Assessing and Improving the Numerical Solution of Atmospheric Physics in E3SM

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Background

Disconcerting sensitivities of CAM and EAM results to numerical choices

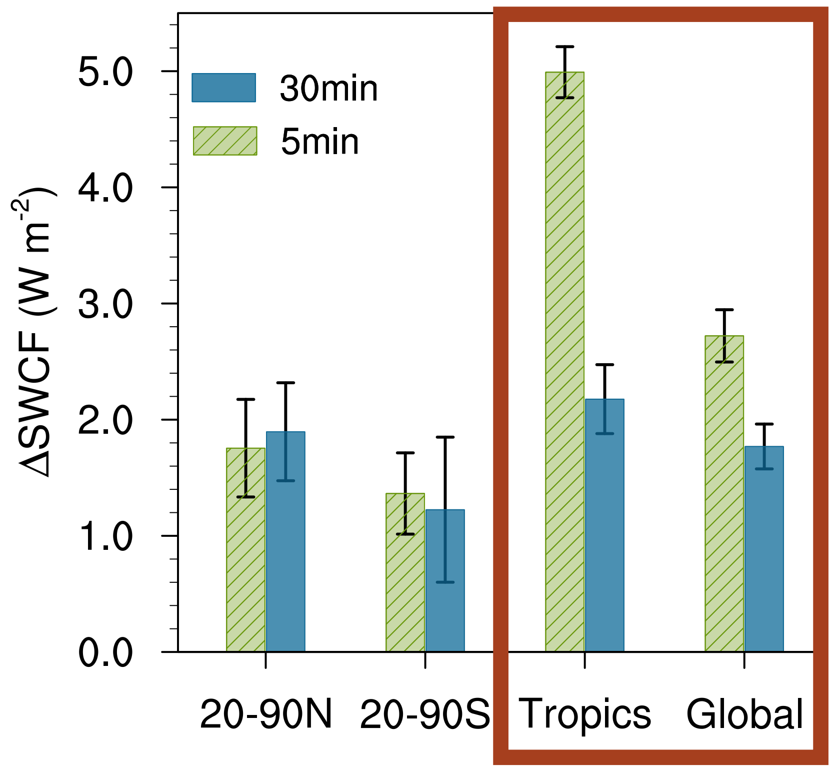
Ultimate Goal

A model that faithfully represents the intended physics

Need to

- Distinguish numerical error from physics error
- Improve numerical accuracy

Shortwave Cloud Forcing Change in Response to 4K SST Increase in EAMv0 (1° resolution)



Numerical Challenge

Poor time step convergence in CAM and EAMv0, v1

- Model behaves in an unexpected way
- Limited accuracy gain from future reduction of time step size in high-resolution models

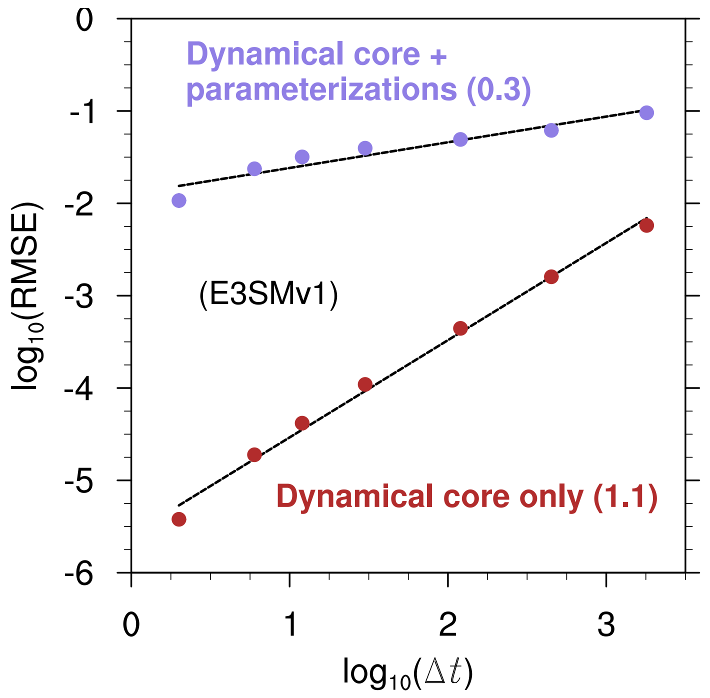
Cultural Challenge

Lack of verification culture in parameterization development

Specific Goals of the Project

- Understand the root causes of poor convergence
- Improve solution convergence and accuracy
- Demonstrate relevance to climate research

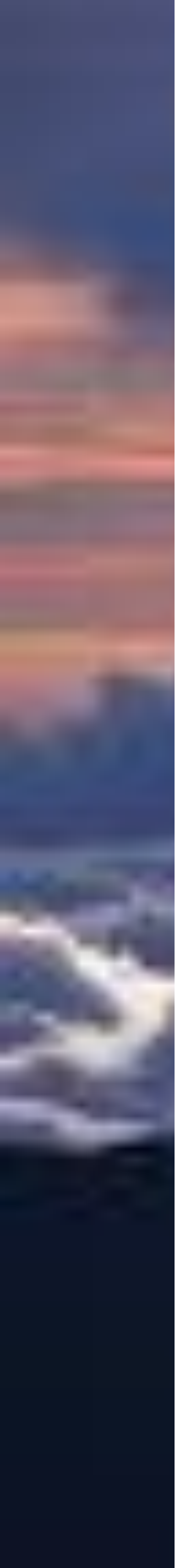
Time-stepping error and solution self-convergence in EAMv1



Simulation setup

- 1 h global simulations
- Δt range: 30 min down to 1s
- 6-member ensembles (spread small, invisible in plots)

(cf. Wan et al., 2015, JAMES for CAM5 results from SciDAC-3)



Resolving Convergence Issues in a Simplified Global Model

Key Accomplishments

- Identified issues in process coupling, closure assumptions, and initialization
- Restored 1st-order convergence in short (weather-scale) simulations
- Revealed substantial impact on long-term climate
- Two companion papers to be submitted to JAMES

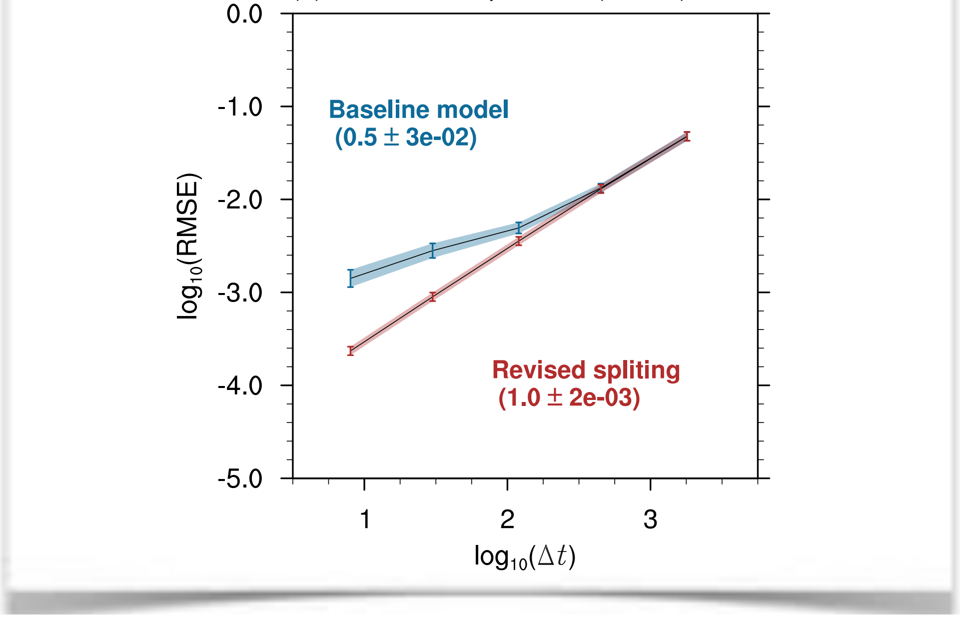
Impacts

- New insights on possible causes of convergence problem
- Improved physical consistency and impact on long-term climate demonstrate relevance to atmospheric physicists

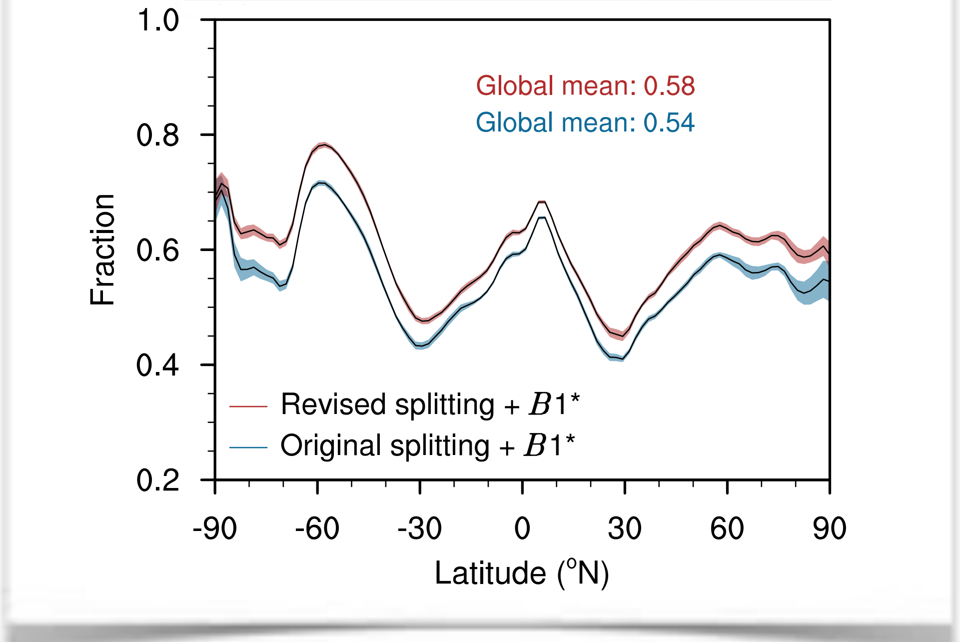
Details of the Investigation

- Bare-bones version of large-scale condensation parameterization used in CAM2-4
- All convergence tests using dynamical core plus only the condensation scheme to help isolate issues
- Formal (theoretical), a priori error analysis indicated the expected convergence rate and revealed conditions for observing that rate
- Suboptimal coupling method, sub-grid closure assumptions, and initialization were found to trigger singular and discontinuous solution; the latter had a root in the model's continuous formulation
- Alternative time integration method was derived to avoid the singularity

Solution error and self-convergence in 1 h simulations with the simplified model



10-year mean total cloud cover simulated with CAM4 physics



Improving Convergence of EAM's Turbulence Parameterization

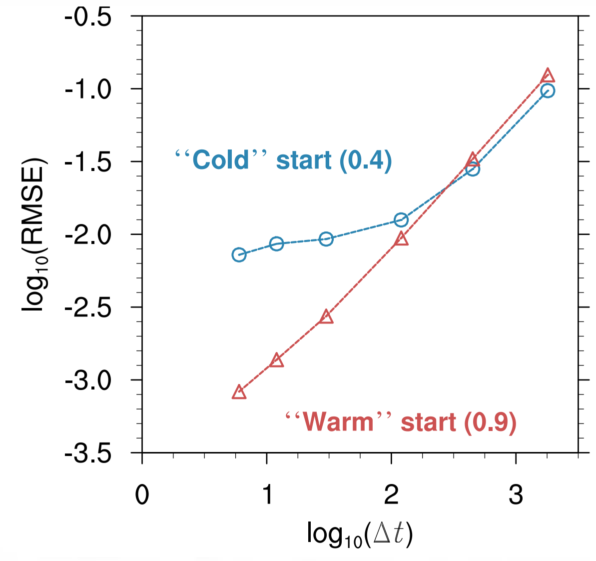
Key Accomplishments

- A bug fix restored convergence in single-column simulations
- Revised initialization improved convergence in 1 h global simulations

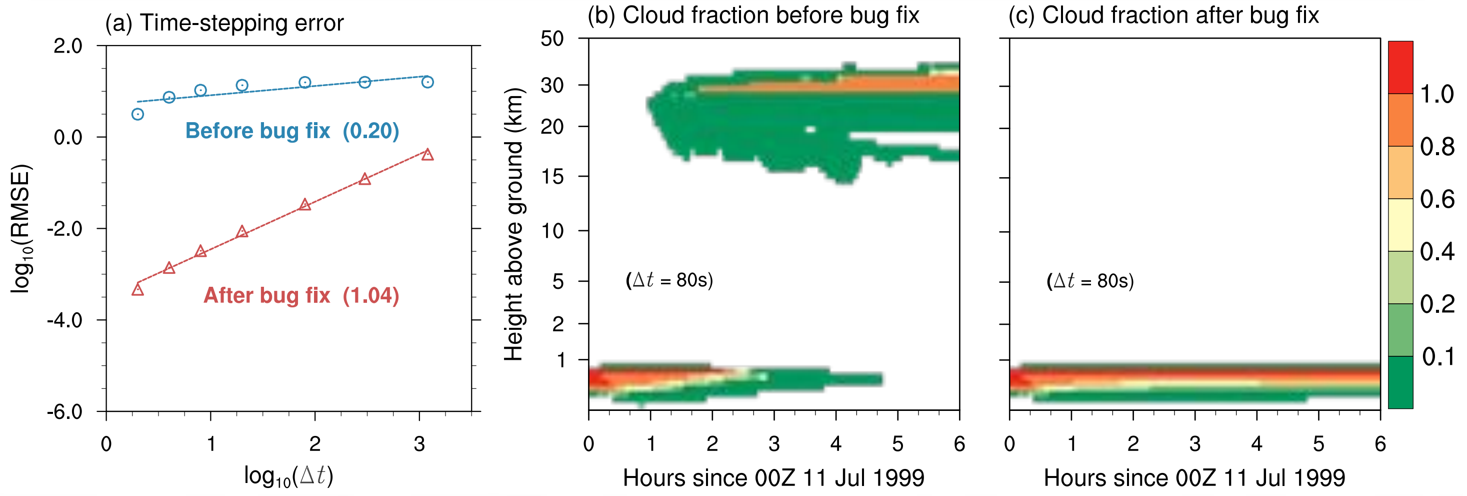
Next Steps

- Improve convergence in longer global simulations. Physics-dynamics coupling and singularities in numerical solution are likely causes of convergence problem

Solution error and self-convergence in 1 h global simulations using EAM's dycore + CLUBB



(a) Solution error and self-convergence and (b)-(c) time evolution of cloud fraction in single-column simulations with CLUBB (case: DYCOMS RF02)



Improving Solution Accuracy and Convergence for *Stochastic* Problems

Significance and Potential Impacts

- Stochastic parameterizations are attractive for ensemble prediction and uncertainty quantification
- Time-stepping methods for deterministic equations can give large errors when applied to stochastic problems

Key Accomplishments

- Derived a generic formulation of the Ito correction
- Demonstrated benefits for solving a stochastic advection-diffusion problem
- Method applicable to a wide range of noise processes
- Manuscript under review for Mon. Wea. Rev.

Current Work

- Idealized 2D problem with stochastic sub-grid turbulence

Intensity of Hurricane Isaac (2012)
Measured by Max. Surface Wind Speed

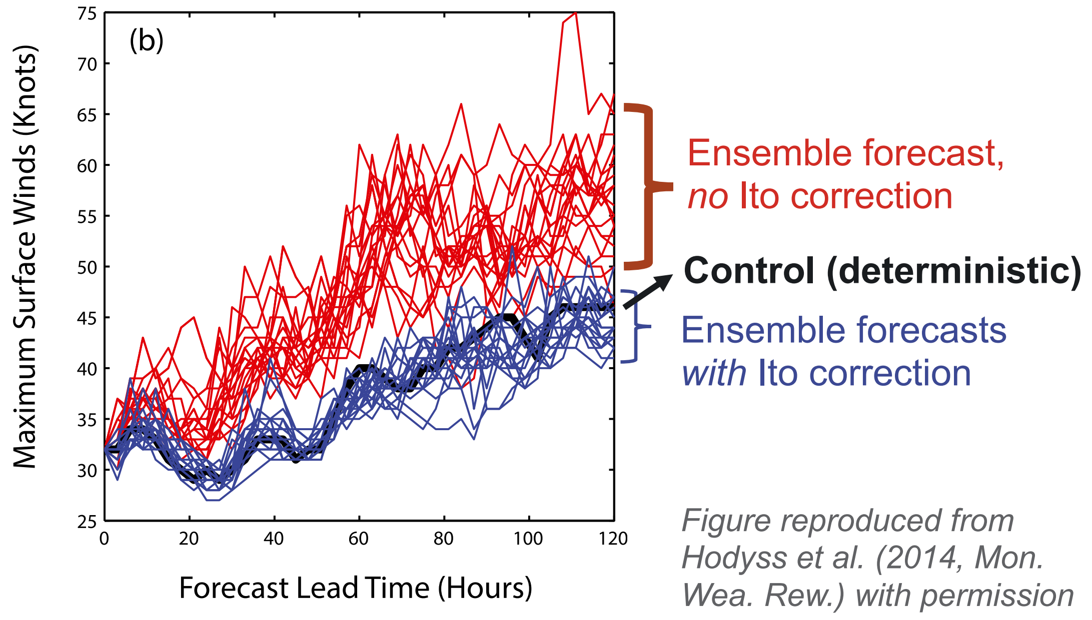
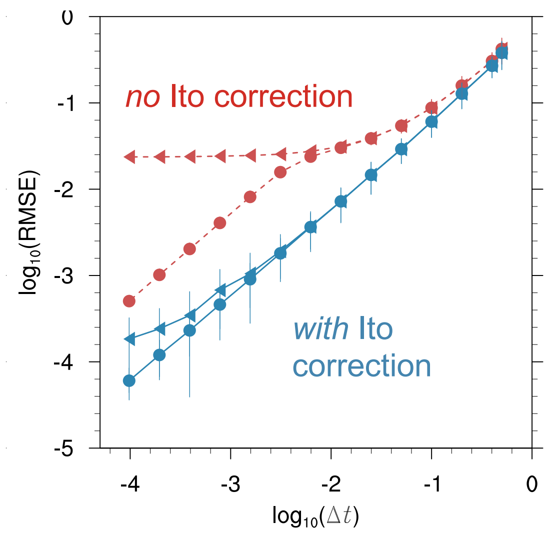


Figure reproduced from Hodyss et al. (2014, Mon. Wea. Rew.) with permission

Solution Error in Stochastic Advection-diffusion Problem after 2 Time Units



Stinis et al. (2019), under review

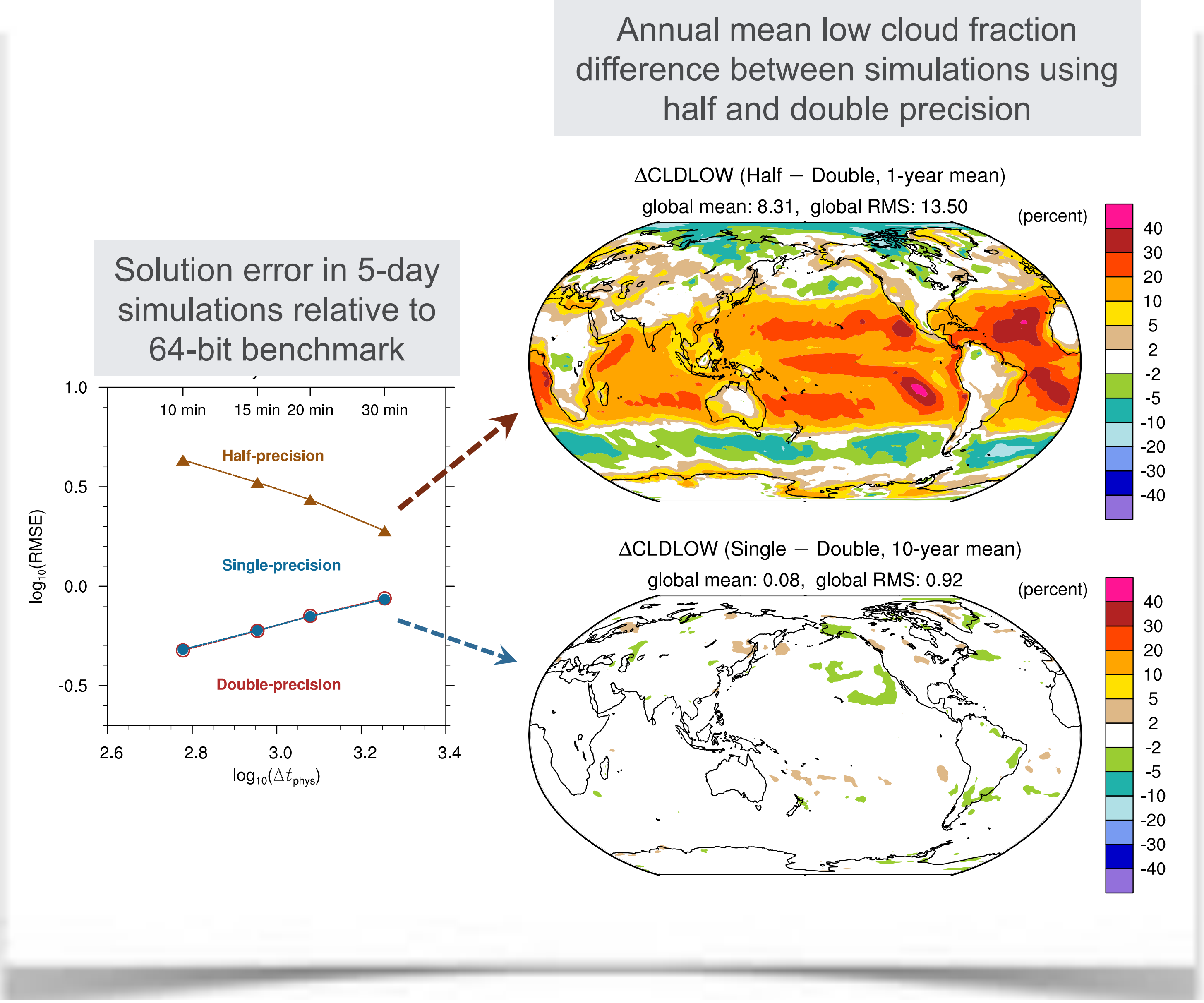
New Tests for Assisting E3SM's Software Development

Key Accomplishments

- Established convergence behavior of solutions computed using reduced or mixed precision
- Designed and verified an objective and inefficient method for assessing solution correctness
- Create a first mix-precision version of EAMv1
- A paper was submitted to JAMES

Impacts

- Proof-of-concept for a single-precision EAM
- Convergence test is hundreds of times cheaper than multi-year simulations; will be particularly useful for high-resolution models



Zhang et al. (2019), submitted

Community Awareness and Activities

- Starting to see increased awareness of numerical issues among atmospheric physicists within and outside the E3SM community
- Review article published on physics-dynamics coupling in weather, climate and Earth System models
  (Gross, Wan, Rasch et al., 2018, Mon. Wea. Rev.)
- Wan as co-organizer of international Physics-Dynamics Coupling workshop series
  (ECMWF 2018, GFDL 2020)
- Invitation from GEWEX/GASS to organize a process-coupling related model intercomparison. First white paper submitted.

Summary

We demonstrated that

- Poor time step convergence in EAM and related models can be understood and improved
- Improving convergence helps to obtain better numerical robustness and physical consistency
- The impact on model climate can be large
- Convergence testing also has other useful applications

Math-climate collaboration was key to the accomplishments

Ongoing Efforts

- Addressing convergence issues in EAM's turbulence parameterization CLUBB
- Develop Ito correction for idealized stochastic turbulence parameterization

Future Work

Improving process coupling using advanced time integration methods

- Radiation, clouds, and turbulence
- Turbulence, surface processes, and dynamics
- Water vapor condensation and deposition

Stochastic modeling and Ito correction for CLUBB

- Avoid undue numerical damping
- Allow for long time steps while retaining accuracy

Turbulent advection of $\overline{w'^3}$ in a single-column simulation of continental shallow convection (ARM)