Assessing and Improving the Numerical Solution of Atmospheric Physics in E3SM

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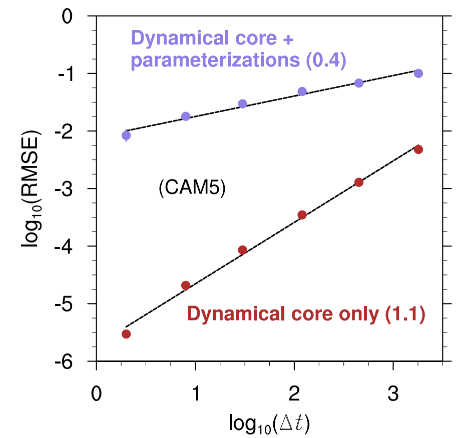
SciDAC PI Meeting, July 2018

The Challenge

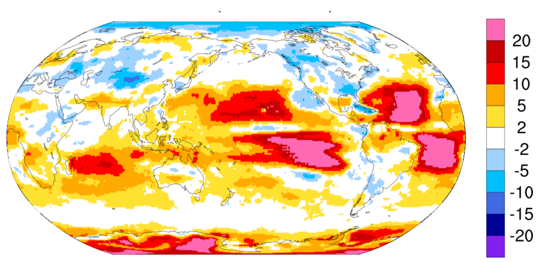
- Poor time-step convergence in EAMv1 and several predecessors
- Accuracy contrast between full-model and dynamical-core-only results

- Implications
  - Poor convergence ➔ code is not doing what it is supposed to do
  - Strong time-step sensitivity ➔ change in step size can lead to physically significant changes in model climate

Time Stepping Error and Self-convergence Rate in E3SMv0



Multi-year Mean Boreal Summer Cloud Fraction Change Caused by Reduction of Time Step Size (5 min – 30 min) in E3SMv0



The Challenge, cont'd

- Poor time-step convergence in EAMv1 and several predecessors
- Accuracy contrast between full-model and dynamical-core-only results

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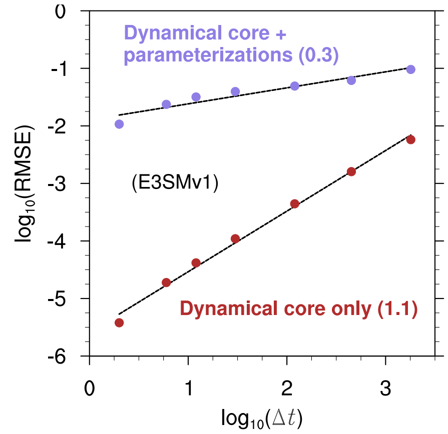
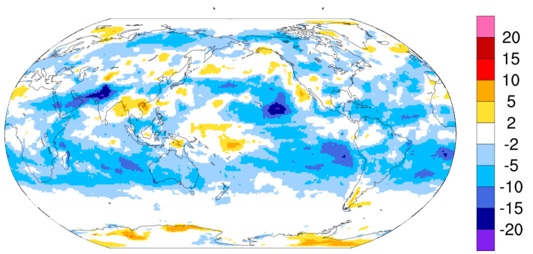
- Atmospheric physics parameterizations
  - Traditional focus on conceptualization of physical understanding
  - Practical motivations to use long step sizes
  - Unit testing and verification are rarely done

Time Stepping Error and Self-convergence Rate in E3SMv1



Multi-year Mean Boreal Summer Cloud Fraction Change Caused by Reduction of Time Step Size (5 min – 30 min) in E3SMv1



Objectives

- Understand causes of poor convergence
- Develop alternative time integration methods to improve solution convergence and accuracy

Our Approach

- Use short ensemble tests to assess solution convergence
- Use a hierarchy of simplified model configurations/formulations to pinpoint problematic model components and code pieces
- Conduct formal mathematical analysis on model formulation and discretization error
- Develop alternative time integration methods using theories of deterministic and stochastic differential equations.

Highlights of First Results

A (not-so-)Simple Cloud Model

- E3SM's dynamical core + cloud formation through large-scale condensation
- Simplified model formulation
  - Facilitates math-climate collaboration
  - Captures essence of commonly used assumptions

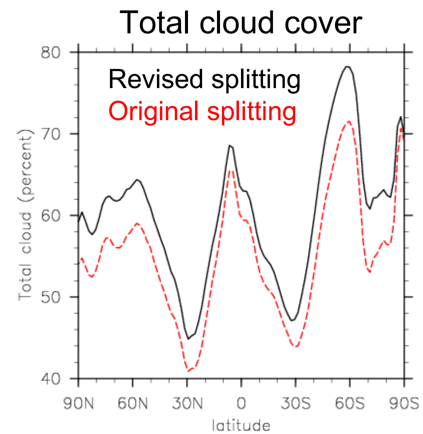
Progress

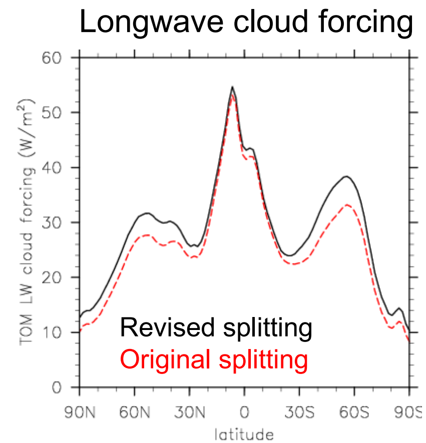
- Restored 1st-order convergence
- Demonstrated loss of convergence due to suboptimal choices made for
  - Model's continuous formulation
  - Physics-dynamics coupling (splitting)
  - Time stepping within physics

Key message to atmosphere modelers:

- Proper convergence is achievable and impactful (see figure)

Mean climate in full-model simulations with CAM4 physics





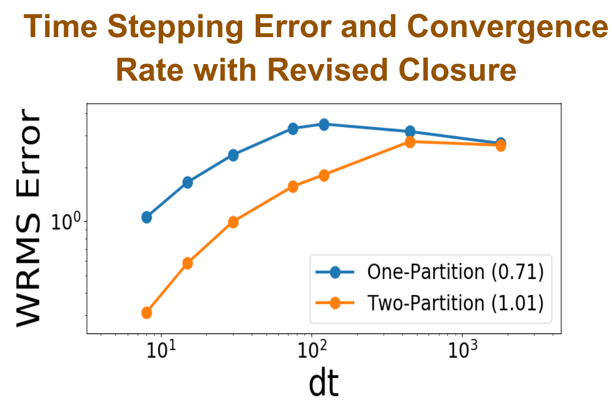
A (not-so-)Simple Cloud Model, cont'd

- Formal error analysis
  - Assuming a two-process integration scheme with/without sequential splitting and finite difference approximations

$$|e_n| \leq |\tilde{e}_0|e^{(t_f-t_0)K} + \frac{e^{(t_f-t_0)K}-1}{2K}\left[\|y''\|_\infty + \|f''\|_\infty + 2K_{f_y}\|DF\|_\infty + 2K_D\|f_yF\|_\infty + 2\|D^2 f_{yy}\|_\infty\right]\Delta t$$

  - Confirmed the expected rate of convergence (1st-order)
  - Clarified the necessary conditions for achieving such a rate
  - Verified failure of model to meet necessary conditions

- Revised closure
  - Avoids the singularity that caused problem in the original model
  - Shows good convergence
  - Is less sensitive to unphysical features in initial condition

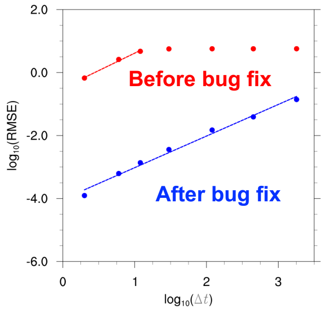


E3SM's Cloud Parameterization — CLUBB

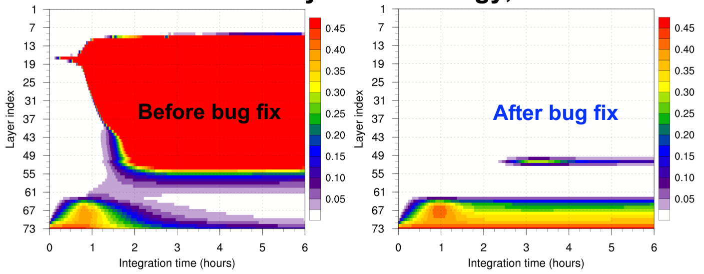
- Comprehensive parameterization of clouds and turbulence
- Convergence slower than 1st-order in E3SM
- Investigation still in early stage

- Currently using single-column configuration to help detangle process interactions and pinpoint issues
  - A significant bug in the single-column model was identified and fixed
  - Pathological behavior not obvious at default time step but prominent at smaller step sizes
  - Bug fix does not affect global simulation, nevertheless demonstrates the value of convergence testing as a good verification tool

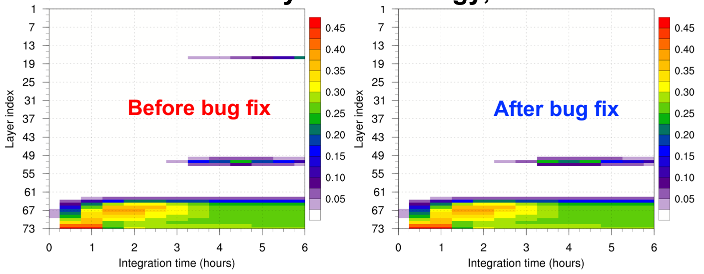
Time-stepping error and self-convergence rate in single-column model



Evolution of eddy kinetic energy, Δt = 1 s



Evolution of eddy kinetic energy, Δt = 1800 s



Exploring Stochastic Modeling

Background:

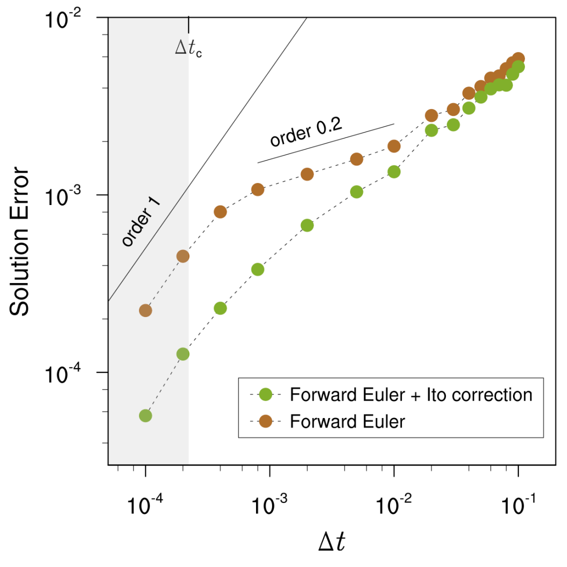
- Sub-grid process are usually fast
- Under-resolved fast processes can appear as noise in solution and affect convergence (Hodyss et al., 2013, Mon. Wea. Rev.)

Goal: Represent the effect of fast processes without explicitly resolving them

Progress:

- Configured an advection-diffusion model with a spectrum of state-dependent fast forcing
- Demonstrated use of Ito correction to restore convergence for white forcing spectra
- Generalized Ito correction for red spectra; improved solution convergence and accuracy
- Started to configure more complex and realistic test problems

Time-stepping Error in Advection-Diffusion Model with a Red Spectrum of Fast Forcing



BER-ASCR Partnership

How We Work Together

- A very integrated project by design
- Tasks are split but also dependent on each other

- Frequent in-depth discussions by teleconferences and on Confluence
- Overcome barriers between two disciplines through team tutorials
    - A task by itself in proposal, 11 tutorials delivered to date
    - Explanation of key concepts/methods and common practices on either side
    - Allow for basic questions and free discussion during and after each tutorial
    - All slides and recordings placed on Confluence for future reference

- Team members learning and using methods/tools from the other side, e.g.
    - Math people running and revising E3SM
    - Atmosphere modelers doing derivations

- Language barrier is still a challenge. Additional tutorials and focused discussions are planned to address that

Lessons Learned

- Math people can go deep in to a physics problem…
  …but only when sufficient documentation is provided
  What we mean by "sufficient"
  - Clear explanation of the physical concept
  - Detailed description of the discretization
  - All assumptions (continuous and discrete) explained
  - All practicalities (clipping, limiters, safeguard parameters) documented

- A culture of verification is lacking in the parameterization development
  - Examples that atmospheric physicists can relate to are needed to help establish the culture
  - It is important to distinguish the first principles, the closures used, and the numerical methods applied
    - Clarifies the goal of verification
    - Avoids the undesirable situation of numerical methods becoming part of the closure.