





# Assessing and Improving the Numerical Solution of Atmospheric Physics in E3SM

Hui Wan<sup>1</sup> (PI), Carol Woodward<sup>2</sup> (Co-lead), Michael Brunke<sup>3</sup>, Huan Lei<sup>1</sup>, Jing Li<sup>1</sup>, Vince Larson<sup>4</sup>, Phil Rasch<sup>1</sup>, Balwinder Singh<sup>1</sup>, Jeremy Sousa<sup>3</sup>, Panos Stinis<sup>1</sup>, Chris Vogl<sup>2</sup>, Xubin Zeng<sup>3</sup>, and Shixuan Zhang<sup>1</sup>

<sup>1</sup>PNNL, <sup>2</sup>LLNL, <sup>3</sup>U. Arizona, <sup>4</sup>U. Wisconsin – Milwaukee

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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 ullet
- 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 ulletstep 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 ۲
- Demonstrate relevance to climate research



Simulation setup • 1 h global simulations •  $\Delta t$  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) E3SMV1 (300s - 1800s)

## **Resolving Convergence Issues in a Simplified Global Model**

### **Key Accomplishments**

- Identified issues in process coupling, closure assumptions, and initialization
- Restored 1<sup>st</sup>-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



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### 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. Physicsdynamics 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 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 









### **Control (deterministic)**

**Ensemble forecasts** with Ito correction

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### **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.



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## **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

### d improved cal consistency

## **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

