Assessing and Improving the Numerical Solution of Atmospheric Physics in E3SM

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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
The Challenge, cont’d

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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
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)
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**

\[ |e_n| \leq |\hat{e}_0|e^{(t_f-t_0)K} + \frac{e^{(t_f-t_0)K}}{2K} \left[ \|y''\|_\infty + \|f''\|_\infty + 2Kf_v\|DF\|_\infty + 2K_D\|f_uF\|_\infty + 2\|D^2f_{yu}\|_\infty \right] \Delta t \]

  - 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 — CLUCCB

- 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
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.