High-order, property-preserving

*semi-Lagrangian tracer transport*

and *physics-dynamics-grid remap*

in EAMv2

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Overview

- **Computational efficiency**: Solution accuracy for given computational resources.
- Two new methods increase E3SM Atmosphere Model (EAM) computational efficiency:
  - *Semi-Lagrangian tracer transport*.
  - Separate physics parameterizations grid with *physics-dynamics-grid remap*.
- Property preserving, to mimic continuum equations:
  - Conserve mass.
  - Limit extrema: no new nodal value, element-neighborhood-local global extrema.
  - Tracer consistent: A constant mixing ratio remains constant.
- High order: Order of accuracy (OOA) is at least two.
  - In general, strict property preservation limits formal OOA to two.
- Speed up EAM by roughly $2 \times$ roughly independent of architecture and problem configuration.
- Work seamlessly in the Regionally Refined Mesh (RRM) configuration.
In EAMv1, Eulerian flux-form tracer transport is the dominant dynamical core cost.

In EAMv2, switch to a semi-Lagrangian method to take very long time steps per communication round.
SL Transport: Algorithms

- Semi-Lagrangian $\Rightarrow$ very long time steps.
- Remap form $\Rightarrow$ communication volume is roughly independent of time step.
- Interpolation $\Rightarrow$ extremely efficient, both in computations and data volume of discrete domain of dependence.
- Use a *communication-efficient density reconstructor*\(^1\) (CEDR) for mass conservation, limiting extrema, and tracer consistency.
  - Exactly one all-reduce(-like) communication round.
  - Clear and practical necessary and sufficient conditions for feasibility.
  - Clear and practical bounds on mass modifications.
- Implemented using an *upwind communication pattern* to communicate no more than what is needed.
- End-to-end on GPU; currently integrating into HOMMEXX-NH.


Software: [github.com/E3SM-Project/COMPOSE](https://github.com/E3SM-Project/COMPOSE).
Nondivergent flow test case.
- Compare (left) tuned parameters and (right) operational parameters.
- SL transport is uniformly more accurate.

SL Transport: Dissipation

- Eulerian flux-form method requires hyperviscosity for stability.
- SL transport does not.
- But optionally can apply hyperviscosity.
- Example: Specific humidity at approximately 500 hPa, on day 30 in DCMIP 2016 moist baroclinic instability test.

Eulerian flux-form  SL, no hyperviscosity  SL with hyperviscosity
SL Transport: Dycore-only performance

- **preqxDycore** is $>2.1 \times$ faster on **KNL** at 1350 nodes (strong-scaling limit) with SL transport.
- **preqxDycore** is $>3.2 \times$ faster on **Edison** at 3600 nodes (strong-scaling limit) with SL transport.

![Graph showing performance as a function of number of tracers](image1)

- **Cori-KNL HOMME**
- **Cori-KNL HOMME/SL**
- **Edison-IB HOMME**
- **Edison-IB HOMME/SL**

![Graph showing 13km NGGPS Benchmark](image2)

- **Cori-KNL HOMME**
- **Cori-KNL HOMME/SL**
- **Edison-IB HOMME**
- **Edison-IB HOMME/SL**

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Physgrid Remap: 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.
Physgrid Remap: Algorithms

Linear operator requirements:

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

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 \( \rightarrow \) physics:

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

Physics \( \rightarrow \) dynamics:

- \( A^{d \rightarrow p} \) and requirements 2 and 4 uniquely specify \( A^{p \rightarrow d} \).
- Satisfies requirement 3.

Nonlinear operator:

- Mass-conserving local limiter.

Communication:

- None in dynamics \( \rightarrow \) physics remap.
- Physics \( \rightarrow \) dynamics requires:
  - Limiter: min/max communication round from HOMME.
  - Final DSS to restore continuity.
Physgrid Remap: Accuracy

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

![Convergence test of high-order, property-preserving, physics-dynamics-grid remap](image)
Mass conservation of a source/sink-less tracer in one year of simulation of an \( n_{e30} \) F-case.

Two orders of magnitude better than EAMv1.
Together: Accuracy

- 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.
Together: Performance

Max timers for

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

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### EAM low-res on 68 Compy nodes

- **EAMv1**
- **EAMv2**

#### Normalized wallclock time

- **Dynamics and Transport**
- **Rest of EAM**

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### EAM RRM on 113 Cori KNL nodes

- **EAMv1**
- **EAMv2**

#### Normalized wallclock time

- **Dynamics and Transport**
- **Rest of EAM**
Current and future work: Ocean passive tracers for BGC

- Remap-form, property-preserving, cell-integrated, semi-Lagrangian passive tracer transport method\(^3\) for MPAS-Ocean.
- 2D correctness and convergence tests on a global MPAS grid sequence:

\[\begin{array}{cccc}
480\text{km} & 48 \text{ steps} & 240\text{km} & 96 \text{ steps} & 120\text{km} & 192 \text{ steps} & 60\text{km} & 384 \text{ steps} & 30\text{km} & 768 \text{ steps}
\end{array}\]

\[\begin{array}{cccc}
10^{-1} & 10^{-2} & 10^{-3} & 10^{-4} & 10^{-5}
\end{array}\]

\[\begin{array}{cccc}
\text{Rotation} & \text{Divergent flow} & \text{Nondivergent flow}
\end{array}\]

\[\begin{array}{cccc}
\text{none} & \text{limiter} & \text{both} & \text{cedr}
\end{array}\]

\[\begin{array}{cccc}
\text{XYZTrig} & \text{GH} & \text{CB} & \text{SC}
\end{array}\]

\[\begin{array}{cccc}
480\text{km} & 48 \text{ steps} & 240\text{km} & 96 \text{ steps} & 120\text{km} & 192 \text{ steps} & 60\text{km} & 384 \text{ steps} & 30\text{km} & 768 \text{ steps}
\end{array}\]

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10^{-1} & 10^{-2} & 10^{-3} & 10^{-4} & 10^{-5}
\end{array}\]

Current and future work: Ultra-accurate atm. tracers

- *Islet* subpackage of COMPOSE will extend current interpolation formula up to 9th-order accuracy.
- Interpolate velocity data from dycore.
- Remap tendencies between grids.
- Increase accuracy by up to $>100\times$. 

![Gaussian Hills](image1)

![Cosine Bells](image2)

![Slotted Cylinders](image3)
Summary

- EAMv2 is roughly 2× faster than EAMv1 roughly independent of architecture and problem configuration.
- NGD NH Atm. (aka SCREAM) and E3SM-MMF are also using these methods.
- We have developed and are developing a set of high-order, property-preserving remap tools for
  - tracer transport in the atmosphere (v2)
  - physics-dynamics-grid remap in the atmosphere (v2)
  - passive tracer transport in the ocean for BGC (target: v3)
- Library: github.com/E3SM-Project/COMPOSE