Sandia National Laboratories

Algorithms and software for fast tracer transport in E3SM

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Problem

EAM v1 computation time

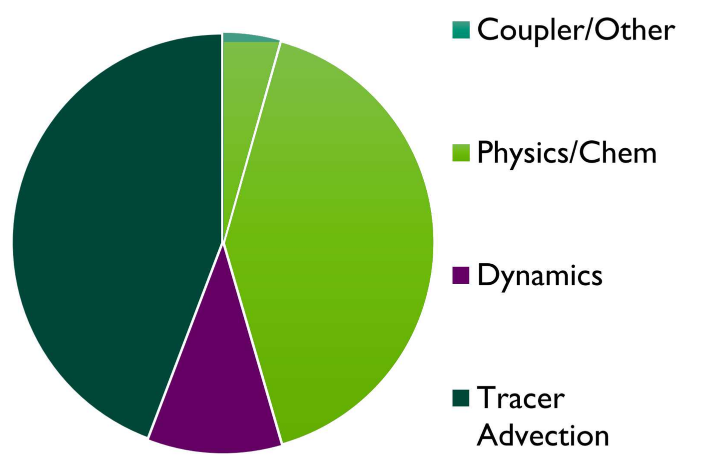


Figure 1. Relative computation time spent in each subcomponent of the E3SM atmosphere model using Eulerian transport, 0.25 deg, 72 levels, 40 tracers.

- National security, energy, water resource mgmt., and land-use missions require accurate regional climate projections.
- Regional climate forecasts require high resolution global simulations and large ensemble sizes for uncertainty quantification.
- Ensembles of high resolution simulations require exascale computing.

Energy Exascale Earth System Model (E3SM)

- High-resolution, performance-portable coupled Earth system model (atmosphere, ocean, land, land ice, sea ice components)
- E3SM's atmosphere model (EAM) requires the most computation; its subcomponents are shown in Figure 1.
- With 40 tracers, the v1 Eulerian spectral element (SE) transport scheme is most costly part of EAM.

Transport schemes

Solve transport equation (1) using density and velocity computed by separate dynamics solver.

$$\frac{\partial(\rho q_i)}{\partial t} + \nabla \cdot (\rho q_i \boldsymbol{u}) = 0 \qquad (1)$$

Requirements:

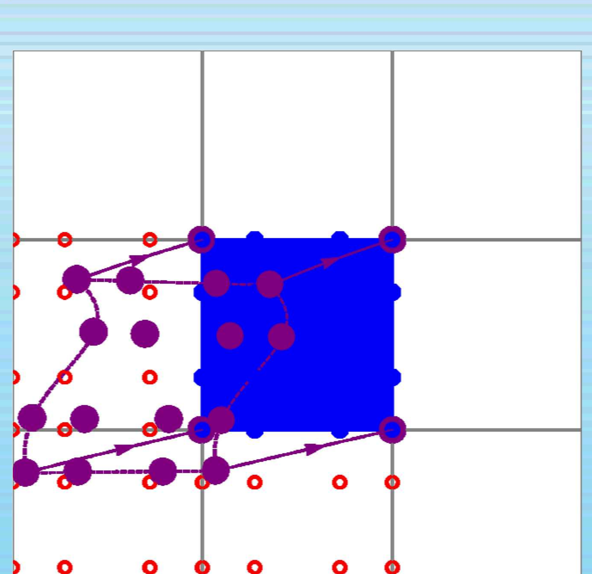
(a) Conserve mass of each tracer species.
(b) Solve (1) accurately.
(c) Preserve shape properties of each tracer species.
(d) Maintain an air density representation consistent with dynamics.
(e) Provide all of the above efficiently using heterogeneous computing architectures.

Approach

Semi-Lagrangian (SL) algorithms for spectral elements

- Large time steps
- Minimize data movement
- **Compact, high order stabilized basis polynomials**
- **Communication-efficient property preservation [1]**
- **"Upwind" MPI comms.**
- **Flexible time step coupling**

Method:	Cell-integrated remap [2]	Pointwise interpolation
Provides:	**(a) Conservation** (b) Accuracy (e) Efficiency (~2x)	(b) Accuracy **(e) Efficiency (~3x)**
	Problem A	**Problem B**
Needs:	(c) Shape preservation (d) Tracer consistency	(a) Conservation (c) Shape preservation (d) Tracer consistency



New to E3SM Master (ready for v2)

- Transport time reduced ~6x (Fig. 2)
- Improved accuracy (Fig. 3)
- New time step coupling (Fig. 4) allows Courant number >> 1.
- Climate validated against EAM v1 (Fig. 5)

Results

EAM/SL computation time

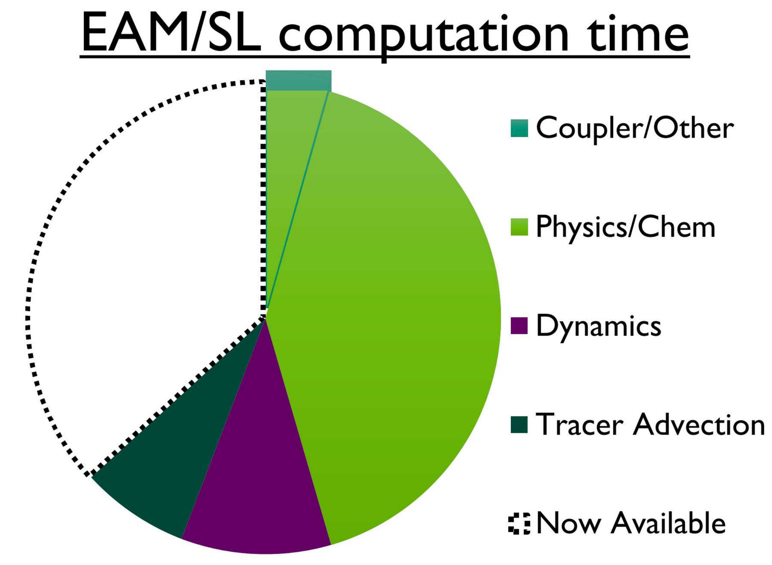


Figure 2. Relative computation time spent in each subcomponent of the E3SM atmosphere model using semi-Lagrangian transport, 0.25 deg, 72 levels, 40 tracers.

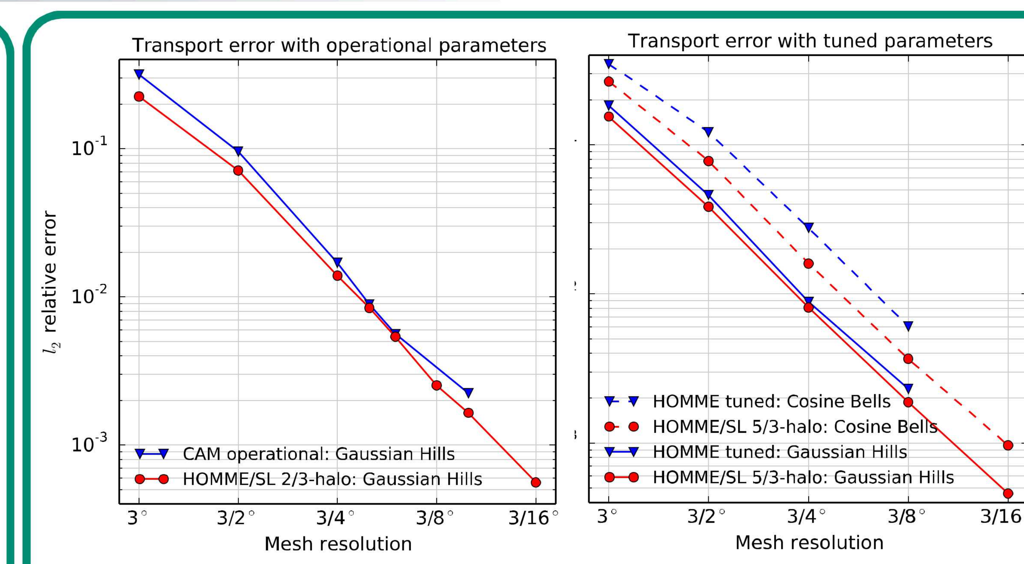


Figure 3. Accuracy comparison of Eulerian SE and pointwise interpolation SL with property preservation. (a) Model parameters tuned for this standalone test; (b) operational parameters. In both cases, the new SL scheme shows improved accuracy.

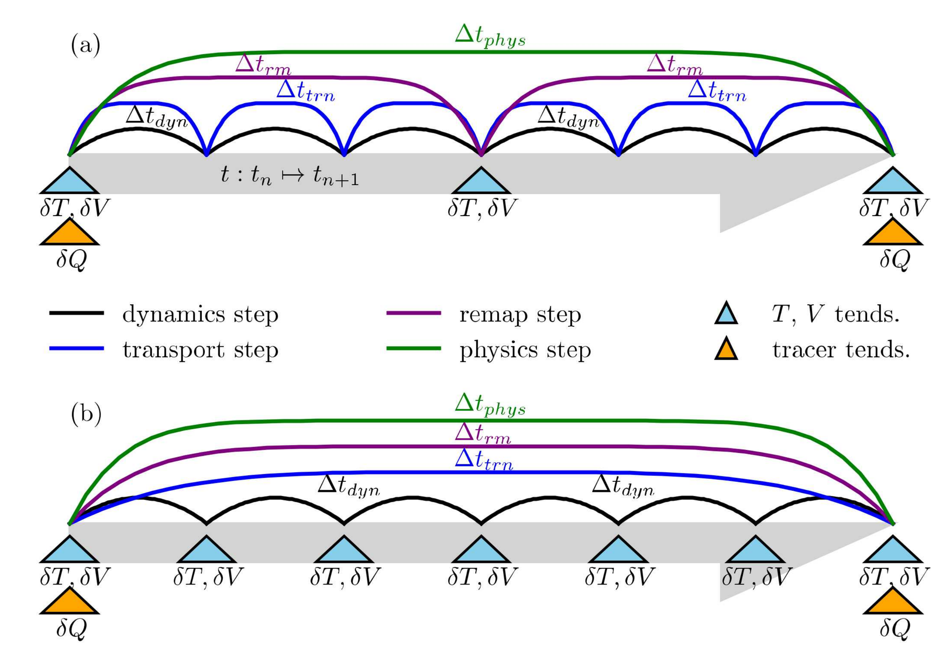


Figure 4. Time step coupling in EAM; light gray arrow depicts a full model time step. In EAM v1 (a), physical tendencies are fixed to remap steps by software restrictions; to support EAM/SL, we decoupled the vertical remap and physical tendencies (b) to permit large tracer time steps.

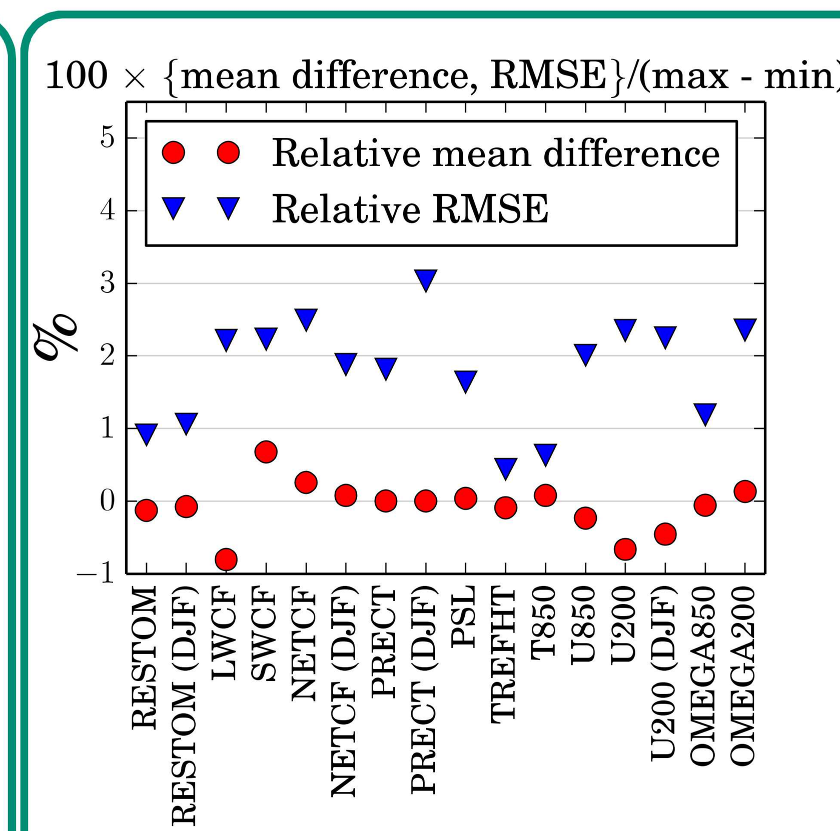


Figure 5. Climate validation results. Standard diagnostics provide mean difference and RMS difference between EAM v1 and EAM with semi-Lagrangian transport. All values are within ±4%.

Significance

Speedup of EAM dycore by ~2-3x (Fig. 6) on node counts ranging from desktops to pre-exascale HPC; **full EAM speedup of ~2x** at scale.

Atm. science no longer constrained by cost of tracer transport (Fig. 7)

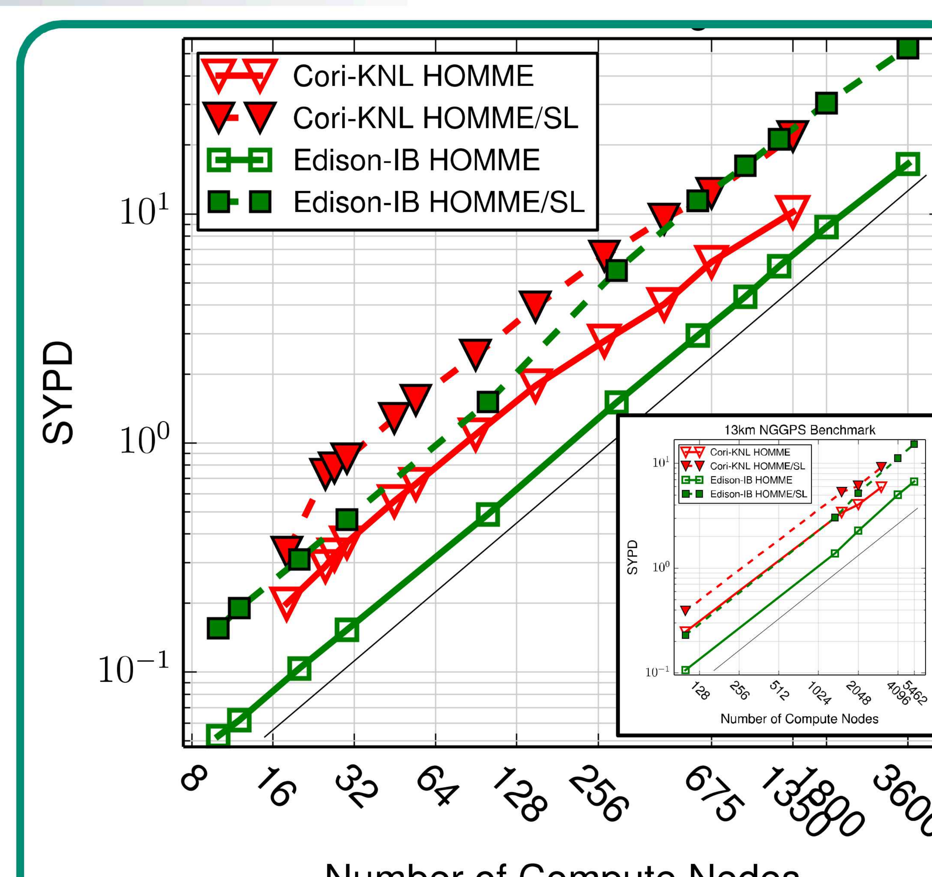


Figure 6. EAM dynamical core (dynamics + transport, no physics) scaling study; simulated years per day (SYPD) vs. number of nodes, 0.25°, 40 tracers. Inset: 0.125°, 10 tracers.

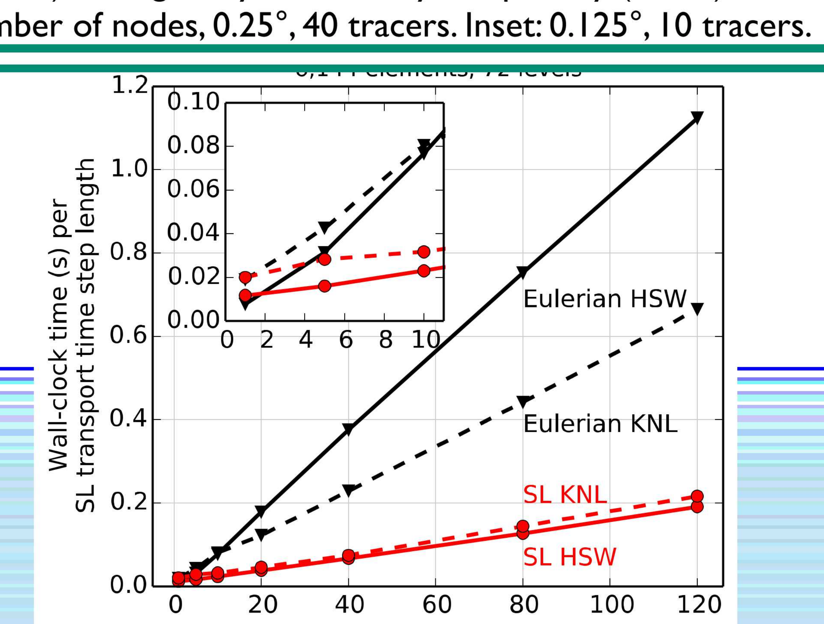


Figure 7. Performance as a function of number of tracers on Haswell and KNL architectures. The SL timestep is 6 times larger than the Eulerian time step.

Publications & software

[1] Bradley, Bosler, Guba, Taylor, Barnett, 2019; Communication-efficient property preservation in tracer transport, *SIAM J. Sci. Comput.*, 41(3), C161—C193.

[2] Bosler, Bradley, Taylor, 2019; Conservative multimoment transport along characteristics for discontinuous Galerkin methods, *SIAM J. Sci. Comput.* (to appear).

[3] Bradley, Guba, Bosler, Taylor, 2019; COMPOSE: Library for communication-efficient property-preserving semi-Lagrangian tracer transport, doi:10.5281/zenodo.2552888; https://github.com/E3SM-Project/COMPOSE

Funding

- Primary: SciDAC4 ASCR/BER pilot project: 1.5 FTE, FY18 — FY23
- Secondary: E3SM NGD, ACME-LEAPT

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