High-order, property-preserving semi-Lagrangian tracer transport and physics-dynamics-grid remap in the E3SMv2 Atmosphere Model

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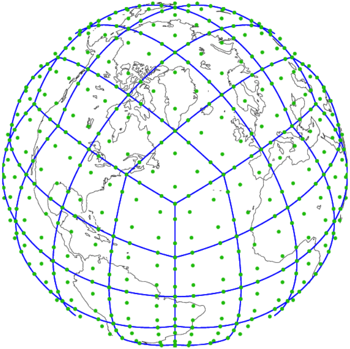
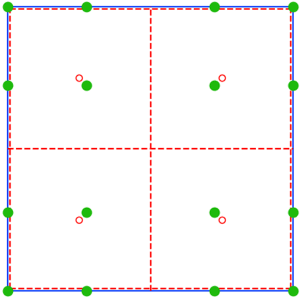
Overview

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

Overview

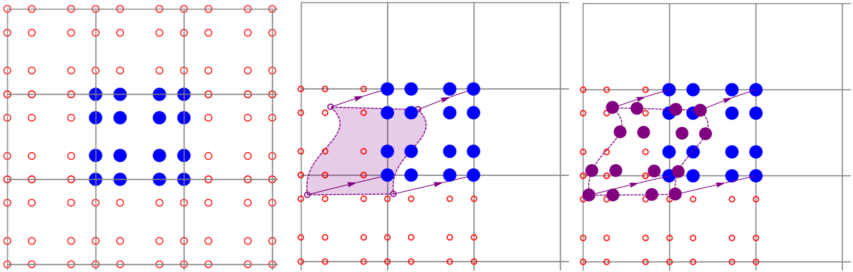
- E3SMv1: Physics column at each dynamics grid GLL point.
- Many ways to define dycore's effective resolution. All imply assigning a physics column to every GLL point is inefficient.
- E3SMv2: Physics column at each subcell of a spectral element.
- "`pg2`" has 4/9 as many columns as in EAMv1, better matching the effective resolution.
  - $>2\times$ greater computational efficiency: approximately the same answer for half the cost.





Tracer transport algorithms

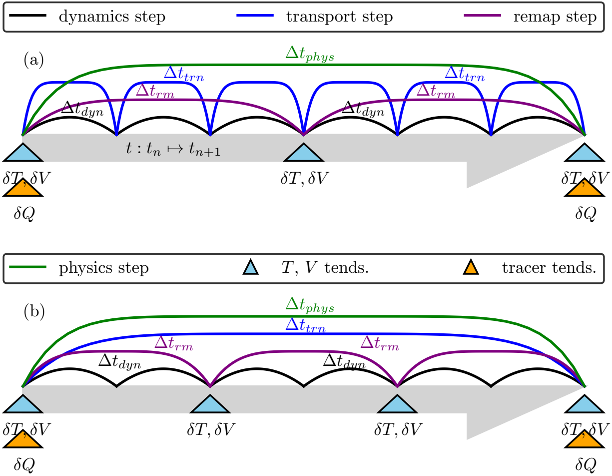
- E3SMv1: Eulerian Spectral Element tracer transport.
- E3SMv2: Semi-Lagrangian $\Rightarrow$ very long time steps.
- Remap form $\Rightarrow$ communication volume is roughly independent of time step.
- Interpolation $\Rightarrow$ extremely efficient, both in computations and data volume of discrete domain of dependence.
- Implementation communicates only partial haloes: no more than what is needed.
- *Communication-efficient density reconstructor* (CEDR) for property preservation.
  - Exactly one all-reduce(-like) communication round.
  - Clear and practical necessary and sufficient conditions for feasibility.
  - Clear and practical bounds on mass modifications.



Tracer transport time stepping

To exceed the dynamics vertical remap time step:

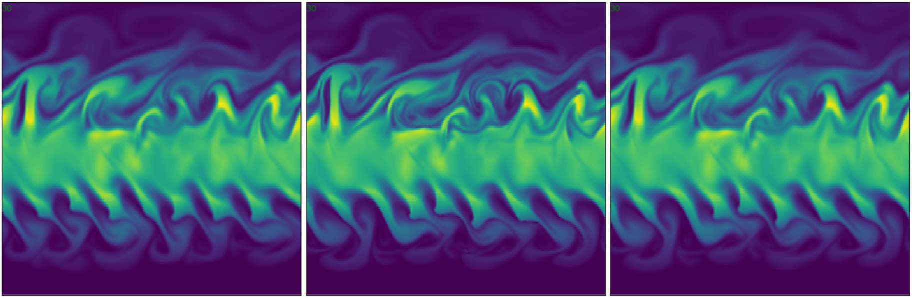
- Reconstruct Lagrangian levels with 2nd-order accuracy.
- Apply 2D advection algorithm within levels.
- Vertically remap to reference levels.
- The CEDR restores properties.



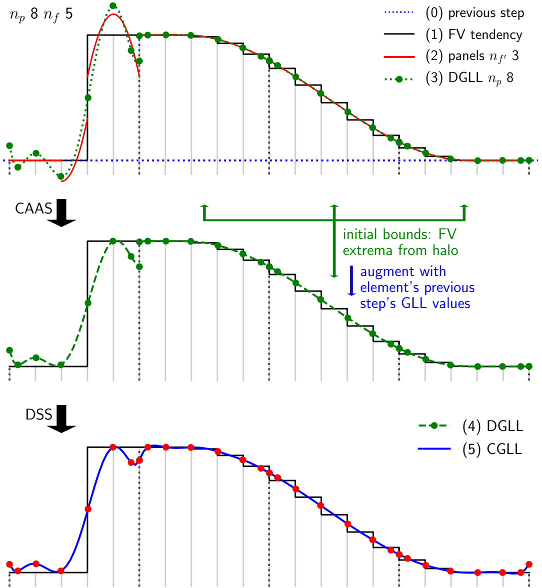
Dissipation

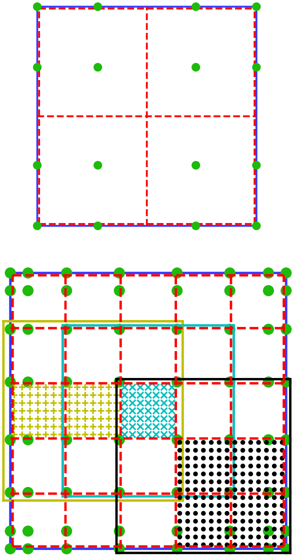
- Eulerian flux-form method requires hyperviscosity for stability.
- SL transport does not.
- But optionally can apply hyperviscosity.
- Example: Specific humidity at approximately 500 hPa, on day 30 in DCMIP 2016 moist baroclinic instability test.

Eulerian flux-form | SL, no hyperviscosity | SL with hyperviscosity



Physics-dynamics grid remap





Figures modified from [PG21]

Physics-dynamics grid remap: Convergence

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

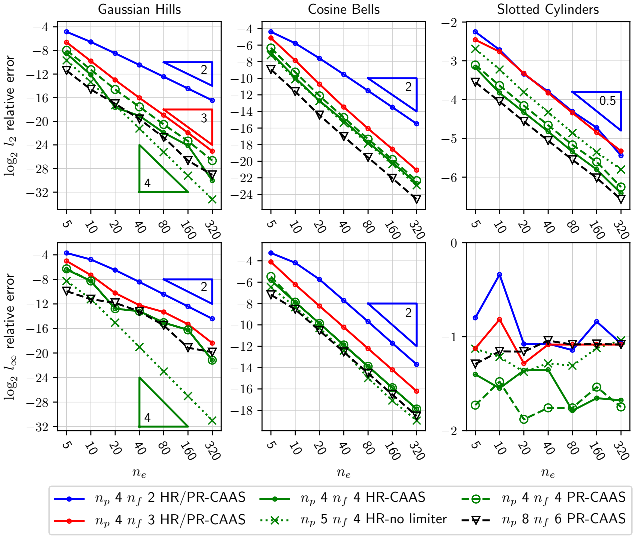
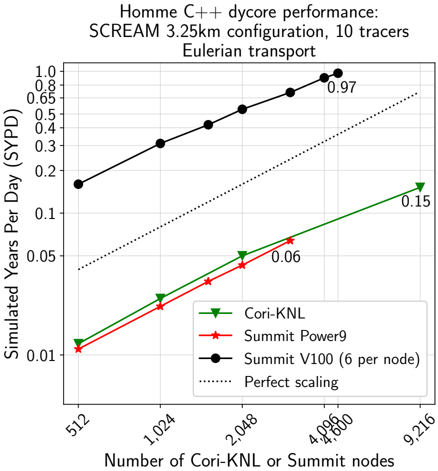
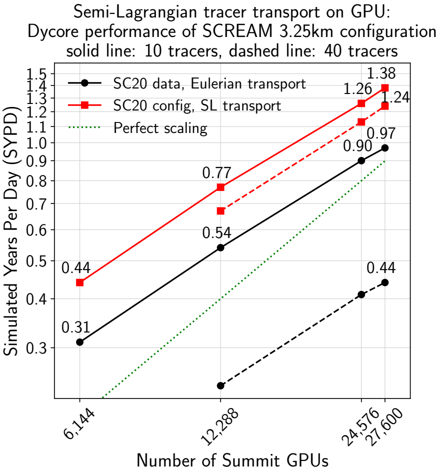


Figure from [PG21]

Performance: C++/Kokkos HOMME

The semi-Lagrangian transport module is available to both the original F90 and new C++/Kokkos dynamical cores. The C++/Kokkos HOMME dynamical core runs on all architectures.

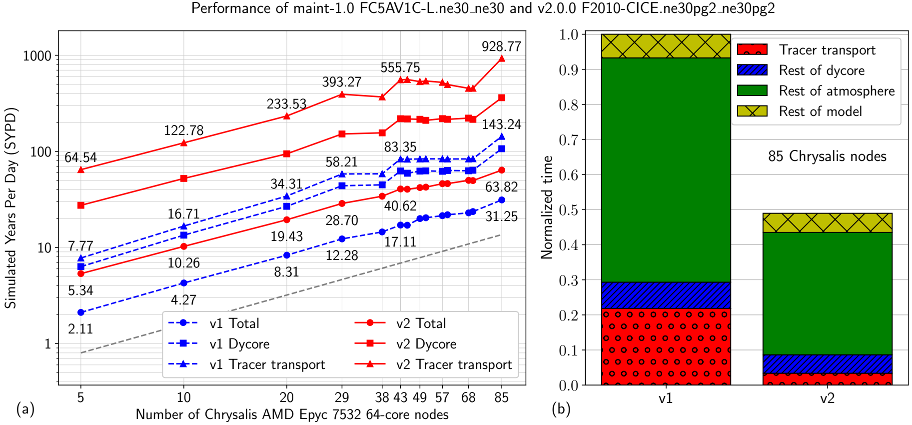




Data from [SC20, ISL21]

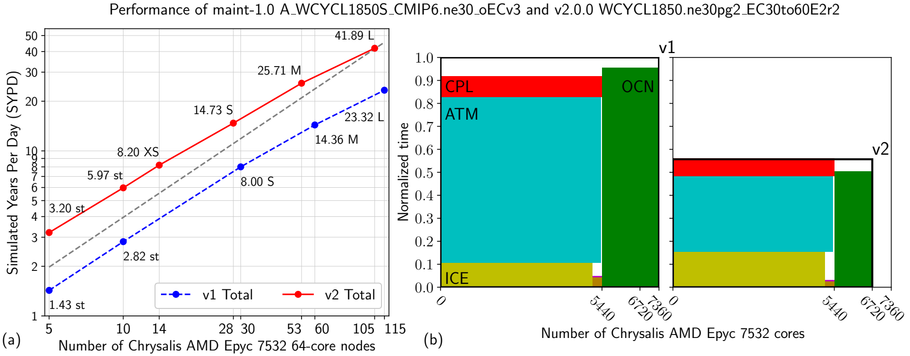
Performance: Atmosphere model

Much of the v2 simulation campaign ran on the ANL LCRC Chrysalis cluster.
Each node has two AMD Epyc 7532 “Rome" 2.4 GHz processors, with 32 cores per processor.
Interconnect: Mellanox HDR200 InfiniBand; fat tree topology.



Performance: Water Cycle coupled model

The standard-resolution coupled model runs at ∼41 SYPD on 105 Chrysalis nodes.
The RRM coupled model runs at ∼12.4 SYPD on 100 Chrysalis nodes.



Summary

- EAMv2 is roughly $2\times$ faster than EAMv1 roughly independent of architecture and problem configuration.
- The Simple Cloud Resolving E3SM Atmosphere Model (SCREAM) and E3SM-MMF are also using these methods.
- These methods work in Regionally Refined Models.
- For details, see:

CEDR19 Bradley, Bosler, Guba, Taylor, Barnett, *Communication-efficient property preservation in tracer transport*, SIAM J. on Sci. Comput., 2019. `https://doi.org/10.1137/18M1165414`

SC20 Bertagna et al., *A Performance-Portable Nonhydrostatic Atmospheric Dycore for the Energy Exascale Earth System Model Running at Cloud-Resolving Resolutions*, SC20. `https://www.osti.gov/servlets/purl/1818055`

PG21 Hannah, Bradley, Guba, Tang, Golaz, Wolfe, *Separating Physics and Dynamics Grids for Improved Computational Efficiency in Spectral Element Earth System Models*, JAMES, 2021. `https://doi.org/10.1029/2020MS002419`

ISL21 Bradley, Bosler, Guba, *Islet: Interpolation semi-Lagrangian element-based transport*, GMDD preprint, 2021. `https://doi.org/10.5194/gmd-2021-296`.

SCREAM21 Caldwell et al., *Convection-Permitting Simulations with the E3SM Global Atmosphere Model*, JAMES, 2021. `https://doi.org/10.1029/2021MS002544`