CAM-SE Dynamics Update: Separating Physics-Dynamics Grids, Tracers, ...

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Continuous Galerkin finite-element method (Taylor et al., 1997) on a cubed-sphere:

- Discretization is mimetic => mass-conservation & total energy conservation
- Conserves axial angular momentum very well (Lauritzen et al., 2014)
- Support static mesh-refinement and retains formal order of accuracy!
- Highly scalable to at least O(100K) processors (Dennis et al., 2012)
- AMIP-climate competitive with CAM-FV (Evans et al., 2012)

Low computational throughput for 1 degree horizontal resolution at “low” processor counts compared to CAM-FV

Lower computational throughput for many-tracer applications

Issues with spinning up coupled simulations (can we blame the dynamical core?)
Continuous Galerkin finite-element method (Taylor et al., 1997) on a cubed-sphere:

- On Yellowstone, CAM-SE is faster than CAM-FV when more than approximately 2100 processors are used
- Users do not necessarily use many processors & it may be hard to get large jobs through the queue on high performance computing systems (“cultural” change needed?)

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A way to accelerate tracer transport: CSLaM scheme (Conservative Semi-Lagrangian Multi-tracer)

Finite-volume Lagrangian form of continuity equation for $\psi = \rho, \rho \phi$:

$$\int_{\Lambda_k} \psi_{k}^{n+1} \, dx \, dy = \int_{\alpha_k} \psi_{k}^{n} \, dx \, dy = \sum_{\ell=1}^{L_k} \left[ \sum_{i+j \leq 2} c_{\ell}^{(i,j)} \omega_{k,\ell}^{(i,j)} \right],$$

where weights $\omega_{k,\ell}^{(i,j)}$ are functions of the coordinates of the vertices of $\alpha_{k,\ell}$.

$\omega_{k,\ell}^{(i,j)}$ can be re-used for each additional tracer (Dukowicz and Baumgardner, 2000)
computational cost for each additional tracer is the reconstruction and limiting/filtering.
CSLAM is stable for long time-steps (CFL>1)

A way to accelerate tracer transport: CSLaM scheme (Conservative Semi-Lagrangian Multi-tracer)

- Highly scalable (Erath et al., 2012)
- Inherently mass-conservative
- Fully two-dimensional
  -> accurate treatment of weak singularities, e.g., cube corners
  -> can be implemented on various spherical grids (cubed-sphere, icosahedral, ...)
- Shape-preserving (no negatives, no spurious grid-scale oscillations)
- Preserves linear correlations (even with shape-preservation) – see next slide!
- Current version is 3rd-order accurate for smooth problems
- Allows for long time-steps (limited by flow deformation not Courant number)
- Multi-tracer efficient (high start-up cost but “cheaper” for each additional tracer):

For every 30 minute physics time-step at 1 degree resolution:

- SE performs 6 tracer time-steps with 5 Runga-Kutta stages => 30 MPI calls
- CSLAM performs 2 tracer time-steps (CN<1) => 2 MPI calls

That said, CSLAM needs a larger halo than SE.

CSLAM implemented in NCAR-DOE HOMME (High-Order Methods Modeling Environment) by Erath et al., (2012); CAM-SE “pulls” SE dynamical core from HOMME
The terminator ‘toy’-chemistry test: A simple tool to assess errors in transport schemes
(Lauritzen et al, 2015, GMDD)
See: http://www.cgd.ucar.edu/cms/pel/terminator.html

Non-linear Terminator ‘toy’ chemistry:
\[ Cl_2 \rightarrow Cl + Cl : k_1 \]
\[ Cl + Cl \rightarrow Cl_2 : k_2 \]

Exact solution: \[ Cl + 2*Cl_2 = \text{constant} \]

Wind field: Nair and Lauritzen deformational flow

Errors are due to non-conservation of linear correlations usually caused by the limiter and/or physics-dynamics coupling!
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- CSLAM uses a “finite-volume”-type grid and SE uses a quadrature grid
Separating physics and dynamics grids in models based on Galerkin methods may not be a “bad” thing!
Atmospheric state passed to physics is at quadrature points:

- Leads to an-isotropic “sampling” of atmospheric state
- High-order basis functions can be oscillatory and are least smooth near element boundaries:
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**Held-Suarez with topography**
Atmospheric state passed to physics is at quadrature points:

- Leads to an-isotropic “sampling” of atmospheric state
- High-order basis functions can be oscillatory and are least smooth near element boundaries.

Note that physics grid averages/moves fields away from boundary of element where the solution is least smooth (in element interior the polynomials are $C^\infty$).
Mapping variables from dynamics to physics:

Integrate atmospheric state (basis functions) over control volumes: **Conservation** and **consistency** (=preservation of a constant) is enforced via a least squares projection onto the space of conservative and consistent maps. *Ullrich and Taylor* (2015)

**Interpolation matrix can be pre-computed**

Lauritzen modification: optimally blend linear map (shape-preserving) with high-order map to provide less diffusive map

![Graph showing element boundaries and interpolation matrix](image-url)
\[2 + \cos(\text{lat})\]

**NE5NP4**

(a) 2+cos(lat)

(b) Default map: difference

(c) 1\textsuperscript{st}-order map: difference

**NE5NP4NC3**

Dynamics: Spectral element

Tracer Advection: CSLAM

Conservation, Semi-Lagrange, multitracer efficient algorithm using cell averaged data

Physics: cell averaged data

Resolution: 6 degrees
Similar method: first-order map that is shape-preserving, conservative and consistent. 
_Ullrich and Taylor_ (2015)
CAM-SE-CSLAM
combining the best of two worlds: high-order spectral dynamics & finite-volume transport

Lander and Hoskins (1997): only pass “believable” scales to physics!
3.2. Cubed-sphere grid models

The assessment includes two dynamical cores that are based on the PPM algorithm that is third-order (Holland and Hakim 1998). An example of a two-dimensional extension is the smallest grid cell area in the domain. The assessment includes two dynamical cores that are based on the Lin and Rood (1996) method but adapted to non-orthogonal cubed-sphere grids (Putman and Lin 2009). Apart from the vertical coordinate the CAM dynamical cores are similar to CAM versions on cubed-sphere grids. The advection scheme is based on the Lin and Rood (1996) method but adapted to non-orthogonal cubed-sphere grids (Putman and Lin 2009). Spectral elements are a type of continuous finite element method (Hesthaven and Warburton 2008) where the advection scheme is used with coefficient of 0.05 × ∆FV. In-
Held-Suarez with topography

Dry dynamics test case: physics package replaced with simple boundary friction and relaxation of T towards zonally symmetric profile
CAM4 Aqua-planet simulations

Idealized surface: no land (or mountains) + specified zonally symmetric sea surface temperatures => free motions, no forced component

Zonal-time averaged total precipitation rate

Data mapped to 1° regular lat-lon grid

PRECT (30 month simulation - 6h data)

Data mapped to 3° regular lat-lon grid
Last step(s) towards CAM-SE-CSLAM: coupling mass

In this presentation I am excluding the massive rewrite of CAM history to allow for the separation of physics and dynamics grids as well as other software engineering tasks needed for adding new capability to the CAM code base

(done by Steve Goldhaber, NCAR)
We are trying to couple to distinct numerical methods (has not been done before!) under the following constraints:

- Mass-conservation and shape-preservation
- Consistency: when mixing ratio is =1 the tracer mass must reduce to the SE mass

Coupling the same method on the same grid but with different time-steps for air mass and tracer mass is widely used (e.g., CAM-FV, CAM-SE, ...):

\[(\rho q)^{n+1} = (\rho q)^n + \langle q^n \rangle \sum_{i=1}^{ksplit} \Delta \rho^{n+i/ksplit}\]
Flux-coupling with CAM-SE-CSLAM:

STEP 1: flux-form version of CSLAM (Harris et al., 2011) – DONE but being rewritten for efficiency and code clarity

STEP 2: implied fluxes through CSLAM control volumes from SE

Received code from Sandia O(week) ago (thanks to Overfelt and Taylor 😊)

For CAM-SE it can be shown that the change in mass within each element is given by a natural flux at each element edge (Taylor and Fournier, 2010). Taylor, Ullrich and Overfelt have recently extended this result to hold for CSLAM control volumes.

Unforeseen issue:
STEP 1 & 2 yields mass-conservation and consistency or consistency and shape-preservation. We need all three! What is the problem? Swept areas implied by CSLAM and SE may have different signs (when u,v are small)
Last step(s) towards CAM-SE-CSLAM: coupling mass

STEP 3: replace trajectory algorithm based on \((u,v)\) with trajectories based on swept areas implied by SE

"CSLAM mass completely slave to SE"!

Straight forward for dimensionally split schemes but not for fully 2D schemes such as CSLAM.

Problem:
Given SE mass flux through each cell wall, find swept areas so that air mass integrated over swept areas equals SE flux while union of the swept areas span the sphere.

Analytical upstream grid
Equivalent perpendicular y-flux
Departure grid based on fluxes
More information: http://www.cgd.ucar.edu/cms/pel
Email: pel@ucar.edu