Islet: Interpolation Semi-Lagrangian Element-based Transport with *p*-refinement for extremely high-resolution tracer transport

Andrew M. Bradley, Peter A. Bosler, Oksana Guba, Mark A. Taylor
Sandia National Laboratories

Funding: LEAP-T (BER), SciDAC (ASCR and BER), NGD Software and Algorithms
Thanks also to Water Cycle, NGD NH Atm., and Performance Groups

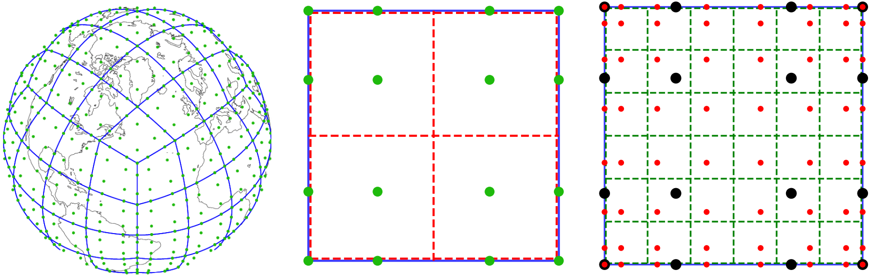
boratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LL
Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE

Overview: E3SMv2

- *Computational efficiency*: Solution accuracy for given computational resources.
- Two new methods together increase the computational efficiency of the E3SM Atmosphere Model (EAM) version 2 (E3SMv2) over version 1 by a factor of approximately two in multiple configurations and on multiple platforms:
  - Interpolation Semi-Lagrangian tracer transport in the Spectral Element dycore.
  - Separate physics parameterizations grid with physics-dynamics-grid remap.
- These are property preserving, to mimic continuum equations:
  - Conserve mass.
  - Limit extrema (shape preservation).
  - Tracer consistent.
- These work seamlessly in the Regionally Refined Mesh (RRM) configuration.
- This talk focuses on extensions to these algorithms to produce
  - an extremely high-resolution tracer transport method, with free parameter n_p^t,
  - and a physics parameterizations grid, with free parameter n_f,
  - coupled to a standard dynamics grid ($n_p^v = 4$).
- The stable time step and number of communication rounds are independent of n_p^t and n_f.
- n_p^t and n_f can be spatially variable.

Islet method: Three grids

Three point grids that share one element grid represent dynamics, tracer transport, and subgrid physics parameterizations.

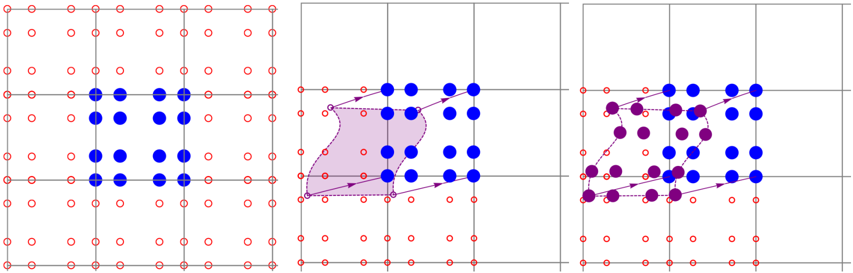


EAMv2 (middle) has the same dynamics and tracer transport grids: $n_p^v = n_p^t = 4$, $n_f = 2$.
The Islet method supports three grids: e.g., $n_p^v = 4$, $n_p^t = 8$, $n_f = 6$ (right).

The dynamics time step depends on n_p^v and so is unaffected. The physics and tracer time steps need not change.

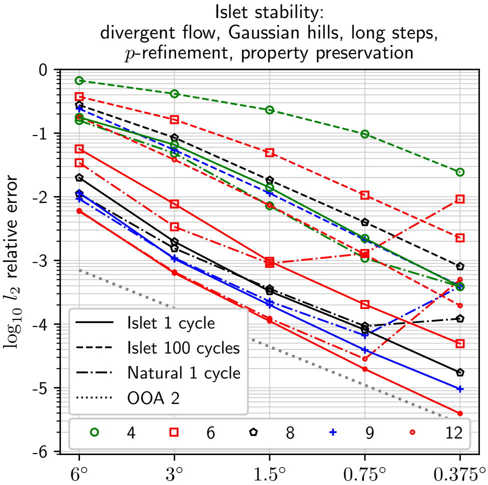
Figures from [PG21], [ISL21]

Our Semi-Lagrangian method computes trajectories backward in time and interpolates data from the Eulerian source grid to the target Lagrangian grid.



Semi-Lagrangian tracer transport: Stability

An ISL method that uses the natural spectral element interpolation basis for $n_p \geq 4$ is unstable. We develop new bases that yield a stabilized method.



Test problems are from Lauritzen, Skamarock, Prather, Taylor: A standard test case suite for two-dimensional linear transport on the sphere, Geosci. Model Dev., 5, 2012.

Figure from [ISL21]

Islet bases: Modified interpolation bases

We construct nested subsets of potential bases and develop search procedures to find bases in two of these subsets that satisfy stability, accuracy, and other conditions.

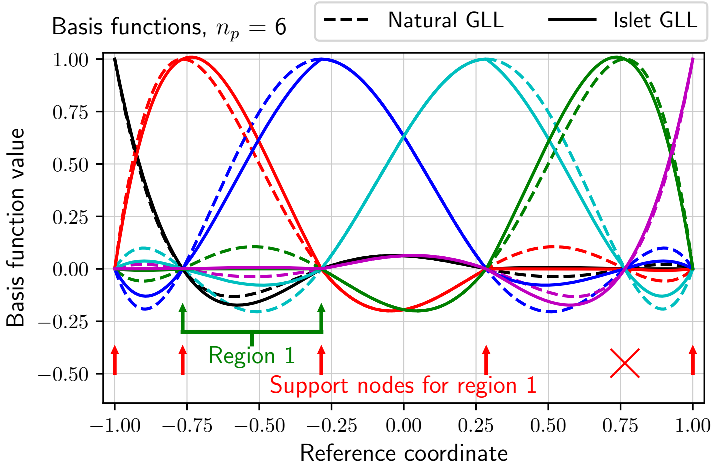
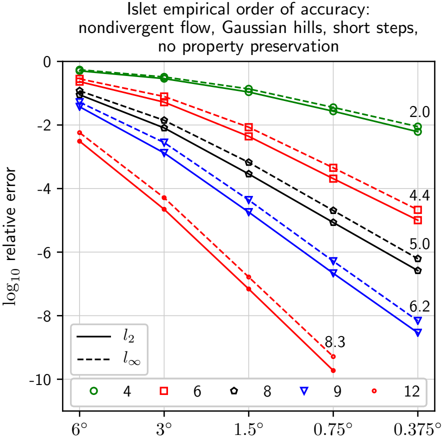


Figure from [ISL21]

Order of accuracy

We find bases having order of accuracy up to 9 (up to 8 shown here) when shape preservation is not applied.

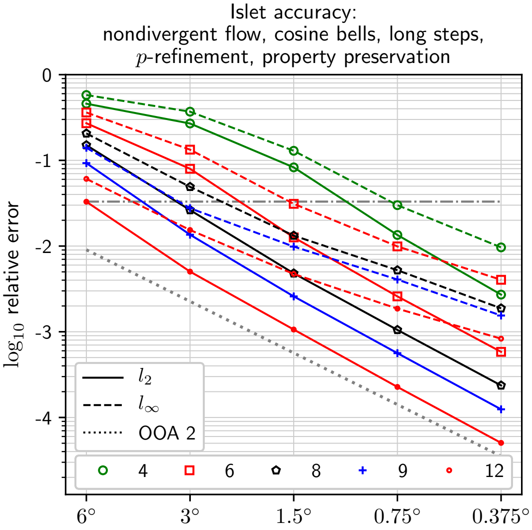


All test problems are run on a cubed-sphere element grid. Resolution is in terms of the np4 grid. Only this test—to reveal full order of accuracy—computes velocities on the tracer grid.

Figure from [ISL21]

Accuracy

The initial condition is C^1. Velocity is computed on the np4 dynamics grid. Property preservation is on.



1.5° corresponds to ne20np4.

Figure from [ISL21]

Filament preservation

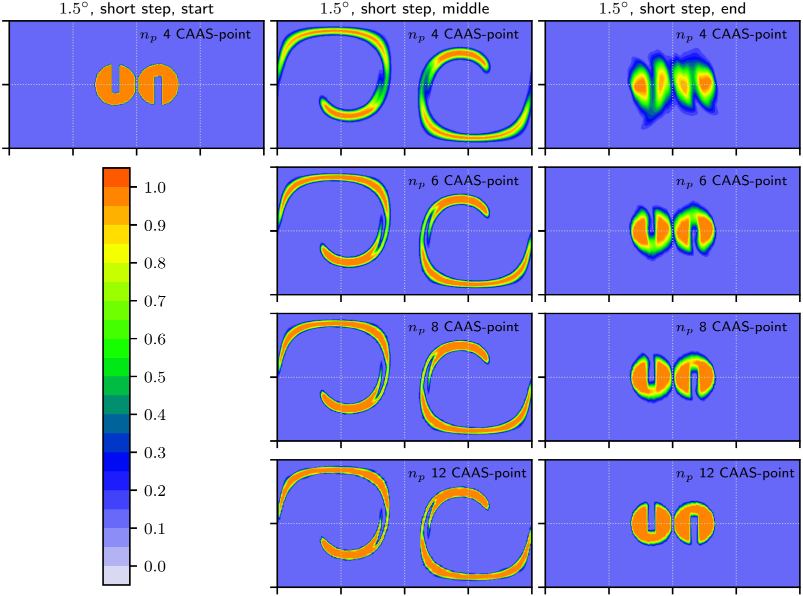


Figure modified from [ISL21]

Mixing diagnostic

This test assesses preservation of nonlinear correlation in two tracers. Perfect correlation corresponds to staying on the upper curve.

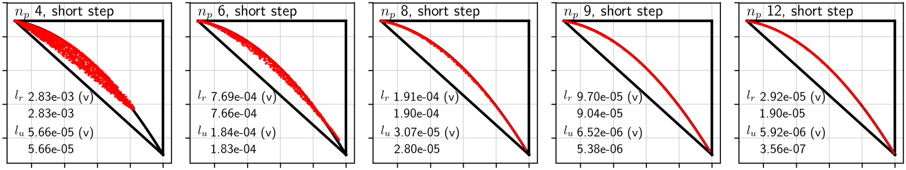
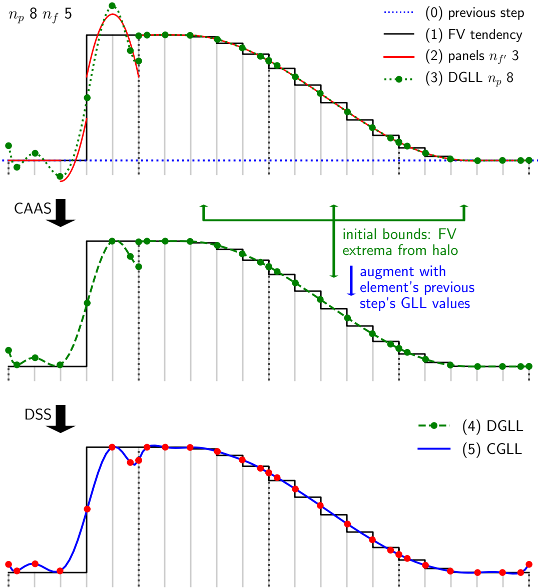
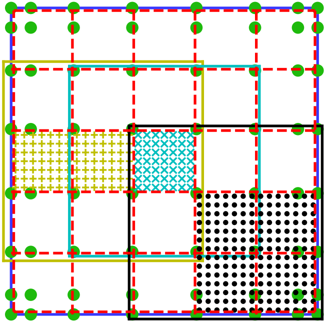


Figure from [ISL21]

Physics-dynamics grid remap

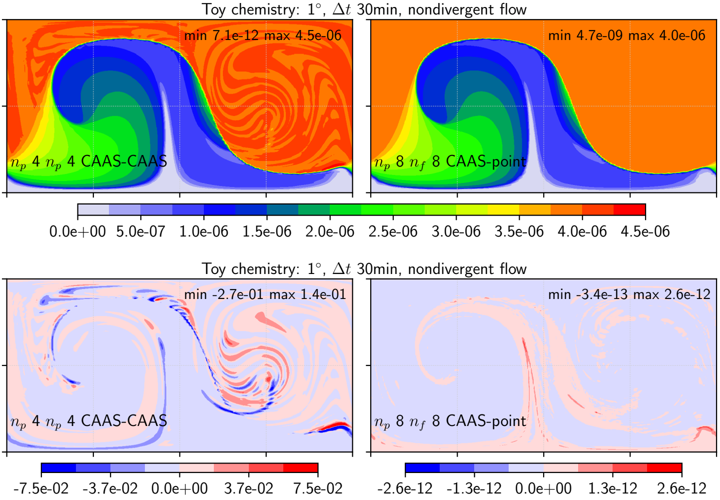




Figures modified from [PG21]

Toy chemistry problem

Tracer transport in both E3SM versions 1 and 2 performs poorly on the *toy chemistry problem*. The Islet method performs well.



Test problem from Lauritzen et al.: The terminator “toy" chemistry test: a simple tool to assess errors in transport schemes, Geosci. Model Dev., 8, 2015.

Figures from [ISL21]

Summary

- We described an atmosphere horizontal grid configuration having
  - one element grid,
  - three point grids with two new parameters n_p^t and n_f that control accuracy,
  - and a stable time step independent of n_p^t and n_f.
- The property-preserving Interpolation Semi-Lagrangian method for element-based transport (Islet) uses newly derived bases satisfying stability and accuracy criteria.
- The transfer of fields between grids is also property preserving.
- The methods run seamlessly in Regionally Refined Mesh 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`

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`.