Final report for SciDAC grant "Physics and dynamics coupling across scales in the next generation CESM: Meeting the challenge of high resolution."

by

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CAM5 contains 4 cloud/turbulence parameterizations: one for deep convection, one for shallow convection, one for stratiform cloud, and one for turbulence. CAM5 also contains 3 microphysics parameterizations: one for stratiform cloud, one for shallow convection, and one for deep convection.

Simultaneously using 7 distinct cloud-related parameterizations makes it difficult to ensure consistency of assumptions between parameterizations. Such inconsistencies, in turn, raise doubts about the validity of climate models. The doubts are difficult to dispel because climate projections cannot be validated until it is too late. Another disadvantage of using 7 distinct cloud parameterizations is complexity: it is difficult to understand the interactions between parameterizations. To avoid such difficulties, we have constructed a version of CAM that has 1 unified cloud/turbulence parameterization and 1 unified microphysics parameterization.

What permits such unification? One key is the existence of an accurate coupling (i.e. interface) between subgrid dynamics and microphysics. An accurate interface is needed because of the strong interactions between dynamics and microphysics. For instance, evaporative cooling of precipiation creates downdrafts, cold pools, gust fronts, new convection, and hence new microphysical particles.

In this SciDAC grant, I and a postdoc supported by the grant, Dr. Kate Thayer-Calder, have implemented into CAM5 a new interface between subgrid dynamics and microphysics. It is a subcolumn sampler called the Subgrid Importance Latin Hypercube Sampler (SILHS). SILHS uses a cloud/turbulence parameterization, CLUBB. The methodology may be outlined as follows. In each grid column at each time step:

1) *CLUBB estimates a subgrid PDF at each grid level.* The PDF describes how turbulence, moisture, heat content, and hydrometeors co-vary within a grid box.

2) *SILHS draws subcolumns from the subgrid PDFs at each grid level.* Subcolumns are drawn via Monte Carlo sampling. The statistical properties of a set of subcolumns converge to CLUBB's PDF when the number of subcolumns is large.

3) *Each subcolumn is fed, individually, into the microphysics parameterization.* Separate microphysical tendencies are computed for each subcolumn.

4) *The microphysical tendencies are averaged and fed back into the model.* In this way, grid-mean tendencies can be computed in a way that accounts for variability in clouds and turbulence.

The resulting model, CAM-CLUBB-SILHS, is about a factor of 2 more expensive than CAM5 when 10 subcolumns are used. However, subcolumn calculations are straightforward to parallelize and hence can make good use of the extremely large number of processors on today's DOE supercomputer.

The CLUBB-SILHS methodology offers several advantages over the status quo, aside from internal consistency and simplicity:

1) *Use of CLUBB-SILHS avoids the unsatisfactory theoretical foundation of mass-flux parameterizations.* Mass-flux parameterizations build dubious assumptions *into their foundation*, which makes them harder to assess and remove. These assumptions detract from the credibility of climate models. In contrast, the higher-order closure approach underlying CLUBB is derived from known governing equations, with assumptions made only after a rigorous framework is in place.

2) *Use of unified parameterizations allows aerosol indirect effects (AIEs) to be computed in all cloud types, including deep convective clouds.* The vast majority of current simulations that compute AIEs compute them only in stratiform clouds. For this reason, today's simulations are seriously lacking.

3) *Use of CLUBB-SILHS faciliates comparison with observations.* SILHS produces subcolumns that are similar to what a vertically pointing ARM instrument or satellite sees.

The results produced by CAM-CLUBB-SILHS are promising. In an appendix, we show simulations that use a modified version of CAM 5.3 in which the Zhang-McFarlane deep convective parameterization is turned off. CLUBB is the only cloud/turbulence parameterization, and MG 1.0 is the only microphysics parameterization. A series of plots is shown in an appendix. Briefly, both short-wave cloud forcing and liquid water path are improved, helping to mitigate a stubborn problem in CAM5. The improvements perhaps come because of better vertical overlap of clouds. Furthermore, both the MJO and Kelvin waves are improved, perhaps because of the more prognostic and unified nature of the cloud parameterization.

A key advantage of the CLUBB-SILHS approach is that it naturally incorporates information about the grid scale. Namely, CLUBB is formulated such that larger grid boxes tend to encompass more variability than smaller grid boxes, as one would expect in nature. This reduces CLUBB's sensitivity to horizontal grid spacing. CLUBB produces largely grid-independent results over scales from 2 to 16 km in idealized tests (Larson et al. 2012). Because CLUBB is scale aware, sub-columns drawn from CLUBB's sub-grid variability inherit scale awareness, and hence the physical parameterizations (for, e.g., cloud microphysics) may remain focused on "local" processes and need not know about the scale. This approach also enables consistent multi-scale physics for variable-resolution grids within a single model simulation. For CAM-CLUBB using the SE dycore, scale insensitivity in variable-resolution grids is demonstrated in the report by Gettelman et al. (2015). Furthermore, the plots in the appendix demonstrate that CAM-CLUBB-SILHS produces substantially similar results at resolutions of 1 and 2 degrees. Finally, CAM-CLUBB-ZM-SE has been run at ¼ resolution, and the results are satisfactory.

Developing a unified parameterization requires testing over a wide range of meteorological conditions. The following papers acknowledge this SciDAC grant.

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.

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.

2013: “Higher-order turbulence closure and its impact on climate simulations in the Community Atmosphere Model." P. A. Bogenschutz, A. Gettelman, H. Morrison, V. E. Larson, C. Craig, and D. P. Schanen, J. Climate, 26, 9655–9676.

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

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

References:

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

APPENDIX: CAM-CLUBB-SILHS simulations compared to CAM5.3.1 and observations

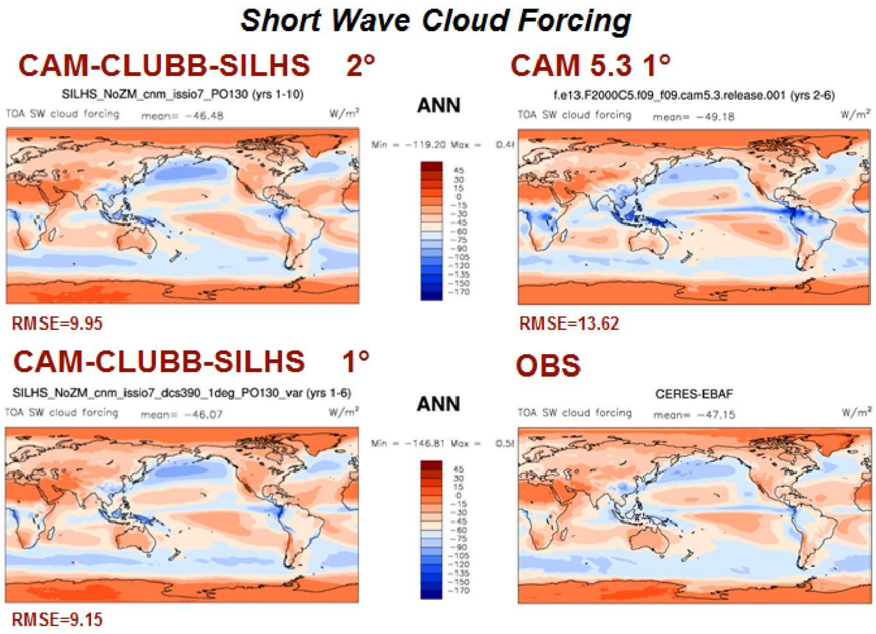


Figure 1: Short-wave cloud forcing. Blue corresponds to cloudier areas. The errors in CAM-CLUBB-SILHS (9 to 10 W/m2) are lower than in CAM5 because the clouds are not so bright over the topical land masses.

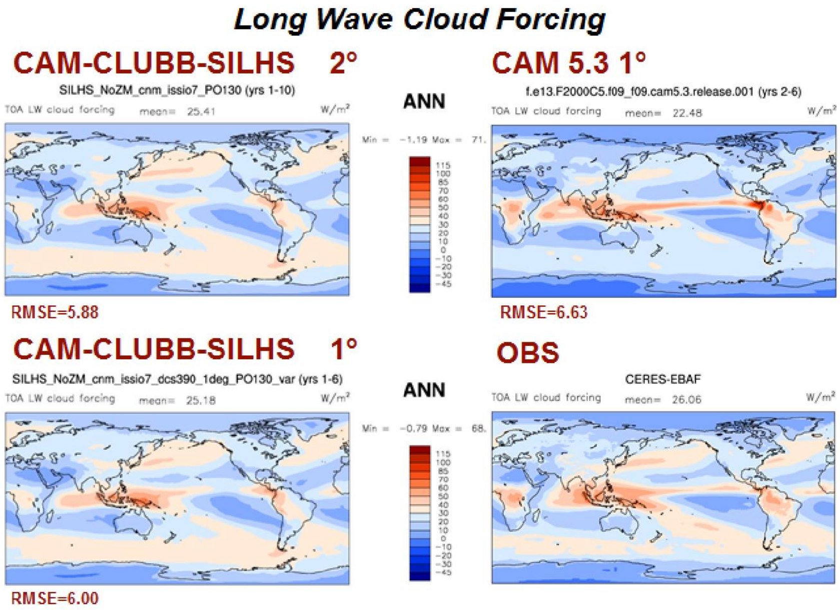
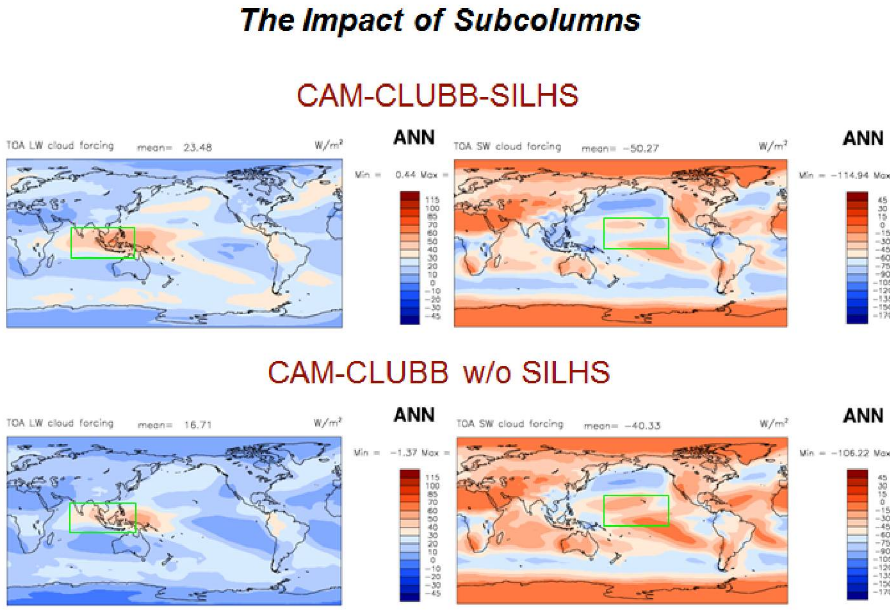


Figure 2: Long-wave cloud forcing (LWCF). The global underestimate of LWCF is reduced in CAM-CLUBB-SILHS, which does not need to rely on convective detrainment of ice.

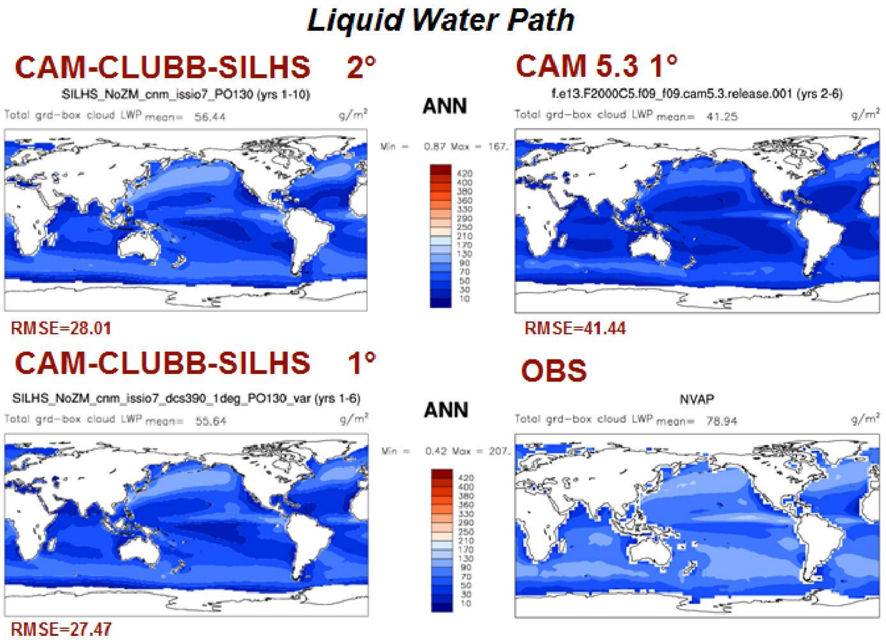


The Impact of Subcolumns

CAM-CLUBB-SILHS

CAM-CLUBB w/o SILHS

Figure 3: SILHS subcolumns help to strengthen deep convection, improving both LWCF and SWCF as compared to CAM-CLUBB without SILHS.



Liquid Water Path

CAM-CLUBB-SILHS 2°

CAM 5.3 1°

CAM-CLUBB-SILHS 1°

OBS

Figure 4: CAM has long underestimated liquid water path (LWP). CAM-CLUBB-SILHS improves LWP while improving SWCF at the same time. I speculate that the reason may be that cloud water is "piled higher," that is, there is more vertical overlap, in CAM-CLUBB-SILHS.

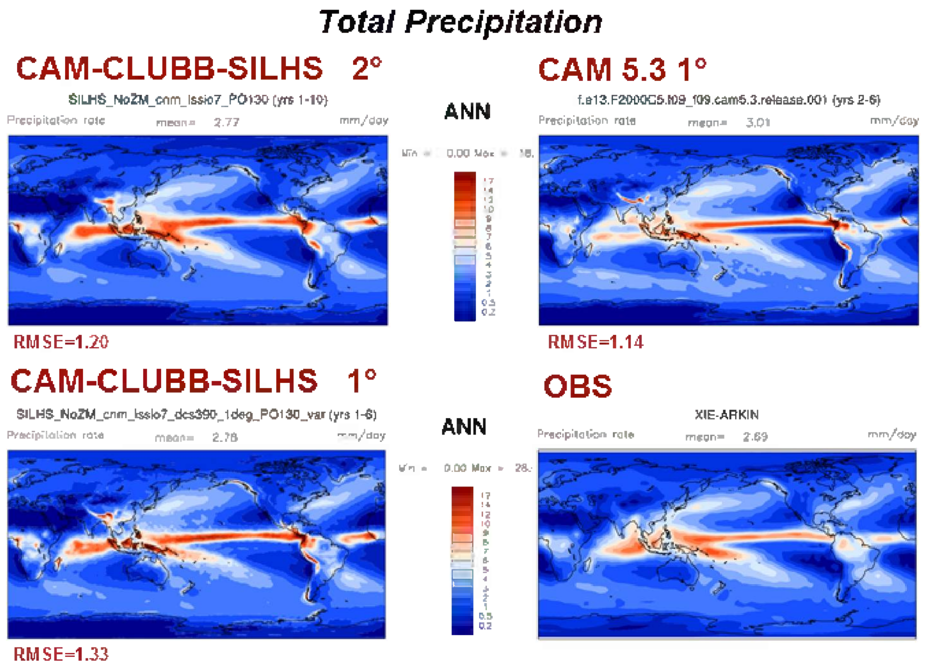


Figure 5: Although the surface precipitation in CAM-CLUBB-SILHS is more speckly than in CAM5, the double ITCZ is reduced as compared to CAM5.

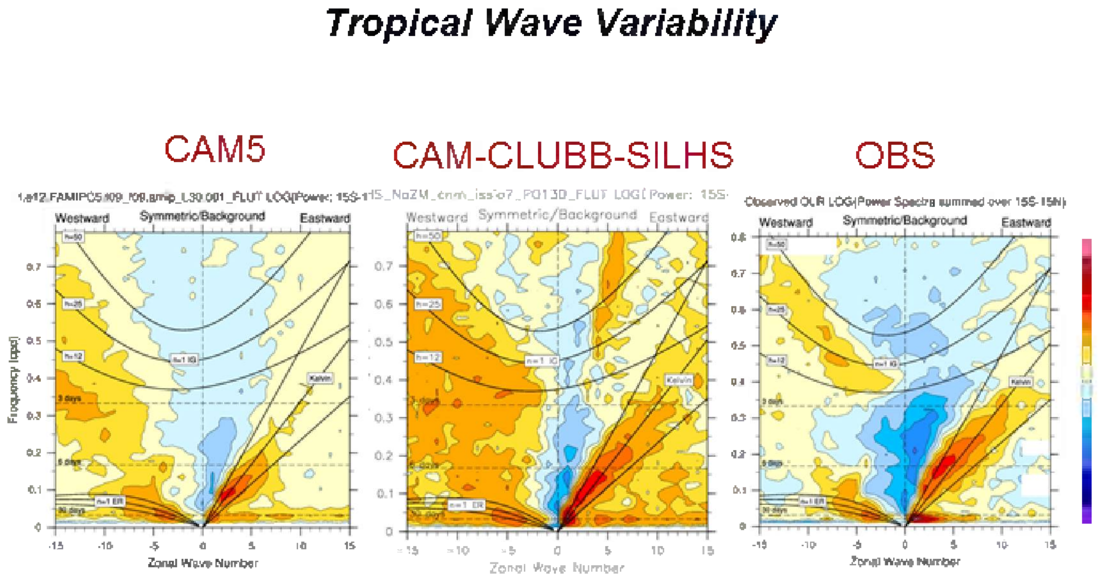


Figure 6: An encouraging piece of evidence is that CAM-CLUBB-SILHS improves both the MJO and Kelvin waves.