Improving Numerical Robustness and Physical Consistency of Atmospheric Physics Parameterizations

Background and Motivation

In DOE's global atmosphere model, EAM

- time integration errors in the physics parameterizations (sub-grid models) are found to be orders of magnitude larger than those in the dynamical core (fluid dynamics solver)
- those errors decrease with time step at a rate substantially slower than expected

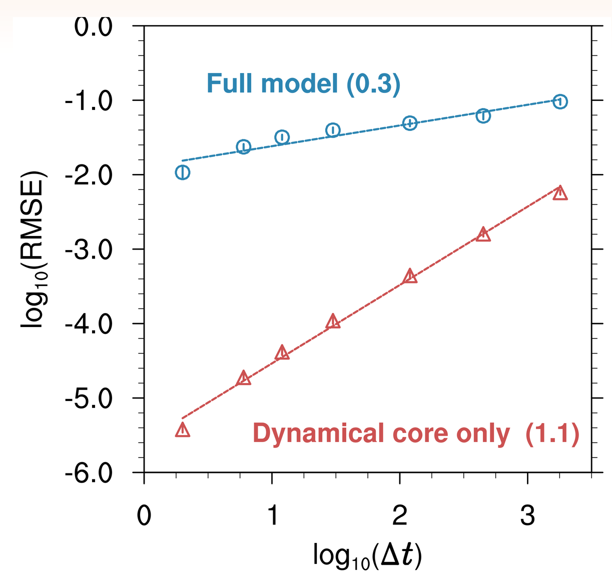

Figure 1. Time integration error and solution self-convergence in 1 h simulations using EAMv1.

The goals of this work are to

- understand the root causes of poor convergence
- improve the time integration to achieve better numerical accuracy

Impacts and Next Steps

- Investigation in time-step convergence has led to improved numerical robustness and physical consistency in the atmosphere model
- Code modifications that improve convergence turn out to have substantial impact on the model's long-term climate (i.e., they matter for both mathematicians and climate scientists)
- Process splitting (coupling) has been found to have major impacts on solution convergence and accuracy. Our future work will focus more on such coupling. Examples include the coupling between clouds, radiation, and aerosols; boundary layer and surface fluxes

Resolving Convergence Issues in a Simplified Cloud Parameterization

- We used a version of EAM containing the dynamical core and a simplified but still representative cloud parameterization.
- **A priori error analysis** indicates the expected convergence rate and reveals necessary conditions for convergence.

Equation:

$$\frac{dy}{dt} = \underbrace{D(y)}_{dynamics} + \underbrace{\frac{y}{f(y)}\frac{df}{dt}}_{physics}$$

Time integration error:

$$|e_n| \leq |\tilde{e}_0| e^{(t_f-t_0)K} + \frac{e^{(t_f-t_0)K}-1}{2K}\left[\|y''\|_\infty + 2\|DP_y\|_\infty\right]\Delta t,$$

$$\|DP_y\|_\infty = \left\| D\left(\frac{y}{f^2}f_y f_t + \frac{y}{f}f_{yt} + \frac{f_t}{f}\right)\right\|_\infty,$$

- **Causes of poor convergence** are identified (i.e., unphysical choices of process splitting and sub-grid distribution assumptions). New splitting and sub-grid reconstruction methods not only restore convergence but also significantly affect long term climate in the full model.

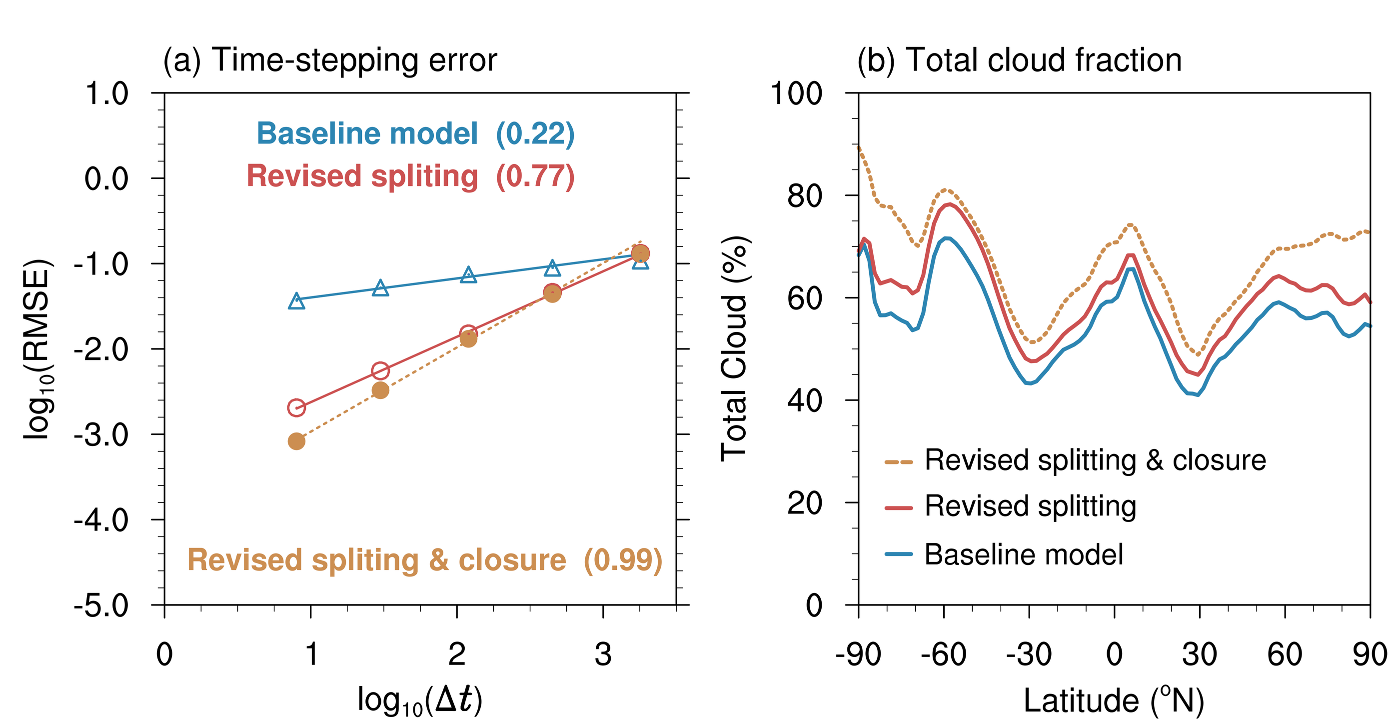

Figure 2. (a) Time integration error and solution self-convergence in 12 h simulations in the simplified model. (b) Multi-year mean zonal mean cloud fraction corresponding to different process splitting schemes and sub-grid distribution assumptions.

Improving Convergence in EAM's Turbulence Parameterization

- Convergence tests helped to identify code bugs in EAMv1

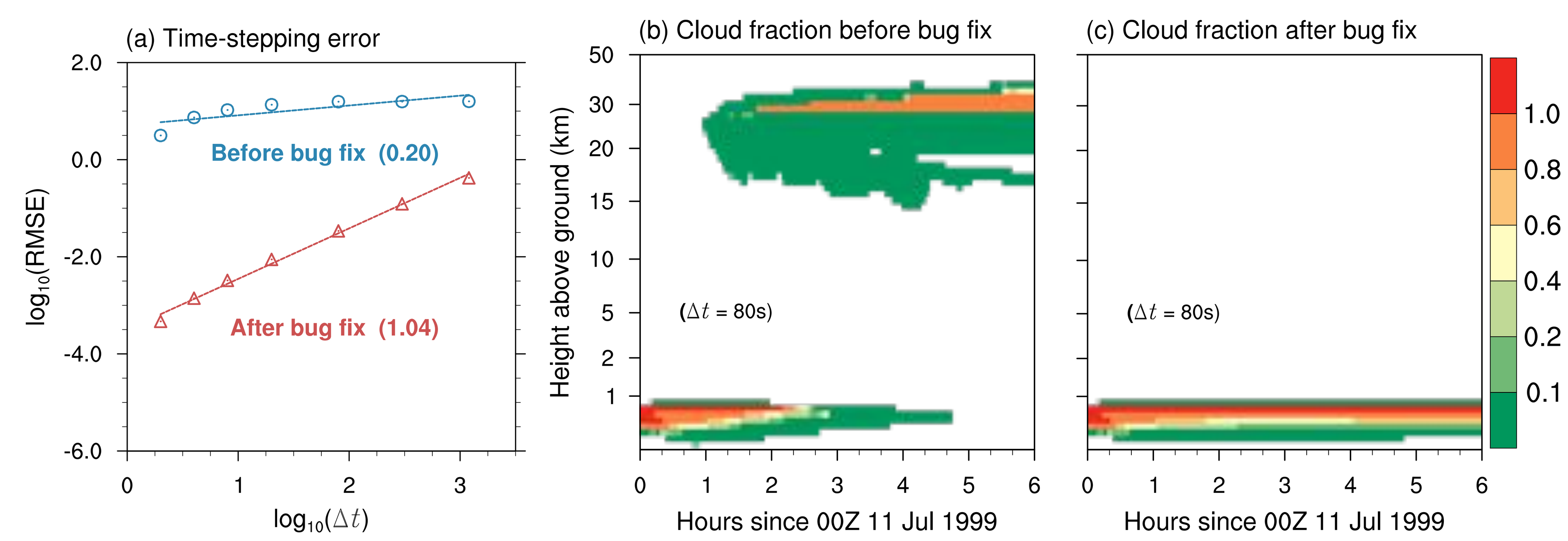

Figure 3. (a) Time-stepping error after 1 h in a stratocumulus case (DYCOMS RF02) simulated by the EAMv1 single-column model. (b), (c): Time evolution of cloud fraction during a 6 h period in simulations with Δt = 80s before and after bug fix.

- Revised model initialization helped to improve convergence in global simulations. The sensitivity points to possible singularities and discontinuities in the numerical solution. Root causes of this behavior are under investigation.

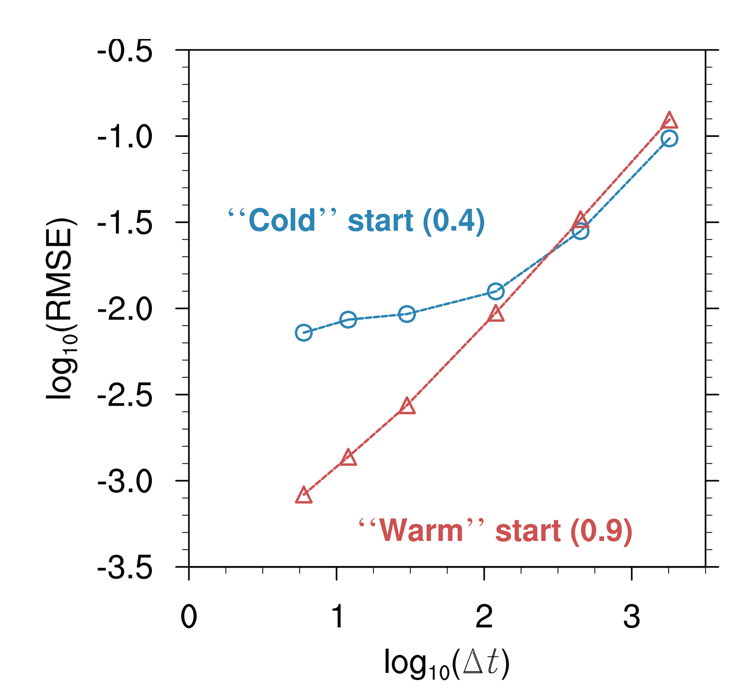

Figure 4. Time-stepping error and solution self-convergence after 1 h in global simulations using EAMv1.

The team: Carol S. Woodward[1], Hui Wan[2], Shixuan Zhang[2], Chris Vogl[1], Vince Larson[3], Panos Stinis[1], Phil Rasch[1], Xubin Zeng[4]

Affiliations: [1]LLNL, [2]PNNL, [3]U. Wisconsin – Milwaukee, [4]U. Arizona

This work is part of the SciDAC project " *Assessing and Improving the Numerical Solution of Atmospheric Physics in E3SM* "