CAM-CLUBB Introduction and Bibliography

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Summary

Cloud Layers Unified By Binormals (CLUBB) is a parameterization of cloud macrophysics and turbulence that has been implemented in CAM5.3.

CAM-CLUBB's formulation is rigorous and has a number of advantages. One advantage is that CLUBB unifies the description of shallow clouds and therefore allows MG2 microphysics to be applied to *all* shallow (and stratiform) clouds. This allows CAM-CLUBB to compute aerosol indirect effects in shallow cumulus clouds. Another advantage is that CLUBB is prognostic: CLUBB prognoses the moments of subgrid distributions and preserves them until the next time step. Because of this, CLUBB well suited to higher resolutions in the 'gray zone'.

CLUBB has been thoroughly evaluated by a broad community of users. Members of the AMWG have evaluated CAM-CLUBB in different configurations, including at high and variable horizontal resolution. CAM-CLUBB accurately simulates many cloud fields, including short-wave cloud forcing (SWCF), long-wave cloud forcing (LWCF), and cloud fraction. CAM-CLUBB has been available as an option for 2 years in release versions of CESM. Recently, CLUBB was interfaced with MG2 microphysics in a consistent manner (e.g., the sub-grid variability assumed in the microphysics is related to CLUBB's PDF).

For all these reasons, CAM-CLUBB is ready for use by the CESM community.

Criteria for judging parameterizations

Any parameterization should be judged according to the following three criteria:

1) Theoretical formulation: How closely does the parameterization adhere to the accepted governing equations of fluid flow and transport?

2) Accuracy of simulations: How accurately does the parameterization simulate present-day climate, using a broad variety of configurations and a variety of observational analyses?

3) Quality of software: How easily can the community work with and enhance the parameterization code?

These criteria should be evaluated in the context of the scientific problems of interest to the community (e.g. projections of global warming) and in the context of expected available computational resources (which are increasing exponentially according to Moore's law).

In the following, we discuss the aforementioned three criteria in turn.

Theoretical formulation

The theoretical formulation of a parameterization is the set of approximate equations that it solves. A parameterization is well formulated if its equation set has minimal structural errors. Soundness of formulation is especially important for projecting future climate because we cannot test future climate projections using observations until it is too late. If a parameterization's equation set is unsound, it may be possible through tuning to simulate present-day climate, but the parameterization cannot be relied upon to generalize to future climates or finer grid spacings. Such doubts hamper the credibility of climate projections. Therefore, in climate modeling, it is not safe to make inconsistent assumptions, even if they lead to better simulation of present-day climate.

Fortunately, the governing equations of the atmosphere --- such as the Navier-Stokes and advection-diffusion equations --- are known. Parameterization developers should take advantage of the governing equations, rather than try to outsmart them. Therefore, the primary tasks of parameterization are 1) analysis of the governing equations and 2) approximation of the governing equations at a reasonable cost.

Higher-order models such as CLUBB extend the set of dynamical equations to include extra equations that transport, generate, and dissipate subgrid moments. CLUBB formulates equations for subgrid higher-order moments such as turbulence kinetic energy and then Reynolds-averages them. This can be done exactly and without approximation. Only once this rigorous framework is in place are approximations made. Approximated quantities include the shape of the subgrid probability density function (PDF) of vertical velocity and thermodynamic variables, and dissipation and pressure terms. However, these assumptions are not built into the foundation of CLUBB, namely, the Reynolds-averaged mathematical framework. This is a key distinction between higher-order parameterizations and other parameterization types.

Of course, CLUBB's approximations have errors. But CLUBB makes the approximations more explicit and easier to evaluate against observations. For instance, PDFs of vertical velocity and thermodynamic variables can be observed at different scales by aircraft and satellite observations.

CLUBB's theoretical formulation offers several practical advantages:

- ***CLUBB unifies the parameterization of stratocumulus and shallow cumulus by using a single equation set to model both.*** CLUBB avoids artificial categorization of low cloud types, which aids the parameterization of intermediate cloud regimes, such as cumulus rising into stratocumulus. CLUBB ensures consistency, in the sense that the same subgrid PDF assumption is used throughout CLUBB. Importantly, CLUBB allows MG microphysics to be used in shallow cumulus clouds, thereby allowing aerosol indirect effects to be treated in shallow cumulus clouds.
- ***CLUBB can be used for a representation of deep convection as well, providing a fully unified treatment of moist turbulence.*** One of the ongoing research areas of CAM-CLUBB development is to remove the deep convective parameterization in CAM and allow CLUBB to treat *all* turbulent motion. See below for details and options.
- ***CLUBB parameterizes turbulent dissipation directly, rather than entrainment.*** Because turbulent dissipation is more precisely defined than is entrainment, dissipation can be estimated more precisely by benchmark large-eddy simulations, providing useful diagnostic information. Since turbulent dissipation varies with grid size, parameterizing dissipation directly opens the door to more scale-aware treatments at high horizontal resolution.
- ***CLUBB assumes a continuous PDF shape rather than a multiple delta function PDF shape.*** CLUBB's more realistic PDF shape allows CLUBB to better drive buoyancy generation terms, and, in future extensions of CLUBB, microphysics and radiation.
- ***CLUBB's higher-order moments are prognosed, rather than diagnosed.*** The prognosed moments contain memory of the prior convective state, which helps parameterize transient phenomena, such as the diurnal cycle of convective precipitation over land.
- ***CLUBB is extensible.*** CLUBB is a general platform that can be built upon. CLUBB's equation set and PDF contain a wealth of information that can be used by other parameterizations, such as that for gravity waves. Because CLUBB's equation set is so general, new features can be integrated in a natural way, rather than bolted on as an afterthought.

CLUBB contains several options for treating deep convection:

1) *Use the Zhang-McFarlane (ZM) scheme.* This is the option used in the submitted candidate simulations. CLUBB plays nicely with ZM, and improves several aspects of the simulations that are normally associated with deep convection, such as the MJO and the diurnal cycle of precipitation.
2) *Use the Zhang-McFarlane (ZM) scheme with `org'.* A version of CAM-CLUBB exists in which the org parameter of Mapes and Neale (2011) has been implemented in ZM. This version is available for use by the community.

3) *Let CLUBB go deep.* CLUBB itself can handle deep convection when the ZM scheme is turned off (Storer et al. 2014). With this option, CLUBB is a fully unified parameterization that handles all cloud types. This option would allow aerosol indirect effects to be parameterized in all cloud types using a single microphysics scheme (MG). This option may be of particular interest at high resolutions at which deep convection becomes partly resolved.

Accuracy of simulations

CAM-CLUBB has been thoroughly evaluated in a variety of configurations and using a variety of observational datasets. Published results are listed below in the annotated bibliography. In summary, CLUBB performs well and is ready for community use.

Test simulations are available at the CAM6 website. Overall, CAM-CLUBB's Taylor score is better than that of CAM5. CAM-CLUBB provides particularly accurate simulations of SWCF and LWCF. In addition, CAM-CLUBB's cloud fraction compares reasonably to CLOUDSAT observations, and CAM-CLUBB's LWP compares well to MODIS-COSP observations. CAM-CLUBB has been run through the AMWG variability diagnostics, and they show that, as compared to CAM5, CAM-CLUBB has an improved MJO and diurnal cycle of surface precipitation.

CLUBB has been tested at a variety of horizontal grid spacings, from the standard resolution of 1 degree, to MMF-CLUBB simulations, in which CLUBB is embedded in a cloud-resolving model with 4-km horizontal grid spacing (Wang et al. 2014). In addition, in an aquaplanet simulation with a variable-resolution mesh, CAM-CLUBB yields similar results in high- and low-resolution regions, as desired. Collectively, these results suggest that CLUBB is fairly insensitive to horizontal grid spacing.

CAM-CLUBB's climate sensitivity is slightly lower than CAM5's.

CAM-CLUBB uses MG2, which prognoses precipitation and thereby reduces the strength of aerosol indirect effects (AIEs). CLUBB itself increases the global AIE because, for the first time, it takes into account aerosol effects on parameterized shallow cumulus. The net effect is little change in AIE as compared to CAM5.

The sensitivity of CAM-CLUBB to changes in parameter values has been tested in global simulations (Guo et al. 2014, submitted to JAMES). This paper provides valuable guidance not only on the practical issue of tuning CAM-CLUBB, but also on the issue of physically understanding how changes in the strength of various small-scale processes affect the emergent cloud behavior. Because CLUBB is tied closely to the governing equations, these sensitivities are instructive.

The computational cost of CLUBB is acceptable. AMWG's timing table shows that, when using the MG1 microphysics in order to compare in a like-to-like way, CAM-CLUBB costs 29% more than CAM5, whereas UNICON costs 67% more. When the MG2 microphysics is substepped 6 times per physics time step, then CAM-CLUBB costs 67% more than CAM5, but this increase in cost is partly caused by the aerosol activation code, which we believe is not necessary to substep. Whatever cloud parameterizations are used in CAM5.5, they will have to interface with MG2, because MG2 is included in CAM5.4. Therefore, the relevant configuration for comparing timing numbers is the configuration using MG1.

Quality of software

A parameterization must be well formulated and accurate, but in addition, its implementation must be maintainable. In particular, the community must be able to diagnose problems that arise in the parameterization, add new physics to the parameterization, and interface the parameterization with other parameterizations that are introduced. It is not enough that the code be understandable to the developers. It must also be usable by others. This is especially important for a community model, where individuals inside and outside of NCAR will wish to build upon the parameterization in their own ways.

For all these reasons, it is important that the parameterization's code be readable. Unfortunately, many parameterizations contain poorly structured code that works but is not well understood by anyone except the developers. Most people are afraid to touch it for fear of breaking it, and the code lies stagnant. This is not the route to a vibrant community model.

Another key desideratum is code transparency. Linus' Law states that "Given enough eyeballs, all bugs are shallow" (Eric Raymond, The Cathedral and the Bazaar). This dictum, coupled with the fact that a flaw is easier to fix the earlier it is noticed, means that making development code available early pays rewards, particularly in a community model with many developers.

CLUBB's code has benefitted from the advice of several skilled software engineers. For instance, CLUBB strives to use short subroutines that do one thing and do it well. CLUBB has a coding standard that encourages the writing of clean, readable code. CLUBB contains assertion checks and unit tests that catch bugs early. CLUBB is regularly tested with four different Fortran compilers, aiding its portability. Finally, CLUBB is "open source in real time." That is, each new commit to the CLUBB code repository is available to the world instantly. UWM has been supporting CLUBB for collaborators for years now, and would be more than happy to support CAM-CLUBB for the CESM community. Other members of the AMWG at NCAR and beyond (including PNNL) have been using CAM-CLUBB extensively and providing results.

Annotated bibliography

Much experience with CLUBB has been accumulated over the years. Since 2001, 30 papers on CLUBB and its associated sampler, SILHS, have been submitted or published in the peer-reviewed literature. The author lists of these papers demonstrate that many members of the community have developed or used CLUBB.

CAM-CLUBB papers

In the following 7 papers, the implementation of CLUBB in CAM is thoroughly tested using a variety of configurations and observational datasets.

Bogenschutz, P.A., A. Gettelman, H. Morrison, Vincent E. Larson, C. Craig, and D. P. Schanen (2013). ``High-order turbulence closure and its impact on climate simulations in the Community Atmosphere Model." ***J Climate*****. 26, 9655-9676.**

In this paper, CLUBB is implemented in CAM and tested in global simulations. CLUBB is used in these simulations to parameterize all shallow (stratocumulus and cumulus) clouds. The resulting model, CAM-CLUBB, is competitive with the standard version of CAM, CAM5. Since the publication of this paper, CAM-CLUBB's performance has improved.

Bogenschutz, P. A., Gettelman, A., Morrison, H., Larson, V. E., Schanen, D. P., Meyer, N., et al. (2012). "Unified parameterization of the planetary boundary layer and shallow convection with a higher-order turbulence closure in the Community Atmosphere Model: single-column experiments." ***Geoscientific Model Development*****, 5, 1407-1423.**

This paper simulates a variety of boundary-layer cloud types using the single-column version of CAM-CLUBB. The solutions are fairly robust to changes in time step and vertical grid spacing.

Wang, M., V. E. Larson, S. Ghan, M. Ovchinnikov, D. P. Schanen, H. Xiao, X. Liu, P. Rasch, and Z. Guo (2014). "A Multi-scale Modelling Framework model (Super-parameterized CAM5) with a higher-order turbulence closure: model description and low cloud simulations" Submitted to ***Journal of Advances in Modeling Earth Systems*****.**

Here CLUBB is implemented in a cloud-resolving model with 4-km horizontal grid spacing, which in turn is implemented in CAM5. The model behavior is similar to CAM-CLUBB at 100-km horizontal grid spacing. This indicates that CLUBB behaves similarly over a range of horizontal grid spacings.

Kubar, T., Stephens, G. L., Lebsock, M., Larson, V. E., and Bogenschutz, P. A., (2014). Regional Assessments of Low Clouds Against Large-Scale Stability in CAM5 and CAM-CLUBB Using MODIS and ECMWF-Interim Reanalysis Data, Accepted to *J. Climate*.

Here, CAM-CLUBB's depiction of low clouds is evaluated using satellite data. CAM-CLUBB simulates a smoother and more realistic transition between marine stratocumulus and shallow cumulus clouds than does CAM5.

Guo, Z., Wang, M., Qian, Y., Larson, V. E., Ghan, S., Ovchinnikov, M., et al. (2014). A sensitivity analysis of cloud properties to CLUBB parameters in the single-column Community Atmosphere Model (SCAM5). *Journal of Advances in Modeling Earth Systems*, 6, 829-858.

Guo, Z., Wang, M., Qian, Y., Larson, V. E., Ghan, S., Ovchinnikov, M., et al. (2014). Parametric Behaviors of CLUBB in Simulations of Low Clouds in the Community Atmosphere Model (CAM). Submitted to *Journal of Advances in Modeling Earth Systems*.

In these two papers, the sensitivity of CAM-CLUBB to changes in parameter values is tested using single-column and global simulations. These papers provide valuable guidance not only on the practical issue of tuning CAM-CLUBB, but also on the issue of understanding how changes in the strength of various small-scale processes affects the emergent cloud behavior.

Gettelman, A., H. Morrison, S. Santos, P. Bogenschutz and P. H. Caldwell (2014). Advanced Two-Moment Microphysics for Global Models. Part II: Global model solutions and Aerosol-Cloud Interactions. Revision submitted to *J. Climate*.

Here CLUBB is interfaced with a method to prognose precipitation that is embedded in version 2 of the Morrison-Gettelman (MG2) microphysics scheme.

Implementation of CLUBB in cloud-resolving, regional, and climate models other than CAM:

The fact that CLUBB works in host models with a wide range of grid spacings (4 to 100 km) suggests that CLUBB is relatively insensitive to horizontal grid spacing.

2012: ``PDF Parameterization of boundary layer clouds in models with horizontal grid spacings from 2 to 16 km." V. E. Larson, D. P. Schanen, M. Wang, M. Ovchinnikov, and Ghan, S. *Mon. Wea. Rev.*, 140, 285-306.

This paper implements CLUBB in a convection-permitting model, SAM. The use of CLUBB in SAM is tested for various boundary-layer cloud cases. We introduce a simple, scale-aware method for damping CLUBB's effects at high resolution, thereby reducing undesirable sensitivities to horizontal grid spacing. We find that the use of CLUBB can improve the simulations for grid spacings of 4 km or greater.

"SILHS: A Monte Carlo interface between clouds and microphysics." V. E. Larson, C. Harlass, and J. Höft, 2013. Preprints, Fourteenth Annual WRF Users' Workshop, Boulder, CO, Natl. Cent. for Atmos. Res.

"Implementation and early tests of a PDF parameterization in WRF." V. E. Larson, C. Harlass, and J. Höft, 2012. Preprints, Thirteenth Annual WRF Users' Workshop, Boulder, CO, Natl. Cent. for Atmos. Res.

These conference papers show simulations of a marine stratocumulus case using CLUBB implemented in a weather-forecast model, WRF, at moderate resolution.

Guo, H., J.-C. Golaz, L. J. Donner, V. E. Larson, D. P. Schanen, and B. M. Griffin (2010). "Multi-variate probability density functions with dynamics for cloud droplet activation in large-scale models: single column tests." *Geosci. Model Dev.*, 3, 475–486.

Guo, H., Golaz, J., & Donner, L. (2011). Aerosol effects on stratocumulus water paths in a PDF-based parameterization. *Geophysical Research Letters*, *38*(17).

Guo, H., Golaz, J., Donner, L. J., Ginoux, P., & Hemler, R. S. (2014). Multivariate Probability Density Functions with Dynamics in the GFDL Atmospheric General Circulation Model: Global Tests. *Journal of Climate*, *27*, 2087-2108.

These three papers assess, using single-column and global simulations, the performance of a version of GFDL's AM3 climate model that includes both CLUBB and the Morrison-Gettelman microphysics.

Coupling CLUBB to microphysical variability:

Larson, V. E., B. J. Nielsen, J. Fan, and M. Ovchinnikov (2011). ``Parameterizing correlations between hydrometeor species in mixed-phase Arctic clouds." ***J. Geophys. Res.*****, 116, D00T02, doi:10.1029/2010JD015570.**

In order to drive microphysics using subgrid variability, we need to know the correlations between hydrometeor species. For instance, the correlation between cloud water and rain water influences the rate of accretion of cloud droplets by rain drops. If cloud and rain are correlated, then cloud and rain co-exist, and accretion occurs rapidly. This paper proposes a method to diagnose correlations based on information that is typically available in cloud models.

Larson, V. E., and B. M. Griffin (2013). ``Analytic upscaling of a local microphysics scheme. Part I: Derivation." ***Quart. J. Roy. Meteor. Soc.*****, 139, 46-57.**

Griffin, B. M., and V. E. Larson (2013). ``Analytic upscaling of a local microphysics scheme. Part II: Simulations." ***Quart. J. Roy. Meteor. Soc.*****, 139, 58-69.**

One reason to predict the subgrid PDF is to drive microphysical parameterizations more accurately. For instance, once we know the subgrid PDF, then we know what percentage of a grid box is precipitating strongly, and so forth. In these papers, we integrate a microphysics scheme analytically over CLUBB's PDF. We are able to do this exactly for the drizzle parameterization of Khairoutdinov and Kogan, which is relatively simple in formulation. We find that, for a marine stratocumulus case, accounting for subgrid variability leads to significantly more simulated drizzle at the ocean surface.

Larson, V. E., J.-C. Golaz, H. Jiang, and W. R. Cotton (2005). ``Supplying local microphysics parameterizations with information about subgrid variability: Latin hypercube sampling." ***J. Atmos. Sci.*****, 62, 4010-4026.** (See also slides 36-60 of the following presentation.)

Larson, V. E. , and D. P. Schanen (2013). "The Subgrid Importance Latin Hypercube Sampler (SILHS): a multivariate subcolumn generator." ***Geosci. Model Dev.*****, 6, 1813–1829.**

The most accurate way to drive microphysics using a PDF is to integrate the relevant microphysical formulas analytically over the PDF. However, this may be intractable for some microphysics schemes or may require rewriting the microphysics code. To avoid this, one may draw sample points from the PDF and input them into the microphysics code one at a time. This allows the use of existing microphysics codes, but it also introduces statistical noise due to imperfect sampling. To reduce the noise, sample points may be spread out in a quasi-random fashion using "Latin hypercube sampling," and the sample points may be clustered in important regions, such as cloud.

Chowdhary, K., Salloum, M., Debusschere, B., and Larson, V. E. (2014). Quadrature Methods for the Calculation of Subgrid Microphysics Moments. Submitted to *Mon. Wea. Rev.*

Analytic integration over microphysics is restricted in applicability, and Monte Carlo sampling introduces sampling noise. Here, the integration is performed using a third alternative: deterministic quadrature. This method is more general than analytic integration and more accurate than Monte Carlo integration.

Storer, R. L., B. M. Griffin, J. Höft, J. K. Weber, E. Raut, V. E. Larson, M. Wang, and P. J. Rasch (2014). "Parameterizing deep convection using the assumed probability density function method." *Geosci. Model Dev. Discuss.*, 7, 3803–3849.

In this paper, variability in ice is included in CLUBB's subgrid PDF, and a truly unified cloud parameterization is created. CLUBB's single equation set is used to do single-column simulations of stratocumulus, shallow cumulus, and deep cumulus layers.

Participation by CLUBB in single-column model intercomparisons:

In single-column intercomparisons, CLUBB has been tested in a wide variety of cloud regimes.

2011: "Evaluation of the diurnal cycle in the atmospheric boundary layer over land as represented by a variety of single column models — the second GABLS experiment." G. Svensson, A.A.M. Holtslag, V. Kumar, T. Mauritsen, G. J. Steeneveld, W. M. Angevine, E. Bazile, A. Beljaars, E.I.F. de Bruijn, A. Cheng, L. Conangla, J. Cuxart, M. Ek, M. J. Falk, F. Freedman, H. Kitagawa, V. E. Larson, A. Lock, J. Mailhot, V. Masson, S. Park, J. Pleim, S. Soderberg, M. Zampieri, and W. Weng, *Bound. Layer Met.*, 140, 177–206.

2014: "The third GABLS intercomparison case for evaluation studies of boundary-layer

models: Part B: results and process understanding**." F. C. Bosveld et al. (including V. E. Larson), Bound. Layer Met., 152, 157–187.**

These two intercomparisons demonstrate that CLUBB can simulate stable boundary layers, including those that form at night after the occurrence of daytime boundary-layer turbulence.

2009: ``Intercomparison of model simulations of mixed-phase clouds observed during the ARM Mixed-Phase Arctic Cloud Experiment. Part I: Single layer cloud." S. A. Klein and Co-authors (including V. E. Larson). ***Quart. J. Royal Met. Soc.*****, 135, 979-1002.**

2009: ``Intercomparison of model simulations of mixed-phase clouds observed during the ARM Mixed-Phase Arctic Cloud Experiment. Part II: Multilayer cloud." H. Morrison and Co-authors (including V. E. Larson). ***Quart. J. Royal Met. Soc.*****, 135, 1003-1019.**

Clouds in the Arctic are often mixed-phase: that is, they often contain both liquid and ice. Long-lived mixed-phase clouds are difficult to simulate because ice naturally tends to grow at the expense of liquid. Models may overdeplete liquid unless the ice particles are limited in number and sediment out of cloud base rapidly enough. Our cloud parameterization, CLUBB, was used to simulate mixed-phase clouds during the M-PACE experiment. CLUBB was able to maintain liquid water in these clouds, as was observed.

2013: ``A single-column model ensemble approach applied to the TWP-ICE experiment." L. A. Davies and Co-authors (including V. E. Larson). ***J. Geophys. Res.*****, 118, 6544-6563.**

This paper compares several internationally recognized parameterizations of deep convection. The simulated observations were obtained during the Tropical Warm Pool International Cloud Experiment (TWP-ICE) near Darwin, Australia. CLUBB simulated this deep convective case using the same configuration that is used to simulate boundary-layer clouds. CLUBB's results for TWP-ICE are competitive with those of the other participating parameterizations. The results suggest that CLUBB contains enough physics to serve as a unified parameterization of both shallow and deep clouds.

2013: "CGILS: Results from the first phase of an international project to understand the physical mechanisms of low cloud feedbacks in single column models." M. Zhang et al. (including V. E. Larson), ***J. Adv. Model. Earth Syst.*****, 5, 826–842.**

This intercomparison demonstrates that CLUBB can simulate marine shallow clouds that are driven to equilibrium in month-long simulations.

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

This paper compared the output from numerous single-column model that were set up identically to simulate a cloud layer observed during the DYCOMS-II field experiment. Part of the challenge was simulating drizzle. In order to couple drizzle to the cloud fields, instead of drawing sample points from the PDF using the Latin hypercube method discussed above, we analytically integrated over the PDF.

Foundational papers:

The following papers discuss the formulation of the core of CLUBB.

2002: ``A PDF-Based Model for Boundary Layer Clouds. Part I: Method and Model Description." J.-C. Golaz, V. E. Larson, W. R. Cotton. *J. Atmos. Sci.*, 59, 3540-3551.

2002: ``A PDF-Based Model for Boundary Layer Clouds. Part II: Model Results." J.-C. Golaz, V. E. Larson, W. R. Cotton. *J. Atmos. Sci.*, 59, 3552-3571.

(See also slides 13-35 of the following presentation, and this short conference paper.)

Traditionally, cloud parameterization has been viewed as a multiplicity of tasks. Such tasks include the prediction of heat flux, moisture flux, cloud fraction, and liquid water. In contrast, the papers above adopt the alternative viewpoint that the goal of parameterization consists largely of a single task: the prediction of the joint PDF of vertical velocity, heat, and moisture. Once the PDF is given, the fluxes, cloud fraction, and liquid water can be diagnosed.

The above papers present a parameterization that can model both stratocumulus and cumulus clouds without case-specific adjustments. This avoids the difficulty of having to construct a ``trigger function" that determines which cloud type should be modeled under which meteorological conditions.

2002: ``Small-Scale and Mesoscale Variability in Cloudy Boundary Layers: Joint Probability Density Functions." V. E. Larson, J.-C. Golaz, W. R. Cotton. *J. Atmos. Sci.*, 59, 3519-3539. (See also the following short conference paper.)

Whereas the prior paper discusses one-dimensional PDFs of cloud water and humidity, this paper discusses joint PDFs that include the vertical velocity. Joint PDFs allow us to diagnose the buoyancy flux, which is the means by which convection generates turbulence. Joint PDFs also allow us to diagnose fluxes of heat and moisture. Therefore, joint PDFs can serve as the foundation of cloud and turbulence parameterizations in numerical models, as proposed and explored in the two following papers.

2005: ``Using Probability Density Functions to Derive Consistent Closure Relationships among Higher-Order Moments." V. E. Larson and J.-C. Golaz. *Mon. Wea. Rev.*, 133, 1023-1042. (See also slides 26-27 of the following presentation.)

The aforementioned papers show that if we choose an accurate PDF family, then we can solve for many of the unknowns in our one-dimensional cloud parameterization. For some of these unknown terms, the present paper lists simple, analytic approximations. All approximated formulas are based on the same PDF and hence are consistent with each other.

A PDF may be constructed from a set of means, variances, and other moments of velocity, moisture, and temperature. It is possible that a particular set of moments does not correspond to any real PDF in the family. We call such a set of moments ``specifically unrealizable." For instance, a set that includes asymmetric moments is specifically unrealizable with respect a PDF family of symmetric, bell-shaped curves. This is because the bell shape family is too restrictive to include asymmetric moments. We show that a broad class of moments is specifically realizable with respect to our PDF family. That is, our PDF family is not restrictive.

2007: ``Elucidating model inadequacies in a cloud parameterization by use of an ensemble-based calibration framework." J.-C. Golaz, V. E. Larson, J. A. Hansen, D. P. Schanen, and B. M. Griffin. *Mon. Wea. Rev.*, 135, 4077-4096. (See also the following oral presentation or slides, and this conference paper.)

It is often easy to see when an atmospheric model disagrees with data. It is usually much harder to locate the ultimate sources of model error.

It is particularly difficult to diagnose errors in a model's structure, that is, errors in the functional form of the model equations. One technique that may help is parameter estimation, that is, the optimization of model parameter values. Typically, parameter estimation is used solely to improve the fit between a model and observational data. In the process, however, parameter estimation may cover up structural model errors.

In a quite opposite application, parameter estimation may be used to uncover the ways in which a model is wrong. The basic idea is to separately optimize model parameters to two different data sets, and then identify parameter values that differ between the two optimizations. When no single value of a particular parameter fits both datasets, then there must exist a related structural error.