Response to reviewer 1 comment:

October 29, 2014

Thank you for your well thought out and useful comments. We have addressed the comments in a revised manuscript by improving text, re-doing figures, and adding an appendix with model equations. We believe these changes have improved the content and clarity of the manuscript. Below are the original reviewer comments in italics with our responses following in plain text.

This article presents single column model results from several cases of deep and shallow convection using a new version of a convective parameterization (originally intended only for shallow convection) that uses the assumed probability density function method. The single column model results for these cases, which are cases that have been used for intercomparisons of convectionpermitting models and single column models in the literature, are compared with 3-D cloud resolving simulations of the same cases using the System for Atmospheric Modeling (SAM). The new parameterization scheme simulates the environment and cloud properties fairly well compared with SAM, although there are some issues with cloud liquid amount, cloud ice amount, and precipitation efficiency. The sensitivities to some new aspects of this version of the parameterization, as well as to time step, vertical resolution. and sub grid sampling, are also shown. The paper is well written and well motivated, since it presents this new version of the parameterization as a step towards a unified convection parameterization for all cloud regimes. My main concerns are: 1, a few more details about methodology should be included in this paper rather than just referred to from previous works, 2, the limitations of using single column models to test convective parameterizations should be addressed, 3, the extent to which this parameterization has already been used and described in previous studies should be made clearer, and 4, some mention of observations for these cases, and how they compare with the single column model and SAM results, should be included. I address these specific comments, as well as some minor technical comments, below. I recommend publication after these points are addressed.

Thank you for these comments. Responses are provided below to each individual comment.

Specific comments:

1. I recommend a bit more explanation of the assumed probability density function method in section 2.1. Specifically, a few examples of the equations for the vertical turbulent fluxes would be helpful. The quantities listed in table 2 could be defined in section 2.1 (some of these are never defined in the paper) and a bit more information on how correlations are estimated could be included so that the reader is better prepared to understand changes in methodology that are introduced in section 2.2.1 and elsewhere.

We have added an appendix with the basic prognostic equation set from CLUBB for reference - this should hopefully help to address any confusion a reader may have about the terms in the equation we are referring to throughout the methods section. In addition, we have expanded the caption for Table 2 to define the terms and reworded the section on correlations that you refer to, which hopefully has improved the clarity.

2. Single column models can be useful to test local processes such as conversion rates from cloud droplets to precipitation (for example). However, they do not allow feedback from local processes on to the large-scale circulation. For deep convection, precipitation is usually balanced mainly by advective moisture convergence, which is prescribed in typical single column model experiments such as these. This paper does not use surface precipitation as a metric for comparison for this very reason, which is appropriate, but the profiles of environmental properties shown here will certainly be affected by changes in the large-scale circulation in a fully three-dimensional model. It would be useful to address this and to mention any plans for testing this parameterization in a fully 3-D weather or climate model.

CLUBB has been tested within CAM5 as a boundary layer/turbulence parameterization (e.g. Bogenschutz et al., 2013). Testing CLUBB as a deep convective parameterization within CAM5 is currently in the early stages. If CLUBB were used as a fully unified cloud parameterization, the large scale forcing from the host model would provide forcing to the CLUBB model, which would then calculate cloud fractions, liquid water, precipitation, etc. which could be then available for the host model to use (e.g. for radiation or dynamics). In this way the local processes and the large scale would directly feed back on each other.

3. This paper should be more clear about the use of CLUBB for deep convection in Davies et al. 2013. In the introduction, it is mentioned that Davies et al. 2013 did include a PDF parameterization for deep convection, but it appears that it was actually CLUBB that was used for deep convection in that paper. This is not clear in the current manuscript. I think that the results from that paper deserve at least a paragraph describing how the version of CLUBB used in that paper compare with the version presented in the current paper. The performance of that version of CLUBB in Davies et al. 2013 compared with observations and other models should also be discussed here in this paper.

Thank you for pointing out how this text was unclear. To add clarity, and some detail on the Davies et al. study, we have changed the text as follows:

Previous: "Despite these advantages for parameterizing deep clouds, to date PDF parameterizations have been applied only to shallow clouds, except in higher-resolution cloud- resolving models (Cheng and Xu, 2006; Bogenschutz and Krueger, 2013) and except in Davies et al. (2013). The present paper takes a PDF parameterization, the Clouds Layers Unified By Binormals (CLUBB) parameterization, that has been used to simulate shallow clouds, and extends it in ways designed to better represent deep convection. In particular, the representation of the subgrid distribution of ice and precipitation is improved."

New: "Despite these advantages for parameterizing deep clouds, to date PDF parameterizations have been applied only to shallow clouds, except in higher resolution cloud resolving models (Cheng and Xu, 2006; Bogenschutz and Krueger, 2013) and except in Davies et al. (2013). Davies et al. (2013) includes a single-column model (SCM) simulation of a tropical del convective case by the Cloud Layers Unified by Binormals (CLUBB) PDF parameterization. However, that study was an intercomparison of several SCMs and hence did not include details of the formulation or evaluation of CLUBB. CLUBB performed comparably to the other SCMs in Davies et al. (2013), but here we take the CLUBB parameterization and extend it in ways designed to better represent deep convection. In particular, the representation of the subgrid distribution of ice and precipitation is improved."

4. Since these case studies include some observational information, it

should be dis- cussed at least to some extent how well both the single column model with the PDF parameterization and the SAM results compare with the observations. This would be especially useful for quantities in which the two models disagree with each other (al- though it would be good to know in general).

One reason we chose SAM as our "truth" for model validation is the fact that SAM was included in model intercomparisons as cited for all 3 of the deep convective cases, and performed well in general characteristics such as precipitation and liquid water path. A detailed comparison of the microphysical variables would be beyond the scope of our study. To mention the general agreement, we've changed:

"We configure the deep convective simulations as per previous model intercomparisons of those cases."

to:

"We configure the deep convective simulations as per previous model intercomparisons of those cases. SAM simulations examined here are comparable to previous simulations and observations in general characteristics such as timing, precipitation, and liquid water path. We conclude, therefore, that they provide good reference simulations for evaluation of CLUBB-SILHS."

Minor (or technical) comments:

Page 3816, line 9: do you have any idea how SAM and CLUBB-SILHS might perform with prognostic droplet number concentration rather than prescribed values?

Using prognostic cloud drop number concentrations leads to small differences in the microphysics profiles, but no significant differences in the mean fields. The decision to prescribe the concentration was made to simplify the microphysical budget calculations and remove a simple source of possible differences - however the overall results would not be largely different with prognostic cloud number.

Page 3816, line 18: have you tried interactive radiation in this model, and how does it look? How does it affect radiation fluxes? Or, if you haven?t tried this, do you have plans to do so?

We have run simulations using the BUGSRAD interactive radiation (Stephens et al., 2001). The radiative fluxes were sensitive - however the mean fields varied little. The CLUBB simulations used in Davies et al. (2013), which produced comparable results to other SCM simulations, utilized BUGSRAD as well.

Page 3818, line 14: usually for deep convection, precipitation is mostly

balanced by moisture convergence (by advection), not surface fluxes, I would expect this to be the case here as well. In other words, it is probably not the prescribed surface fluxes that are constraining your surface rain rates but rather the prescribed moisture convergence from advection.

To remove confusion, we changed "constrained by surface evaporation rates." to "constrained by prescribed large-scale forcings."

Page 3818, line 16: it looks to me like liquid water path is too high especially in the early part of the simulation, might there be a reason for this?

Generally, a too-high liquid water path with a reasonable rain water path implies that the precipitation efficiency is too low. In combination with the low cloud ice that you point out, it is possible that some of this is due to an issue with the correlations between cloud and ice hydrometeors. We have stated this in the text.

Page 3818, line 18: the cloud ice is not completely accurate, it is somewhat lower than SAM and slightly out of phase.

This is a good point. As mentioned above, we corrected this in the text. Page 3819, line 17: the models also disagree on snow, is this for the same reason?

Yes. The large nucleation rates mean that there are large numbers of smaller ice crystals produced, leading to less efficient snow production. We added a sentence about this.

Page 3819, line 27: here and elsewhere, including in some of the figure captions, be careful with terms like "cloud fraction" or "cloud water mixing ratio" because you are only including liquid cloud for these terms, so I would replace these with "liquid cloud fraction" "cloud liquid water mixing ratio" throughout

Thank you for pointing this out. We have made this change.

page 3820, line 8: is "including non-zero precipitation fraction" the same as "allowing a hydrometeor free region" as described in 2.2.1? I?m not sure how these could be the same thing, but they seem to be used interchangeably.

Yes, though the wording was confusing here. It should have read nonunity, rather than non-zero. The precipitation fraction allows for a region of the PDF that is hydrometeor free - hydrometeors including cloud ice, snow, graupel, and rain - whereas the previous formation essentially had a precipitation fraction equal to one (with all hydrometeors occurring througout the entire region). We have changed the wording in this paragraph to be more consistent with the description in 2.2.1.

Page 3823, line 20: it would be nice to have a little more discussion and

explanation of how these biases are symptoms of low precipitation efficiency. This is not necessarily obvious, and I think it would enhance the paper to go into a little more detail.

We have added the following sentence further clarifying what we mean by precipitation efficiency: "That is, the amount of precipitation produced in CLUBB-SILHS for an amount of condensate is too low in these cases leaving too much cloud water remaining compared to the SAM simulations."

Table 2 caption: "an another? -¿ ?another?

Thank you for pointing this out. We have fixed this.

table 2: I recommend listing the variable names downwards along the left (or right) side of the table to make it easier to find corresponding correlations. Also, as mentioned in the main comments, at least six of the variables listed here are never defined in the paper or in this caption.

Thank you for pointing this out - we have added the extra column and defined the variables in the caption for clarity.

Figures: in general, I would make the lines thinner because some of the detail is lost and it is sometimes difficult to compare the two lines (this is especially bad in some panels of Figure 7 and Figure 15). I would also use days (for longer cases) or hours (for shorter cases) instead of minutes for the x-axes since most people are not used to interpreting large numbers of minutes (e.g. to look at the phase of the diurnal cycle). The legend boxes only need to appear once per figure, not in every panel; this will help with issues such as the fact that the legend box is blocking the curve in at least one panel of figure 1. This will also allow legend boxes to be made larger for figures.

Thank you for these suggestions. We have re-done the figures and legends to make them clearer to see.

Figures 10-11: in the captions, I would refer to these figures as showing the "sensitivity to the inclusion of the new xxxx? rather than "the effect of including (or boosting) xxxx?. Or alternatively, these could be labeled as "the effect of not including (or boosting) xxxx?. Otherwise, it makes it confusing whether these new additions to the scheme were included in the parameterizations used for the previous figures or whether they are only being tested in versions in these figures.

We have made this change, thank you for mentioning this confusion.

Figures 11-14: please include the time range for each experiment during which the mean profiles have been averaged.

They have been averaged over the same time periods as used in previous figures - we added a note of this to the captions.

Response to reviewer 2 comment:

October 29, 2014

Thank you for your well thought out and useful comments. We have addressed the comments in a revised manuscript by adding a section and figure on convective dynamics, as well as an appendix with the model equations, which we believe have improved the manuscript. Below are the original reviewer comments in italics with our responses following in plain text.

This is a valuable paper that extended the pdf-based CLUBB to deep convections. It showed SCM simulation results and comparison with LES results for three cases of deep convection and two cases of shallow clouds. The paper is a valuable contribution to document a potentially viable scheme of deep convection and its performance in SCM setting. I therefore recommend acceptance of the paper subject to the following improvements. Major comments: In extending the CLUBB to deep convection, the paper emphasized cloud and precipitation microphysical process. The paper did not discuss the viability of CLUBB to describe the dynamics of deep convection, i.e., the profiles of vertical velocity and its properties in deep convective clouds. Ultimately, one needs to have credible dynamics to trust the microphysics. The authors should also try to discuss why CLUBB works for the dynamics of deep convection since it was initially designed for shallow convection and turbulence, and show results that it works.

You have raised an important point. We have added a section about dynamics, including a plot with several relevant variables. CLUBB does a reasonable job of reproducing most of the dynamic variables, though some work still needs to be done on improving the coupling between microphysics and dynamics.

Some key basic controlling equations of the moments should be included

so that the readers can see where the modifications are made and why only these are chosen but not others.

This is a good point. We have added an appendix with the basic prognostic equations for reference for the reader.

The sensitivities of the results to time step and vertical resolution make the scheme unsuitable for practical use. Some discussions will be useful on what should be done.

It was expected that the simulations would be sensitive to temporal and spatial resolution, however CAM is sensitive to these parameters as well. CLUBB-SILHS is being tested within CAM5 in order to see what biases might be introduced. The current simulations have not been tested or tuned at all for use within a GCM host model, and so more work will need to be done to determine how suitable the SCM is.

Minor comments: Page 3812, line 15, ?correlated?, do you mean ?collo-cated??

Yes, that is a more appropriate word, thank you.

For the second assumption on page 3812, why do you need to make this assumption?

Thank you for catching this. This assumption was made in an earlier version of the code, but has since been remedied.

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Parameterizing deep convection using the assumed probability density function method

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Abstract

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Due to their coarse horizontal resolution, present-day climate models must parameterize deep convection. This paper presents single-column simulations of deep convection using a probability density function (PDF) parameterization. The PDF parameterization predicts the PDF of subgrid variability of turbulence, clouds, and hydrometeors. That variability is interfaced to a prognostic microphysics scheme using a Monte Carlo sampling method.

The PDF parameterization is used to simulate tropical deep convection, the transition from shallow to deep convection over land, and mid-latitude deep convection. These parameterized single-column simulations are compared with 3D reference simulations. The agreement is satisfactory except when the convective forcing is weak.

The same PDF parameterization is also used to simulate shallow cumulus and stratocumulus layers. The PDF method is sufficiently general to adequately simulate these five deep, shallow, and stratiform cloud cases with a single equation set. This raises hopes that it may be possible in the future, with further refinements at coarse time step and grid spacing, to parameterize all cloud types in a large-scale model in a unified way.

1 Introduction

Deep convective clouds are an integral part of the climate system, yet representing these clouds accurately in climate models is a challenge. Explicitly resolving these clouds in decades-long climate simulations is not yet computationally feasible; thus it is beneficial to parameterize deep convection (e.g. Molinari and Dudek, 1992; Weisman et al., 1997; Warner and Hsu, 2000; Sato et al., 2009; Noda et al., 2010). Deep convective clouds are difficult to parameterize, however, partly because they produce copious ice and precipitation, which interact strongly with storm dynamics. For instance, convective rain may partially evaporate before reaching the ground, creating cold pools that spawn further convection (e.g. Liu et al., 1997; Tompkins, 2001; Khairoutdinov and Randall, 2006).

Deep convection has often been parameterized by the use of mass-flux schemes (e.g. Arakawa

and Schubert, 1974; Kain and Fritsch, 1990; Donner, 1993; Zhang and McFarlane, 1995; Arakawa, 2004; Kain, 2004; Gerard, 2007; Arakawa et al., 2011; Mapes and Neale, 2011; Bechtold et al., 2014). However, parameterization of deep convective clouds and turbulence may be aided by the use of the assumed probability density function (PDF) method. In the assumed PDF method, several lower-order subgrid moments are prognosed at each time step (e.g. Sommeria and Deardorff, 1977; Mellor, 1977; Smith, 1990; Lewellen and Yoh, 1993; Bony and Emanuel, 2001; Tompkins, 2002). The lower-order moments, along with an assumption about PDF shape, are used to estimate a joint PDF of subgrid scale (SGS) moisture, temperature, vertical velocity, and hydrometeors. The subgrid PDF is then used to calculate various unclosed higher-order moments that appear in the equation set, thereby allowing the solution to be advanced another time step.

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PDF parameterizations possess several advantages for the purpose of parameterizing deep convection. First, the use of a PDF that includes hydrometeor species and vertical velocity allows for a detailed representation of microphysics and dynamics, and of the coupling between them. For instance, a PDF representation that are appresentation of microphysics are presented by the presentation of the coupling between them.

them. For instance, a PDF parameterization that *prognoses* lower-order moments is compatible with *prognostic* microphysics. The use of a prognostic microphysics scheme, in turn, allows for precipitation to be preserved between computational time steps, providing a better representation of hydrometeor collection (e.g. Posselt and Lohmann, 2009; Gettelman and Morrison, 2014). Representation of collection also benefits from the ability of PDF parameterizations to prescribe the correlations among hydrometeors, thereby estimating the degree of collocation among the hydrometeor types. Another benefit of a PDF parameterization is the detailed and rigorous treatment of the distribution of SGS vertical velocity, which in turn is important for parameterizing vertical turbulent transport.

Despite these advantages for parameterizing deep clouds, to date PDF parameterizations have been applied only to shallow clouds, except in higher-resolution cloud-resolving higher resolution cloud resolving models (Cheng and Xu, 2006; Bogenschutz and Krueger, 2013) and except in Davies et al. (2013). The present paper takes a PDF parameterization, the Clouds Layers Unified By Davies et al. (2013) includes a single-column model (SCM) simulation of a tropical del convective case by the Cloud Layers Unified by Binormals (CLUBB) parameterization, that has been used to simulate shallow clouds, and extends PDF parameterization. However, that study was an intercomparison of several SCMs and hence did not include details of the formulation or evaluation of CLUBB. CLUBB performed comparably to the other SCMs in Davies et al. (2013), but here we take the CLUBB parameterization and extend it in ways designed to better represent deep convection. In particular, the representation of the subgrid dis-

tribution of ice and precipitation is improved.

The modified version of CLUBB is then used to perform single-column simulations of three deep convective cases: a tropical case, a case of transition from shallow to deep convection, and a mid-latitude case. To demonstrate that the modified version of CLUBB can still simulate shallow cloud cases, we also simulate a shallow cumulus layer and stratocumulus layer. To assess the quality of the single-column CLUBB simulations, we compare the deep convective cases to cloud-resolving simulations and the shallow cases to large-eddy simulations.

The remainder of this paper is organized as follows. In Section 2, we will describe the single-column model CLUBB and the recent changes to it implemented in order to obtain improved
¹⁵ simulations of deep convective clouds. In Section 3, results from CLUBB for three deep convective cases will be compared to cloud-resolving model simulations. In Section 4, we will show results of sensitivity tests to basic model setup, including reducing vertical and time resolution such as might be required to interface CLUBB with a climate model. In Section 5, we will show results of two simulations of shallow clouds, demonstrating that this model frame²⁰ work can be used in simulations of both deep and shallow cloud types. In Section 6, we will finish with discussion and conclusions.

2 Methodology

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2.1 Description of single-column model: CLUBB-SILHS

Cloud Layers Unified By Binomials (CLUBB) is a single-column model of clouds and turbulence in the atmosphere (Golaz et al., 2002; Larson and Golaz, 2005; Larson and Griffin, 2013; Griffin and Larson, 2013). CLUBB is designed to model a variety of cloud types and turbulence regimes in a unified way with a single equation set. CLUBB parameterizes both cumulus and stratocumulus clouds, and both dry convective and stably stratified boundary layers. The equation set consists of prognostic equations for various subgrid-scale higher-order moments. The moments include variances of vertical velocity $(\overline{w'^2})$, total water mixing ratio $(\overline{r'_t}^2)$, and liquid cloud water potential temperature $(\overline{\theta'_l}^2)$. It also includes subgrid vertical turbulent fluxes of total water $(\overline{w'r'_t})$ and liquid cloud water potential temperature, $\overline{w'\theta'_l}$. (Here an overbar denotes a grid box average, and a prime denotes a subgrid deviation from a grid box average.) CLUBB's equation set is summarized in Bogenschutz et al. (2013) Appendix A. CLUBB has been coupled to the double-moment microphysics scheme of Morrison et al. (2009). The coupled model prognoses grid-mean number concentration and mixing ratios of rain, snow, graupel and cloud ice. The spatial variances of these hydrometeors are assumed to be proportional to the grid

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mean values squared. CLUBB's equation set contains various higher-order moments that are unclosed. CLUBB closes many of these moments using the assumed probability density function (PDF) method. That is, CLUBB assumes a functional form of the subgrid PDF and integrates over it in order to estimate the unclosed moments. CLUBB's subgrid PDF is a single, multivariate PDF with a double Gaussian (sum of two normals) distribution for vertical velocity w, total water mixing ratio r_t , and liquid water potential temperature θ_l (Larson et al., 2001) and a delta

function/lognormal distribution for the hydrometeor variates (Griffin and Larson, 2014). The
delta-lognormal PDF adds a delta function representing precipitation-free areas to the lognormal distribution of Larson and Griffin (2013). It is described further in Section 2.2.1 below.

In order to drive microphysical processes, CLUBB has the option to call a microphysics scheme using a variant of traditional Monte Carlo sampling (McKay et al., 1979; Owen, 2003). This sampler is called the Subgrid Importance Latin Hypercube Sampler (SILHS, Larson et al. (2005); Larson and Schanen (2013)). SILHS draws one or more sample points per grid box and time step from CLUBB's joint subgrid PDF. SILHS collects a sample from each grid level into a subcolumn by assuming that correlation drops off exponentially with vertical distance and by using CLUBB's turbulent length scale to estimate the e-folding distance (Larson and Schanen, 2013). Each subcolumn is then fed into a microphysics scheme, one at a time. For

each subcolumn, the microphysics scheme produces outputs, e.g. autoconversion rate. Then the resulting ensemble of autoconversion rates is averaged, yielding an estimate of the grid box mean autoconversion rate.

In summary, CLUBB-SILHS parameterizes subgrid variability as follows (Larson and Schanen, 2013):

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- 1. *Construct the multivariate PDF of subgrid-scale variability (performed by CLUBB).* CLUBB predicts a single, joint PDF for each grid box and time step that contains the following variates: heat content, moisture content, vertical velocity, and all relevant hydrometeor mixing ratios and number concentrations.
- 2. *Draw subcolumns from the subgrid PDF (performed by SILHS).* A sample point is drawn from each grid level. These sample points, taken together, form a single vertically correlated profile, i.e. "subcolumn." The sampling is repeated until a set of subcolumns is constructed that collectively approximates the statistical properties of the grid column.
 - 3. *Feed subcolumns into physical parameterizations and compute process rate tendencies (performed by a microphysics scheme).* Each subcolumn is fed into a microphysics scheme. For each subcolumn, the microphysics scheme computes a separate tendency.
 - 4. Average microphysics tendencies from each subcolumn to form a grid box average profile. The set of tendencies is averaged to form a grid box mean tendency, which can then be fed back into the appropriate host model equations. The average may be a weighted average, with each subcolumn corresponding to different-sized area within the grid column.

The computational cost of CLUBB-SILHS is acceptable. CLUBB adds 20% to the computational cost of Version 5 of the Community Atmosphere Model (CAM5, Bogenschutz et al. (2013)). SILHS's computational cost, when two sample points are used, is similar to that of CLUBB (Larson and Schanen, 2013).

²⁵ Both CLUBB and SILHS are contained in a single svn code repository that is freely available for non-commercial use at http://clubb.larson-group.com. The simulations presented here can be reproduced by checking out svn revision 6840 of the branch located at http://carson.math.uwm.edu/repos/clubb_repos/branches/storer_et_al_paper_clubb/, compiling the source code, and running ./run_scm_all.bash. Complete details of all algorithms are available in the source code in the svn repository, along with numerous code comments and a README file that serves as a user manual. SAM output used for plotting and for prescribing radiative forcing can be found at http://www.larson-group.com/storer/.

2.2 Coupling subgrid variability to liquid and ice microphysics

In order to better simulate deep convection using CLUBB, we have generalized the treatment of subgrid variability. In particular, we have generalized CLUBB's multivariate PDF to include ice, incorporated the effects of ice and rain on subgrid buoyancy production, improved the vertical transport of hydrometeors, and allowed changes in the microphysics to affect scalar fluxes and variances.

2.2.1 Subgrid PDF of hydrometeors

CLUBB represents vertical velocity, liquid water potential temperature, and total water mixing ratio using a double Gaussian PDF. However, a double Gaussian is unbounded and hence is
 not well suited to representing hydrometeors. In this context, hydrometeors include the mixing ratios and number concentrations of cloud ice, snow, graupel, and rain. These quantities are non-negative but often have small values.

In order to represent hydrometeors realistically and fully, a subgrid PDF should have two features. First, it should be multivariate, so that it can represent the collection of one hydrometeor species by another. Second, the subgrid PDF should include a hydrometeor-free region, so that hydrometeors do not suffer excessive evaporation or sublimation in otherwise clear regions.

The marginal subgrid PDF shape that we choose for the hydrometeor variates is a sum of a delta function and a multivariate lognormal. The delta function represents the portion of a grid box that is devoid of all hydrometeors (except liquid cloud droplets). The multivariate lognormal represents the hydrometeor-filled portion, i.e. the precipitation fraction. Details of the formulation of the lognormal are provided by the source code and in Larson and Griffin (2013)

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and in Griffin and Larson (2013). Although those papers used a multivariate lognormal to represent only the number concentration and mixing ratio of rain, here the multivariate lognormal is extended straightforwardly to represent the within-hydrometeor number concentrations and mixing ratios of all hydrometeors except liquid cloud water, which is diagnosed via saturation adjustment from total water.

At altitudes above the freezing level, the precipitation fraction is set equal to the fraction of a grid box that is supersaturated with respect to ice. Below the freezing level, the precipitation fraction is determined by a calculation similar to that of Morrison and Gettelman (2008). More details of the formulation are provided in Griffin and Larson (2014) and the source code.

The assumed PDF method requires that variances of each variate be provided. The withinhydrometeor standard deviation (σ_i) of the *i*th hydrometeor mixing ratio or number concentration, with mean μ_i , is calculated as

$$\sigma_i = \sqrt{V_i} \mu_i, \tag{1}$$

where V_i is the prescribed constant ratio between the variance and the mean squared of each 10 variate. Values for V_i used in the single-column simulations are provided in Table 1.

For multivariate PDFs, correlations among hydrometeor species must also be provided. In these simulations, the correlations are prescribed, with values based loosely on cloud-resolving simulations. However, CLUBB assumes that the correlations are assumed to be constant within

- cloud, unlike the throughout the course of the simulations. In order to assign values for 15 these correlations, we examined the range of values found within cloud-resolving simulations. Correlations model simulations (which vary in space and time), and prescribed correlations that were representative. The correlations used for cloudy levels are shown in Table 2. As with the variances, the correlations are within-hydrometeor values. In future work, instead of prescribing correlations, one could attempt to diagnose correlations, following, e.g., Larson et al. (2011).
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2.2.2 Incorporating the effects of latent heating of ice and rain on subgrid turbulence

Turbulence kinetic energy and turbulent fluxes of heat and moisture are influenced by the buoyancy of air parcels in local updrafts and downdrafts. The buoyancy variable in CLUBB is the virtual potential temperature θ_v , where θ_v includes the effects on buoyancy of water vapor and cloud droplet loading. In CLUBB, buoyancy affects turbulence through four buoyancy generation terms that appear on the right-hand side of prognostic equations for moments (see Equations A5, A9, A10, A11). If g/θ_0 denotes the acceleration due to gravity divided by a constant reference temperature, then $(g/\theta_0)\overline{w'\theta'_v}$ is a buoyancy term that generates (that is, contributes to the tendency of) $\overline{w'^2}$, $(g/\theta_0)\overline{w'^2\theta'_v}$ generates $\overline{w'^3}$, $(g/\theta_0)\overline{\theta'_l\theta'_v}$ generates $\overline{w'\theta'_l}$, and $(g/\theta_0)\overline{r'_t\theta'_v}$ generates $\overline{w'r'_t}$. These buoyancy terms, in turn, are influenced by latent heating associated with phase change of hydrometeors and gravitational loading due to hydrometeors.

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In prior versions of CLUBB, the only source of latent heating *for the higher-order moments* was condensation and evaporation of liquid cloud droplets, and the only source of loading was cloud liquid water mixing ratio. In other words, in the aforementioned four generation terms, the buoyancy perturbation θ'_v accounted only for variability due to the latent heating and water loading associated with cloud liquid water mixing ratio. (However, *grid-mean* values of θ_l in prior versions of CLUBB were subject to the latent heating associated with rain and ice hydrometeors, where relevant, through microphysical calculations.)

For the present simulations, we have incorporated a crude method to account for the latent heating and water loading associated with rain and ice hydrometeors in the four aforementioned buoyancy generation terms. Namely, we assume that

For for the purpose of calculating the four buoyancy generation terms, rain and all ice hydrometeors are assumed to be perfectly correlated collocated in space with cloud liquid water mixing ratio.

— Latent heat of sublimation is approximated as the latent heat of vaporization for the buoyancy generation terms (but not grid means), thereby neglecting the latent heat of fusion and incurring a 12error.

²⁵ With these two (crude) assumptions With this simple assumption, CLUBB's calculation of the four buoyancy generation terms remains unchanged, except that total condensate — including cloud liquid water, rain and ice mixing ratios — is input into the calculation in place of cloud liquid water. Conservation of heat and moisture for *grid means* still holds because the two assumptions this change only apply to the buoyancy generation terms. In the future, however, it

would be desirable to relax these two assumptions examine the effects of this assumption.

2.2.3 Parameterizing transport of hydrometeors

Turbulent updrafts and downdrafts transport hydrometeors in the vertical, thereby acting to broaden the vertical extent of the hydrometeor profiles. In CLUBB, the tendency of turbulence to broaden the hydrometeor profiles is modeled by eddy diffusion. Although it is not obvious *a*

- ⁵ to broaden the hydrometeor profiles is modeled by eddy diffusion. Although it is not obvious *a priori* that an eddy diffusion model is appropriate for cumulus layers, our large-eddy simulations indicate that eddy diffusion parameterizes the sign of hydrometeor transport satisfactorily in cumulus layers, but that the magnitude of the eddy diffusion is one or two orders of magnitude larger in cumulus than in stratocumulus layers (not shown).
- 10 CLUBB models the transport of a generic hydrometeor, r_x , as

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$$\overline{w'r'_x} = -cK\frac{\partial\overline{r_x}}{\partial z} \tag{2}$$

where w denotes the vertical velocity, c = 0.75 a dimensionless constant, and z the altitude. The eddy diffusivity for hydrometeors, K, is given by

$$K = \sqrt{eL} \left(\frac{\sqrt{\overline{r_x'^2}}}{\overline{r_x}} \right) (1 + |Sk_w|) \tag{3}$$

where e is the subgrid turbulence kinetic energy and L is CLUBB's turbulent mixing length (Golaz et al., 2002; Larson et al., 2012). The two last factors in parentheses are designed to increase K by up to a factor of 100 in cumulus layers while leaving K small in stratocumulus layers. These two factors rely on the fact that spatial variability of rain and skewness of vertical velocity, Sk_w , are larger in cumulus layers than in stratocumulus layers.

2.2.4 Allowing microphysical sources to influence subgrid distribution shape

Microphysical processes influence not only grid-box means, but also the *shape* of the subgrid PDF. For instance, microphysical processes such as autoconversion and accretion occur prefer-

entially in moister portions of a grid box. Such processes, in conjunction with sedimentation of precipitation, tend to remove moisture from the moistest part of a grid box, thereby diminishing the variance of total water in cloud layers (Khairoutdinov and Randall, 2002). In addition, evaporation of rain below cloud may at times occur in the coolest part of a grid box, thereby increasing variance of temperature below cloud. The increased sub-cloud temperature variance may, in principle, help initiate further convection.

These effects are estimated using SILHS subcolumns. Each subcolumn is fed into the microphysics separately, and each produces a separate microphysical update to r_t and θ_l . Therefore, the sample variance among the set of subcolumns is different before and after the microphysics is computed. This change in variance can be added as a source term in CLUBB's prognostic equation for the scalar variance of r_t or θ_l . A similar calculation is made for the scalar fluxes of r_t and θ_l .

For a generic variable x, SILHS estimates the microphysical source as

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$$\left(\frac{\partial \overline{x^{\prime 2}}}{\partial t}\right)_{\text{microphys}} \approx \frac{\text{Var}(x)|_{\text{after}} - \text{Var}(x)|_{\text{before}}}{\Delta t}.$$
(4)

where Var(x) is the sample variance of x among subcolumns, which is calculated before and 15 after the call to the microphysics, t denotes time, and Δt is the time between microphysics calculations. Here

$$\operatorname{Var}(x) = \sum_{i=1}^{n} p_i (x_i - \overline{x})^2 \tag{5}$$

where n is the number of subcolumns, x_i is the value of x in the *i*th subcolumn, \overline{x} is the average over all subcolumns, and p_i is the probability of choosing subcolumn *i*. The probability p_i equals 1/n in the case of equally weighted subcolumns, and the probability weights must sum to 1. An analogous calculation is performed in order to update covariances between two

²⁰ sum to 1. An analogous calculation is performed in order to update covariances between tw variates.

In our simulations, the following prognostic moments are updated by microphysical source terms: $\overline{r_t'^2}$, $\overline{\theta_l'^2}$, $\overline{r_t'\theta_l'}$, $\overline{w'r_t'}$, and $\overline{w'\theta_l'}$. The prognostic equations for moments that involve only w, such as $\overline{w'^2}$ and $\overline{w'^3}$, do not contain microphysical source terms, even in theory.

2.3 Model configurations and case descriptions

⁵ The following analysis compares two models, a single-column model (CLUBB-SILHS), and a 3D cloud-resolving/large-eddy model (System for Atmospheric Modeling, SAM, Khairoutdinov and Randall (2003)) that provides reference simulations.

In order to assess the feasibility of unified parameterization, CLUBB-SILHS's configuration of all shallow and deep cloud layers is identical, other than case-specific options for droplet number concentration and radiative transfer that are described below. For all cloud cases,

- number concentration and radiative transfer that are described below. For all cloud cases, CLUBB-SILHS uses a 1-minute computational time step and a 128-level stretched vertical grid, with a vertical grid spacing of approximately 100 m at an altitude of 1000 m. CLUBB-SILHS's microphysics is identical to the Morrison microphysics option in SAM, which is a two-moment scheme that predicts cloud water, rain, cloud ice, snow, and graupel (Morrison
- ¹⁵ et al., 2009). (However, our simulations prescribe cloud droplet number.) SILHS generates 16 sample subcolumns per time step.

We compare each CLUBB-SILHS single-column simulation with a three-dimensional simulation performed by SAM. In order to help isolate model errors in CLUBB-SILHS, we configure SAM and CLUBB-SILHS identically in a number of aspects. Namely, SAM uses the same two-

20 moment microphysics scheme, the same value of prescribed within-cloud cloud droplet number concentration, and the same treatment of radiative transfer. SAM is set up similarly in shallow and deep cases, except that SAM uses smaller grid spacing and time step for the shallow cases. More SAM options for all cases are described below in Table 3.

2.3.1 Deep convective cases

²⁵ We choose to simulate three deep convective cases that have been studied in prior model intercomparisons, in part because doing so allows us to compare our 3D simulations with

those intercomparison results, building confidence in our 3D simulations. We configure the deep convective simulations as per previous model intercomparisons of those cases. SAM simulations examined here are comparable to previous simulations and observations in general characteristics such as timing, precipitation, and liquid water path. We conclude, therefore, that they provide good reference simulations for evaluation of CLUBB-SILHS. For deep convective

5 cases, both SAM and CLUBB-SILHS prescribe droplet number concentration to be 100 cm⁻³, and both use the same 128-level vertical grid. SAM uses 1-km grid spacing in the horizontal.

The first deep convective case we present is from the Tropical Warm Pool International Cloud Experiment (TWP-ICE), which took place near Darwin, Australia in early 2006 (May et al.,

2008). The TWP-ICE case is a week-long simulation, beginning on January 19 and exhibiting 10 multiple diurnal cycles of convective activity. Large-scale conditions are set up for the SAM simulation and CLUBB simulations as in previous model intercomparison studies (Fridlind et al., 2012; Davies et al., 2013). Radiation in the SAM simulation is calculated by the Rapid Radiation Transfer Model (RRTM) (Iacono et al., 2008), and radiative heating values from SAM output are used to prescribe radiation in CLUBB-SILHS. 15

The second case was taken from the Tropical Rainfall Measuring Mission Large-Scale Biosphere-Atmosphere (TRMM-LBA) experiment which took place in Brazil in early 1999 (Silva Dias et al., 2002). The LBA case occurred on February 23, and consists of the transition from shallow to deep convection over land from early morning to early afternoon. Model configurations for SAM and CLUBB-SILHS follow a previous model intercomparison (Grabowski et al., 2006; 20 Khairoutdinov and Randall, 2006). In this case, both SAM and CLUBB-SILHS use prescribed radiation, as specified in the intercomparison.

Third, we examine a mid-latitude summertime deep convective case that occurred during the 1997 Intensive Observation Period of the Atmospheric Radiation Measurement (ARM) program

(ARM97). ARM97 is a 4-day simulation starting on June 26 that exhibits two weak precipi-25 tating convective events followed by a strong convective event. We configure the case as in a previous intercomparison (Xu et al., 2002; Khairoutdinov and Randall, 2003). As in TWP-ICE, SAM uses RRTM to compute radiation, and SAM output is used to prescribe radiation in the **CLUBB-SILHS** simulation.

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2.3.2 Shallow cloud-layer cases

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The shallow cases are configured as in previous intercomparison studies, including the appropriate options for radiation and cloud drop number concentration. The vertical grid spacing and time step for CLUBB-SILHS are identical to that used for the deep convective cases. SAM's configuration is summarized in Table 3.

The first shallow case we present is a 3-day simulation of drizzling trade-wind cumulus clouds observed during the Rain in shallow Cumulus over the Ocean (RICO) field campaign (Rauber et al., 2007). We configure RICO as in the intercomparison of vanZanten et al. (2011). As per the intercomparison specifications, we prescribe a cloud drop number concentration of 70 cm^{-3} in both CLUBB-SILHS and SAM, and radiation is turned off in both models.

10 The second shallow case was taken from the DYnamics and Chemistry Of Marine Stratocumulus (DYCOMS-II) field campaign (Stevens et al., 2003). We simulate the Research Flight 2 (RF02) case, which is a 6-hour simulation of a nocturnal drizzling stratocumulus layer off the coast of California (Wyant et al., 2007). DYCOMS-II RF02 uses a cloud drop number concentration of 55 cm⁻³ in both CLUBB-SILHS and SAM simulations (Ackerman et al., 2009).

15 Both models use a simplified analytic radiation model which ties radiative heating to the liquid water path (Stevens et al., 2005; Wyant et al., 2007; Larson et al., 2007).

3 **Results: simulated time series and profiles**

This section presents time series and profiles from our tropical deep convective case (TWP-ICE), our shallow-to-deep transitional case (LBA), and our mid-latitude deep convective case 20 (ARM97). For each of the three cases, we plot time series of the following vertically averaged quantities: liquid water path (LWP), rain water path (RWP), cloud ice water path (IWP), and snow water path (SWP). In addition, we plot profiles from selected time periods of liquid water potential temperature (θ_l), total water mixing ratio (vapor + cloud liquid water) (r_t), the fraction of a grid box that is occupied by liquid cloud water, and liquid cloud cloud liquid water mixing 25 ratio (r_c) .

3.1 Tropical deep convection: TWP-ICE

Time series of the four vertically integrated quantities from the TWP-ICE simulation are shown in Figure 1. This was a convectively active period, and a strong diurnal signal can be seen in the time series. Because TWP-ICE is a tropical case, rainfall rate at the surface is constrained by surface evaporation ratesprescribed large-scale forcings. Instead, we show rain water path. Rain water path simulated by CLUBB-SILHS mimics that in SAM, as does snow water path. LWP in CLUBB-SILHS is too high compared to SAM, particularly in the convectively active periods, suggesting that CLUBB-SILHS's precipitation efficiency while cloud ice is too low, which may mean that the correlations between liquid and ice hydrometeors are not well tuned. CLUBB-SILHS accurately simulates time series of cloud ice and snow water paths.

Figure 2 depicts four profiles averaged over the heaviest precipitation event, which occurs during minutes 6000–8000. In this case, CLUBB-SILHS agrees well with SAM and exhibits only a few discrepancies. Liquid water potential temperature (θ_l) is slightly too cool in the mid and upper levels, and the liquid cloud fraction is slightly too large in the lower levels. Figure 2 shows mean profiles of the mixing ratios of budrometeors, again guarantee due the strengest

¹⁵ 3 shows mean profiles of the mixing ratios of hydrometeors, again averaged over the strongest convective episode. All of CLUBB-SILHS's profiles reproduce the corresponding SAM profiles results well.

3.2 Transition from shallow to deep convection: LBA

LBA is a difficult case to simulate because it evolves substantially over a short (six-hour) time period as it transitions from shallow to deep convection. Hence it is a challenge to simulate the timing of ice and precipitation formation. Time series from LBA are shown in Figure 4. LWP in CLUBB-SILHS matches that in SAM well until the last hour of simulation time. In the last hour, LWP is depleted too much because rain forms more than an hour too late, and when it does form, it produces excessive rain water path. The rain is delayed because precipitation efficiency is too low during the early period of weak forcing, possibly because of an inaccurate representation of the correlations among hydrometeors. The simulation overestimates cloud ice water path because the simulation produces too much cloud liquid aloft (Figure 5).

Figure 5 shows profiles averaged over the last hour of the simulation, by which point the convection in SAM has reached a mature stage. CLUBB-SILHS's profiles of θ_l and r_t match those of SAM because none of the mean profiles has time to evolve during the six-hour simulation. However, CLUBB-SILHS produces too much cloud liquid in the upper levels. CLUBB-SILHS's hydrometeor profiles agree with those in SAM, with the exception of cloud ice mixing ratio (Figure 6). Cloud ice is overpredicted because the excess liquid aloft leads to large rates of contact nucleation (not shown). The large numbers of nucleated ice crystals also lead to decreased snow production from autoconversion due to the smaller crystal sizes.

3.3 Mid-latitude continental convection: ARM97

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¹⁰ Time series plots for ARM97 are shown in Figure 7. The timing and magnitude of LWP is reasonably captured in CLUBB-SILHS. In the first convective event, however, CLUBB-SILHS's cloud does not grow deep enough for the production of ice, and little rain is produced. The later convective episodes are better simulated, although CLUBB-SILHS's time series are too noisy. Mean profiles for ARM97 are shown in Figure 8, averaged over the third and strongest convective event (minutes 4320–5580). Similar to what was seen in TWP-ICE, θ_l in CLUBB-SILHS is too cool aloft, and r_t and liquid cloud fraction are too large through the lowest 6-7 km of the column. Hydrometeor profiles (Figure 9) match fairly well to the SAM CRM simulation, though CLUBB-SILHS does not produce enough ice aloft. The undesirably low precipitation efficiency seen in TWP-ICE is also evident in this case, as too much liquid is needed to produce the correct amount of rain.

3.4 Examining the representation of dynamics

Deep convection can have important effects on large scale dynamics through various feedbacks with microphysics (e.g. Liu et al., 1997; Tompkins, 2001; Khairoutdinov and Randall, 2006). As such, it is useful to examine the performance of CLUBB-SILHS with regard to dynamical fields such as vertical velocity. Figure 10 demonstrates some dynamic fields, the variance of vertical

²⁵ such as vertical velocity. Figure 10 demonstrates some dynamic fields, the variance of vertical velocity and the turbulent flux of liquid water potential temperature and total water mixing ratio,

in all three deep convective simulations. CLUBB-SILHS does a reasonable job of representing the variance of vertical velocity in all three cases. The turbulent flux of total water is quite similar in CLUBB-SILHS and SAM, though in ARM97 is a bit low. The turbulent flux of liquid water potential temperature is too low, particularly in TWP-ICE and ARM97. These cases are the most convectively active, so it is not surprising that the SCM would have the hardest time representing their dynamics. It is worth considering ways to improve the dynamics in future work, particularly by improving the coupling between microphysics and dynamics. Adding complexity to the formulation described in Section 2.2.2 may be one way to accomplish this; however at current CLUBB-SILHS does a reasonable job in simulating the subgrid scale

10 dynamic variability.

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4 Effects of our new methodology on deep convective simulations

Two of the changes to CLUBB described in Section 2.2 have significant effects on the simulation of deep convection.

First, improving the PDF for hydrometeors by including non-zero a non-unity precipitation
fraction (Section 2.2.1) - that is, allowing a region free of hydrometeors (cloud ice, snow, graupel, and rain) - improved LBA (Figure 11). With the previous formulation, liquid cloud water increases to overly large values by the end of the simulation, and the excessive cloud water nucleates to form excessive cloud ice. However, no rain forms during the 6-hour simulation. The use of non-zero precipitation fraction addition of a hydrometeor free region improves (increases) the precipitation efficiency of CLUBB-SILHS, allowing rain to form and remove

excessive liquid cloud water.

Second, it turns out to be important for the simulations of deep convective cases to have strong turbulent transport of hydrometeors. The changes introduced to the eddy diffusivity calculation in Section 2.2.3 allow for stronger values in convective cases (while not degrading shallow cases, as shown in Section 6). Larger values of eddy diffusivity smooth the profiles

shallow cases, as shown in Section 6). Larger values of eddy diffusivity smooth the profiles of hydrometeors and transport hydrometeors farther upward, leading to closer agreement with SAM (see Figure 12). The other two methodological changes — adding latent heating to subgrid moments (Section 2.2.2) and adding microphysical source terms to prognosed second-order moments (Section 2.2.4) — have more minor effects on the simulations.

5 Sensitivity to time step, number of samples, and vertical grid spacing

- Aside from the errors explicitly mentioned above, the CLUBB-SILHS results presented here agree well with SAM. However, the configuration of CLUBB-SILHS used with its fine vertical resolution, short time step, and numerous sample points is computationally expensive. In this section, we present results that use configurations that are more computationally affordable.
- ¹⁰ Simulations presented in prior sections use a 1-minute time step. Figure 13 plots the effects on the deep convective simulations of increasing the time step to 5 minutes; the two lines plotted represent identical simulations except for the time step. A profile of <u>liquid</u> cloud fraction is shown alongside a time series of snow water path for each case in order to illustrate the changes that occur when changing the time step. The timing of convective events is little affected.
- ¹⁵ However, the cases are too convectively active, leading to too much <u>liquid</u> cloud fraction aloft. This may be partly related to an underprediction of sub-cloud evaporative cooling that occurs when prognostic microphysics schemes with sequential time splitting of sedimentation allow hydrometeors to sediment long distances between calls to the microphysical sources and sinks, such as evaporation (personal communication, H. Morrison, March 2014).
- It is possible to use CLUBB-SILHS with any (even) number of subcolumns. Using more subcolumns leads to better sampling and hence more accurate estimates of averages of SGS variability (Larson and Schanen, 2013). However, feeding fewer subcolumns into the microphysics scheme reduces computational cost. We have presented results using 16 subcolumns, which is a compromise between accuracy and computational cost. Shown in Figure 14 are the results of reducing the number of sample columns from 16 to 4. The results are similar, with the exception of LBA, which, with 4 sample points, does not produce surface precipitation, thereby permitting large amounts of cloud water to remain aloft.

Computational cost can also be reduced by coarsening the vertical resolution. To test the effects of this, Figure 15 plots simulations of the deep convective cases, configured identically as before except that they use the 30-level stretched grid that is used in the Community Atmosphere Model (CAM) climate model (Neale et al., 2012). The simulations are adequate, but they are too convectively active and contain too much condensate. This is particularly apparent in LBA, which again has excessive cloud water aloft because the precipitation efficiency is too low. Nevertheless. the simulations-

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That the results of the CLUBB-SILHS simulations degrade some when (vertical/temporal/sampling) resolution is decreased is not surprising. Such sensitivities are typical in all scales of models.

For example, CAM has been shown to be sensitive to both horizontal and vertical resolution and 10 the physics time step used (Bogenschutz et al., 2012; Reed et al., 2012; Williamson, 2013; Williamson The degradation of SCM simulations when brought to a resolution more realistic for including in Paper a host model like CAM suggests that some more testing and tuning may be necessary; however the simulations show initial promise.

How does the generalized coupling to microphysics influence shallow cloud simula-6 15 tions?

Using the same configuration as used for the deep convective cases, we also simulate two shallow cloud cases. We find that these two cases are not degraded by the modifications introduced into CLUBB-SILHS in order to improve deep convective simulations.

Results from the RICO shallow cumulus case are shown in Figure 16. CLUBB-SILHS 20 simulates this trade-wind cumulus case reasonably well, although CLUBB-SILHS underestimates cloud liquid water. However, the underestimate is not introduced by the modifications to CLUBB-SILHS. Rather, these errors are typical of some prior versions of CLUBB.

Results from the DYCOMS-II RF02 drizzling stratocumulus simulation are shown in Figure 17. The mean fields are comparable to those in SAM, although, once again, cloud liquid and 25 rain water path are underestimated in the CLUBB-SILHS simulation. The underestimate of liquid is mostly attributable not to the modifications made to CLUBB, but rather to the coarse resolution of CLUBB-SILHS versus SAM — in the 128-level grid, only 15 levels reside in the lowest 1200 meters of the domain. At higher resolutions, CLUBB-SILHS simulates greater liquid water content for the DYCOMS-II RF02 case (Griffin and Larson, 2013).

Although further study is necessary, the fact that reasonable results can be obtained for shallow convection with the same model configuration as for deep convection hints that a unified PDF parameterization may indeed be possible, with one equation set representing all turbulence and cloud types.

7 Conclusions

This paper presents single-column simulations of deep and shallow cloud layers. To simulate
these clouds, our model contains one component (CLUBB) that estimates the subgrid PDF of clouds, turbulence, and hydrometeors, and a second component (SILHS) that draws samples from this PDF and feeds them into a microphysics scheme. This methodology provides a detailed representation of subgrid dynamics and hydrometeors, and also provides a mechanism to couple the two at the subgrid scale. The detailed coupling is particularly important for deep convection, which has strong interactions between dynamics and microphysics.

Most of the simulated fields are satisfactory, although there exist a few deficiencies. One is that rain forms 100 minutes too late in the LBA case of transition from shallow to deep convection (see Figure 4). Another deficiency is that precipitation does not form in the first of the three convective events in ARM97 (see Figure 7). Both these deficiencies suggest that

- 20 CLUBB-SILHS produces insufficient precipitation when convection is weakly forced. Furthermore, when CLUBB-SILHS's time step is degraded to 5 min (see Figure 13) or the number of vertical grid levels is degraded to 30 (see Figure 15), the simulated updrafts are too strong, the surface precipitation is too weak, and too much cloud forms aloft. Again, these are symptoms of low precipitation efficiency. That is, the amount of precipitation produced in CLUBB-SILHS
- ²⁵ for an amount of condensate is too low in these cases leaving too much cloud water remaining compared to the SAM simulations.

Nevertheless, CLUBB-SILHS produces quite acceptable overall results for both deep and

shallow simulations. In particular, most profiles of clouds and hydrometeors match those of SAM acceptably, given the stochastic nature of convective precipitation. What ingredients in CLUBB-SILHS allow it to simulate deep convection? One is CLUBB-SILHS's detailed representation of and coupling between turbulence and microphysics, and in particular, ice microphysics. CLUBB-SILHS uses a delta-lognormal subgrid PDF of hydrometeors, which allows the average is in the stochastic precipitation of an experimentation of an event of a subgrid PDF of hydrometeors.

- ⁵ physics. CLUBB-SILHS uses a delta-lognormal subgrid PDF of hydrometeors, which allows the possibility of a hydrometeor-free region of a grid box and also allows the hydrometeors to fall preferentially through liquid cloud water. This, in turn, allows more precipitation to reach the ground, reducing cloud water aloft (see Figure 11). Although the precipitation efficiency is still somewhat too low in the simulations, the delta-lognormal PDF does improve precipitation efficiency. Another key ingredient is vertical turbulent transport of hydrometeors, which
- increases the altitude reached by snow and other hydrometeors.

These simulations suggest that — with improvements at coarse time steps and vertical grid spacings — it is feasible to develop a unified parameterization of deep convection, shallow convection, stratiform clouds, and turbulence. Such a parameterization would parameterize all cloud types in a large-scale model with a single equation set. A unified parameterization would avoid the artificial categorization of clouds that is inherent in parameterization suites that use separate schemes for separate regimes. Use of a unified parameterization would also make it easier to ensure consistency of assumptions throughout a model. Greater consistency, in turn, would instill more confidence in a model's formulation.

20 Appendix A CLUBB Equations

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CLUBB includes predictive equations for the horizontal winds (*u* and *v*), total water r_t (liquid + vapor), liquid water potential temperature θ_l , and several higher order moments. Following are the prognostic equations in the CLUBB model, provided for reference:

$$\frac{\partial \bar{u}}{\partial t} = -\bar{w}\frac{\partial \bar{u}}{\partial z} - f(v_g - \bar{v}) - \frac{1}{\rho_s}\frac{\partial \rho_s \overline{u'w'}}{\partial z} + \frac{\partial \bar{u}}{\partial t}\Big|_{ls}$$
(A1)

$$\frac{\partial \bar{v}}{\partial t} = -\bar{w} \frac{\partial \bar{v}}{\partial z} + f(u_g - \bar{u}) - \frac{1}{\rho_s} \frac{\partial \rho_s \overline{v' w'}}{\partial z} + \frac{\partial \bar{v}}{\partial t}\Big|_{ls}$$
(A2)
$$\frac{\partial \bar{r}_t}{\partial t} = -\bar{w} \frac{\partial \bar{r}_t}{\partial z} - \frac{1}{\rho_s} \frac{\partial \rho_s \overline{w' r'_t}}{\partial z} + \frac{\partial \bar{r}_t}{\partial t}\Big|_{ls}$$
(A3)
$$\frac{\partial \bar{\theta}_l}{\partial t} = -\bar{w} \frac{\partial \bar{\theta}_l}{\partial z} - \frac{1}{\rho_s} \frac{\partial \rho_s \overline{w' \theta'_l}}{\partial z} + \bar{R} + \frac{\partial \bar{\theta}_l}{\partial t}\Big|_{ls}$$
(A4)

$$-\overline{w}\frac{\partial\overline{w'^{2}}}{\partial z} - \frac{1}{\rho_{s}}\frac{\partial\rho_{s}\overline{w'^{3}}}{\partial z} - 2\overline{w'^{2}}\frac{\partial\overline{w}}{\partial z} + \frac{2g}{\theta_{vs}}\overline{w'\theta'_{v}} - \frac{C_{4}}{\tau}\left(\overline{w'^{2}} - \frac{2}{3}\overline{e}\right)$$

$$-C_{5}\left(-2\overline{w'^{2}}\frac{\partial\overline{w}}{\partial z} + \frac{2g}{\theta_{vs}}\overline{w'\theta'_{v}}\right) + \frac{2}{3}C_{5}\left(\frac{g}{\theta_{vs}}\overline{w'\theta'_{v}} - \overline{u'w'}\frac{\partial\overline{u}}{\partial z} - \overline{v'w'}\frac{\partial\overline{v}}{\partial z}\right)$$

$$-\frac{C_{1}}{\tau}\left(\overline{w'^{2}} - w|_{\text{tol}}^{2}\right) + \frac{\partial}{\partial z}\left[\left(K_{w1} + \nu_{1}\right)\frac{\partial}{\partial z}\overline{w'^{2}}\right] (5)$$

$$-\bar{w}\frac{\partial \overline{r_{t}^{\prime 2}}}{\partial z} - \frac{1}{\rho_{s}}\frac{\partial \rho_{s}\overline{w'r_{t}^{\prime 2}}}{\partial z} - 2\overline{w'r_{t}^{\prime}}\frac{\partial \bar{r}_{t}}{\partial z} - \frac{C_{2}}{\tau}\left(\overline{r_{t}^{\prime 2}} - r_{t}\big|_{\text{tol}}^{2}\right)$$
$$+ \frac{\partial}{\partial z}\left[\left(K_{w2} + \nu_{2}\right)\frac{\partial}{\partial z}\overline{r_{t}^{\prime 2}}\right] (6)$$

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$$-\bar{w}\frac{\partial\overline{\theta_{l}^{\prime 2}}}{\partial z} - \frac{1}{\rho_{s}}\frac{\partial\rho_{s}\overline{w^{\prime}\theta_{l}^{\prime 2}}}{\partial z} - 2\overline{w^{\prime}\theta_{l}^{\prime}}\frac{\partial\overline{\theta_{l}}}{\partial z} - \frac{C_{2}}{\tau}\left(\overline{\theta_{l}^{\prime 2}} - \theta_{l}\big|_{\text{tol}}^{2}\right)$$
$$+ \frac{\partial}{\partial z}\left[\left(K_{w2} + \nu_{2}\right)\frac{\partial}{\partial z}\overline{\theta_{l}^{\prime 2}}\right] (7)$$

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$$-\bar{w}\frac{\partial \overline{r_t'\theta_l'}}{\partial z} - \frac{1}{\rho_s}\frac{\partial \rho_s \overline{w'r_t'\theta_l'}}{\partial z} - \overline{w'r_t'}\frac{\partial \bar{\theta}_l}{\partial z} - \overline{w'\theta_l'}\frac{\partial \bar{\tau}_t}{\partial z} - \frac{C_2}{\tau}\overline{r_t'\theta_l'} + \frac{\partial}{\partial z}\left[(K_{w2} + \nu_2)\frac{\partial}{\partial z}\overline{r_t'\theta_l'} \right]$$
(8)

$$-\overline{w}\frac{\partial\overline{w'r'_{t}}}{\partial z} - \frac{1}{\rho_{s}}\frac{\partial\rho_{s}w'^{2}r'_{t}}{\partial z} - \overline{w'^{2}}\frac{\partial\overline{r}_{t}}{\partial z} - \overline{w'r'_{t}}\frac{\partial\overline{w}}{\partial z} + \frac{g}{\theta_{vs}}\overline{r'_{t}\theta'_{v}} - \frac{C_{6}}{\tau}\overline{w'r'_{t}}$$
$$+C_{7}\overline{w'r'_{t}}\frac{\partial\overline{w}}{\partial z} - C_{7}\frac{g}{\theta_{vs}}\overline{r'_{t}\theta'_{v}} + \frac{\partial}{\partial z}\left[(K_{w6} + \nu_{6})\frac{\partial}{\partial z}\overline{w'r'_{t}}\right]$$
(9)

$$-\bar{w}\frac{\partial \overline{w'\theta'_{l}}}{\partial z} - \frac{1}{\rho_{s}}\frac{\partial \rho_{s}\overline{w'^{2}\theta'_{l}}}{\partial z} - \overline{w'^{2}}\frac{\partial \bar{\theta}_{l}}{\partial z} - \overline{w'\theta'_{l}}\frac{\partial \bar{w}}{\partial z} + \frac{g}{\theta_{vs}}\overline{\theta'_{l}\theta'_{v}} - \frac{C_{6}}{\tau}\overline{w'\theta'_{l}} + C_{7}\overline{w'\theta'_{l}}\frac{\partial \bar{w}}{\partial z} - C_{7}\frac{g}{\theta_{vs}}\overline{\theta'_{l}\theta'_{v}} + \frac{\partial}{\partial z}\left[(K_{w6} + \nu_{6})\frac{\partial}{\partial z}\overline{w'\theta'_{l}}\right]$$
(10)

$$-\overline{w}\frac{\partial \overline{w'^3}}{\partial z} - \frac{1}{\rho_s}\frac{\partial \rho_s w'^4}{\partial z} + 3\frac{\overline{w'^2}}{\rho_s}\frac{\partial \rho_s w'^2}{\partial z} - 3\overline{w'^3}\frac{\partial \overline{w}}{\partial z} + \frac{3g}{\theta_{vs}}\overline{w'^2\theta'_v} \\ -C_{15}K_m \left(\frac{g}{\theta_{vs}}\frac{\partial \overline{w'\theta'_v}}{\partial z} - \left(\frac{\partial (\overline{u'w'}\frac{\partial \overline{u}}{z})}{\partial z} + \frac{\partial (\overline{v'w'}\frac{\partial \overline{v}}{z})}{\partial z}\right)\right)$$

$$-\frac{C_8}{\tau}\overline{w^{\prime 3}} - C_{11}\left(-3\overline{w^{\prime 3}}\frac{\partial \bar{w}}{\partial z} + \frac{3g}{\theta_{vs}}\overline{w^{\prime 2}\theta_v^{\prime}}\right) + \frac{\partial}{\partial z}\left[\left(K_{w8} + \nu_8\right)\frac{\partial}{\partial z}\overline{w^{\prime 3}}\right] (11)$$

10

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where \overline{R} is the radiative heating rate, f the Coriolis parameter, u_g and v_g the geostrophic winds, and g is acceleration due to gravity. The equations are anelastic, where ρ_s is the dry, static, base-state density and θ_{vs} is the dry, base-state θ_v , which both base-state variables change only with respect to altitude. In all of the equations, an overbar denotes a grid box average, and a prime denotes a subgrid deviation from that average. The subscript $|_{tol}$ refers to a minimum

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threshold value and $|_{1s}$ denotes large scale forcing. Not shown are terms relevant for hole-filling, clipping, and damping. For more details on the various constants and closures used in this equation set, see Golaz et al. (2002); Larson et al. (2012).

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Fig. 1. Time series of liquid water path (upper left), rain water path (upper right), ice water path (lower left), and snow water path (lower right) from the TWP-ICE deep convective simulation. Liquid water path is too high in the CLUBB-SILHS simulation, suggesting a low precipitation efficiency; however the other hydrometeors follow SAM fairly closely.



Fig. 2. Profiles of liquid water potential temperature (θ_l) (upper left), total water mixing ratio (r_t) (vapor + liquid) (upper right), liquid cloud fraction (lower left), and cloud liquid water mixing ratio (lower right) from the TWP-ICE deep convective simulation. Profiles are averaged over minutes 6000–8000, capturing the strongest convective event. CLUBB-SILHS matches SAM well, with some small differences notable in θ_l and liquid cloud fraction.



Fig. 3. Profiles of rain water mixing ratio (upper left), cloud ice mixing ratio (upper right), snow mixing ratio (lower left), and graupel mixing ratio (lower right) from the TWP-ICE deep convective simulation, averaged over the same time period as Figure 2 (minutes 6000–8000). CLUBB-SILHS hydrometeor profiles match well with those simulated in SAM.



Fig. 4. Time series of liquid water path (upper left), rain water path (upper right), ice water path (lower left), and snow water path (lower right) from the LBA deep convective simulation. Rain forms too late in the CLUBB-SILHS simulation, as there is an excess of ice that is not growing fast enough to form precipitation sized particles; however the timing and magnitude of liquid water path is simulated adequately.



Fig. 5. Profiles of liquid water potential temperature (θ_l) (upper left), total water mixing ratio (r_t) (vapor + liquid) (upper right), <u>liquid</u> cloud fraction (lower left), and cloud <u>liquid</u> water mixing ratio (lower right) from the LBA deep convective simulation. Profiles are averaged over the last hour of the simulation (minutes 301–360). The CLUBB-SILHS simulation matches the CRM simulation well, aside from a lack of cloud in lower levels.



Fig. 6. Profiles of rain water mixing ratio (upper left), cloud ice mixing ratio (upper right), snow mixing ratio (lower left), and graupel mixing ratio (lower right) from the LBA deep convective simulation, averaged over the same time period as Figure 5 (minutes 301–360). Profiles are consistent with what was seen in Figure 4.



Fig. 7. Time series of liquid water path (upper left), rain water path (upper right), ice water path (lower left), and snow water path (lower right) from the ARM97 deep convective simulation. CLUBB-SILHS's simulation of the first event produces cloud liquid water but no precipitation. However, CLUBB-SILHS's simulation of the other two events match SAM well in timing and magnitude.



Fig. 8. Profiles of liquid water potential temperature (upper left), total water mixing ratio (vapor + liquid) (upper right), <u>liquid</u> cloud fraction (lower left), and cloud <u>liquid</u> water mixing ratio (lower right) from the ARM97 deep convective simulation. Profiles are averaged over the third convective event (minutes 4321–5580). CLUBB-SILHS is slightly too cool in the upper troposphere and too moist in the lower troposphere; <u>liquid</u> cloud fraction is too large.



Fig. 9. Profiles of rain water mixing ratio (upper left), cloud ice mixing ratio (upper right), snow mixing ratio (lower left), and graupel mixing ratio (lower right) from the ARM97 deep convective simulation, average over the same time as Figure 8 (minutes 4321–5580). The hydrometeor profiles match the CRM fairly well, though the ice hydrometeors are too few and do not reach high enough in the clouds.



Fig. 10. CLUBB-SILHS simulations of TWP-ICE (above), LBA (middle), and ARM97 (below) demonstrating the ability of CLUBB-SILHS to simulate dynamics for the deep convective cases. For each case, the variance of vertical velocity is shown on the left, the turbulent flux of liquid water potential temperature is in the middle, and the turbulent flux of total water mixing ratio is on the right (averaged over the same time periods as in previous figures). CLUBB-SILHS matches the CRM well in variance of vertical velocity, but underestimates the magnitude of some of the turbulent fluxes, particularly in the more convectively active cases.



Fig. 11. LBA simulations showing the effect sensitivity to the inclusion of including the new precipitation fraction. The thick black line is the SAM CRM simulation, the orange red dashed line is the CLUBB-SILHS (default) simulation presented in Section 3.2, which includes non-zero the precipitation fraction, and the blue dotted line is CLUBB-SILHS with with the same configuration as in the orange red line, but with the option for the precipitation fraction set to false. Above are profiles of cloud liquid water mixing ratio (left) and cloud ice mixing ratio (right), averaged over the last hour of the simulation (minutes 301–360). Below are time series of liquid water path (left) and rain water path (right). Non-zero precipitation fraction is important for LBA, because it increases4precipitation efficiency, allowing more rain to leave the atmosphere, thereby removing excess cloud liquid water aloft and reducing excessive ice formation



Fig. 12. TWP-ICE (above), LBA (middle), and ARM97 (below) simulations showing the <u>effects of</u> boosting <u>sensitivity to the boosted</u> eddy diffusivity for convective cases. For each case, graupel mixing ratio is shown on the left and snow mixing ratio on the right. The <u>thick</u> black line is the SAM CRM simulation, the <u>orange red</u> dashed line is the CLUBB-SILHS simulation <u>configured exactly as that</u> presented earlier in Section 3, and the blue <u>dotted</u> line is CLUBB-SILHS <u>with</u> with the same configuration as in the <u>orange red</u> line, but without the new diffusivity calculation. The new formulation for eddy diffusivity smooths the hydrometeor profiles and transports hydrometeors farther aloft.



Fig. 13. CLUBB-SILHS simulations of TWP-ICE (above), LBA (middle), and ARM97 (below) showing sensitivity of simulations to the time step. For each case, liquid cloud fraction is shown on the left (averaged over the same time periods as in previous figures) and a time series of snow water path is shown on the right. The thick-black line is the SAM CRM simulation, the orange red dashed line is the (default) CLUBB-SILHS simulation presented earlier in Section 3, and the blue dotted line is CLUBB-SILHS with the same configuration as in the orange-red line, but using a 5-minute time step, rather than 1 minute. With an increased time step, the CLUBB-SILHS simulations are too convectively active; however, the simulations are still reasonable when gempared to the SAM CRM simulations.



Fig. 14. CLUBB-SILHS simulations of TWP-ICE (above), LBA (middle), and ARM97 (below) showing sensitivity of simulations to the number of subcolumns utilized in SILHS. For each case, liquid cloud fraction is shown on the left (averaged over the same time periods as in previous figures) and a time series of snow water path is shown on the right. The thick-black line is the SAM CRM simulation, the orange red dashed line is the CLUBB-SILHS simulation presented earlier in Section 3, and the blue dotted line is CLUBB-SILHS with the same configuration as in the orange red line, but using only 4 subcolumns for SILHS, rather than 16. Results are degraded only slightly with a reduced number of subcolumns, except in the LBA case, where too much cloud forms aloft.



Fig. 15. CLUBB-SILHS simulations of TWP-ICE (above), LBA (middle), and ARM97 (below) showing sensitivity of simulations to the number of vertical grid levels. For each case, liquid cloud fraction is shown on the left (averaged over the same time periods as in previous figures) and a time series of snow water path is shown on the right. The thick-black line is the SAM CRM simulation, the orange red dashed line is the (default) CLUBB-SILHS simulation presented in Section 3, and the blue dotted line is CLUBB-SILHS with the same configuration as in the orange red line, but using a 30-level vertical grid, rather than a 128-level grid. The CLUBB-SILHS simulations with decreased vertical resolution contain too much condensate, which is particularly_apparent in the LBA case.



Fig. 16. Results from the RICO simulation of shallow cumulus clouds. Above are time series of liquid water path (upper left) and rain water path (upper right). Below are mean profiles of liquid water potential temperature (middle left), total water mixing ratio (middle right), liquid cloud fraction (lower left), and cloud liquid water mixing ratio (lower right). Profiles are averaged over the last 2 hours of the simulation (minutes 4301–4320). The CLUBB-SILHS simulation looks comparable to SAM, though there is too little cloud water produced.



Fig. 17. Results from the DYCOMS-II RF02 simulation of stratocumulus clouds. Above are time series of liquid water path (upper left) and rain water path (upper right). Below are mean profiles of liquid water potential temperature (middle left), total water mixing ratio (middle right), liquid cloud fraction (lower left), and cloud liquid water mixing ratio (lower right). Profiles are averaged over the last hour of the simulation (minutes 301–360). CLUBB-SILHS does a reasonable job of simulating these shallow stratocumulus clouds, though the amount of liquid is too low, which is related to the coarse vertical grid spacing.

Table 1. The prescribed ratio (V_i) between the within-precipitation variance and the mean squared of hydrometeors. Below-cloud values are the same values as used for cloudy levels.

| Variable | Variance Ratio |
|--------------------------------|----------------|
| Rain Mixing Ratio | 4.0 |
| Rain Number Concentration | 2.0 |
| Snow Mixing Ratio | 1.0 |
| Snow Number Concentration | 0.5 |
| Cloud Ice Mixing Ratio | 1.0 |
| Cloud Ice Number Concentration | 0.5 |
| Graupel Mixing Ratio | 1.0 |
| Graupel Number Concentration | 0.5 |

Table 2. Hydrometeor correlations used for all 5 cases. The variables included in the correlation matrix are, from left to right or top to bottom: extended liquid water mixing ratio, orthogonal extended liquid water mixing ratio, vertical velocity, extended cloud drop number concentration, and the mixing ratios and number concentrations of rain, cloud ice, snow, and graupel. Shown are the within-cloud values. For below cloud, an another correlation table is used, and for our purposes is identical except for the correlation between s and t. This correlation is set to 0.3 below cloud. The correlation matrix is symmetric, so the values below the diagonal are not filled in.

| | s | t | W | Ncn | rrain | Nr | rice | Ni | rsnow | Nsnow | rgraupel | Ng |
|----------|-----|------|-------|-------|--------|--------|--------|-------|-------|-------|----------|-----|
| s | 1.0 | -0.6 | 0.09 | 0.09 | 0.5 | 0.5 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.0 |
| t | | 1.0 | 0.027 | 0.027 | 0.0726 | 0.0855 | -0.024 | 0.084 | 0.018 | 0.012 | 0.0 | 0.0 |
| W | | | 1.0 | 0.34 | 0.2 | 0.2 | 0.1 | 0.15 | 0.0 | 0.0 | 0.0 | 0.0 |
| Ncn | | | | 1.0 | 0.0 | 0.0 | 0.39 | 0.29 | 0.14 | 0.21 | 0.0 | 0.0 |
| rrain | | | | | 1.0 | 0.7 | 0.0 | 0.0 | 0.1 | 0.1 | 0.2 | 0.0 |
| Nr | | | | | | 1.0 | 0.1 | 0.1 | 0.0 | 0.0 | 0.2 | 0.0 |
| rice | | | | | | | 1.0 | 0.7 | 0.5 | 0.5 | 0.3 | 0.0 |
| Ni | | | | | | | | 1.0 | 0.5 | 0.5 | 0.3 | 0.0 |
| rsnow | | | | | | | | | 1.0 | 0.7 | 0.4 | 0.0 |
| Nsnow | | | | | | | | | | 1.0 | 0.4 | 0.0 |
| rgraupel | | | | | | | | | | | 1.0 | 0.0 |
| Ng | | | | | | | | | | | | 1.0 |

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Table 3. Options for SAM simulations of the 5 cases

TWP-ICE LBA ARM97 RICO DYCOMS-II RF02 Number of grid Levels 128 128 128 100 99 Vertical Grid Spacing (m) 25 – 250 25 – 250 25 – 250 40 5 – 49 Horiz Grid Spacing (m) 1000 1000 1000 100 50 Horiz Domain Size (km) 128 128 128 12.8 6.4 Time step (s) 6 6 4 1 0.5 Radiation Scheme RRTM Prescribed RRTM none Analytical SGS Turbulence Scheme Smagorinsky Smagorinsky Smagorinsky TKE Smagorinsky

| | | TKE Smagorina | бку | | |
|---------------------------|-------------|---------------|-------------|------|----------------|
| | TWP-ICE | LBA | ARM97 | RICO | DYCOMS-II RF02 |
| Number of grid Levels | 128 | 128 | 128 | 100 | 99 |
| Vertical Grid Spacing (m) | 25 - 250 | 25 - 250 | 25 - 250 | 40 | 5 – 49 |
| Horiz Grid Spacing (m) | 1000 | 1000 | 1000 | 100 | 50 |
| Horiz Domain Size (km) | 128 | 128 | 128 | 12.8 | 6.4 |
| Time step (s) | 6 | 6 | 4 | 1 | 0.5 |
| Radiation Scheme | RRTM | Prescribed | RRTM | none | Analytical |
| SGS Turbulence Scheme | Smagorinsky | Smagorinsky | Smagorinsky | TKE | Smagorinsky |
| | | | | | |

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Parameterizing deep convection using the assumed probability density function method

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Abstract

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Due to their coarse horizontal resolution, present-day climate models must parameterize deep convection. This paper presents single-column simulations of deep convection using a probability density function (PDF) parameterization. The PDF parameterization predicts the PDF of subgrid variability of turbulence, clouds, and hydrometeors. That variability is interfaced to a prognostic microphysics scheme using a Monte Carlo sampling method.

The PDF parameterization is used to simulate tropical deep convection, the transition from shallow to deep convection over land, and mid-latitude deep convection. These parameterized single-column simulations are compared with 3D reference simulations. The agreement is satisfactory except when the convective forcing is weak.

The same PDF parameterization is also used to simulate shallow cumulus and stratocumulus layers. The PDF method is sufficiently general to adequately simulate these five deep, shallow, and stratiform cloud cases with a single equation set. This raises hopes that it may be possible in the future, with further refinements at coarse time step and grid spacing, to parameterize all cloud types in a large-scale model in a unified way.

1 Introduction

Deep convective clouds are an integral part of the climate system, yet representing these clouds accurately in climate models is a challenge. Explicitly resolving these clouds in decades-long climate simulations is not yet computationally feasible; thus it is beneficial to parameterize deep convection (e.g. Molinari and Dudek, 1992; Weisman et al., 1997; Warner and Hsu, 2000; Sato et al., 2009; Noda et al., 2010). Deep convective clouds are difficult to parameterize, however, partly because they produce copious ice and precipitation, which interact strongly with storm dynamics. For instance, convective rain may partially evaporate before reaching the ground, creating cold pools that spawn further convection (e.g. Liu et al., 1997; Tompkins, 2001; Khairoutdinov and Randall, 2006).

Deep convection has often been parameterized by the use of mass-flux schemes (e.g. Arakawa

and Schubert, 1974; Kain and Fritsch, 1990; Donner, 1993; Zhang and McFarlane, 1995; Arakawa, 2004; Kain, 2004; Gerard, 2007; Arakawa et al., 2011; Mapes and Neale, 2011; Bechtold et al., 2014). However, parameterization of deep convective clouds and turbulence may be aided by the use of the assumed probability density function (PDF) method. In the assumed PDF method, several lower-order subgrid moments are prognosed at each time step (e.g. Sommeria and Deardorff, 1977; Mellor, 1977; Smith, 1990; Lewellen and Yoh, 1993; Bony and Emanuel, 2001; Tompkins, 2002). The lower-order moments, along with an assumption about PDF shape, are used to estimate a joint PDF of subgrid scale (SGS) moisture, temperature, vertical velocity, and hydrometeors. The subgrid PDF is then used to calculate various unclosed higher-order moments that appear in the equation set, thereby allowing the solution to be advanced another time step.

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PDF parameterizations possess several advantages for the purpose of parameterizing deep convection. First, the use of a PDF that includes hydrometeor species and vertical velocity allows for a detailed representation of microphysics and dynamics, and of the coupling between them. For instance, a PDF parameterization that *prognoses* lower-order moments is compatible

them. For instance, a PDF parameterization that *prognoses* lower-order moments is compatible with *prognostic* microphysics. The use of a prognostic microphysics scheme, in turn, allows for precipitation to be preserved between computational time steps, providing a better representation of hydrometeor collection (e.g. Posselt and Lohmann, 2009; Gettelman and Morrison, 2014). Representation of collection also benefits from the ability of PDF parameterizations to prescribe the correlations among hydrometeors, thereby estimating the degree of collocation among the hydrometeor types. Another benefit of a PDF parameterization is the detailed and rigorous treatment of the distribution of SGS vertical velocity, which in turn is important for parameterizing vertical turbulent transport.

Despite these advantages for parameterizing deep clouds, to date PDF parameterizations have been applied only to shallow clouds, except in higher resolution cloud resolving models (Cheng and Xu, 2006; Bogenschutz and Krueger, 2013) and except in Davies et al. (2013). Davies et al. (2013) includes a single-column model (SCM) simulation of a tropical del convective case by the Cloud Layers Unified by Binormals (CLUBB) PDF parameterization. However, that study was an intercomparison of several SCMs and hence did not include details of the formulation or evaluation of CLUBB. CLUBB performed comparably to the other SCMs in Davies et al. (2013), but here we take the CLUBB parameterization and extend it in ways designed to better represent deep convection. In particular, the representation of the subgrid distribution of ice and precipitation is improved.

The modified version of CLUBB is then used to perform single-column simulations of three deep convective cases: a tropical case, a case of transition from shallow to deep convection, and a mid-latitude case. To demonstrate that the modified version of CLUBB can still simulate shallow cloud cases, we also simulate a shallow cumulus layer and stratocumulus layer. To assess the quality of the single-column CLUBB simulations, we compare the deep convective cases to cloud-resolving simulations and the shallow cases to large-eddy simulations.

The remainder of this paper is organized as follows. In Section 2, we will describe the singlecolumn model CLUBB and the recent changes to it implemented in order to obtain improved simulations of deep convective clouds. In Section 3, results from CLUBB for three deep convective cases will be compared to cloud-resolving model simulations. In Section 4, we will show results of sensitivity tests to basic model setup, including reducing vertical and time resolution such as might be required to interface CLUBB with a climate model. In Section 5, we will show results of two simulations of shallow clouds, demonstrating that this model framework can be used in simulations of both deep and shallow cloud types. In Section 6, we will finish with discussion and conclusions.

20 2 Methodology

2.1 Description of single-column model: CLUBB-SILHS

Cloud Layers Unified By Binomials (CLUBB) is a single-column model of clouds and turbulence in the atmosphere (Golaz et al., 2002; Larson and Golaz, 2005; Larson and Griffin, 2013; Griffin and Larson, 2013). CLUBB is designed to model a variety of cloud types and turbulence regimes in a unified way with a single equation set. CLUBB parameterizes both cumulus and stratocumulus clouds, and both dry convective and stably stratified boundary layers. The equa-

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tion set consists of prognostic equations for various subgrid-scale higher-order moments. The moments include variances of vertical velocity $(\overline{w'^2})$, total water mixing ratio (r'^2_t) , and liquid cloud water potential temperature $(\theta_1^{\prime 2})$. It also includes subgrid vertical turbulent fluxes of total water $(\overline{w'r'_t})$ and liquid cloud water potential temperature, $\overline{w'\theta'_t}$. (Here an overbar denotes a grid box average, and a prime denotes a subgrid deviation from a grid box average.) CLUBB's equation set is summarized in Appendix A. CLUBB has been coupled to the double-moment microphysics scheme of Morrison et al. (2009). The coupled model prognoses grid-mean number concentration and mixing ratios of rain, snow, graupel and cloud ice. The spatial variances of these hydrometeors are assumed to be proportional to the grid mean values squared.

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CLUBB's equation set contains various higher-order moments that are unclosed. CLUBB 10 closes many of these moments using the assumed probability density function (PDF) method. That is, CLUBB assumes a functional form of the subgrid PDF and integrates over it in order to estimate the unclosed moments. CLUBB's subgrid PDF is a single, multivariate PDF with a double Gaussian (sum of two normals) distribution for vertical velocity w, total water mixing ratio r_t , and liquid water potential temperature θ_l (Larson et al., 2001) and a delta 15 function/lognormal distribution for the hydrometeor variates (Griffin and Larson, 2014). The delta-lognormal PDF adds a delta function representing precipitation-free areas to the lognormal distribution of Larson and Griffin (2013). It is described further in Section 2.2.1 below.

In order to drive microphysical processes, CLUBB has the option to call a microphysics scheme using a variant of traditional Monte Carlo sampling (McKay et al., 1979; Owen, 2003). 20 This sampler is called the Subgrid Importance Latin Hypercube Sampler (SILHS, Larson et al. (2005); Larson and Schanen (2013)). SILHS draws one or more sample points per grid box and time step from CLUBB's joint subgrid PDF. SILHS collects a sample from each grid level into a subcolumn by assuming that correlation drops off exponentially with vertical distance and by using CLUBB's turbulent length scale to estimate the e-folding distance (Larson and 25 Schanen, 2013). Each subcolumn is then fed into a microphysics scheme, one at a time. For each subcolumn, the microphysics scheme produces outputs, e.g. autoconversion rate. Then the resulting ensemble of autoconversion rates is averaged, yielding an estimate of the grid box mean autoconversion rate.

- 1. Construct the multivariate PDF of subgrid-scale variability (performed by CLUBB). CLUBB predicts a single, joint PDF for each grid box and time step that contains the following variates: heat content, moisture content, vertical velocity, and all relevant hydrometeor mixing ratios and number concentrations.
- 2. *Draw subcolumns from the subgrid PDF (performed by SILHS).* A sample point is drawn from each grid level. These sample points, taken together, form a single vertically correlated profile, i.e. "subcolumn." The sampling is repeated until a set of subcolumns is constructed that collectively approximates the statistical properties of the grid column.
- 3. *Feed subcolumns into physical parameterizations and compute process rate tendencies (performed by a microphysics scheme).* Each subcolumn is fed into a microphysics scheme. For each subcolumn, the microphysics scheme computes a separate tendency.
- 4. Average microphysics tendencies from each subcolumn to form a grid box average profile. The set of tendencies is averaged to form a grid box mean tendency, which can then be fed back into the appropriate host model equations. The average may be a weighted average, with each subcolumn corresponding to different-sized area within the grid column.

The computational cost of CLUBB-SILHS is acceptable. CLUBB adds 20% to the computational cost of Version 5 of the Community Atmosphere Model (CAM5, Bogenschutz et al. (2013)). SILHS's computational cost, when two sample points are used, is similar to that of CLUBB (Larson and Schanen, 2013).

Both CLUBB and SILHS are contained in a single svn code repository that is freely available for non-commercial use at http://clubb.larson-group.com. The simulations presented here can be reproduced by checking out the branch located at

²⁵ http://carson.math.uwm.edu/repos/clubb_repos/branches/storer_et_al_paper_clubb/, compiling the source code, and running ./run_scm_all.bash. Complete details of all algorithms are available in

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the source code in the svn repository, along with numerous code comments and a README file that serves as a user manual. SAM output used for plotting and for prescribing radiative forcing can be found at http://www.larson-group.com/storer/.

2.2 Coupling subgrid variability to liquid and ice microphysics

⁵ In order to better simulate deep convection using CLUBB, we have generalized the treatment of subgrid variability. In particular, we have generalized CLUBB's multivariate PDF to include ice, incorporated the effects of ice and rain on subgrid buoyancy production, improved the vertical transport of hydrometeors, and allowed changes in the microphysics to affect scalar fluxes and variances.

10 2.2.1 Subgrid PDF of hydrometeors

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CLUBB represents vertical velocity, liquid water potential temperature, and total water mixing ratio using a double Gaussian PDF. However, a double Gaussian is unbounded and hence is not well suited to representing hydrometeors. In this context, hydrometeors include the mixing ratios and number concentrations of cloud ice, snow, graupel, and rain. These quantities are non-negative but often have small values.

In order to represent hydrometeors realistically and fully, a subgrid PDF should have two features. First, it should be multivariate, so that it can represent the collection of one hydrometeor species by another. Second, the subgrid PDF should include a hydrometeor-free region, so that hydrometeors do not suffer excessive evaporation or sublimation in otherwise clear regions.

The marginal subgrid PDF shape that we choose for the hydrometeor variates is a sum of a delta function and a multivariate lognormal. The delta function represents the portion of a grid box that is devoid of all hydrometeors (except liquid cloud droplets). The multivariate lognormal represents the hydrometeor-filled portion, i.e. the precipitation fraction. Details of the formulation of the lognormal are provided by the source code and in Larson and Griffin (2013) and in Griffin and Larson (2013). Although those papers used a multivariate lognormal to represent only the number concentration and mixing ratio of rain, here the multivariate lognormal is extended straightforwardly to represent the within-hydrometeor number concentrations and mixing ratios of all hydrometeors except liquid cloud water, which is diagnosed via saturation adjustment from total water.

At altitudes above the freezing level, the precipitation fraction is set equal to the fraction of a grid box that is supersaturated with respect to ice. Below the freezing level, the precipitation 5 fraction is determined by a calculation similar to that of Morrison and Gettelman (2008). More details of the formulation are provided in Griffin and Larson (2014) and the source code.

The assumed PDF method requires that variances of each variate be provided. The withinhydrometeor standard deviation (σ_i) of the *i*th hydrometeor mixing ratio or number concentration, with mean μ_i , is calculated as

$$\sigma_i = \sqrt{V_i}\mu_i,\tag{1}$$

where V_i is the prescribed constant ratio between the variance and the mean squared of each variate. Values for V_i used in the single-column simulations are provided in Table 1.

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For multivariate PDFs, correlations among hydrometeor species must also be provided. In these simulations, the correlations are assumed to be constant within cloud throughout the course of the simulations. In order to assign values for these correlations, we examined the range of values found within cloud-resolving model simulations (which vary in space and time), and prescribed correlations that were representative. The correlations used for cloudy levels are shown in Table 2. As with the variances, the correlations are within-hydrometeor values. In 15 future work, instead of prescribing correlations, one could attempt to diagnose correlations,

following, e.g., Larson et al. (2011).

2.2.2 Incorporating the effects of latent heating of ice and rain on subgrid turbulence

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Turbulence kinetic energy and turbulent fluxes of heat and moisture are influenced by the buoyancy of air parcels in local updrafts and downdrafts. The buoyancy variable in CLUBB is the virtual potential temperature θ_v , where θ_v includes the effects on buoyancy of water vapor and cloud droplet loading. In CLUBB, buoyancy affects turbulence through four buoyancy generation terms that appear on the right-hand side of prognostic equations for moments (see Equations A5, A9, A10, A11). If g/θ_0 denotes the acceleration due to gravity divided by a constant reference temperature, then $(g/\theta_0)\overline{w'\theta'_v}$ is a buoyancy term that generates (that is, contributes to the tendency of) $\overline{w'^2}$, $(g/\theta_0)\overline{w'^2\theta'_v}$ generates $\overline{w'^3}$, $(g/\theta_0)\overline{\theta'_l\theta'_v}$ generates $\overline{w'\theta'_l}$, and $(g/\theta_0)\overline{r'_t\theta'_v}$ generates $\overline{w'r'_t}$. These buoyancy terms, in turn, are influenced by latent heating associated with phase change of hydrometeors and gravitational loading due to hydrometeors.

In prior versions of CLUBB, the only source of latent heating *for the higher-order moments* was condensation and evaporation of liquid cloud droplets, and the only source of loading was cloud liquid water mixing ratio. In other words, in the aforementioned four generation terms, the buoyancy perturbation θ'_v accounted only for variability due to the latent heating and water loading associated with cloud liquid water mixing ratio. (However, *grid-mean* values of θ_l in prior versions of CLUBB were subject to the latent heating associated with rain and ice hydrometeors, where relevant, through microphysical calculations.)

For the present simulations, we have incorporated a crude method to account for the latent heating and water loading associated with rain and ice hydrometeors in the four aforemen-¹⁵ tioned buoyancy generation terms. Namely, we assume that for the purpose of calculating the four buoyancy generation terms, rain and all ice hydrometeors are assumed to be perfectly collocated in space with cloud liquid water mixing ratio. With this simple assumption, CLUBB's calculation of the four buoyancy generation terms remains unchanged, except that total condensate — including cloud liquid water, rain and ice mixing ratios — is input into the calculation in place of cloud liquid water. Conservation of heat and moisture for *grid means* still holds because this change only apply to the buoyancy generation terms. In the future, however, it would be desirable to examine the effects of this assumption.

2.2.3 Parameterizing transport of hydrometeors

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Turbulent updrafts and downdrafts transport hydrometeors in the vertical, thereby acting to broaden the vertical extent of the hydrometeor profiles. In CLUBB, the tendency of turbulence to broaden the hydrometeor profiles is modeled by eddy diffusion. Although it is not obvious *a priori* that an eddy diffusion model is appropriate for cumulus layers, our large-eddy simulations indicate that eddy diffusion parameterizes the sign of hydrometeor transport satisfactorily in

cumulus layers, but that the magnitude of the eddy diffusion is one or two orders of magnitude larger in cumulus than in stratocumulus layers (not shown).

CLUBB models the transport of a generic hydrometeor, r_x , as

$$\overline{w'r_x'} = -cK\frac{\partial \overline{r_x}}{\partial z} \tag{2}$$

where w denotes the vertical velocity, c = 0.75 a dimensionless constant, and z the altitude. The eddy diffusivity for hydrometeors, K, is given by

$$K = \sqrt{eL} \left(\frac{\sqrt{\overline{r_x'^2}}}{\overline{r_x}} \right) \left(1 + |Sk_w| \right) \tag{3}$$

where e is the subgrid turbulence kinetic energy and L is CLUBB's turbulent mixing length (Golaz et al., 2002; Larson et al., 2012). The two last factors in parentheses are designed to increase K by up to a factor of 100 in cumulus layers while leaving K small in stratocumulus layers. These two factors rely on the fact that spatial variability of rain and skewness of vertical velocity, Sk_w , are larger in cumulus layers than in stratocumulus layers.

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2.2.4 Allowing microphysical sources to influence subgrid distribution shape

Microphysical processes influence not only grid-box means, but also the *shape* of the subgrid PDF. For instance, microphysical processes such as autoconversion and accretion occur preferentially in moister portions of a grid box. Such processes, in conjunction with sedimentation of precipitation, tend to remove moisture from the moistest part of a grid box, thereby diminishing the variance of total water in cloud layers (Khairoutdinov and Randall, 2002). In addition,

- evaporation of rain below cloud may at times occur in the coolest part of a grid box, thereby increasing variance of temperature below cloud. The increased sub-cloud temperature variance may, in principle, help initiate further convection.
- These effects are estimated using SILHS subcolumns. Each subcolumn is fed into the microphysics separately, and each produces a separate microphysical update to r_t and θ_l . Therefore,

the sample variance among the set of subcolumns is different before and after the microphysics is computed. This change in variance can be added as a source term in CLUBB's prognostic equation for the scalar variance of r_t or θ_l . A similar calculation is made for the scalar fluxes of r_t and θ_l .

For a generic variable x, SILHS estimates the microphysical source as

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$$\left(\frac{\partial \overline{x'^2}}{\partial t}\right)_{\text{microphys}} \approx \frac{\text{Var}(x)|_{\text{after}} - \text{Var}(x)|_{\text{before}}}{\Delta t}.$$
(4)

where Var(x) is the sample variance of x among subcolumns, which is calculated before and after the call to the microphysics, t denotes time, and Δt is the time between microphysics calculations. Here

$$\operatorname{Var}(x) = \sum_{i=1}^{n} p_i (x_i - \overline{x})^2 \tag{5}$$

where n is the number of subcolumns, x_i is the value of x in the *i*th subcolumn, \overline{x} is the average over all subcolumns, and p_i is the probability of choosing subcolumn *i*. The probability p_i equals 1/n in the case of equally weighted subcolumns, and the probability weights must sum to 1. An analogous calculation is performed in order to update covariances between two variates.

In our simulations, the following prognostic moments are updated by microphysical source terms: $\overline{r_{t}^{\prime 2}}, \overline{\theta_{l}^{\prime 2}}, \overline{r_{t}^{\prime}\theta_{l}^{\prime}}, \overline{w^{\prime}r_{t}^{\prime}}$, and $\overline{w^{\prime}\theta_{l}^{\prime}}$. The prognostic equations for moments that involve only w, such as $\overline{w^{\prime 2}}$ and $\overline{w^{\prime 3}}$, do not contain microphysical source terms, even in theory.

2.3 Model configurations and case descriptions

The following analysis compares two models, a single-column model (CLUBB-SILHS), and a 3D cloud-resolving/large-eddy model (System for Atmospheric Modeling, SAM, Khairoutdi-²⁰ nov and Randall (2003)) that provides reference simulations.

In order to assess the feasibility of unified parameterization, CLUBB-SILHS's configuration of all shallow and deep cloud layers is identical, other than case-specific options for droplet number concentration and radiative transfer that are described below. For all cloud cases, CLUBB-SILHS uses a 1-minute computational time step and a 128-level stretched vertical grid, with a vertical grid spacing of approximately 100 m at an altitude of 1000 m. CLUBB-SILHS's microphysics is identical to the Morrison microphysics option in SAM, which is a two-moment scheme that predicts cloud water, rain, cloud ice, snow, and graupel (Morrison et al., 2009).

SILHS generates 16 sample subcolumns per time step.

We compare each CLUBB-SILHS single-column simulation with a three-dimensional simulation performed by SAM. In order to help isolate model errors in CLUBB-SILHS, we configure 10 SAM and CLUBB-SILHS identically in a number of aspects. Namely, SAM uses the same twomoment microphysics scheme, the same value of prescribed within-cloud cloud droplet number concentration, and the same treatment of radiative transfer. SAM is set up similarly in shallow and deep cases, except that SAM uses smaller grid spacing and time step for the shallow cases. More SAM options for all cases are described below in Table 3. 15

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Deep convective cases 2.3.1

We choose to simulate three deep convective cases that have been studied in prior model intercomparisons, in part because doing so allows us to compare our 3D simulations with those intercomparison results, building confidence in our 3D simulations. We configure the deep convective simulations as per previous model intercomparisons of those cases. SAM simulations examined here are comparable to previous simulations and observations in general characteristics such as timing, precipitation, and liquid water path. We conclude, therefore, that they provide good reference simulations for evaluation of CLUBB-SILHS. For deep convective cases, both SAM and CLUBB-SILHS prescribe droplet number concentration to be 100 cm⁻³, and both use the same 128-level vertical grid. SAM uses 1-km grid spacing in the horizontal.

The first deep convective case we present is from the Tropical Warm Pool International Cloud Experiment (TWP-ICE), which took place near Darwin, Australia in early 2006 (May et al., 2008). The TWP-ICE case is a week-long simulation, beginning on January 19 and exhibiting

multiple diurnal cycles of convective activity. Large-scale conditions are set up for the SAM and CLUBB simulations as in previous model intercomparison studies (Fridlind et al., 2012; Davies et al., 2013). Radiation in the SAM simulation is calculated by the Rapid Radiation Transfer Model (RRTM) (Iacono et al., 2008), and radiative heating values from SAM output are used to prescribe radiation in CLUBB-SILHS.

The second case was taken from the Tropical Rainfall Measuring Mission Large-Scale Biosphere-Atmosphere (TRMM-LBA) experiment which took place in Brazil in early 1999 (Silva Dias et al., 2002). The LBA case occurred on February 23, and consists of the transition from shallow to deep convection over land from early morning to early afternoon. Model configurations for SAM and CLUBB-SILHS follow a previous model intercomparison (Grabowski et al., 2006; Khairoutdinov and Randall, 2006). In this case, both SAM and CLUBB-SILHS use prescribed

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radiation, as specified in the intercomparison.

Third, we examine a mid-latitude summertime deep convective case that occurred during the 1997 Intensive Observation Period of the Atmospheric Radiation Measurement (ARM) program

(ARM97). ARM97 is a 4-day simulation starting on June 26 that exhibits two weak precipitating convective events followed by a strong convective event. We configure the case as in a previous intercomparison (Xu et al., 2002; Khairoutdinov and Randall, 2003). As in TWP-ICE, SAM uses RRTM to compute radiation, and SAM output is used to prescribe radiation in the CLUBB-SILHS simulation.

20 2.3.2 Shallow cloud-layer cases

The shallow cases are configured as in previous intercomparison studies, including the appropriate options for radiation and cloud drop number concentration. The vertical grid spacing and time step for CLUBB-SILHS are identical to that used for the deep convective cases. SAM's configuration is summarized in Table 3.

The first shallow case we present is a 3-day simulation of drizzling trade-wind cumulus clouds observed during the Rain in shallow Cumulus over the Ocean (RICO) field campaign (Rauber et al., 2007). We configure RICO as in the intercomparison of vanZanten et al. (2011). As per the intercomparison specifications, we prescribe a cloud drop number concentration of
70 cm^{-3} in both CLUBB-SILHS and SAM, and radiation is turned off in both models.

The second shallow case was taken from the DYnamics and Chemistry Of Marine Stratocumulus (DYCOMS-II) field campaign (Stevens et al., 2003). We simulate the Research Flight 2 (RF02) case, which is a 6-hour simulation of a nocturnal drizzling stratocumulus layer off the

⁵ coast of California (Wyant et al., 2007). DYCOMS-II RF02 uses a cloud drop number concentration of 55 cm⁻³ in both CLUBB-SILHS and SAM simulations (Ackerman et al., 2009). Both models use a simplified analytic radiation model which ties radiative heating to the liquid water path (Stevens et al., 2005; Wyant et al., 2007; Larson et al., 2007).

3 Results: simulated time series and profiles

¹⁰ This section presents time series and profiles from our tropical deep convective case (TWP-ICE), our shallow-to-deep transitional case (LBA), and our mid-latitude deep convective case (ARM97). For each of the three cases, we plot time series of the following vertically averaged quantities: liquid water path (LWP), rain water path (RWP), cloud ice water path (IWP), and snow water path (SWP). In addition, we plot profiles from selected time periods of liquid water ¹⁵ potential temperature (θ_l), total water mixing ratio (vapor + cloud liquid water) (r_t), the fraction of a grid box that is occupied by liquid cloud water, and cloud liquid water mixing ratio (r_c).

3.1 Tropical deep convection: TWP-ICE

Time series of the four vertically integrated quantities from the TWP-ICE simulation are shown in Figure 1. This was a convectively active period, and a strong diurnal signal can be seen in the time series. Because TWP-ICE is a tropical case, rainfall rate at the surface is constrained by prescribed large-scale forcings. Instead, we show rain water path. Rain water path simulated by CLUBB-SILHS mimics that in SAM, as does snow water path. LWP in CLUBB-SILHS is too high compared to SAM, while cloud ice is too low, which may mean that the correlations between liquid and ice hydrometeors are not well tuned.

²⁵ Figure 2 depicts four profiles averaged over the heaviest precipitation event, which occurs

during minutes 6000–8000. In this case, CLUBB-SILHS agrees well with SAM and exhibits only a few discrepancies. Liquid water potential temperature (θ_l) is slightly too cool in the mid and upper levels, and the liquid cloud fraction is slightly too large in the lower levels. Figure 3 shows mean profiles of the mixing ratios of hydrometeors, again averaged over the strongest convective episode. All of CLUBB-SILHS's profiles reproduce the corresponding SAM profiles results well.

3.2 Transition from shallow to deep convection: LBA

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LBA is a difficult case to simulate because it evolves substantially over a short (six-hour) time period as it transitions from shallow to deep convection. Hence it is a challenge to simulate the timing of ice and precipitation formation. Time series from LBA are shown in Figure 4. LWP in CLUBB-SILHS matches that in SAM well until the last hour of simulation time. In the last hour, LWP is depleted too much because rain forms more than an hour too late, and when it does form, it produces excessive rain water path. The rain is delayed because precipitation efficiency is too low during the early period of weak forcing, possibly because of an inaccurate representation of the correlations among hydrometeors. The simulation overestimates cloud ice water path because the simulation produces too much cloud liquid aloft (Figure 5).

Figure 5 shows profiles averaged over the last hour of the simulation, by which point the convection in SAM has reached a mature stage. CLUBB-SILHS's profiles of θ_l and r_t match those of SAM because none of the mean profiles has time to evolve during the six-hour simulation. However, CLUBB-SILHS produces too much cloud liquid in the upper levels. CLUBB-

20 tion. However, CLUBB-SILHS produces too much cloud liquid in the upper levels. CLUBB-SILHS's hydrometeor profiles agree with those in SAM, with the exception of cloud ice mixing ratio (Figure 6). Cloud ice is overpredicted because the excess liquid aloft leads to large rates of contact nucleation (not shown). The large numbers of nucleated ice crystals also lead to decreased snow production from autoconversion due to the smaller crystal sizes.

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Time series plots for ARM97 are shown in Figure 7. The timing and magnitude of LWP is reasonably captured in CLUBB-SILHS. In the first convective event, however, CLUBB-SILHS's cloud does not grow deep enough for the production of ice, and little rain is produced. The later convective episodes are better simulated, although CLUBB-SILHS's time series are too noisy.

- Mean profiles for ARM97 are shown in Figure 8, averaged over the third and strongest convective event (minutes 4320–5580). Similar to what was seen in TWP-ICE, θ_l in CLUBB-SILHS is too cool aloft, and r_t and liquid cloud fraction are too large through the lowest 6-7 km of the column. Hydrometeor profiles (Figure 9) match fairly well to the SAM CRM simulation,
- though CLUBB-SILHS does not produce enough ice aloft. The undesirably low precipitation efficiency seen in TWP-ICE is also evident in this case, as too much liquid is needed to produce the correct amount of rain.

3.4 Examining the representation of dynamics

Deep convection can have important effects on large scale dynamics through various feedbacks with microphysics (e.g. Liu et al., 1997; Tompkins, 2001; Khairoutdinov and Randall, 2006). 15 As such, it is useful to examine the performance of CLUBB-SILHS with regard to dynamical fields such as vertical velocity. Figure 10 demonstrates some dynamic fields, the variance of vertical velocity and the turbulent flux of liquid water potential temperature and total water mixing ratio, in all three deep convective simulations. CLUBB-SILHS does a reasonable job of representing the variance of vertical velocity in all three cases. The turbulent flux of total water 20 is quite similar in CLUBB-SILHS and SAM, though in ARM97 is a bit low. The turbulent flux of liquid water potential temperature is too low, particularly in TWP-ICE and ARM97. These cases are the most convectively active, so it is not surprising that the SCM would have the hardest time representing their dynamics. It is worth considering ways to improve the dynamics in future work, particularly by improving the coupling between microphysics and dynamics. 25 Adding complexity to the formulation described in Section 2.2.2 may be one way to accomplish this; however at current CLUBB-SILHS does a reasonable job in simulating the subgrid scale

4 Effects of our new methodology on deep convective simulations

Two of the changes to CLUBB described in Section 2.2 have significant effects on the simulation of deep convection.

First, improving the PDF for hydrometeors by including a non-unity precipitation fraction (Section 2.2.1) – that is, allowing a region free of hydrometeors (cloud ice, snow, graupel, and rain) – improved LBA (Figure 11). With the previous formulation, liquid cloud water increases to overly large values by the end of the simulation, and the excessive cloud water nucleates to form excessive cloud ice. However, no rain forms during the 6-hour simulation. The addition of a hydrometeor free region improves (increases) the precipitation efficiency of CLUBB-SILHS, allowing rain to form and remove excessive liquid cloud water.

Second, it turns out to be important for the simulations of deep convective cases to have strong turbulent transport of hydrometeors. The changes introduced to the eddy diffusivity calculation in Section 2.2.3 allow for stronger values in convective cases (while not degrading shallow cases, as shown in Section 6). Larger values of eddy diffusivity smooth the profiles of hydrometeors and transport hydrometeors farther upward, leading to closer agreement with SAM (see Figure 12).

The other two methodological changes — adding latent heating to subgrid moments (Section 2.2.2) and adding microphysical source terms to prognosed second-order moments (Section 2.2.4) — have more minor effects on the simulations.

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5 Sensitivity to time step, number of samples, and vertical grid spacing

Aside from the errors explicitly mentioned above, the CLUBB-SILHS results presented here agree well with SAM. However, the configuration of CLUBB-SILHS used — with its fine vertical resolution, short time step, and numerous sample points — is computationally expensive.

In this section, we present results that use configurations that are more computationally affordable.

Simulations presented in prior sections use a 1-minute time step. Figure 13 plots the effects on the deep convective simulations of increasing the time step to 5 minutes; the two lines plotted
⁵ represent identical simulations except for the time step. A profile of liquid cloud fraction is shown alongside a time series of snow water path for each case in order to illustrate the changes that occur when changing the time step. The timing of convective events is little affected. However, the cases are too convectively active, leading to too much liquid cloud fraction aloft. This may be partly related to an underprediction of sub-cloud evaporative cooling that occurs
when prognostic microphysics schemes with sequential time splitting of sedimentation allow hydrometeors to sediment long distances between calls to the microphysical sources and sinks, such as evaporation (personal communication, H. Morrison, March 2014).

It is possible to use CLUBB-SILHS with any (even) number of subcolumns. Using more subcolumns leads to better sampling and hence more accurate estimates of averages of SGS variability (Larson and Schanen, 2013). However, feeding fewer subcolumns into the microphysics scheme reduces computational cost. We have presented results using 16 subcolumns, which is a compromise between accuracy and computational cost. Shown in Figure 14 are the results of reducing the number of sample columns from 16 to 4. The results are similar, with the exception of LBA, which, with 4 sample points, does not produce surface precipitation, thereby permitting large amounts of cloud water to remain aloft.

Computational cost can also be reduced by coarsening the vertical resolution. To test the effects of this, Figure 15 plots simulations of the deep convective cases, configured identically as before except that they use the 30-level stretched grid that is used in the Community Atmosphere Model (CAM) climate model (Neale et al., 2012). The simulations are adequate, but they are too convectively active and contain too much condensate. This is particularly apparent in LBA, which again has excessive cloud water aloft because the precipitation efficiency is too low.

25

That the results of the CLUBB-SILHS simulations degrade some when (vertical/temporal/sampling) resolution is decreased is not surprising. Such sensitivities are typical in all scales of models. For example, CAM has been shown to be sensitive to both horizontal and vertical resolution

and the physics time step used (Bogenschutz et al., 2012; Reed et al., 2012; Willianson, 2013; Williamson, 2013; Wehner et al., 2014). The degradation of SCM simulations when brought to a resolution more realistic for including in a host model like CAM suggests that some more testing and tuning may be necessary; however the simulations show initial promise.

5 6 How does the generalized coupling to microphysics influence shallow cloud simulations?

Using the same configuration as used for the deep convective cases, we also simulate two shallow cloud cases. We find that these two cases are not degraded by the modifications introduced into CLUBB-SILHS in order to improve deep convective simulations.

Results from the RICO shallow cumulus case are shown in Figure 16. CLUBB-SILHS simulates this trade-wind cumulus case reasonably well, although CLUBB-SILHS underestimates cloud liquid water. However, the underestimate is not introduced by the modifications to CLUBB-SILHS. Rather, these errors are typical of some prior versions of CLUBB.

Results from the DYCOMS-II RF02 drizzling stratocumulus simulation are shown in Figure
17. The mean fields are comparable to those in SAM, although, once again, cloud liquid and rain water path are underestimated in the CLUBB-SILHS simulation. The underestimate of liquid is mostly attributable not to the modifications made to CLUBB, but rather to the coarse resolution of CLUBB-SILHS versus SAM — in the 128-level grid, only 15 levels reside in the lowest 1200 meters of the domain. At higher resolutions, CLUBB-SILHS simulates greater

liquid water content for the DYCOMS-II RF02 case (Griffin and Larson, 2013).

20

Although further study is necessary, the fact that reasonable results can be obtained for shallow convection with the same model configuration as for deep convection hints that a unified PDF parameterization may indeed be possible, with one equation set representing all turbulence and cloud types.

7 Conclusions

5

This paper presents single-column simulations of deep and shallow cloud layers. To simulate these clouds, our model contains one component (CLUBB) that estimates the subgrid PDF of clouds, turbulence, and hydrometeors, and a second component (SILHS) that draws samples from this PDF and feeds them into a microphysics scheme. This methodology provides a detailed representation of subgrid dynamics and hydrometeors, and also provides a mechanism to couple the two at the subgrid scale. The detailed coupling is particularly important for deep convection, which has strong interactions between dynamics and microphysics.

Most of the simulated fields are satisfactory, although there exist a few deficiencies. One is that rain forms 100 minutes too late in the LBA case of transition from shallow to deep convection (see Figure 4). Another deficiency is that precipitation does not form in the first of the three convective events in ARM97 (see Figure 7). Both these deficiencies suggest that CLUBB-SILHS produces insufficient precipitation when convection is weakly forced. Furthermore, when CLUBB-SILHS's time step is degraded to 5 min (see Figure 13) or the number of

vertical grid levels is degraded to 30 (see Figure 15), the simulated updrafts are too strong, the surface precipitation is too weak, and too much cloud forms aloft. Again, these are symptoms of low precipitation efficiency. That is, the amount of precipitation produced in CLUBB-SILHS for an amount of condensate is too low in these cases - leaving too much cloud water remaining compared to the SAM simulations.

Nevertheless, CLUBB-SILHS produces quite acceptable overall results for both deep and shallow simulations. In particular, most profiles of clouds and hydrometeors match those of SAM acceptably, given the stochastic nature of convective precipitation. What ingredients in CLUBB-SILHS allow it to simulate deep convection? One is CLUBB-SILHS's detailed representation of and coupling between turbulence and microphysics, and in particular, ice micro-physics. CLUBB-SILHS uses a delta-lognormal subgrid PDF of hydrometeors, which allows

the possibility of a hydrometeor-free region of a grid box and also allows the hydrometeors to fall preferentially through liquid cloud water. This, in turn, allows more precipitation to reach the ground, reducing cloud water aloft (see Figure 11). Although the precipitation efficiency

is still somewhat too low in the simulations, the delta-lognormal PDF does improve precipitation efficiency. Another key ingredient is vertical turbulent transport of hydrometeors, which increases the altitude reached by snow and other hydrometeors.

These simulations suggest that — with improvements at coarse time steps and vertical grid
spacings — it is feasible to develop a unified parameterization of deep convection, shallow convection, stratiform clouds, and turbulence. Such a parameterization would parameterize all cloud types in a large-scale model with a single equation set. A unified parameterization would avoid the artificial categorization of clouds that is inherent in parameterization suites that use separate schemes for separate regimes. Use of a unified parameterization would also make it
easier to ensure consistency of assumptions throughout a model. Greater consistency, in turn, would instill more confidence in a model's formulation.

Appendix A CLUBB Equations

CLUBB includes predictive equations for the horizontal winds (u and v), total water r_t (liquid + vapor), liquid water potential temperature θ_l , and several higher order moments. Following are the prognostic equations in the CLUBB model, provided for reference:

$$\frac{\partial \bar{u}}{\partial t} = -\bar{w}\frac{\partial \bar{u}}{\partial z} - f(v_g - \bar{v}) - \frac{1}{\rho_s}\frac{\partial \rho_s \overline{u'w'}}{\partial z} + \frac{\partial \bar{u}}{\partial t}\Big|_{\rm ls} \tag{A1}$$

$$\frac{\partial \bar{v}}{\partial t} = -\bar{w}\frac{\partial \bar{v}}{\partial z} + f(u_g - \bar{u}) - \frac{1}{\rho_s}\frac{\partial \rho_s \overline{v'w'}}{\partial z} + \frac{\partial \bar{v}}{\partial t}\Big|_{\rm ls} \tag{A2}$$

$$\frac{\partial \bar{r}_t}{\partial t} = -\bar{w}\frac{\partial \bar{r}_t}{\partial z} - \frac{1}{\rho_s}\frac{\partial \rho_s \overline{w'r'_t}}{\partial z} + \frac{\partial \bar{r}_t}{\partial t}\Big|_{ls}$$
(A3)

$$\frac{\partial \bar{\theta}_l}{\partial t} = -\bar{w} \frac{\partial \bar{\theta}_l}{\partial z} - \frac{1}{\rho_s} \frac{\partial \rho_s \overline{w' \theta_l'}}{\partial z} + \bar{R} + \frac{\partial \bar{\theta}_l}{\partial t} \Big|_{\rm ls} \tag{A4}$$

$$\frac{\partial \overline{w'^2}}{\partial t} = -\bar{w} \frac{\partial \overline{w'^2}}{\partial z} - \frac{1}{\rho_s} \frac{\partial \rho_s \overline{w'^3}}{\partial z} - 2\overline{w'^2} \frac{\partial \bar{w}}{\partial z} + \frac{2g}{\theta_{vs}} \overline{w'\theta'_v} - \frac{C_4}{\tau} \left(\overline{w'^2} - \frac{2}{3} \bar{e} \right)
- C_5 \left(-2\overline{w'^2} \frac{\partial \bar{w}}{\partial z} + \frac{2g}{\theta_{vs}} \overline{w'\theta'_v} \right) + \frac{2}{3} C_5 \left(\frac{g}{\theta_{vs}} \overline{w'\theta'_v} - \overline{u'w'} \frac{\partial \bar{u}}{\partial z} - \overline{v'w'} \frac{\partial \bar{v}}{\partial z} \right)$$

$$- \frac{C_1}{\tau} \left(\overline{w'^2} - w |_{\text{tol}}^2 \right) + \frac{\partial}{\partial z} \left[(K_{w1} + \nu_1) \frac{\partial}{\partial z} \overline{w'^2} \right]$$
(A5)

$$\frac{\partial \overline{r_t'^2}}{\partial t} = -\bar{w} \frac{\partial \overline{r_t'^2}}{\partial z} - \frac{1}{\rho_s} \frac{\partial \rho_s \overline{w'r_t'^2}}{\partial z} - 2\overline{w'r_t'} \frac{\partial \bar{r}_t}{\partial z} - \frac{C_2}{\tau} \left(\overline{r_t'^2} - r_t|_{\text{tol}}^2\right)
+ \frac{\partial}{\partial z} \left[(K_{w2} + \nu_2) \frac{\partial}{\partial z} \overline{r_t'^2} \right]$$
(A6)

$$\frac{\partial \overline{\theta_l'}^2}{\partial t} = -\bar{w} \frac{\partial \overline{\theta_l'}^2}{\partial z} - \frac{1}{\rho_s} \frac{\partial \rho_s \overline{w' \theta_l'}^2}{\partial z} - 2\overline{w' \theta_l'} \frac{\partial \bar{\theta}_l}{\partial z} - \frac{C_2}{\tau} \left(\overline{\theta_l'}^2 - \theta_l \big|_{\text{tol}}^2 \right) + \frac{\partial}{\partial z} \left[(K_{w2} + \nu_2) \frac{\partial}{\partial z} \overline{\theta_l'}^2 \right]$$

$$\frac{\partial \overline{r'_t \theta'_l}}{\partial t} = -\bar{w} \frac{\partial \overline{r'_t \theta'_l}}{\partial z} - \frac{1}{\rho_s} \frac{\partial \rho_s \overline{w' r'_t \theta'_l}}{\partial z} - \overline{w' r'_t} \frac{\partial \bar{\theta}_l}{\partial z} - \overline{w' \theta'_l} \frac{\partial \bar{r}_t}{\partial z} - \frac{C_2}{\tau} \overline{r'_t \theta'_l} + \frac{\partial}{\partial z} \left[(K_{w2} + \nu_2) \frac{\partial}{\partial z} \overline{r'_t \theta'_l} \right]$$
(A8)

$$\frac{\partial \overline{w'r_t'}}{\partial t} = -\bar{w}\frac{\partial \overline{w'r_t'}}{\partial z} - \frac{1}{\rho_s}\frac{\partial \rho_s \overline{w'^2r_t'}}{\partial z} - \overline{w'^2}\frac{\partial \bar{r}_t}{\partial z} - \overline{w'r_t'}\frac{\partial \bar{w}}{\partial z} + \frac{g}{\theta_{vs}}\overline{r_t'\theta_v'} - \frac{C_6}{\tau}\overline{w'r_t'} + C_7\overline{w'r_t'}\frac{\partial \bar{w}}{\partial z} - C_7\frac{g}{\theta_{vs}}\overline{r_t'\theta_v'} + \frac{\partial}{\partial z}\left[(K_{w6} + \nu_6)\frac{\partial}{\partial z}\overline{w'r_t'}\right]$$
(A9)

(A7)

$$\frac{\partial \overline{w'\theta_l'}}{\partial t} = -\bar{w}\frac{\partial \overline{w'\theta_l'}}{\partial z} - \frac{1}{\rho_s}\frac{\partial \rho_s \overline{w'^2\theta_l'}}{\partial z} - \overline{w'^2}\frac{\partial \bar{\theta}_l}{\partial z} - \overline{w'\theta_l'}\frac{\partial \bar{w}}{\partial z} + \frac{g}{\theta_{vs}}\overline{\theta_l'\theta_v'} - \frac{C_6}{\tau}\overline{w'\theta_l'} + C_7\overline{w'\theta_l'}\frac{\partial \bar{w}}{\partial z} - C_7\frac{g}{\theta_{vs}}\overline{\theta_l'\theta_v'} + \frac{\partial}{\partial z}\left[(K_{w6} + \nu_6)\frac{\partial}{\partial z}\overline{w'\theta_l'}\right]$$
(A10)

$$\frac{\partial \overline{w'^{3}}}{\partial t} = -\bar{w}\frac{\partial \overline{w'^{3}}}{\partial z} - \frac{1}{\rho_{s}}\frac{\partial \rho_{s}\overline{w'^{4}}}{\partial z} + 3\frac{\overline{w'^{2}}}{\rho_{s}}\frac{\partial \rho_{s}\overline{w'^{2}}}{\partial z} - 3\overline{w'^{3}}\frac{\partial \bar{w}}{\partial z} + \frac{3g}{\theta_{vs}}\overline{w'^{2}\theta'_{v}}
- C_{15}K_{m}\left(\frac{g}{\theta_{vs}}\frac{\partial \overline{w'\theta'_{v}}}{\partial z} - \left(\frac{\partial \left(\overline{u'w'}\frac{\partial \bar{u}}{z}\right)}{\partial z} + \frac{\partial \left(\overline{v'w'}\frac{\partial \bar{v}}{z}\right)}{\partial z}\right)\right)
- \frac{C_{8}}{\tau}\overline{w'^{3}} - C_{11}\left(-3\overline{w'^{3}}\frac{\partial \bar{w}}{\partial z} + \frac{3g}{\theta_{vs}}\overline{w'^{2}\theta'_{v}}\right) + \frac{\partial}{\partial z}\left[(K_{w8} + \nu_{8})\frac{\partial}{\partial z}\overline{w'^{3}}\right]$$
(A11)

where \overline{R} is the radiative heating rate, f the Coriolis parameter, u_g and v_g the geostrophic winds, and g is acceleration due to gravity. The equations are anelastic, where ρ_s is the dry, static, base-state density and θ_{vs} is the dry, base-state θ_v , which both base-state variables change only with respect to altitude. In all of the equations, an overbar denotes a grid box average, and a prime denotes a subgrid deviation from that average. The subscript $|_{tol}$ refers to a minimum threshold value and $|_{ls}$ denotes large scale forcing. Not shown are terms relevant for holefilling, clipping, and damping. For more details on the various constants and closures used in this equation set, see Golaz et al. (2002); Larson et al. (2012).

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Fig. 1. Time series of liquid water path (upper left), rain water path (upper right), ice water path (lower left), and snow water path (lower right) from the TWP-ICE deep convective simulation. Liquid water path is too high in the CLUBB-SILHS simulation, suggesting a low precipitation efficiency; however the other hydrometeors follow SAM fairly closely.



Fig. 2. Profiles of liquid water potential temperature (θ_l) (upper left), total water mixing ratio (r_t) (vapor + liquid) (upper right), liquid cloud fraction (lower left), and cloud liquid water mixing ratio (lower right) from the TWP-ICE deep convective simulation. Profiles are averaged over minutes 6000–8000, capturing the strongest convective event. CLUBB-SILHS matches SAM well, with some small differences notable in θ_l and liquid cloud fraction.



Fig. 3. Profiles of rain water mixing ratio (upper left), cloud ice mixing ratio (upper right), snow mixing ratio (lower left), and graupel mixing ratio (lower right) from the TWP-ICE deep convective simulation, averaged over the same time period as Figure 2 (minutes 6000–8000). CLUBB-SILHS hydrometeor profiles match well with those simulated in SAM.



Fig. 4. Time series of liquid water path (upper left), rain water path (upper right), ice water path (lower left), and snow water path (lower right) from the LBA deep convective simulation. Rain forms too late in the CLUBB-SILHS simulation, as there is an excess of ice that is not growing fast enough to form precipitation sized particles; however the timing and magnitude of liquid water path is simulated adequately.



Fig. 5. Profiles of liquid water potential temperature (θ_l) (upper left), total water mixing ratio (r_t) (vapor + liquid) (upper right), liquid cloud fraction (lower left), and cloud liquid water mixing ratio (lower right) from the LBA deep convective simulation. Profiles are averaged over the last hour of the simulation (minutes 301–360). The CLUBB-SILHS simulation matches the CRM simulation well, aside from a lack of cloud in lower levels.



Fig. 6. Profiles of rain water mixing ratio (upper left), cloud ice mixing ratio (upper right), snow mixing ratio (lower left), and graupel mixing ratio (lower right) from the LBA deep convective simulation, averaged over the same time period as Figure 5 (minutes 301–360). Profiles are consistent with what was seen in Figure 4.



Fig. 7. Time series of liquid water path (upper left), rain water path (upper right), ice water path (lower left), and snow water path (lower right) from the ARM97 deep convective simulation. CLUBB-SILHS's simulation of the first event produces cloud liquid water but no precipitation. However, CLUBB-SILHS's simulation of the other two events match SAM well in timing and magnitude.



Fig. 8. Profiles of liquid water potential temperature (upper left), total water mixing ratio (vapor + liquid) (upper right), liquid cloud fraction (lower left), and cloud liquid water mixing ratio (lower right) from the ARM97 deep convective simulation. Profiles are averaged over the third convective event (minutes 4321–5580). CLUBB-SILHS is slightly too cool in the upper troposphere and too moist in the lower troposphere; liquid cloud fraction is too large.



Fig. 9. Profiles of rain water mixing ratio (upper left), cloud ice mixing ratio (upper right), snow mixing ratio (lower left), and graupel mixing ratio (lower right) from the ARM97 deep convective simulation, average over the same time as Figure 8 (minutes 4321–5580). The hydrometeor profiles match the CRM fairly well, though the ice hydrometeors are too few and do not reach high enough in the clouds.



Fig. 10. CLUBB-SILHS simulations of TWP-ICE (above), LBA (middle), and ARM97 (below) demonstrating the ability of CLUBB-SILHS to simulate dynamics for the deep convective cases. For each case, the variance of vertical velocity is shown on the left, the turbulent flux of liquid water potential temperature is in the middle, and the turbulent flux of total water mixing ratio is on the right (averaged over the same time periods as in previous figures). CLUBB-SILHS matches the CRM well in variance of vertical velocity, but underestimates the magnitude of some of the turbulent fluxes, particularly in the more convectively active cases. 39



Fig. 11. LBA simulations showing the sensitivity to the inclusion of the new precipitation fraction. The black line is the SAM CRM simulation, the red dashed line is the CLUBB-SILHS (default) simulation presented in Section 3.2, which includes the precipitation fraction, and the blue dotted line is CLUBB-SILHS with the same configuration as in the red line, but with the option for the precipitation fraction set to false. Above are profiles of cloud liquid water mixing ratio (left) and cloud ice mixing ratio (right), averaged over the last hour of the simulation (minutes 301–360). Below are time series of liquid water path (left) and rain water path (right). Non-zero precipitation fraction is important for LBA, because it increases precipitation efficiency, allowing more rate to leave the atmosphere, thereby removing excess cloud liquid water aloft and reducing excessive ice formation and growth.



Fig. 12. TWP-ICE (above), LBA (middle), and ARM97 (below) simulations showing the sensitivity to the boosted eddy diffusivity for convective cases. For each case, graupel mixing ratio is shown on the left and snow mixing ratio on the right. The black line is the SAM CRM simulation, the red dashed line is the CLUBB-SILHS simulation configured exactly as that presented earlier in Section 3, and the blue dotted line is CLUBB-SILHS with the same configuration as in the red line, but without the new diffusivity calculation. The new formulation for eddy diffusivity smooths the hydrometeor profiles and transports hydrometeors farther aloft.



Fig. 13. CLUBB-SILHS simulations of TWP-ICE (above), LBA (middle), and ARM97 (below) showing sensitivity of simulations to the time step. For each case, liquid cloud fraction is shown on the left (averaged over the same time periods as in previous figures) and a time series of snow water path is shown on the right. The black line is the SAM CRM simulation, the red dashed line is the (default) CLUBB-SILHS simulation presented earlier in Section 3, and the blue dotted line is CLUBB-SILHS with the same configuration as in the red line, but using a 5-minute time step, rather than 1 minute. With an increased time step, the CLUBB-SILHS simulations are too convectively active; however, the simulations are still reasonable when compared to $\frac{1}{100}$ SAM CRM simulations.

1 min

Liquid Cloud Fraction

40

cloud_frac (%)

Llouid Cloud Fraction

12

and a second second

cloud_frac (%)

Llouid Cloud Fraction

15 20 25 30

cloud frac (%)

SAM

15

Helght (km)

18

12

18

Helght (km)

Helght (km)



13 Helght (km)

11

12

18

Helght (km)

Helght (km)

Fig. 14. CLUBB-SILHS simulations of TWP-ICE (above), LBA (middle), and ARM97 (below) showing sensitivity of simulations to the number of subcolumns utilized in SILHS. For each case, liquid cloud fraction is shown on the left (averaged over the same time periods as in previous figures) and a time series of snow water path is shown on the right. The black line is the SAM CRM simulation, the red dashed line is the CLUBB-SILHS simulation presented earlier in Section 3, and the blue dotted line is CLUBB-SILHS with the same configuration as in the red line, but using only 4 subcolumns for SILHS, rather than 16. Results are degraded only slightly with a reduced number of subcolumns, except in the LBA case, where too much cloud forms aloft. 43



Fig. 15. CLUBB-SILHS simulations of TWP-ICE (above), LBA (middle), and ARM97 (below) showing sensitivity of simulations to the number of vertical grid levels. For each case, liquid cloud fraction is shown on the left (averaged over the same time periods as in previous figures) and a time series of snow water path is shown on the right. The black line is the SAM CRM simulation, the red dashed line is the (default) CLUBB-SILHS simulation presented in Section 3, and the blue dotted line is CLUBB-SILHS with the same configuration as in the red line, but using a 30-level vertical grid, rather than a 128-level grid. The CLUBB-SILHS simulations with decreased vertical resolution contain too much condensate, which is particularly apparent in the LBA case. 44



Fig. 16. Results from the RICO simulation of shallow cumulus clouds. Above are time series of liquid water path (upper left) and rain water path (upper right). Below are mean profiles of liquid water potential temperature (middle left), total water mixing ratio (middle right), liquid cloud fraction (lower left), and cloud liquid water mixing ratio (lower right). Profiles are averaged over the last 2 hours of the simulation (minutes 4301–4320). The CLUBB-SILHS simulation looks comparable to SAM, though there is too little cloud water produced.



Fig. 17. Results from the DYCOMS-II RF02 simulation of stratocumulus clouds. Above are time series of liquid water path (upper left) and rain water path (upper right). Below are mean profiles of liquid water potential temperature (middle left), total water mixing ratio (middle right), liquid cloud fraction (lower left), and cloud liquid water mixing ratio (lower right). Profiles are averaged over the last hour of the simulation (minutes 301–360). CLUBB-SILHS does a reasonable job of simulating these shallow stratocumulus clouds, though the amount of liquid is too low, which is related to the coarse vertical grid spacing.

Table 1. The prescribed ratio (V_i) between the within-precipitation variance and the mean squared of hydrometeors. Below-cloud values are the same values as used for cloudy levels.

| Variable | Variance Ratio |
|--------------------------------|----------------|
| Rain Mixing Ratio | 4.0 |
| Rain Number Concentration | 2.0 |
| Snow Mixing Ratio | 1.0 |
| Snow Number Concentration | 0.5 |
| Cloud Ice Mixing Ratio | 1.0 |
| Cloud Ice Number Concentration | 0.5 |
| Graupel Mixing Ratio | 1.0 |
| Graupel Number Concentration | 0.5 |

Table 2. Hydrometeor correlations used for all 5 cases. The variables included in the correlation matrix are, from left to right or top to bottom: extended liquid water mixing ratio, orthogonal extended liquid water mixing ratio, vertical velocity, extended cloud drop number concentration, and the mixing ratios and number concentrations of rain, cloud ice, snow, and graupel. Shown are the within-cloud values. For below cloud, another correlation table is used, and for our purposes is identical except for the correlation between s and t. This correlation is set to 0.3 below cloud. The correlation matrix is symmetric, so the values below the diagonal are not filled in.

| | s | t | W | Ncn | rrain | Nr | rice | Ni | rsnow | Nsnow | rgraupel | Ng |
|----------|-----|------|-------|-------|--------|--------|--------|-------|-------|-------|----------|-----|
| s | 1.0 | -0.6 | 0.09 | 0.09 | 0.5 | 0.5 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.0 |
| t | | 1.0 | 0.027 | 0.027 | 0.0726 | 0.0855 | -0.024 | 0.084 | 0.018 | 0.012 | 0.0 | 0.0 |
| W | | | 1.0 | 0.34 | 0.2 | 0.2 | 0.1 | 0.15 | 0.0 | 0.0 | 0.0 | 0.0 |
| Ncn | | | | 1.0 | 0.0 | 0.0 | 0.39 | 0.29 | 0.14 | 0.21 | 0.0 | 0.0 |
| rrain | | | | | 1.0 | 0.7 | 0.0 | 0.0 | 0.1 | 0.1 | 0.2 | 0.0 |
| Nr | | | | | | 1.0 | 0.1 | 0.1 | 0.0 | 0.0 | 0.2 | 0.0 |
| rice | | | | | | | 1.0 | 0.7 | 0.5 | 0.5 | 0.3 | 0.0 |
| Ni | | | | | | | | 1.0 | 0.5 | 0.5 | 0.3 | 0.0 |
| rsnow | | | | | | | | | 1.0 | 0.7 | 0.4 | 0.0 |
| Nsnow | | | | | | | | | | 1.0 | 0.4 | 0.0 |
| rgraupel | | | | | | | | | | | 1.0 | 0.0 |
| Ng | | | | | | | | | | | | 1.0 |

| | TWP-ICE | LBA | ARM97 | RICO | DYCOMS-II RF02 |
|---------------------------|-------------|-------------|-------------|------|----------------|
| Number of grid Levels | 128 | 128 | 128 | 100 | 99 |
| Vertical Grid Spacing (m) | 25 - 250 | 25 - 250 | 25 - 250 | 40 | 5 – 49 |
| Horiz Grid Spacing (m) | 1000 | 1000 | 1000 | 100 | 50 |
| Horiz Domain Size (km) | 128 | 128 | 128 | 12.8 | 6.4 |
| Time step (s) | 6 | 6 | 4 | 1 | 0.5 |
| Radiation Scheme | RRTM | Prescribed | RRTM | none | Analytical |
| SGS Turbulence Scheme | Smagorinsky | Smagorinsky | Smagorinsky | TKE | Smagorinsky |

 Table 3. Options for SAM simulations of the 5 cases