University of Texas at Austin CM4 Project
Final Technical Report
DE-SC0016401
October 4, 2019

Charles Jackson – Co-PI

A. Highlights

Global climate models fail to adequately represent shallow cumulus conditions. The activities at the University of Texas at Austin focus on deploying advanced statistical approaches to identify linkages between numerical models and observations using the E3SM-Single Column Model (SCM) and different ARM campaigns focused on shallow cumulus conditions at SGP. The current version of the SCM uses CLUBB to represent shallow cumulus. The parameterization represents a significant evolution from older generation parameterizations insofar as it contains a number of prognostic equations that keep track of the turbulent nature of the environment that are carried forward in time. The parameters associated with this scheme address the rate at which different prognostic quantities that determine vertical turbulent fluxes of heat and moisture decay with time. The large number of parameters gives the CLUBB scheme a lot of flexibility. The expectation of its developers is that it should represent any shallowly convective environment. The concern among developers and other theorists was not whether it could represent any one environment, but whether a single judicious choice of parameters would allow it to predict the turbulent characteristics of a range of environments. Through several exhaustive studies that made use of Bayesian statistical calibration, tens of thousands of SCM experiments, and ensembles of observations of shallow cumulus at SGP that were also modeled using Large Eddy Simulations (LES), we have only achieved partial success in using CLUBB within SCM to capture important aspects of what has been observed and modeled with LES at SGP. Even as we worked to improve observational tests and make a more scientifically focused attempt at modifying subsets of CLUBB parameters, model performance continues to be lacking in some important respects. In one calibration, we were able to achieve a near perfect match to observed properties of liquid water path, cloud radiative effects, and cloud fraction but with clouds that were trapped within a shallow layer and without the highly turbulent fluxes and vertical extent observed with ARM data and modeled with LES (Figure 1). The conclusion we are reaching is that shallow cumulus conditions are much more challenging to represent than was previously thought. This result is also prompting us to consider some aspects of the experiment design that may be limiting the performance of SCM in this case. The work has garnered the attention of Vincent Larson (CLUBB developer at Univ. Wisconsin – Milwaukee) and model developers Steven Klein and Yunyan Zhang (LLNL) with whom this work and will continue.

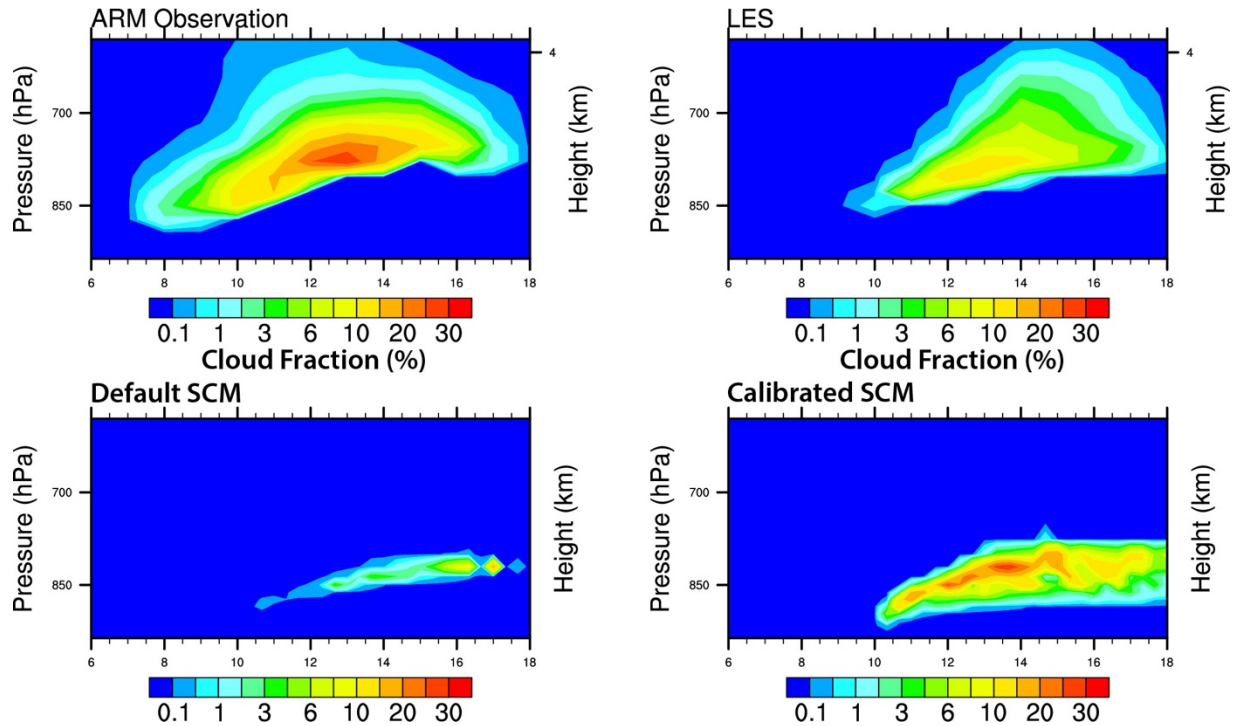

Figure 1. Formal approaches to SCM model calibration (lower right panel) fail to capture vertical extent of shallow convection as observed at SGP and modeled within Large Eddy Simulations (upper panels) although improve, relative to the default, observed liquid water path, cloud radiative effects, and total cloud fraction (lower left panel).

B. Closer examination of findings

Setup: In this section of the report I document some of the process we developed to make use of ARM data to test E3SM-SCM physics. As stated above, our primary finding is that there remains a significant (and unexpected) gap between model simulations and observations. The interest in that gap grows more profound as one reviews all that has been done to explore and close that gap.

We first targeted three days of shallow cumulus observations that were during the RACORO campaign at the SGP facility. These observations were the focus of earlier studies about shallow cumulus that also documented the failure of previous generation SCMs to generating enough turbulent motions within the boundary layer to represent observations (Vogelmann et al., 2015; Endo et al., 2015; Lin et al., 2015). These earlier studies also set the experiment protocols for how ARM data would be used to generate boundary conditions for LES and SCM modeling experiments. In this case the LES experiments were more consistent with ARM data than the SCM experiments. With our effort, we were using a version of E3SM-SCM that included CLUBB, a next generation boundary layer scheme. So the initial hypothesis was that this new physics would better capture the observations. Moreover CLUBB has significant flexibility insofar as it

has approximately 10 “active” parameters and a huge amount of flexibility. Nevertheless nothing really worked.

Bayesian calibration is a formal process within statistics for selecting sets of uncertain parameters that allow a model to be consistent with observational data. A description of the process as we have applied it to climate models was summarized in two publications (Wagman and Jackson, 2018; and Stephens et al., 2019). In summary, a test statistic is developed to determine the level of consistency with observational data. A sampling algorithm steps through parameter space and uses the test statistic to accept or reject parameter combinations. This type of sampling chain is repeated 24 times (one chain for every CPU on a node), each one starting from a random spot in parameter space and completing about 200 experiments. Since each SCM experiment is rather cheap, taking about 5 minutes per experiment (mostly used to run E3SM model setup scripts, cloning, and re-writing of namelists), one may generate several thousand experiments in a single day. The result is an ensemble of model configurations that collectively represent the different ways the model can be configured to be consistent with observational data. Here we typically show a few samples that illustrate our point, however we also make use of the scatter in parameter settings and model outcomes to evaluate the solution robustness (and uncertainty).

RACORO: The calibration result that targeted three days of shallow cumulus within RACORO campaign showed much improved match to the targeted observations, however the solution was unique insofar as those improvements were due to compensating errors. In particular portions of the solution that were not included in the test statistic were much worse. In review of using RACORO as the target (at least the 3 days that were selected), we learned that large-scale conditions were on the verge of forcing deep convection. This motivated a second approach and use of CASS ensemble target which we will describe next.

CASS: The CASS ensemble (Zhang et al., 2017) addresses the main concern that arose in using the RACORO target as was done in (Lin et al., 2015). There is a range of conditions that result in shallow cumulus. CASS ensemble includes 70 days of shallow cumulus cases. We used the ensemble mean as the target. Ensemble mean forcing of a LES experiment produced results similar to the observations.

We conducted two calibrations with the CASS ensemble. The first calibration found a region of parameter space that produced a perfect match to the targeted observations, however the structure of the clouds were much different from what was observed. That is, our target included the some aspects of observed clouds such as shortwave cloud radiative effects, total cloud fraction, and liquid water path, but the solutions looked too shallow. Comparison between the vertical eddy fluxes between the SCM and the LES showed there were large structural differences between the two. In general the results were too stratiform-like, with very little cloud amounts being produced above the boundary layer as was observed (Figure 1).

A second calibration included cloud base height and thickness as targets. This second calibration with CASS as a target were not any better. This was after nearly 6000 experiments.

This is a fairly exhaustive search and that if any match to observational data were to be found in the parameter space we would have found it. Since we feel that the CLUBB parameterization has all the necessary physics to exhibit observed behavior we were left with two possible interpretations: 1) Total cloud fraction in observations is not being interpreted similarly to how it is being treated in the model. These types of errors are not represented in the calculation (although one could), or 2) the SCM is too reliant on boundary condition forcing of elevations above 700 mb. The nudging toward environmental conditions may preclude solutions that require heating/dissipation in the column to be driven from the surface. We are currently exploring both these possibilities.

C. Synthesis of research activities

The research activities at UT-Austin is benefitting from strong engagement with several groups within and outside the CM4 project who are also interested in seeing these activities continue. At present the strongest collaboration exists with 1) CLUBB developer Vincent Larson (Univ. Wisconsin – Milwaukee) and 2) cloud observation and modeling experts Steve Klein and Yunyan Zhang (LLNL). Both these groups have expressed interest in working with me to deploy formal strategies in testing new physics parameterizations and have expressed an interest in furthering this work either through existing funding to Labs or forthcoming solicitations. Both groups are actively involved with E3SM development. Also both of these collaborations arose out of participation in the ASR/ARM PI Spring meetings.

One of the achievements of our current work that will help with such collaborations is the deployment of our ensemble control system to handle E3SM on NERSC computing resources. It is now feasible to rapidly develop a Bayesian calibration for any new physics package or sets of observations that is introduced into the E3SM repository.

As a scientist whose primary expertise is in global climate modeling, it was very helpful to have the CMDV program target SCM and LES modeling strategies as bridge capabilities for interpreting the significance of ARM observations. In particular it was extremely helpful to work with Andy Vogelmann on understanding ARM data and LES modeling and Peter Bogenschutz on SCM modeling capabilities. Early work focused on a case of shallow cumulus from the RACORO campaign and we learned a key insight about the probable interference of deep convection on that case from a discussion about challenges we were having within and outside CM4 project scientists. This eventually led us to consider the CASS observational target for shallow convection developed by Yunyan Zhang and Steve Klein.

D. Lessons Learned

As a person who is deeply invested in how we make use of observational data to test global climate modelling capabilities, I have a much better awareness of the difficulties in bringing these two sets of activities together. I benefited greatly from the development of LES and SCM modeling tools and targeted experiments for shallow convection. Nevertheless I don't think enough thought has gone into what is needed from an observational point of view to take full

advantage of these modeling tools. The discovery of the CASS ensemble was a revelation to me and a strategy that I think is worth emulating for other phenomena besides shallow convection. It is important to establish a range of conditions under which we observe a targeted phenomenon. Early effort in our project focused on a limited number of cases which turned out to be end-member examples of shallow convection. As we test parameterizations to predict a range of environments, it will be helpful from an experimental design perspective to better characterize what is normal or anomalous about each environment to test for model robustness.

E. Sharing of data and results

The products related to this effort include the scripts and data involved in setting up, executing, and storing of large ensembles of SCM integrations. All of these will be documented through a publication and shared (if allowed) through the ARM data archive. If software or data formats are not allowed, then we will consider one of several open source free data repositories such as https://zenodo.org that allow archives up to 50GB in size. ESGF is not an appropriate solution insofar as it is specifically designated for CMIP activities such as model intercomparison projects.

Publications (students indicated by *)

Stephens*, B.A., C.S. Jackson, and B.M. Wagman*, 2019: Effect of Tropical Non-Convective Condensation on Uncertainty in Modeled Projections of Rainfall. *J. Climate*, https://doi.org/10.1175/JCLI-D-18-0833.1

Muldoon*, G. R., C. S. Jackson, D. A. Young, and D. D. Blankenship, 2018. Bayesian estimation of englacial radar chronology in Central West Antarctica. *Dynamics and Statistics of the Climate System*, **3**(1), 1-13, doi:10.1093/climsys/dzy004.

Wagman*, B.M. and C.S. Jackson, 2018: A test of emergent constraints on cloud feedback and climate sensitivity using a calibrated single-model ensemble. *J. Climate,* https://doi.org/10.1175/JCLI-D-17-0682.1

Conference Presentations

University of Leeds, UK (January 2019) "Quantifying Risk within Single Model Ensembles"

Jackson, C, and B. Wagman (2018) "The outsized importance of northern hemisphere summer clouds and rainfall to global climate models" A130-2696, AGU 2018 Winter Meeting.

Seminars

Texas A&M University (February 2019) "Likelihood of abrupt climate change"

UK Met Office (January 2019) “Statistical approaches to (un)learning how cloud feedbacks work”

References

Endo, S. et al., 2015. RACORO continental boundary layer cloud investigations: 2. Large-eddy simulations of cumulus clouds and evaluation with in situ and ground-based observations. Journal of Geophysical Research: Atmospheres, 120, pp.5993–6014.

Lin, W. et al., 2015. RACORO continental boundary layer cloud investigations: 3. Separation of parameterization biases single-column model CAM5 simulations of shallow cumulus. Journal of Geophysical Research: Atmospheres, 120, pp.6015–6033.

Stephens, B.A., Jackson, C.S. & Wagman, B.M., 2019. Effect of Tropical Nonconvective Condensation on Uncertainty in Modeled Projections of Rainfall. Journal Of Climate, 32(19), pp.6571–6588. Doi:10.1175/JCLI-D-18-0833.1.

Vogelmann, A.M. et al., 2015. RACORO continental boundary layer cloud investigations: 1. Case study development and ensemble large-scale forcings. Journal of Geophysical Research: Atmospheres, 120, pp.5962–5992.

Wagman, B.M., and C.S. Jackson, 2018. A test of emergent constraints on cloud feedback and climate sensitivity using a calibrated single-model ensemble. J. Climate, 31, 7515–7532, doi:10.1175/JCLI-D-17-0682.1.

Zhang, Y., S.A. Klein, J. Fan, A. Chandra, P. Kollias, S. Xie, and S. Tang, 2017. Large-eddy simulation of shallow cumulus over land: A composite case based on ARM long-term observations at its Southern Great Plains site. Journal of the Atmospheric Sciences, 74(10), pp.3229–3251. Doi: 10.1175/JAS-D-16-0317.1