI-D-14-00087.1

Randall, D., S. Krueger, C. Bretherton, J. Curry, Duynkerke, M. Moncireff, B. Ryan, D. Starr, M. Miller, W. Rossow, G. Tselioudis, and B. Wielicki, 2003: Confronting models with data: The GEWEX Cloud Systems Study. *Bull. Amer. Meteorol. Soc.*, **84**, 455-469, doi:10.1175/BAMS-84-4-455.

Rauber, R. M., et al., 2007: Rain in Shallow Cumulus Over the Ocean: The RICO campaign, *Bull. Am. Meteorol. Soc.*, **88 (12)**, 1912–1928.

J. H. Richter and P. J. Rasch, 2008: Effects of Convective Momentum Transport on the Atmospheric Circulation in the Community Atmosphere Model, Version 3. *J. Climate*, **21**, 1487–1499.

Schubert, W. H., J. S. Wakefield, E. J. Steiner, and S. K. Cox (1979b), Marine stratocumulus convection. Part I: Governing equations and horizontally homogeneous solutions, *J. Atmos. Sci*., **36**(7), 1286–1307.

Siebesma, A. P., and Coauthors, 2003: A large eddy simulation intercomparison study of shallow cumulus convection, *J. Atmos. Sci.*, **60**, 1201–1219.

Sobel, A. H. and C. S. Bretherton, 2000: Modeling Tropical Precipitation in a Single Column. *J. Climate*, **13**, 4378–4392.

Stevens, B, Moeng C-H, Ackerman AS, Bretherton CS, Chlond A, de Roode S, Edwards J, Golaz J-C, Jiang H, Khairoutdinov M, Kirkpatrick MP, Lewellen DC, Lock A, Muller F, Stevens DE, Whelan E, Zhu P., 2005: Evaluation of large-eddy simulations via observations of nocturnal marine stratocumulus, *Mon. Weather Rev.*, **133**, 1443–1462.

vanZanten, M. ~~C., and B. Stevens, 2005: Observations of the Structure of Heavily Precipitating Marine Stratocumulus, *J. Atmos. Sci.*, **62**, 4327–4342. doi: http://dx.doi.org/10.1175/JAS3611.1~~

~~vanZanten, M.~~ C., and Coauthors, 2011: Controls on precipitation and cloudiness in simulations of trade-wind cumulus as observed during RICO, *J. Adv. Model. Earth Syst.*, **3**, M06001, doi:10.1029/2011MS000056.

Wyant, M. C. et al., 2007: A single-column model intercomparison of a heavily drizzling stratocumulus-topped boundary layer, *J. Geophys. Res.*, **112**, D24204, doi:10.1029/2007JD008536.

Xie, S., X. Liu, C. Zhao, and Y. Zhang (2013), Sensitivity of CAM5 simulated Arctic clouds and radiation to ice nucleation parameterization, *J. Climate*, **26**, 5981–5999, doi: http://dx.doi.org/10.1175/JCLI-D-12-00517.1.

Xu, K., -M, and D. A. Randall, 2000: Explicit Simulation of Midlatitude Cumulus Ensembles: Comparison with ARM Data. *J. Atmos. Sci.*, **57**, 2839–2858. doi: http://dx.doi.org/10.1175/1520-0469(2000)057<2839:ESOMCE>2.0.CO;2

~~Young, K. C., 1974: The role of contact nucleation in ice phase initiation of clouds, *J. Atmos. Sci.*, **31**, 768–776.~~

Zhang, G. J., and N. A. McFarlane, 1995: Sensitivity of climate simulate simulation to the parameterization of cumulus convection in the Canadian Climate center general circulation model, *Atmos. Ocean*, **33**, 407-446.

Zhang, M. H., J. L. Lin, R. T. Cederwall, J. J. Yio, and S. C. Xie, 2001: Objective analysis of ARM IOP Data: Method and sensitivity, *Mon. Weather Rev.*, **129**, 295-311.

Zhu, P., and Coauthors, 2005: Intercomparison and Interpretation of Single-Column Model Simulations of a Nocturnal Stratocumulus-Topped Marine Boundary

Layer. *Mon. Wea. Rev.*, **133**, 2741–2758. doi: http://dx.doi.org/10.1175/MWR2997.1

Table 1: Initial and boundary conditions for DYCOMS RF02, MPACE-B, and RICO cases. All heights *z* are in meters and all pressures *p* are in hPa. Boundary layer height and vertical velocity are (respectively) z_i and *w* in height coordinates and p_i and ω in pressure coordinates. N/A indicates a quantity which is not used or is calculated by the model itself. q_t is total water mixing ratio, θ is potential temperature, and θ_l is liquid water potential temperature. One of the 3 aerosol modes for each case is omitted because it has zero mass.

	DYCOMS RF02	***MPACE-B***	***RICO***
run time (hrs):	6	12	24
SHF (W m^{-2}):	93	136.5	N/A
LHF (W m^{-2}):	16	107.7	N/A
u (m s^{-1}):	3 + 4.3z/1000	-13	-1.9-8 min(z, z_i)/z_i
v (m s^{-1}):	-9 + 5.6 z/1000	-3	-3.8
vert veloc:	$w = -3.75 \times 10^{-6} z$ (m s^{-1})	$\omega = 80 \min(p, p_i)/p_i$ (mb day^{-1})	$w = -0.5 \min(z, 2260)/2260$ (m s^{-1})
Large-scale q_t tend (g $kg^{-1} day^{-1}$):	0	$\min\{-0.164, -3[1-(p_s-p)/151.71]\}$	-1+1.3456 min{z,2980}/2980
Large-scale T tend (K day^{-1}):	0	min{-4,-15[1-(p_s - p)/218.18]}	-2.5
init q_t (g kg^{-1}):	9.45 g kg^{-1} if $z < z_i$, else $5 - 3(1 - e^{(z_i - z)/500})^{1/3}$	1.95 if $p > p_i$, else $0.291 + 0.00204(p - 590)$	$16 - 2.2\,z/740$ if $z < 740$, $13.8 - 11.4(z - 740)/2520$ if $740 < z < 3260$ $2.4 - 0.6\,(z - 3260)/740$ else
init θ_l (K):	288.3 K if $z < z_i$, else $295 + (z - z_i)^{1/3}$	269.2 if $p > p_i$, else $275.33 + 0.0791(815 - p)$	297.9 if $z < 740$, *else* $297.9 + 19.1(z - 740)/(4000 - 740)$
For FixHydro			
N_d (# cm^{-3}):	55	50	70
N_i	N/A	0.16 L^{-1}	N/A
For ObsAero			
Mode:	Aitken	Accumulation	Aitken
compos:	100% SO4	70% SO_4, 30% particulate organic matter	100% SO_4
# concentr :	125 cm^{-3}	72.2 cm^{-3}	90 cm^{-3}
mode radius:	0.011 µm	0.052 µm	0.03 µm
geometric σ:	1.2	2.04	1.28
Mode:	Accumulation	Coarse	Accumulation
compos:	100% SO4	10% SO_4 , 85% sea salt, 5% dust	100% SO_4
# concentr:	65 cm^{-3}	1.8 cm^{-3}	150 cm^{-3}
mode radius:	0.06 µm	1.3 µm	0.14 µm
geometric σ:	1.7	2.5	1.75

Table 2: Data averaged over~~1: Averages of N_d, N_i, w_e, z_b, z_i, and Surf Pr during~~ the last two hours of the DYCOMS RF02~~6 hour DYCOMSRF02~~ simulations. Observations~~The observations~~ are from W07. ~~Wyant et al. (2007).~~

	N_d (cm^{-3})	**LWP_{pre} (g m^{-2})**	**LWP_{post} (g m^{-2})**	**w_e (mm s^{-1})**	**z_b (m)**	**z_i (m)**	**Surf Pr (mm/day)**
Obs	55	80-120	80-120	6-7.6	~450	~800	0.35
Default	33	103	73	4.2	475	803	0.31
PrescAero	139	137	126	4.0	473	816	0.04
ObsAero	74	146	119	3.4	492	815	8.5e-6
FixHydro	55	174	145	3.6	465	818	6.9e-6

~~Table 2: Averages of~~ N_d is~~, N_i, w_e, z_b, z_i, and Surf Pr during~~ the average over~~last four hours of~~ the in-cloud portion of all cloudy levels of the column.~~12 hour MPACEB case simulations. The observations are from Klein et al. (2009).~~

Table 3: As in Table 2, but for MPACE-B using the last 4 simulated hours. Observations are from K09.

	N_i (L^{-1}), N_d (cm^{-3})	**LWP (g m^{-2})**	**IWP (g m^{-2})**	**w_e (mm s^{-1})**	**z_b (m)**	**z_i (m)**	**Surf Pr (mm/day)**
Obs~~Observation~~	0.16,50	110-210	8-30	-	~600	~1500	0.25
Default	0.4,0	3.96e-9	0.022	11.46	918	1476	0.82
PrescAero	0.7,0	3.69e-9	0.018	15.37	984	1537	0.69
ObsAero	0.6,0	3.64e-9	0.014	15.37	985	1537	0.68
FixHydro	0.16,50	133	0.63	12.37	872	1783	0.50

Table 4: Data averaged over the last four 4 hrs of RICO runs. LES data are from VZ11.

	N_d (cm^{-3})	**SHF (w m^{-2})**	**LHF (wm^{-2})**	**CBMF (m s$^{-1)}$**	**Cloud Cover**	**LWP (g m^{-2})**

LES	70	8.5	158	0.026		0.19	19
Default	30	12.29	207.81	0.06		0.18	19.0
PrescAero	32	12.41	207.94	0.06	0.18	19.2	
ObsAero	14	12.42	207.83	0.06	0.18	19.8	
FixHydro	70	12.37	207.83	0.06	0.18	19.6	

~~Table 3: Averages of N_d, SHF, LHF, CBMF, Cloud Cover, and LWP during the last four hours of the 24 hours simulations at RICO. LES data are from vanZanten et al. (2011).~~

~~Figure Captions~~

1. ~~Profiles of in-cloud droplet number concentrations (N_d) for DYCOMSRF02. 3D CAM values are 10 years July average global CAM extracted at the location of DYCOMSRF02. a) Convective detrainment turned on b) Convective detrainment turned off.~~
2. ~~Time series of liquid water path (LWP) for DYCOMSRF02 case for the 6 hours simulation period. Red=before microphysics; Blue=after microphysics. The shaded area indicates the range of the LES values averaged over the last 4hrs of the simulation period (Stevens and Seifert, 2008). The dots indicate the approximate measurement (what the measurements are) ranges (from Stevens et al., 2003). a) Default case, b) PrescAero case, c) ObsAero case and d) FixHydro case.~~
3. ~~Profiles of liquid water content (LWC) and ice water content (IWC) as function of scaled height (z/z_b-1) for MPACEB. Dashed lines indicate values before microphysics and solid lines indicate values after microphysics. a) LWC profiles as function of scaled height. Dark shaded region ranges, light shaded region and black solid line depict the median value, the inner 50% and the outer 50% the envelope of the high frequency observed aircraft data respectively (from Klein et al. 2009). b) the same as figure 3a but for IWC (including snow). c) same as figure 6a but using radar data as observations. d) same as figure 3a but excluding snow.~~
4. ~~Profiles of in-cloud N_i values for MPACE-B case. 3D CAM values are 10 years July average global CAM extracted at the location of MPACE-B. Note: N_i values (3D CAM N_i are divided by 10 to fit in the plot).~~
5. ~~Time-averaged profiles of cloud cover from models and observations as function of height during the MPACE IOP period. The observations panel depicts the fraction of time at each height that cloud was observed from remote sensors (black line with open squares) at Barrow (SHUPE-TURNER) and the two aircraft flights (aircraft 1 dashed line with solid triangle, aircraft 2 solid line with solid diamond). Observations are from Klein et al., 2009.~~

6. ~~Time series of liquid water path (LWP) during the RICO IOP period. Red=before microphysics and Blue=after microphysics. a) Default case, b) PrescAero case, c) ObsAero case and d) FixHydro case.~~
7. ~~The same as figure 1 but for RICO case.~~
8. ~~Time-averaged profiles of condensate amount (a), and mass-flux profile (b) during RICO IOP. Colors indication the four cases (but are not all visible because the lay on top of one another). Shading in figure 8b indicates ensemble inter quartile range and the solid black line is the ensemble mean. LES data are from vanZanten et al., 2011.~~
9. ~~Time-averaged profiles of: a) total cloud cover, b) deep convective cloud fraction, c) shallow convective cloud fraction, and d) stratiform cloud fraction from models and LES as function of height during the RICO IOP period (but are not all visible because the lay on top of one another). Shading indicates total cloud cover ensemble inter quartile range and the solid black line is the ensemble mean. LES data are from vanZanten et al., 2011.~~
10. ~~Time series of: a) LWP and b) IWC during the ARM95 IOP period. Red=Default and Blue=PrescAero. The solid black line is observations from Xu and Randall, 2000.~~
11. ~~Profiles of in-cloud droplet number concentrations (N_d) during the ARM95 IOP period. Blue=Default case and Red= PrescAero case; Cyan= 10 years July average default global CAM extracted at the location of ARM95; Yellow= 10 years July average PrescAero global CAM extracted at the location of ARM95.~~

Figure Captions

~~12.~~1. Profiles of in-cloud droplet number concentrations (N_d) for DYCOMS RF02. GCM values are July climatologies extracted from a 10-yr long prognostic aerosol GCM run at the location of DYCOMS RF02. Panel a is for runs where condensate is detrained (the default model behavior) and panel b shows runs where all detrained water is in vapor phase.

~~13.~~2. Time series of LWP before and after microphysics for DYCOMS RF02.The shaded area indicates the range of LES values averaged over the last 4hrs of the simulation period from Stevens and Seifert (2008) and the area bounded by dots indicates the range of observational uncertainty from Stevens et al. (2003).

~~14.~~3. LWC and IWC profiles as a function of scaled height (z/z_b-1) for MPACE-B. Dashed lines indicate values before microphysics and solid lines indicate values after microphysics. a) LWC profiles as function of scaled height. Dark shaded region ranges, light shaded region and black solid line depict the median value, the inner 50% and the outer 50% the envelope of the high frequency observed aircraft data respectively (from K09). b) the same as figure 3a but for IWC (including snow). c) same as figure 6b but using radar data from K09 as observations. d) same as figure 3b but excluding snow.

~~15.~~4. Profiles of in-cloud N_i values for MPACE-B. GCM values are 10 year July averages extracted at the location of MPACE-B divided by 10 in order to fit in the plot.

~~16.~~5. Time-averaged profiles of cloud fraction from models and observations as a function of height during the MPACE-B period. All observations are taken from K09.

~~17.~~6. Time series of LWP during the RICO IOP period. LES data comes from VZ11.

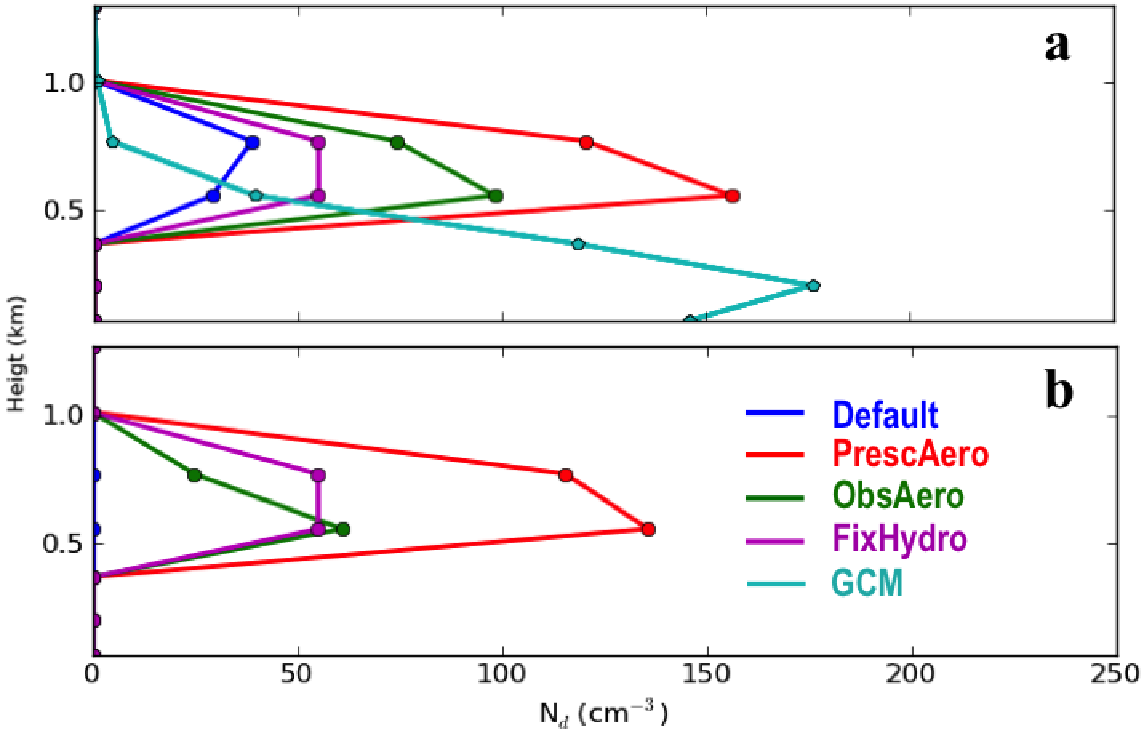
~~18.~~7. Time-averaged profiles of a) condensate amount and b) mass-flux for RICO simulations. The colored line shows the SCM results (all simulations lie on top of one another). Shading in figure 8b indicates ensemble inter quartile range and the solid black line is the ensemble mean. LES data are from VZ11.

~~19.~~8. Time-averaged profiles cloud fraction (CF) quantities from RICO simulations. Default, PrescAero, and ObsAero all lie on top of one another. LES data are from VZ11.

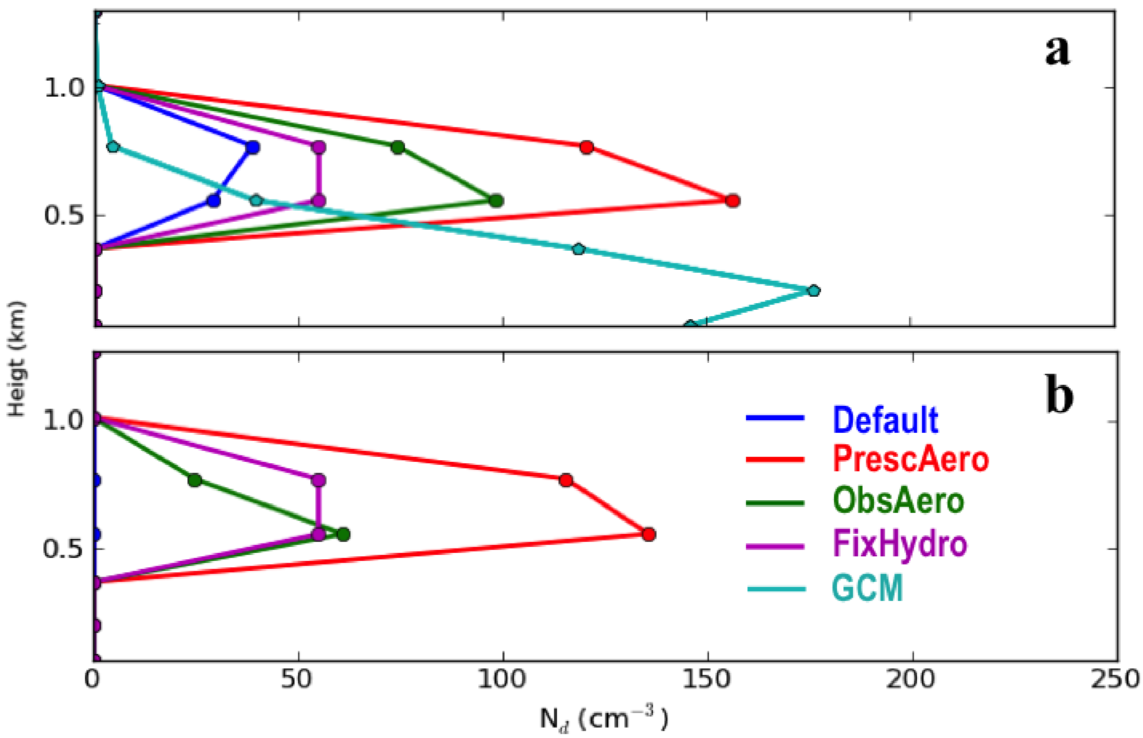
~~20.~~9. Time series of: a) LWP and b) IWC during the ARM95 IOP period. The solid black line in panel a) gives observations from Xu and Randall (2000).

~~21.~~10. Profiles of in-cloud droplet number concentrations (N_d) during the ARM95 IOP period. Blue=Default case and Red= PrescAero case; Cyan= 10 years July average default global CAM extracted at the location of ARM95; Yellow= 10 years July average PrescAero global CAM extracted at the location of ARM95.

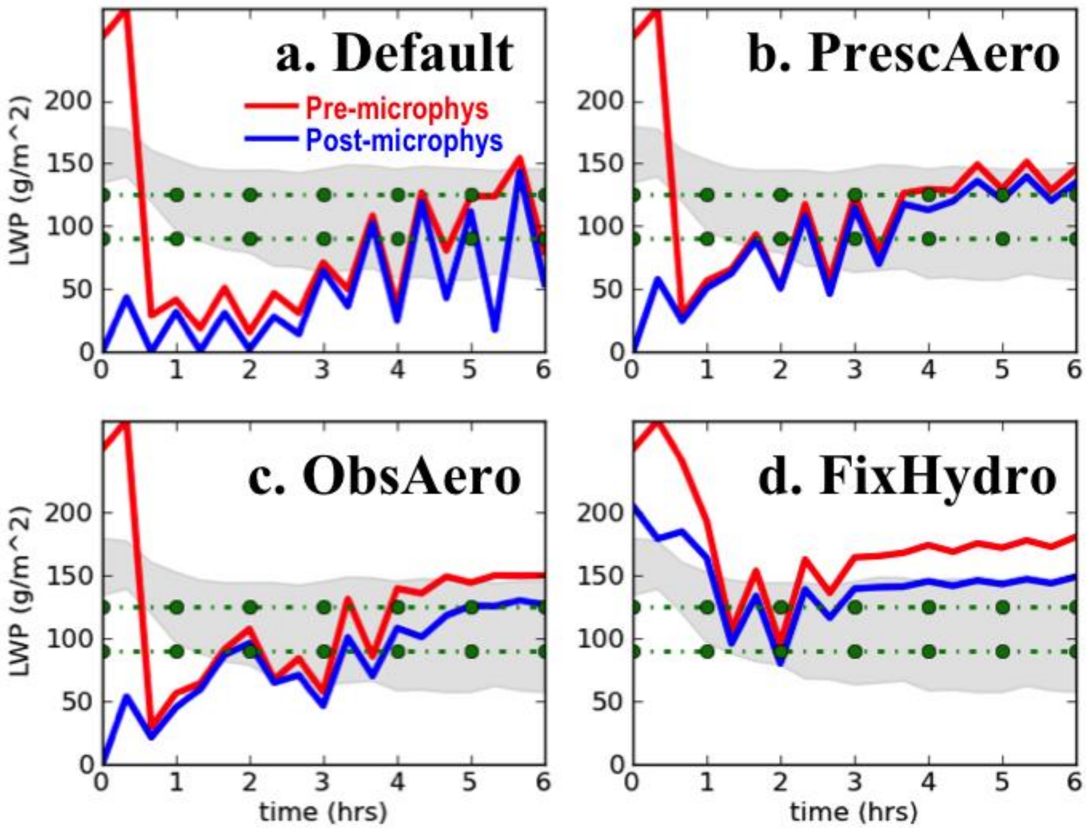
1168



a
b
1.0
0.5
Heigt (km)
Default
PrescAero
ObsAero
FixHydro
GCM
0
50
100
150
200
250
N_d (cm^{-3})



~~22.~~11. Figure 1: Profiles of in-cloud droplet number concentrations (N_d) for DYCOMS RF02. GCM values are July climatologies extracted from a 10-yr long prognostic aerosol GCM run at the location of DYCOMS RF02. Panel a is for runs where condensate is detrained (the default model behavior) and panel b shows runs where all detrained water is in vapor phase.


a. Default
b. PrescAero
c. ObsAero
d. FixHydro
Pre-microphys
Post-microphys
LWP (g/m^2)
time (hrs)

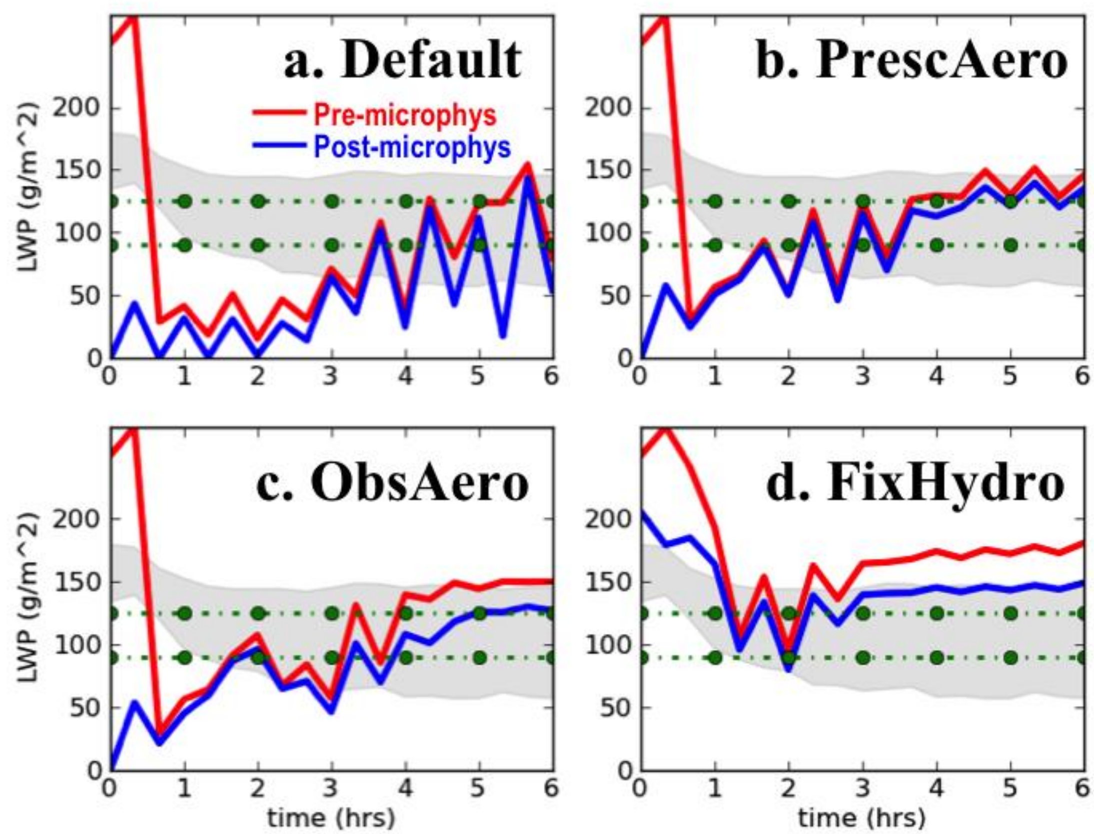


Figure 2. Time series of LWP before and after microphysics for DYCOMS RF02.The shaded area indicates the range of LES values averaged over the last 4hrs of the simulation period from Stevens and Seifert (2008) and the area bounded by dots indicates the range of observational uncertainty from Stevens et al. (2003).

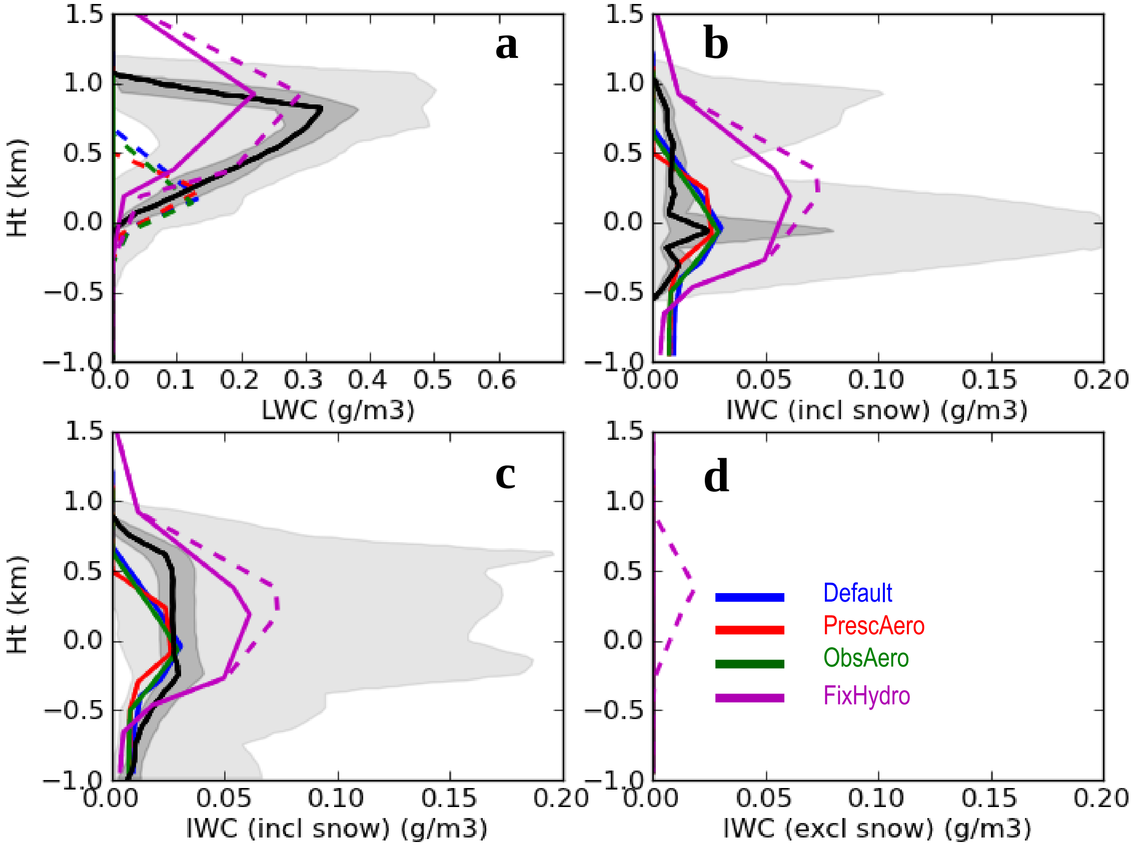
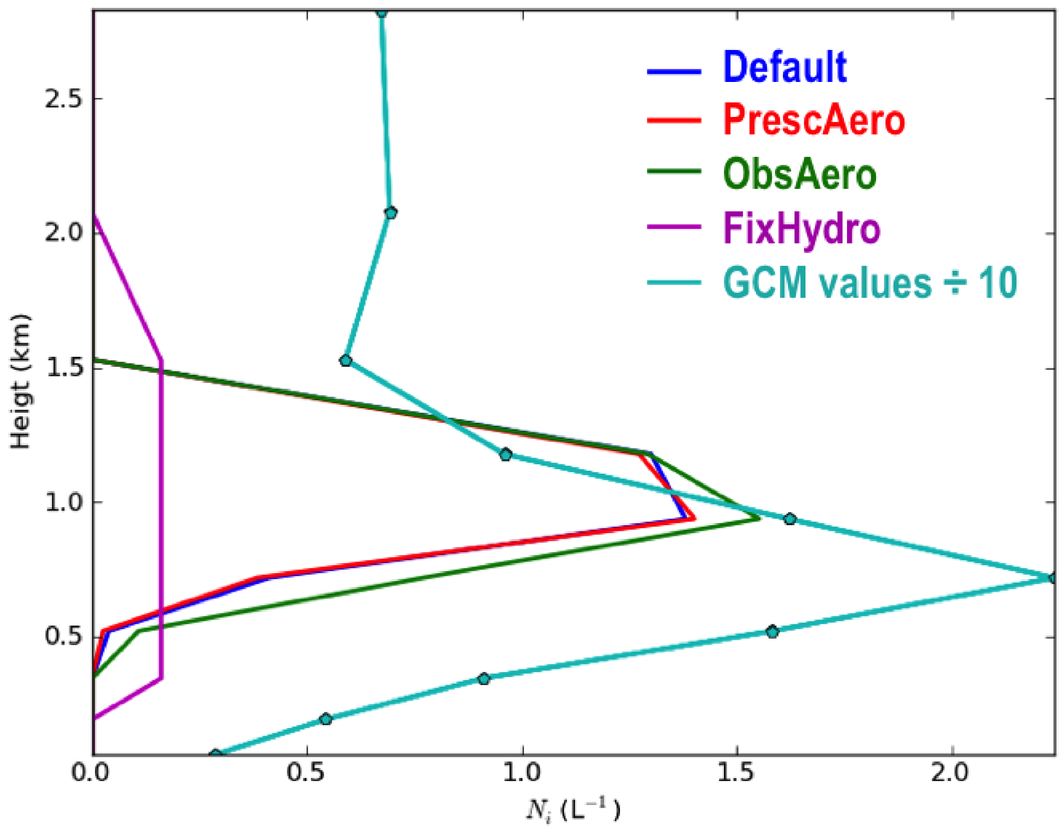


Figure 3. LWC and IWC profiles as a function of scaled height (z/z_b-1) for MPACE-B. Dashed lines indicate values before microphysics and solid lines indicate values after microphysics. a) LWC profiles as function of scaled height. Dark shaded region ranges, light shaded region and black solid line depict the median value, the inner 50% and the outer 50% the envelope of the high frequency observed aircraft data respectively (from K09). b) the same as figure 3a but for IWC (including snow). c) same as figure 6b but using radar data from K09 as observations. d) same as figure 3b but excluding snow.


Default
PrescAero
ObsAero
FixHydro
GCM values ÷ 10
Heigt (km)
N_i (L^{-1})
0.0
0.5
1.0
1.5
2.0
2.5

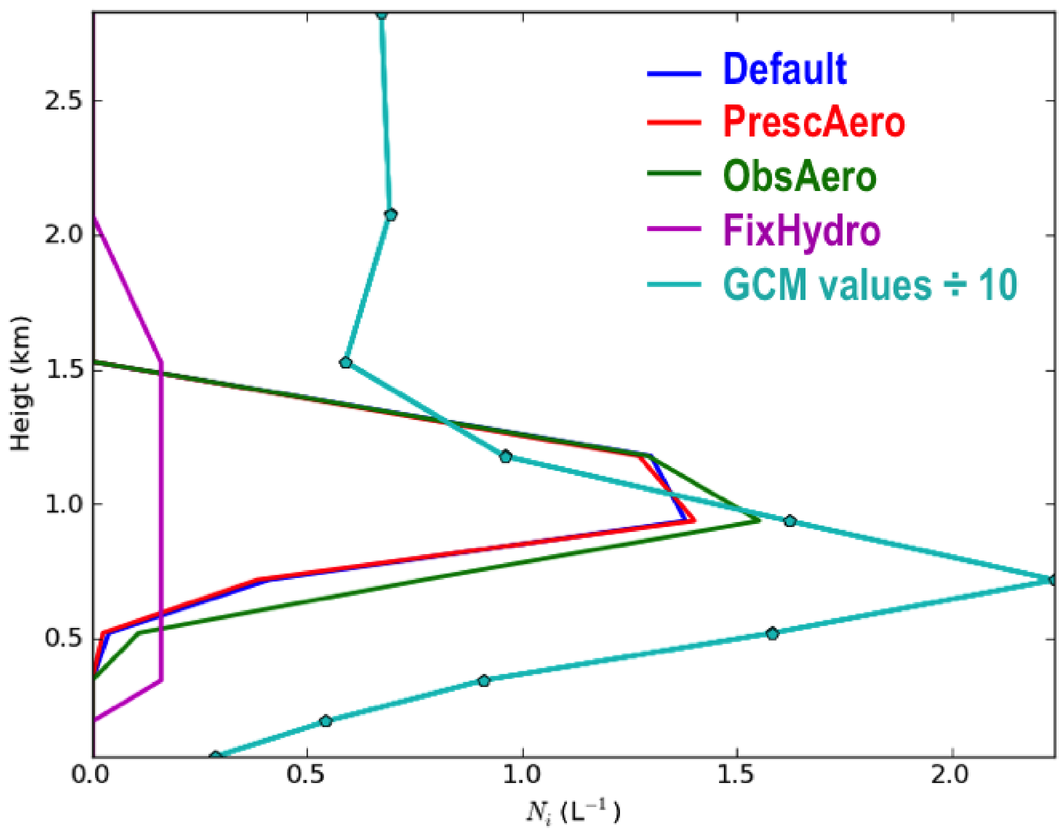
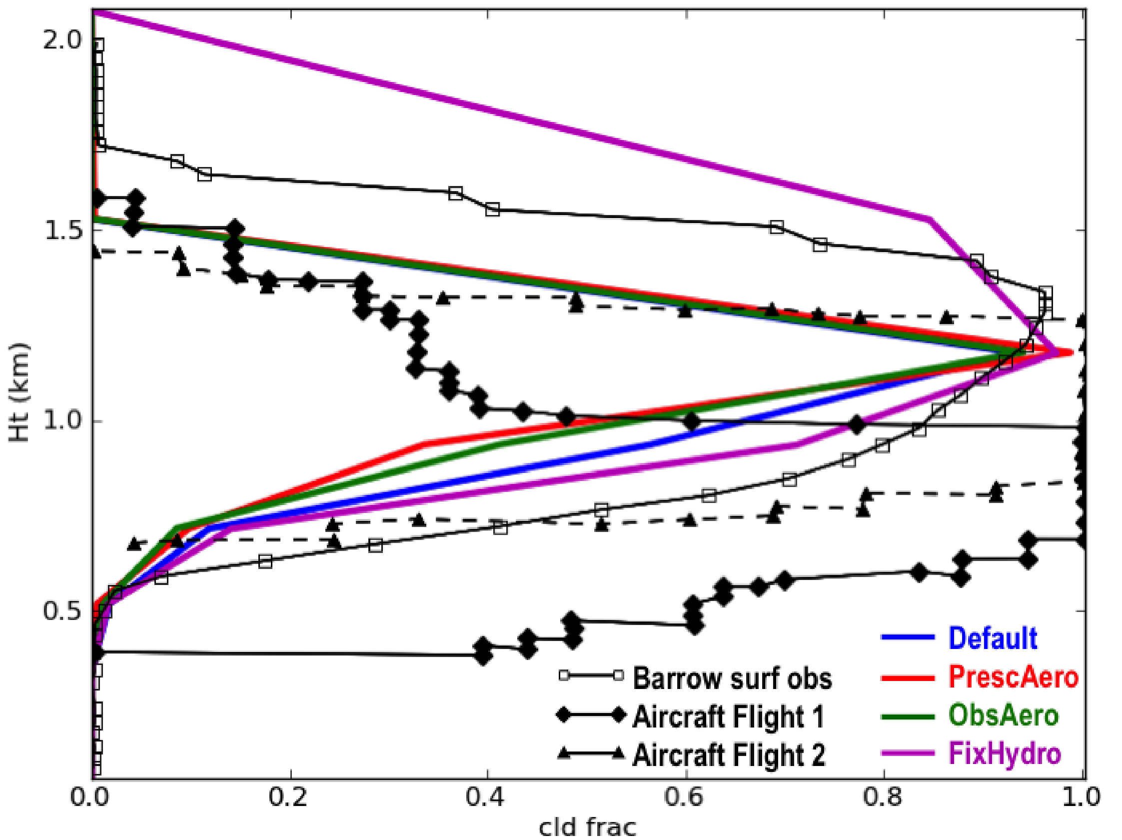


Figure 4. Profiles of in-cloud N_i values for MPACE-B case. GCM values are 10 year July averages extracted at the location of MPACE-B divided by 10 in order to fit in the plot.


Ht (km)
cld frac
2.0
1.5
1.0
0.5
0.0
0.2
0.4
0.6
0.8
1.0
Barrow surf obs
Aircraft Flight 1
Aircraft Flight 2
Default
PrescAero
ObsAero
FixHydro

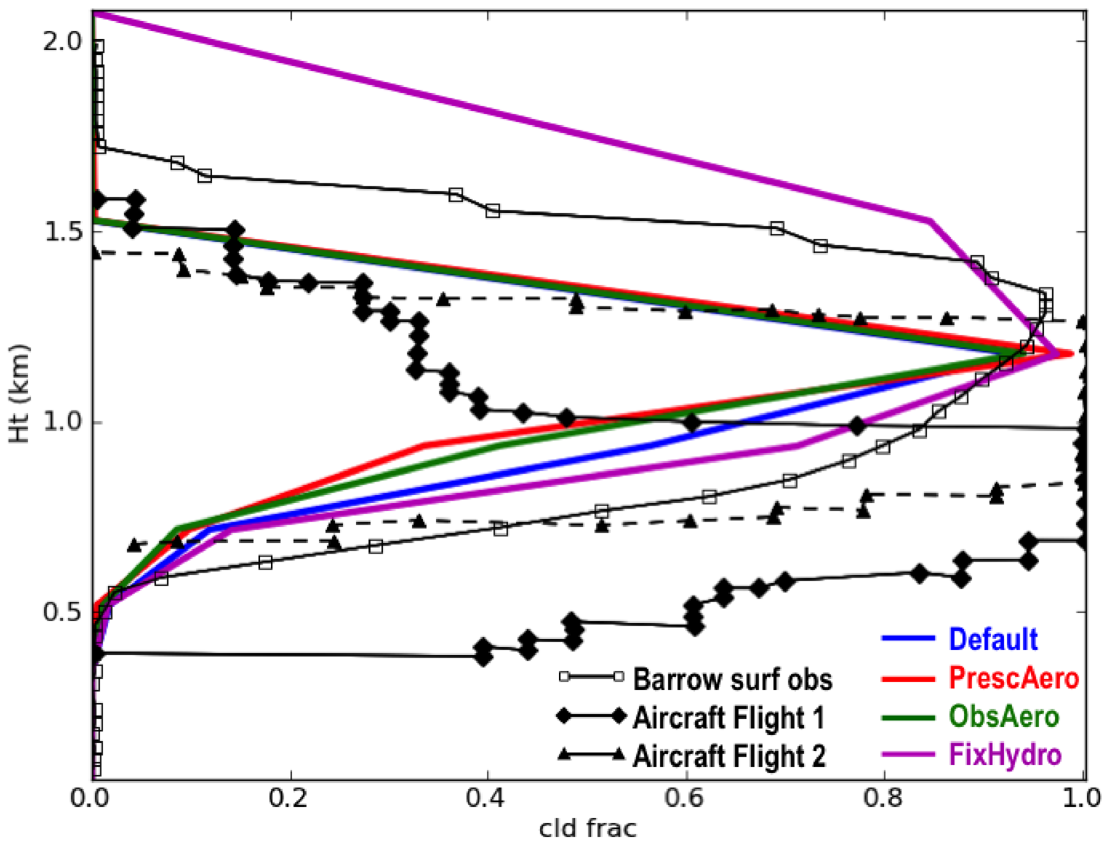
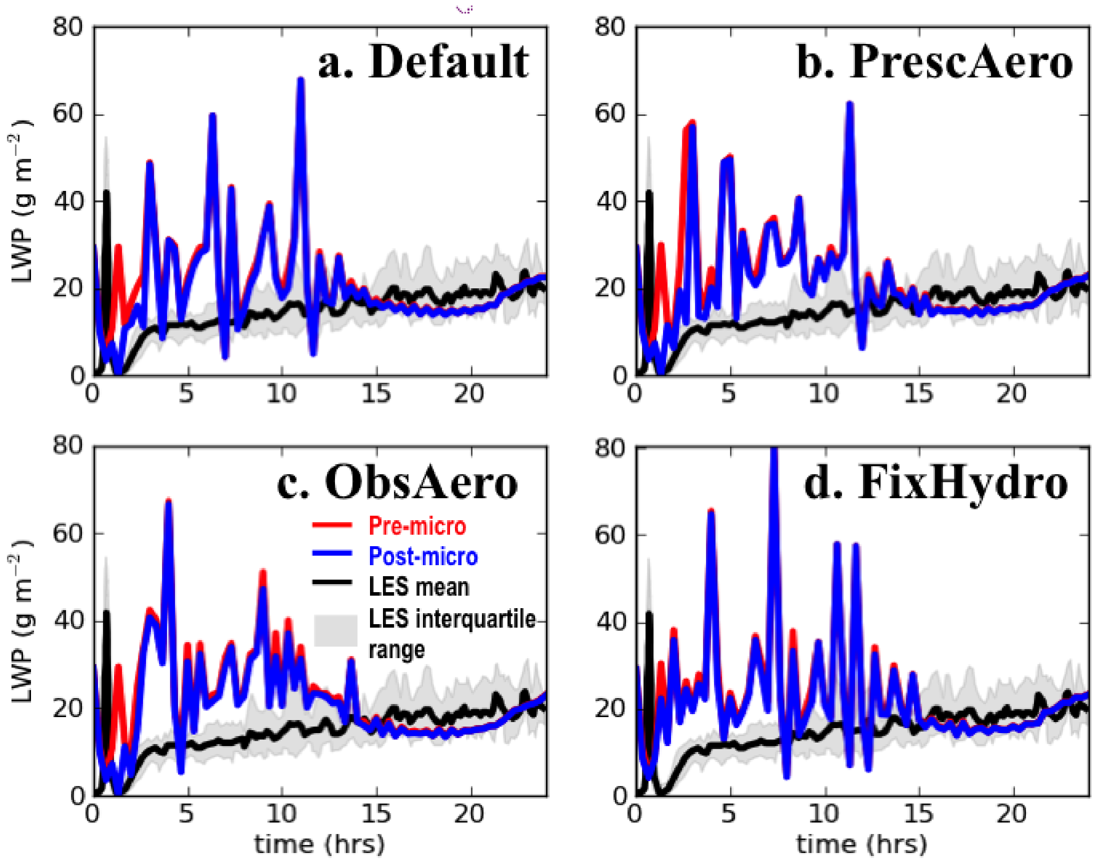


Figure 5. Time-averaged profiles of cloud fraction from models and observations as a function of height during the MPACE-B period. All observations are taken from K09.


a. Default
b. PrescAero
c. ObsAero
d. FixHydro
Pre-micro
Post-micro
LES mean
LES interquartile range
LWP (g m^{-2})
time (hrs)

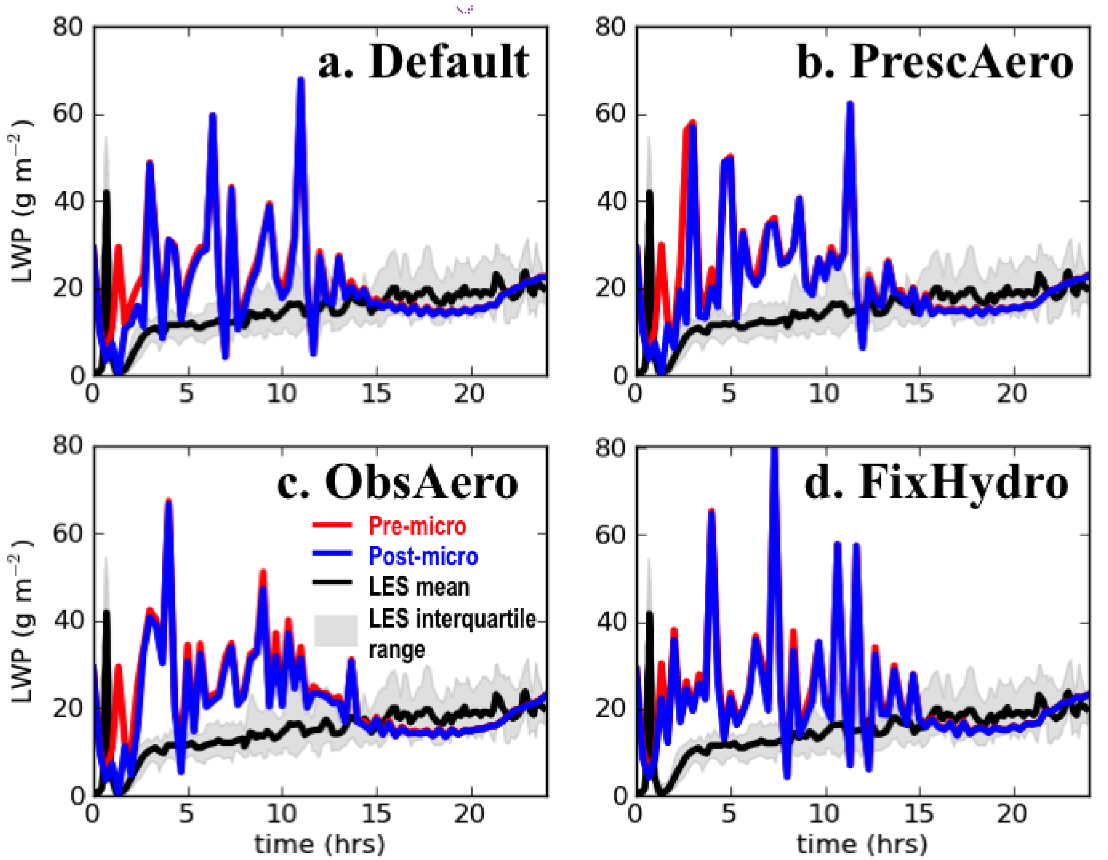


Figure 6. Time series of LWP during the RICO IOP period. LES data comes from VZ11.

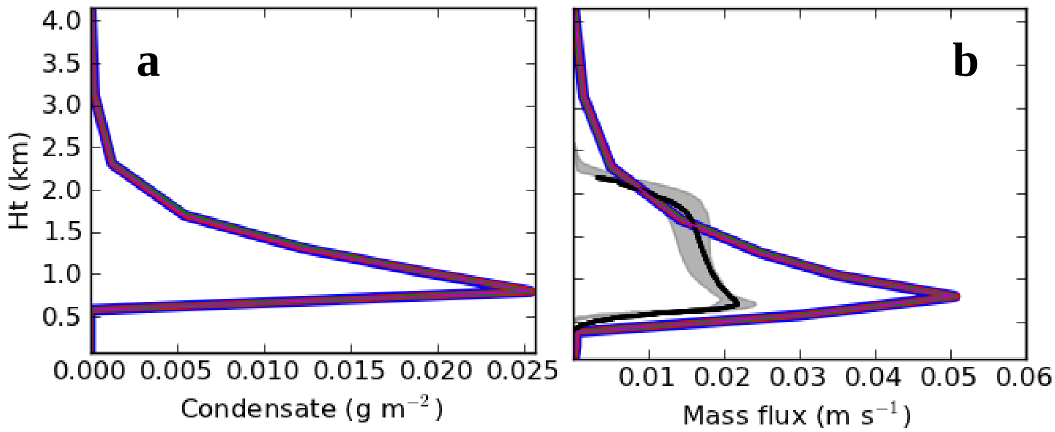
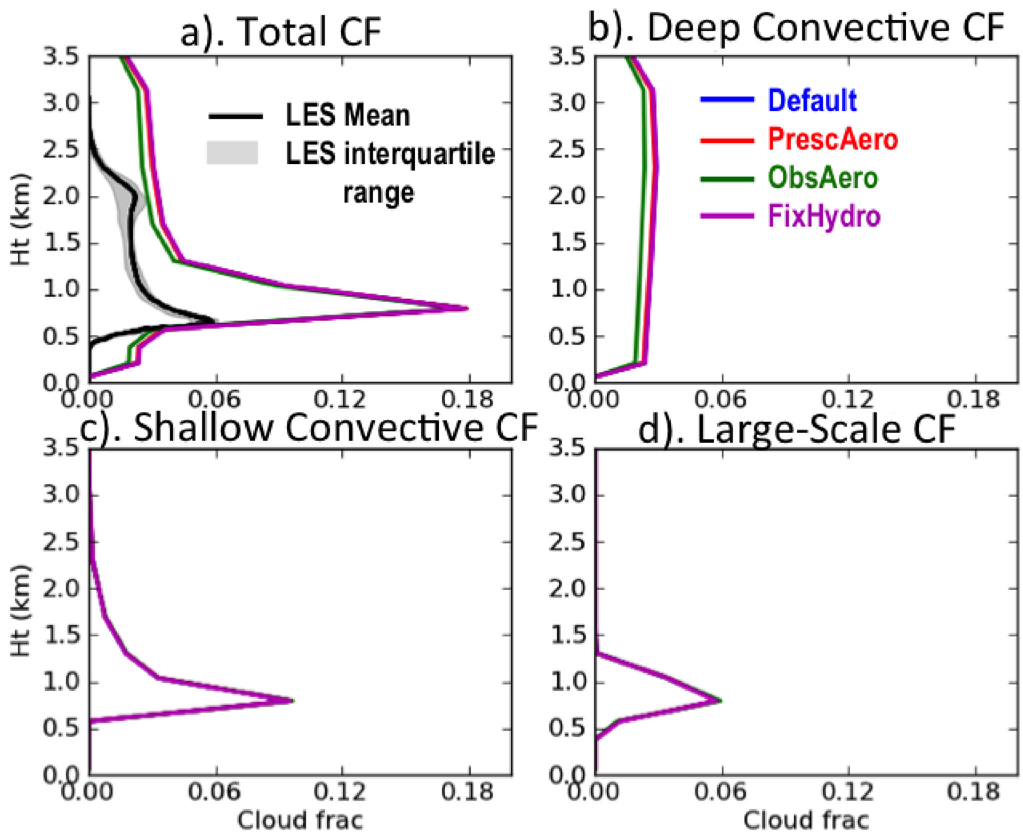


Figure 7. Time-averaged profiles of a) condensate amount and b) mass-flux for RICO simulations. The colored line shows the SCM results (all simulations lie on top of one another). Shading in figure 8b indicates ensemble inter quartile range and the solid black line is the ensemble mean. LES data are from VZ11.

1239



a). Total CF
b). Deep Convective CF
c). Shallow Convective CF
d). Large-Scale CF
LES Mean
LES interquartile range
Default
PrescAero
ObsAero
FixHydro
Ht (km)
Cloud frac
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0.00
0.06
0.12
0.18

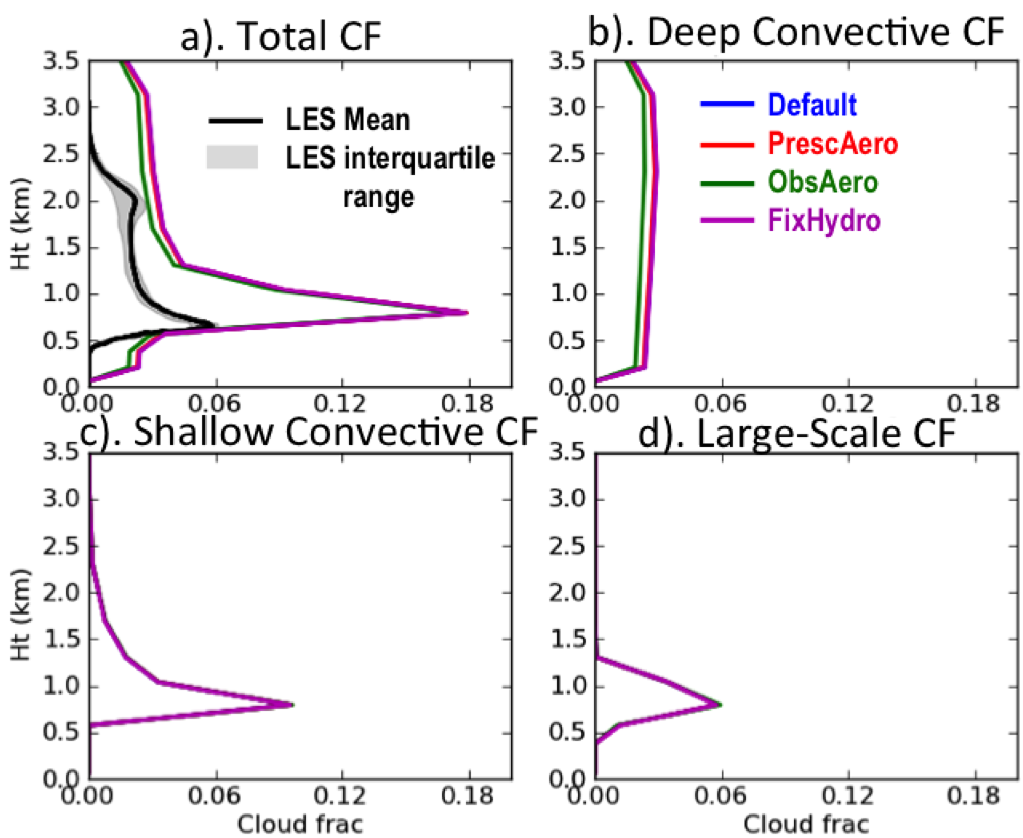


Figure 8. Time-averaged profiles cloud fraction (CF) quantities from RICO simulations. Default, PrescAero, and ObsAero all lie on top of one another. LES data are from VZ11.

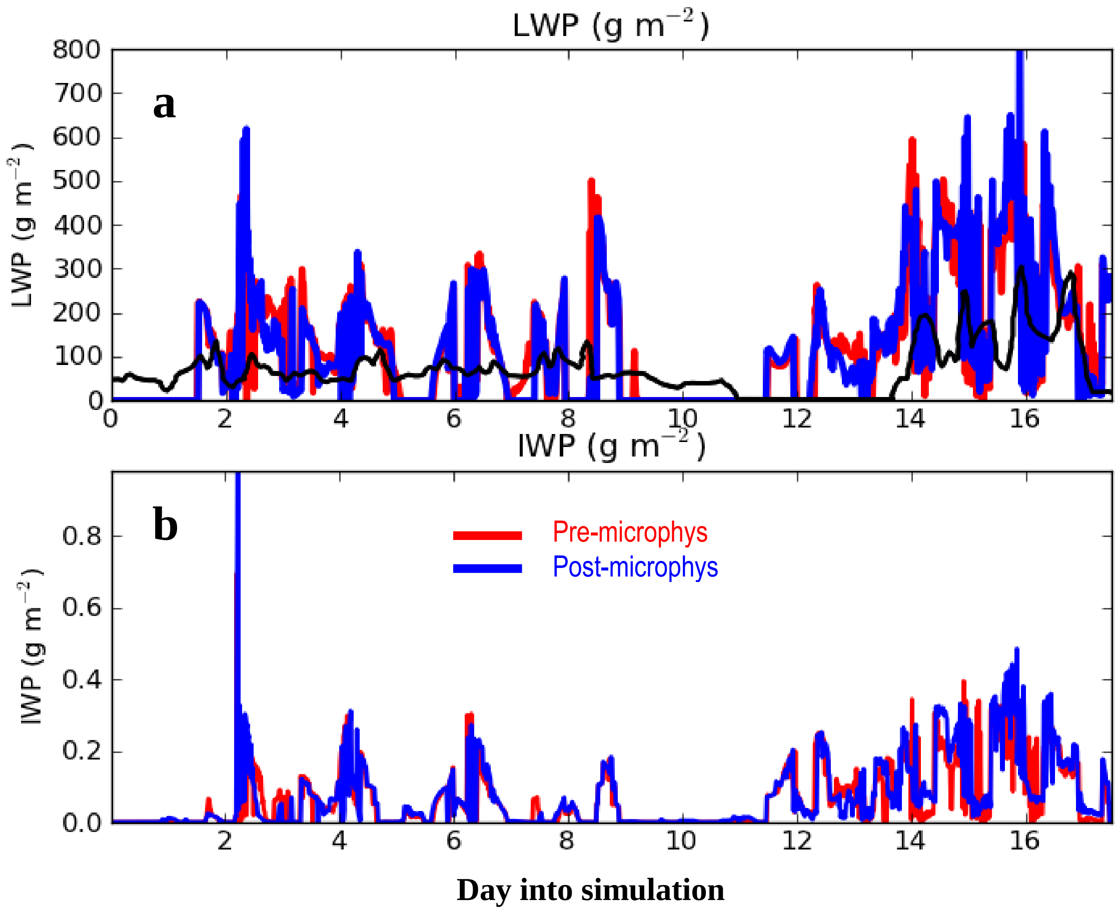
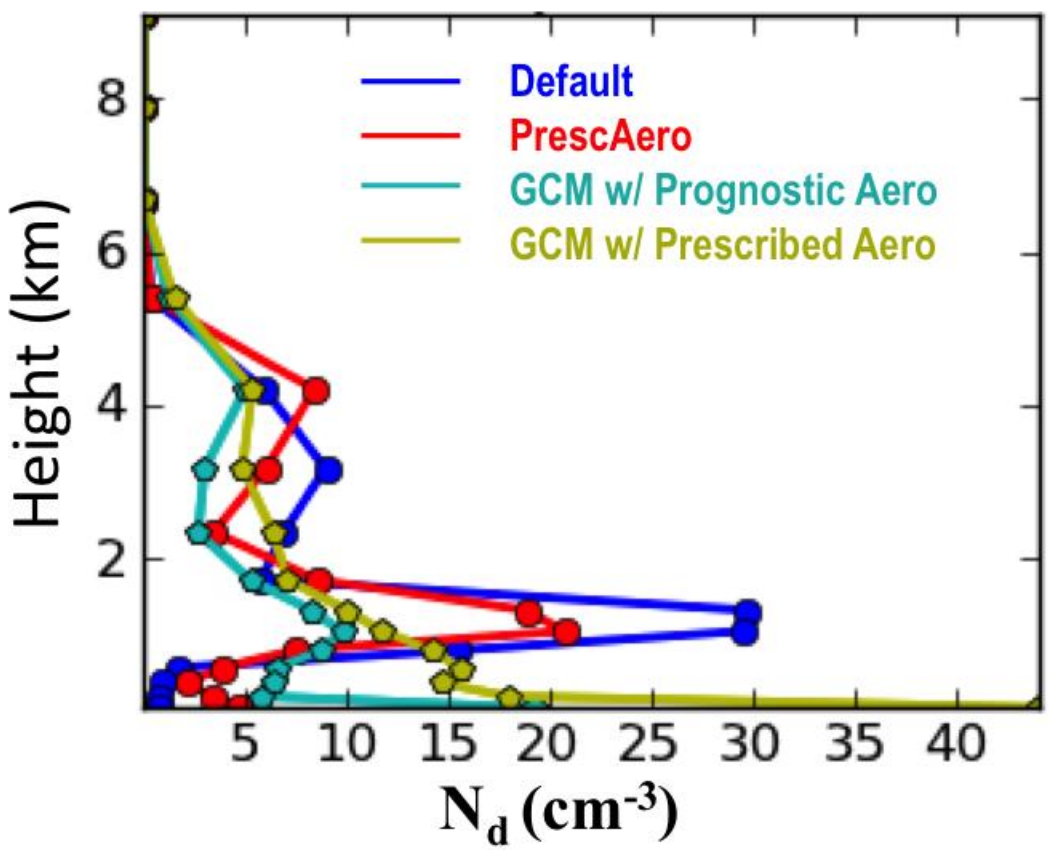


Figure 9. Time series of: a) LWP and b) IWC during the ARM95 IOP period. The solid black line in panel a) gives observations from Xu and Randall (2000).


Default
PrescAero
GCM w/ Prognostic Aero
GCM w/ Prescribed Aero
Height (km)
N_d (cm^{-3})
2
4
6
8
5
10
15
20
25
30
35
40

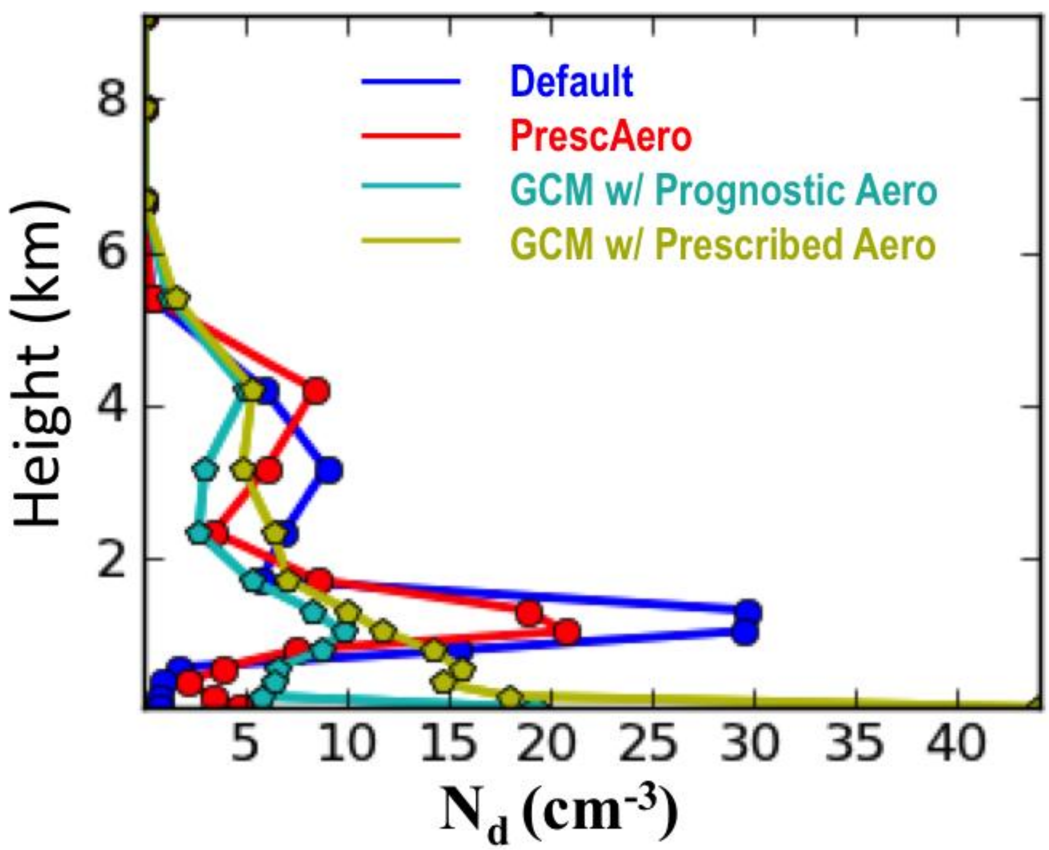


Figure 10. Profiles of in-cloud droplet number concentrations (N_d) during the ARM95 IOP period. GCM results are climatological July averages extracted at the location of ARM95.