Assessing and Improving the Numerical Solution of Atmospheric Physics in E3SM

Hui Wan¹ (PI), Carol Woodward² (Co-lead),
Michael Brunke³, Huan Lei¹, Jing Li¹, Vince Larson⁴, Phil Rasch¹, Balwinder Singh¹,
Jeremy Sousa³, Panos Stinis¹, Chris Vogl², Xubin Zeng³, and Shixuan Zhang¹

¹PNNL, ²LLNL, ³U. Arizona, ⁴U. Wisconsin – Milwaukee

SciDAC PI Meeting, July 17, 2019
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
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

Simulation setup
- 1 h global simulations
- ∆t 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
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.
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 Itô 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

---

Int. **Int.**
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
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