Preparing CAM-SE for multi-tracer applications: CAM-SE-CSLAM

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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 on element
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 similar to current workhorse CAM-FV (Evans et al., 2012)
Computational throughput for many-tracer applications
A way to accelerate tracer transport:

CSLaM scheme (Conservative Semi-Lagrangian Multi-tracer)

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

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

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

\( \omega_{k \ell}^{(i,j)} \) 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 3\textsuperscript{rd}-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):

CSLAM implemented in NCAR-DOE HOMME (High-Order Methods Modeling Environment) by Erath et al., (2012); CAM-SE “pulls” SE dynamical core from HOMME

MPI communication

For every 30 minute physics time-step
- SE performs 6 tracer time-steps with 5 Runga-Kutta stages => 15 MPI calls
- CSLAM performs 2 tracer time-steps (CN<1) => 2 MPI calls

That said, CSLAM needs a larger halo than SE.
The terminator ‘toy’-chemistry test: A simple tool to assess errors in transport schemes

(Lauritzen et al, 2014, GMDD)
See: http://www.cgd.ucar.edu/cms/pel/terminator.html

Non-linear Terminator ‘toy’ chemistry:

\[ \text{Cl}_2 \rightarrow \text{Cl} + \text{Cl} : k_1 \]
\[ \text{Cl} + \text{Cl} \rightarrow \text{Cl}_2 : k_2 \]

Exact solution:

\[ \text{Cl} + 2^{\ast} \text{Cl}_2 = \text{constant} \]

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/tracer and dynamics grids with 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:
Current physics-dynamics coupling

Atmospheric state passed to physics is at quadrature points:

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- High-order basis functions can be oscillatory and are least smooth near element boundaries:

  **Held-Suarez with topography**
“Equal-area” physics grid

Integrate atmospheric state (basis functions) over control volumes using mass-conservative, shape-preserving and consistent algorithm by *Ullrich and Taylor* (2014; submitted)

Note that physics grid averages/moves fields away from boundary of element where the solution is least smooth (in element interior the polynomials are $C^\infty$)
Lander and Hoskins (1997): only pass “believable” scales to physics!

**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!

**Coarser physics grid**

**Finer physics grid**

**Tracers**

**Physics**

**u, v, T, p**

**Cam-SE-CSLAM**

development on cubed-sphere grids. The finite-volume cubed-sphere model (GEOS-3) is a cubed-sphere grid model. The third-order is given by subtracting the external-mode damping coefficients. In contrast to CAM, the GEOS-3 model applies no digital or FFT versions of CAM. Like CAM, the GEOS-3 version of CAM uses a 3-layer sponge. In ISEN, the cubed-sphere grid is based on central angles. The angles are chosen to form an equal-distance grid at the cubed-sphere edges (undocumented). The equal-distance grid is similar to an equidistant cubed-sphere grid that is expanded on cubed-sphere grids. The standard Space Flight Center. The advection scheme is developed at the Geophysical Fluid Dynamics Laboratory (GFDL) and the NASA Goddard Space Flight Center. The advection scheme is a type of a continuous finite element method (HOMME) (Thomas and Loft 2004, Nair et al. 2009). Spectral elements are a type of a continuous Galerkin method with polynomial order. Rather than using cell averages as prognostic variables as in physics, the spectral element method uses polynomials to represent the prognostic variables inside each element. The spectral element method is elementwise mass-conservative (to avoid the properties of the divergence, gradient and curl operators, the spectral element method is used with coefficients. In JAMES-D, the spectral element method uses a 3-layer sponge. In ISEN, the cubed-sphere grid is based on hexagons and pentagons. The hexagonal grid.

3.2. Cubed-sphere grid models

The assessment includes two dynamical cores that are based on the PPM algorithm that is third-order is given by subtracting the external-mode damping coefficients. In contrast to CAM, the GEOS-3 model applies no digital or FFT versions of CAM. Like CAM, the GEOS-3 version of CAM uses a 3-layer sponge. In ISEN, the cubed-sphere grid is based on central angles. The angles are chosen to form an equal-distance grid at the cubed-sphere edges (undocumented). The equal-distance grid is similar to an equidistant cubed-sphere grid that is expanded on cubed-sphere grids. The standard Space Flight Center. The advection scheme is developed at the Geophysical Fluid Dynamics Laboratory (GFDL) and the NASA Goddard Space Flight Center. The advection scheme is a type of a continuous finite element method (HOMME) (Thomas and Loft 2004, Nair et al. 2009). Spectral elements are a type of a continuous Galerkin method with polynomial order. Rather than using cell averages as prognostic variables as in physics, the spectral element method uses polynomials to represent the prognostic variables inside each element. The spectral element method is elementwise mass-conservative (to avoid the properties of the divergence, gradient and curl operators, the spectral element method is used with coefficients. In JAMES-D, the spectral element method uses a 3-layer sponge. In ISEN, the cubed-sphere grid is based on hexagons and pentagons. The hexagonal grid.
3.2. Cubed-sphere grid models

The assessment includes two dynamical cores that are based on the PPM algorithm that is third-order. An example of a two-dimensional extension volume implementation (i.e., the Lin and Rood, 1996, hexagonal grid. (c) icosahedral grid based on hexagons and pentagons. The Figure 3: (a) The latitude-longitude grid, (b) the cubed-sphere grid based on an equi-angular central projection and contrast to CAM towards the model top to de

is the smallest grid cell area in the domain.

The strength of the divergence damping increases to non-orthogonal cubed-sphere grids (Putman and Lin 2007, 2009). Like CAM version of CAM to di
e

Coarser physics grid

tracers

u,v,T,p

tracers

Coarser physics grid

Lander and Hoskins (1997): only pass “believable” scales to physics!

CAM-SE-physgrid
Held-Suarez with topography
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 towards CAM-SE-CSLAM: coupling mass

Conventional flux-form tracer-mass coupling: air sub-cycled with respect to tracers

(a) SE density flux (sub-cycled)

(b) CSLAM mixing ratio “flux”

\[(\rho q)^{n+1} = (\rho q)^n + \langle q^n \rangle \left[ \sum_{i=1}^{ksplit} \Delta \rho^{n+i/ksplit} \right] \]

Spectral element fluxes across CSLAM control volumes are needed:

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 and Ullrich have recently extended this result to hold for CSLAM control volumes.
More information: http://www.cgd.ucar.edu/cms/pel
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