# High-order, property-preserving physics-dynamics-grid remap in E3SM

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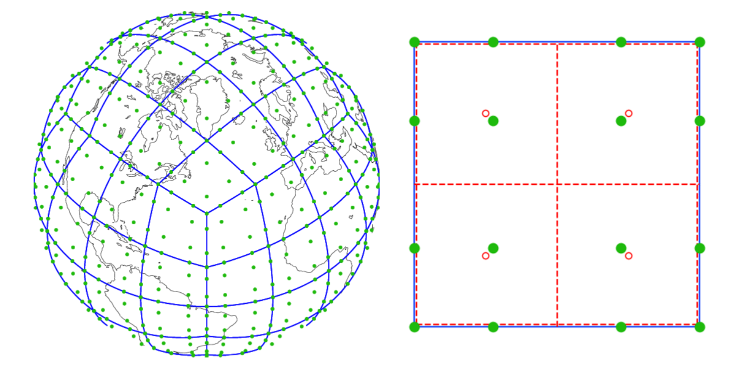
# Overview

- *Computational efficiency*: Solution accuracy for given computational resources.
- Two new methods increase E3SM Atmosphere Model (EAM) computational efficiency:
  - Separate physics parameterizations grid with *physics-dynamics-grid remap* (this talk).
  - Semi-Lagrangian tracer transport.
- Property preserving, to mimic continuum equations:
  - Conserve mass.
  - Limit extrema.
  - Tracer consistent.
- High order: Order of accuracy (OOA) is at least 2.
  - In general, strict property preservation limits formal OOA to 2-3.
- Speed up EAM by roughly $2\times$ roughly independent of architecture and problem configuration.
- Work seamlessly in the Regionally Refined Mesh (RRM) configuration.

# Overview

- Previously: Physics column at each dynamics grid GLL point.
- Many ways to define dycore's effective resolution. All imply assigning a physics column to every GLL point is inefficient.
- New: Physics column at each subcell of a spectral element.
- "`pg2`" has 4/9 as many columns as in EAMv1, better matching the effective resolution.
  - $>2\times$ greater computational efficiency: approximately the same answer for half the cost.



# Remap algorithms

Linear operator requirements:

1. Mass conserving.
2. Remap is local to the element.
3. If $\boldsymbol{d} = A^{p \to d} \boldsymbol{p}$, then $A^{d \to p} \boldsymbol{d} = \boldsymbol{p}$.
4. If $\boldsymbol{p} = A^{d \to p} \boldsymbol{d}$, and $\boldsymbol{d} = \mathcal{I}^{d' \to d} \boldsymbol{d'}$ with $n_{d'} = n_p$, then $A^{p \to d} \boldsymbol{p} = \boldsymbol{d}$.

Rationale:

- Requirement 2 means there is no communication round beyond what is strictly necessary.
- Requirements 3 and 4 specify limited forms of idempotence; these help to minimize dissipation from remap.
- Requirement 4 assures the remap operator has order of accuracy $n_{d'} = n_p$ because an $n_{d'}$-basis-representable field is recovered exactly.

Dynamics $\to$ physics:

- Simply average the GLL density over the physics subcell.
- Call this $A^{d \to p}$.
- Satisfies requirements 1, 2.

Physics $\to$ dynamics:

- $A^{d \to p}$ and requirements 2 and 4 uniquely specify $A^{p \to d}$.
- Satisfies requirement 3.

Nonlinear operator:

- Mass-conserving local limiter.

Communication:

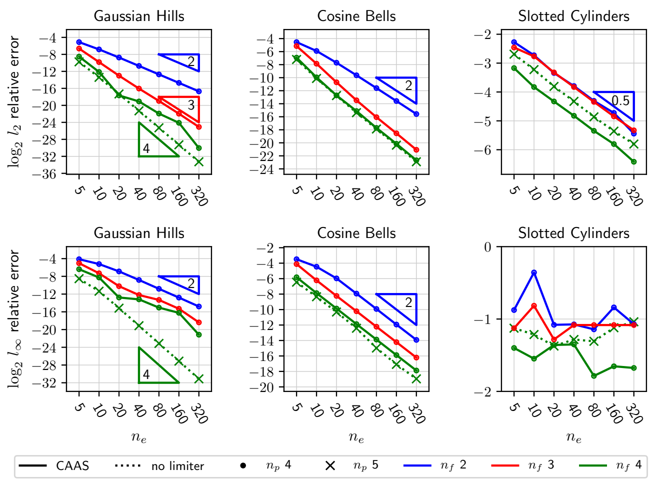
- None in dynamics $\to$ physics remap.
- Physics $\to$ dynamics requires:
  - Limiter: min/max communication round from HOMME.
  - Final DSS to restore continuity.

# Infrastructure

- Tri-grid + physgrid $\Rightarrow$ GLL dual grid is no longer needed.
  - Makes setting up new atmosphere grids much easier.
- Topography:
  - New file format: GLL $\phi$ + FV $\phi$ and subgrid variance data.
  - GLL $\phi$ maps to FV $\phi$.
  - Limiter applied so FV $\phi$ element extrema are bounded by GLL $\phi$ extrema.
  - Tools note:
    - Topography generation was the one other spot the GLL dual grid was used. We don't want to use that grid.
    - Instead, with existing topo tool, map to a pg grid—can be pg4—for example.
    - Then map these FV data to GLL with new tool.
    - Smooth with existing tool.
    - Map smooth GLL $\phi$ to the final pg2 grid with new tool.
- Map types in v2:
  - Conservative, first-order (and so monotone) maps for fluxes and fine-to-coarse state maps.
  - Bilinear interpolation (and so monotone but not conservative) for coarse-to-fine state maps.

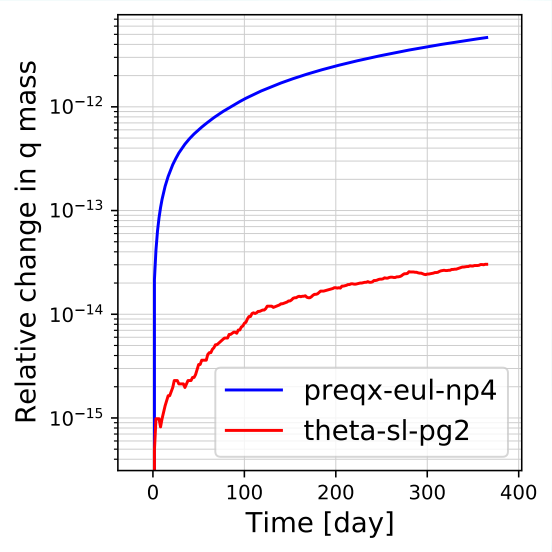
# Convergence test

- Remap a test function from dynamics grid to physics grid and then back.
- Compare error under cubed-sphere grid refinement.



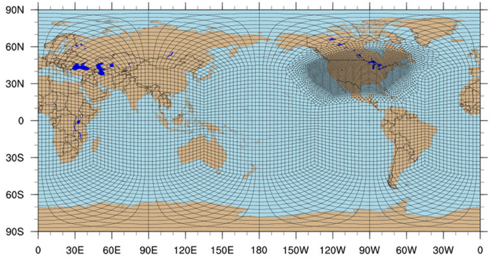
# Mass conservation

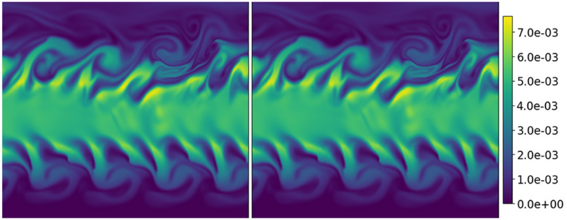
- Mass conservation of a source/sink-less tracer in one year of simulation of an `ne30` F-case.
- Two orders of magnitude better than EAMv1.



# Accuracy

- Works immedately for RRM because the remap methods only use topology data local to the element.
- Example:
  - Specific humidity at approximately 600 hPa on day 25 from DCMIP 2016 Test 1: Moist Baroclinic Instability on the CONUS 1/4-degree RRM grid.
  - Left image shows Eulerian flux-form transport with physics on the dynamics grid.
  - Right image shows SL transport with the pg2 grid configuration.

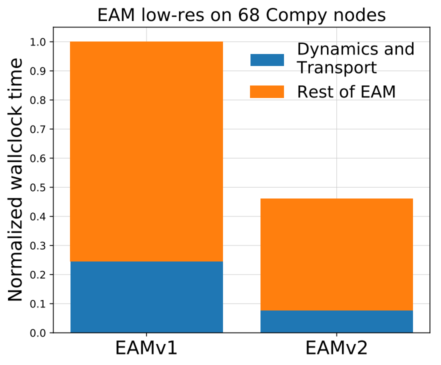


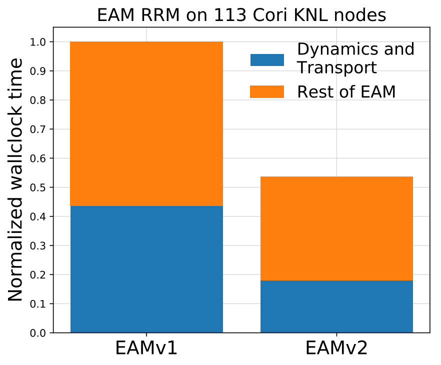



# EAMv2 performance

Max timers for

- `CPL:RUN_LOOP` (total time-stepping time) and
- `CAM_run3` (total dycore time-stepping time).



# Summary

- EAMv2 is roughly 2$\times$ faster than EAMv1 roughly independent of architecture and problem configuration.
- NGD NH Atm. (aka SCREAM) and E3SM-MMF are also using these methods.
- These methods work immediately for RRM.