Bayesian calibration of central plains shallow cumulus within E3SM-SCM using the CASS observational ensemble

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with significant input from
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Problem

Difficult for GCMs to represent shallow cumulus.
A test based on RACORO campaign data

• Use of ARM data from RACORO campaign, central plains, Oklahoma.
• Data assimilation to determine boundary conditions and forcings for select days
• Large eddy simulations (LES) to model turbulent fluxes from boundary layer.
• E3SM Single Column Atmosphere Model (SCM) to test shallow convection parameterization.
RACORO continental boundary layer cloud investigations: 1. Case study development and ensemble large-scale forcings

Andrew M. Vogelmann¹, Ann M. Fridling², Tami Toto¹, Satoshi Endo¹, Wuyin Lin¹, Jian Wang¹, Sha Feng³, Yunyan Zhang⁵, David D. Turner⁶, Yangang Liu¹, Zhijin Li⁴,³, Shaocheng Xie⁵, Andrew S. Ackerman², Minghua Zhang⁷, and Marat Khairoutdinov⁷

RACORO continental boundary layer cloud investigations: 2. Large-eddy simulations of cumulus clouds and evaluation with in situ and ground-based observations

Satoshi Endo¹, Ann M. Fridling², Wuyin Lin¹, Andrew M. Vogelmann¹, Tami Toto¹, Andrew S. Ackerman², Greg M. McFarquhar³, Robert C. Jackson³, Haflidi H. Jonsson⁴, and Yangang Liu¹

RACORO continental boundary layer cloud investigations: 3. Separation of parameterization biases single-column model CAM5 simulations of shallow cumulus

Wuyin Lin¹, Yangang Liu¹, Andrew M. Vogelmann¹, Ann Fridling², Satoshi Endo¹, Hua Song¹, Sha Feng³, Tami Toto¹, Zhijin Li³,⁴, and Minghua Zhang⁵
Single Column Model does poorly

From Lin et al. (JGR 2015)

Single Column Model w/o Deep Convection
Large Eddy Simulations do ok

Single Column Model performance

Observations

Cloud Fraction

Cost = 76.7 (best) Configuration

Default
Cost = 88.5
Bayesian Calibration Results

4900 experiments

log likelihood frequency

number of model configurations

log likelihood

“Cost”

default

88.5
**CASS target**

*Continental Active Surface-forced Shallow-cumulus*

- Collaboration with Yunyan Zhang and Steve Klein who developed the CASS target (Zhang et al, 2017).
- Ensemble of 76 days of shallow cumulous around SGP site.
- Addresses potential issues with RACORO target where large-scale forcing is close to triggering deep convection.
CASS forcing result (default SCM)

Maximum SCM cloud fraction is half of what it should be and 3.5 hours late.
E3SM-SCM Bayesian Calibration

• MECS manages E3SM workflow over HPC resources.
• Completes 4000 SCM experiments in a day on a single node of Cori.
• Target CASS ensemble (Zhang et al, 2017).
• At noon compares SCM output with ARM products for
  • Total cloud fraction (target = 33% ± 1%)
  • Shortwave cloud radiative effects (target = 110 Wm^-2 ± 5 Wm^-2)
  • Liquid water path (target = 30 gm^-2 ± 2.5 gm^-2)
  • Boundary layer height (target = 1600 m ± 60 m)
  • Absence of high clouds
• Uncertainty in observations based on scatter in CASS ensemble or knowledge of product errors.
Bayesian expression for observational constraints on parameter value selection

\[
PPD(\mathbf{m} \mid \mathbf{d}_{\text{obs}}, g(\mathbf{m})) \propto \exp \left[ -\frac{1}{2} (g(\mathbf{m}) - \mathbf{d}_{\text{obs}})^T \mathbf{C}_{\text{noise}}^{-1} (g(\mathbf{m}) - \mathbf{d}_{\text{obs}}) \right] \cdot \text{prior}(\mathbf{m})
\]

**Likelihood test statistic**

\[\mathbf{m} = \text{parameters} \]
\[g(\mathbf{m}) = \text{model output} \]
\[\mathbf{d}_{\text{obs}} = \text{observations} \]
\[\mathbf{C}^{-1} = \text{uncertainty} \]
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Default</th>
<th>Search range</th>
</tr>
</thead>
<tbody>
<tr>
<td>beta</td>
<td>Plume width variance</td>
<td>2.4</td>
<td>0 to 3</td>
</tr>
<tr>
<td>gamma</td>
<td>Skewness of vertical fluxes</td>
<td>0.32</td>
<td>0 to 0.83</td>
</tr>
<tr>
<td>C1</td>
<td>Dissipation of mean($w'^2$)</td>
<td>1.335</td>
<td>0 to 3</td>
</tr>
<tr>
<td>C2rt</td>
<td>Dissipation of mean($r'^2$)</td>
<td>1.75</td>
<td>0 to 3</td>
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<tr>
<td>C6rt</td>
<td>Low-skewness value of pressure damping of mean($w'r'$)</td>
<td>4.0</td>
<td>2 to 8</td>
</tr>
<tr>
<td>C6rtb</td>
<td>High-skewness value of pressure damping of mean($w'r'$)</td>
<td>6.0</td>
<td>2 to 8</td>
</tr>
<tr>
<td>C7=C7b</td>
<td>Buoyancy portion of pressure damping mean($w'r'$) and mean($w'r'h'$)</td>
<td>0.5</td>
<td>0 to 1</td>
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<tr>
<td>C8</td>
<td>Pressure damping of mean($w'^3$)</td>
<td>4.3</td>
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<tr>
<td>C11</td>
<td>Low-skewness value of buoyancy pressure damping mean($w'^3$)</td>
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<td>0 to 1</td>
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<tr>
<td>C11b</td>
<td>High-skewness value of buoyancy pressure damping mean($w'^3$)</td>
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<td>0 to 1</td>
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<tr>
<td>C14</td>
<td>Dissipation of kinetic energy variance mean($u'^2$) and mean($v'^2$)</td>
<td>1.3</td>
<td>0 to 3</td>
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<tr>
<td>K10</td>
<td>Eddy diffusivity for surface momentum fluxes</td>
<td>0.3</td>
<td>0 to 1</td>
</tr>
<tr>
<td>rhmin1</td>
<td>Critical relative humidity for low clouds</td>
<td>0.95</td>
<td>0.8 to 0.99</td>
</tr>
</tbody>
</table>
Welcome to CLUBBB

Larson “CLUBB-SILHS: A parameterization of subgrid variability in the atmosphere”

\[
\begin{align*}
\frac{\partial w' r'_t}{\partial t} &= -\frac{\bar{w} w' r'_t}{w} \frac{\partial w}{\partial z} - \frac{1}{\rho_s} \frac{\partial \bar{w} w'^2 r'_t}{\partial z} - w'^2 \frac{\partial r'_t}{\partial z} - w' r'_t \frac{\partial w}{\partial z} + \frac{g}{\theta_{vs}} r'_t \theta'_v + w' \frac{\partial r'_t}{\partial t}_{mc} - \frac{1}{\rho_s} \frac{\partial p'}{\partial z} - \epsilon_{wr_t} \\
\frac{\partial w' \theta'_l}{\partial t} &= -\frac{\bar{w} w' \theta'_l}{w} \frac{\partial w}{\partial z} - \frac{1}{\rho_s} \frac{\partial \bar{w} w'^2 \theta'_l}{\partial z} - w'^2 \frac{\partial \theta'_l}{\partial z} - w' \theta'_l \frac{\partial w}{\partial z} + \frac{g}{\theta_{vs}} \theta'_l \theta'_v + w' \frac{\partial \theta'_l}{\partial t}_{mc} - \frac{1}{\rho_s} \frac{\partial p'}{\partial z} - \epsilon_{w\theta_l} \\
\frac{\partial r'^2_t}{\partial t} &= -\frac{\bar{w} r'^2_t}{w} \frac{\partial r'^2_t}{\partial z} - \frac{1}{\rho_s} \frac{\partial \bar{w} w' r'^2_t}{\partial z} - 2w' r'_t \frac{\partial r_t}{\partial z} + 2r'_t \frac{\partial r_t}{\partial t}_{mc} - \epsilon_{r_t r_t}
\end{align*}
\]
Example of where C2 parameter fits in.

\[
\frac{\partial \bar{r}_t'^2}{\partial t} = -\frac{\bar{w}}{w} \frac{\partial \bar{r}_t'^2}{\partial z} - \frac{1}{\rho_s} \frac{\partial \rho_s \bar{w}' \bar{r}_t'^2}{\partial z} - 2\bar{w}' \bar{r}_t' \frac{\partial \bar{r}_t'}{\partial z} + 2r_t' \frac{\partial r_t'}{\partial t} \mid_{\text{mc}} - \epsilon_{r_t r_t} \mid_{\text{dissip}}
\]

\[
\frac{\partial \bar{r}_t'^2}{\partial t} = -\bar{w} \frac{\partial \bar{r}_t'^2}{\partial z} - \frac{1}{\rho_s} \frac{\partial \rho_s \bar{w}' \bar{r}_t'^2}{\partial z} - 2\bar{w}' \bar{r}_t' \frac{\partial \bar{r}_t'}{\partial z} \mid_{\text{ma}} + \frac{\partial}{\partial z} \left[ (K_{w2} + \nu_2) \frac{\partial \bar{r}_t'^2}{\partial z} \right] \mid_{\text{dp2}} + \frac{\partial \bar{r}_t'^2}{\partial t} \mid_{\text{mc}} \mid_{\text{dp2}}
\]

\[
\frac{\partial \bar{r}_t'^2}{\partial t} \mid_{\text{dissip}} = -\frac{C_2}{\tau} \left( \bar{r}_t'^2 - r_{t,\text{tol}}^2 \right) \mid_{\text{dp1}} \frac{\partial}{\partial t} \mid_{\text{pd}} \frac{\partial \bar{r}_t'^2}{\partial t} \mid_{\text{cl}}
\]
12000 experiments

Sampling finds “perfect” match to observational targets

Marginals built from samples with cost < 100

Closer to obs

default

further from obs
Calibrated E3SM SCM Result

Obs target = 24% cloud fraction (at noon)

Default

New optimal

Uses only observations from noon. Is able to reproduce these observations as well as timing of maximum cloud fraction.
Skewness of vertical fluxes

Less damping of vertical wind variance

Much less damping of moisture variance

More vertical fluxes of moisture
Make more stratus-like

Surface production of momentum fluxes is surprisingly relevant.
CASS Obs as compared to LES and SCM
Although better, SCM still not producing enough vertical moisture fluxes.
Next steps

• Target CASS ensemble cloud base height and thickness.
• Average model and observations between noon and 2 pm.
• Included observed covariances from CASS ensemble.
Summary

• CLUBB presents a large functional space to work with, which presents opportunities and challenges.
• “Smart” narrowing of space led to a failure. (some results not shown here)
• Hitting target observations for good but misleading reasons. Need to strengthen test.
• Keen on idea of targeting ensembles of observations.