Physics-Dynamics Coupling with Galerkin methods: Equal-Area Physics Grid

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Workshop on Physics-dynamics coupling in geophysical models – bridging the gap
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Getting away from the lat-lon grid ...

CAM=NCAR’s Community Atmosphere Model

CAM-FV (finite volume)
Lin (2004)

CAM-SE (spectral elements)
Dennis et al., (2012)

- Scalability
- Static mesh-refinement capability
- ...
CAM-SE (spectral element dynamical core); (Dennis et al., 2012)

CAM-SE uses a continuous Galerkin finite element method (Taylor et al., 1997) referred to as Spectral Elements (SE):

- **Physical domain**: Tile the sphere with quadrilaterals using the gnomonic cubed-sphere projection
- **Computational domain**: Mapped local Cartesian domain
- **Each element operates with a Gauss-Lobatto-Legendre (GLL) quadrature grid**
  - Gaussian quadrature using the GLL grid will integrate a polynomial of degree $2N - 1$ exactly, where $N$ is degree of polynomial
- **Elementwise the solution is projected onto a tensor product of 1D Legendre basis functions**
  - by multiplying the equations of motion by test functions; weak Galerkin formation
  - all derivatives inside each element can be computed analytically!
• Computational grid: 3 elements, 4 quadrature points in each element (np=4)
• This quadrature will integrate polynomials of degree 3 exactly
• Note: quadrature points are duplicated on element edges
• Let the initial condition for GLL point values be a degree 3 polynomial.
• Let the initial condition for GLL point values be a degree 3 polynomial
• The polynomial basis exactly represents initial condition
• Within each element the dynamical core advances one Runga-Kutta step
• Note each element advances the solution in time independently
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• Note each element advances the solution in time independently
• Discontinuities may develop at element edges – averaging at element edges
- This process is repeated for every Runge-Kutta stage (currently 5 times per dynamics time-step)
- Physics is “run on GLL grid”
• Physics update: say it perturbs one point value
• Physics update: say it perturbs one point value
• **Polynomial basis changed in element 2**
• **Basis functions only C⁰ at element edges – typically where noise appears**
CAM-SE dynamical core properties

- Discretization preserves adjoint properties of divergence, gradient and curl (mimetic)
  -> CAM5.2 conserves moist energy
  -> Machine precision mass-conservation (at the element level)

- Option to run with Eulerian finite-difference discretization (CAM5.2) in the vertical and floating Lagrangian vertical coordinates (CAM5.3)

- Supports static mesh-refinement (and retains formal order of accuracy)

- Conserves axial angular momentum very well (Lauritzen et al., 2014)

- CAM-SE is hydrostatic

How do we couple the dynamical core with sub-grid scale parameterizations (physics)?
Traditionally physics and dynamics grids are collocated

- smoothly varying grid in terms of grid size
- Much higher resolution near poles, however, dynamical core usually has filter in the polar regions to filter out small scales
- Aside: Lat-lon grid is “optimal” for minimizing zonal flow errors! ... when grid is no longer aligned errors get rather large ....
Jablonski steady-state test case

Lauritzen et al. (2010; JAMES)

Surface pressure (hPa) at day 9 for models based on a regular latitude-longitude and cubed-sphere grids for different rotation grid rotated at the angle Figure 1: Lauritzen et al. high resolution reference solutions (JW06). Other idealized and convergence can be established based on an ensemble of for the baroclinic wave test and therefore the 'exact' solution provided the model utilizes a hydrostatic or non-hydrostatic flow. An analytic solution exists for the steady-state test case performance of the model and its ability to retain a balanced of a steady-state solution and a baroclinic wave resulting from additions suggested in this paper are schematically explained in the latitude circles throughout the domain. The grid rota-
tional grid lines at a slantwise angle. Therefore the contrast to flows that predominantly traverse the computa-
tional grid. However, usually the dynamical core should be invariant under rota-
tion where the physical flow remains the same but the computa-
tional grid. Ideally the dynamical cores were suggested by Wedi and Smolarkiewicz (scales) converge to the hydrostatic model reference solutions. White (JOURNAL OF ADVANCES IN MODELING EARTH SYSTEMS 2006a, Staniforth and White (2011)). Global non-hydrostatic models should also be able to Jablonowski test cases somewhat favors regular latitude-
aligned or quasi-aligned with the computational grid in numerical algorithms are less challenged when the flow is aligned with the coordinate lines throughout the global Jablonowski et al. (2009). Apart from its educational aspects the colloquium was entitled Numerical Techniques and was part of the annual National Center for Atmospheric Research (NCAR) in 2008. White solid lines show the regular latitude-longitude grid, (left), that are superimposed upon the rotated coordinate system in geographical coordinates. The white thick lines depict a zonally symmetric flow field. The grid rota-
tional grid is rotated with respect to the physical flow. Where the physical flow remains the same but the computa-
tional grid. Rotated test cases and dynamical core intercomparisons

Jablonskiski steady-state test case
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If you construct control volumes around the quadrature points so that the area of the control volumes equals the Gaussian quadrature weight (times metric term) then a very anisotropic grid results

Gets “worse” with:

- mesh-refined grids
- increasing polynomial order

\( N_p = 4 \)
Figure 1. An orthographic view of the hexahedral grid points used in this study for NSEAM. Six elements on one face in one direction and 8th polynomial order of the basis functions are selected for this study. This horizontal...
Figure 3: (a) The latitude-longitude grid, (b) the cubed-sphere grid based on an equi-angular central projection and (c) icosahedral grid based on hexagons and pentagons. The triangular grids used by models herein are the dual of the hexagonal grid.

Current physics/"coupler" grid

Finite-volume equi-angular gnomonic grid

Separate physics-dynamics grids?
CAM-SE “default” NE30NP4 configuration

Dynamics: Spectral element dynamics on Gauss-Lobatto nodal values (not quite equally spaced at CAM-SE default 4x4, p=3)

Tracer Advection: Spectral element. Locally conservative and monotone on Gauss-Lobatto nodes

Physics: physics columns computed at Gauss-Lobatto nodal values

Slide courtesy of M. Taylor
CAM-SE/CSSLAM physics grid

Dynamics: Spectral element
SE air mass consistently coupled to CSLAM tracers via traditional finite-volume flux-coupling method (implementation in progress)

Tracer Advection: CSLAM Conservative, Semi-Lagrangian, multi-tracer efficient algorithm using cell averaged data

Physics: cell averaged data.

Slide courtesy of M. Taylor

NCAR Earth System Laboratory
CAM-SE physics grid  NE30NP4NC3 configuration

Dynamics: Spectral element

Tracer Advection: Spectral element.

Physics: physics columns computed with cell averaged data. Physics can use a coarser, identical, or finer resolution grid.

Slide courtesy of M. Taylor
Should we run physics and dynamics on the same resolution grids? Coarser? Finer?

Physics: physics columns computed with cell averaged data. Physics can use a coarser, identical, or finer resolution grid

Slide courtesy of M. Taylor
CAM-SE physics grid NE30NP4NC3 configuration

We need to transfer data to and from dynamics-physics grids!!!

Physics: physics columns computed with cell averaged data. Physics can use a coarser, identical, or finer resolution grid.

 Slide courtesy of M. Taylor
CAM-SE  physics grid  NE30NP4NC3 configuration

Notation:

- NE*NE elements on each cubed-sphere panel
- NP*NP quadrature points in each element
  (note quadrature points are duplicated on the element boundary)
- NC*NC physics grid columns in each element

Physics: physics columns computed with cell averaged data.
Physics can use a coarser, identical, or finer resolution grid

Slide courtesy of M. Taylor
Separating physics and dynamics grids was a major software engineering task in CAM – affected many parts of the code:

- history (output)
- initialization/restart
- Some parameterizations assumed grids were collocated
- Initially our results were terrible: it was due to passing updated state from physics to dynamics rather than tendencies (so even if physics did nothing the interpolation truncation errors were “passed” to dynamics …)
Interpolator properties: passing state to physics and returning tendencies to dynamics

- Conservation (coupled climate modeling)
- Shape-preservation (in particular, no negatives)
- Preserve tracer correlations (important for coupling with chemistry)
- Consistent (preserves a constant)
- Other? Total energy?

Implementation constraints/limitations (not “physical” limitations):

- Physics-grid must be a sub-grid of the element
  With some extra software engineering we can relax this constraint!
  (example application: mesh-refinement)

- To reduce MPI communication no halo exchange for physics-dynamics coupling except for boundary exchange at end of interpolation
  (could also be relaxed at the expense of computational cost)
Passing state \((v, T, q, \ldots)\) to physics:
For conservation we interpolate \(dp^*u, dp^*T, dp^*q\)
Passing state \((v, T, q, \ldots)\) to physics:
For conservation we interpolate \(dp*u, dp*T, dp*q\)

Integrate continuous basis functions in each control volume. Conservation and consistency are enforced via a least squares projection onto the space of conservative and consistent maps

!!! this approach is high-order!!!

Ulrich and Taylor (2014, submitted)
Passing state \((v, T, q, \ldots)\) to physics:
For conservation we interpolate \(dp^*u, dp^*T, dp^*q\)

- Interpolation matrix can be pre-computed (it is a linear map)!!!
- After application of interpolation matrix there is a boundary exchange that averages point values on the element boundaries!
- Note: fundamentally different than finite-volume-type remapping where a halo is needed for the reconstruction

Ullrich and Taylor (2014, submitted)
Passing state \((v,T,q,\ldots)\) to physics: basis functions oscillatory!

Given GLL point values, \(U_{j,k}(t) = \{0,0,1,0\}\) for \(k=0,\ldots,3\), the Lagrange “reconstruction” is shown on the Figure below:
Monotonicity is enforced via a two-step procedure.

- instead of the regular FEM basis functions we use a set of monotone basis functions (ones whose range is $[0,1]$).
- This would be sufficient except for the fact that the least squares projection onto conservative/consistent maps could produce some (small) negative values in the mapping coefficients. To fix that problem we then “linearly interpolate” between the conservative/consistent map and the simplest first-order conservative/consistent/monotone map. This has roughly the effect of “borrowing mass” from other GLL nodes within the element.

Ullrich and Taylor (2014, submitted)
Monotone linear map

Potential problem: a monotone linear map that does not have any knowledge of the GLL values (i.e. not flow dependent) can at most be 1\textsuperscript{st} order!

Modification to Ullrich-Taylor algorithm:

Since any linear combination of linear maps is conservative and consistent one may “optimally” blend the maps for shape-preservation (“FCT-like method”)

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Ullrich and Taylor (2014, submitted)
“FCT” version of Ullrich-Taylor algorithm

\[ A_{\text{non-mono}} \cdot \text{GLL} = \text{PHYS}_{\text{non-mono}} \]

\[ A_{\text{mono}} \cdot \text{GLL} = \text{PHYS}_{\text{mono}} \]

\[ [\alpha \cdot A_{\text{mono}} + (1-\alpha) \cdot A_{\text{non-mono}} \cdot \text{GLL}] = \text{PHYS}_{\text{mono}} \]

where

\[ \alpha = (\max(\text{GLL}) - \text{PHYS}_{\text{non-mono}}) / (\text{PHYS}_{\text{mono}} - \text{PHYS}_{\text{non-mono}}) \]

or

\[ \alpha = (\min(\text{GLL}) - \text{PHYS}_{\text{non-mono}}) / (\text{PHYS}_{\text{mono}} - \text{PHYS}_{\text{non-mono}}) \]
Dynamics to physics grid mapping

Properties we are looking for: Preserve smooth fields and at the same time not generate new extrema for rough distributions (and be mass-conservative and consistent)
Smooth field ("spherical harmonic")

1st order monotone map (not flow dependent): see grid

Physics: cell averaged data.


CAM3SE/CSLAM physics grid
Smooth field ("spherical harmonic")

**Optimally blend conservative and monotone map**
Rough field ("slotted cylinder")

Optimally blend conservative and monotone map

NE5NP4 to NC3 (6 degrees global resolution)
Rough field ("slotted cylinder")

Non-monotone conservative
Passing tendencies \((f_v, f_T, f_q, \ldots)\) to dynamics:
Use a 1\(^{st}\)-order, shape-preserving, conservative linear map
CAM4 forcing: Aqua-planet

Atmospheric model with complete parameterization suite
Idealized surface: no land (or mountains), no sea ice
specified global sea surface temperatures everywhere

=> Free motions, no forced component

Why CAM4? More resolution sensitivity than CAM5 (and it is cheaper!)
Efficiency measures in SYPD (= simulated years per day) on 2096 processors with I/O.

Data mapped to 3° lat-lon grid for analysis

Length of simulations: 30 months
Min/max moisture forcing
\( Q = \text{Specific humidity} \)
RELHUM = Relative humidity

Zonal-time averaged RELHUM

NE30NP4_APE

percent

NE30NP4NC2_APE

percent

NE30NP4NC3_APE

percent

NE30NP4NC4_APE

percent

NCAR Earth System Laboratory
Zonal-time averaged total cloud

- NE30NP4NC4_APE
- NE30NP4NC3_APE
- NE30NP4NC2_APE
- NE30NP4_APE

- Monotonic decrease in LVCF also seen in CAM 3.1 Aqua Planet Experiments (Williamson, Tellus 2008)
- Cloud Fraction monotonically decreases with resolution
- CAM-SE simulations (shown) are similar.

CLDTOT ± 2σ

hPa

latitudes

Zonal-time averaged total cloud

Cloud Fraction

NCAR Earth System Laboratory
Zonal-time averaged CLOUD

NE30NP4_APE

NE30NP4NC2_APE

NE30NP4NC3_APE

NE30NP4NC4_APE

Pressure [hPa]

60N 30N 0

Pressure [hPa]

60N 30N 0

Pressure [hPa]

60N 30N 0

Pressure [hPa]

60N 30N 0

NCAR Earth System Laboratory
Zonal-time averaged total precipitation rate

Williamson (2004)
PDF
PRECT (30 month simulation - 6h data)

Data mapped to 3° lat-lon grid

Fraction

Precipitation (mm/day)

NCAR Earth System Laboratory
Stationary grid scale forcing
Note that physics grid averages/moves fields away from boundary of element where the solution is least smooth (in element interior the polynomials are $C^\infty$).
Topography smoothing in CAM

Figure 2. Surface elevation in kilometers for a cross section along latitude $30^\circ$S (through Andes mountain range) for different representations of surface elevation. The labeling is the same as in Figure 1.

Topography smoothing in CAM

30 year AMIP simulations

OMEGA, JJA, model level 16 (approximately 323 hPa)

Notation: 2.5xdiv = 2.5 times more divergence damping than vorticity damping

Topography smoothing in CAM

30 year AMIP simulations

Total precipitation rate

Mean sea level pressure differences, DJF, diff

Topography smoothing in CAM

Lauritzen et al. (2014), in prep: NCAR Global Model Topography Generation Software for Unstructured Grids
Held-Suarez with topography

Vertical velocity at 500 mbar pressure surface

Pa/s
Held-Suarez with topography

Vertical velocity at 500 mbar pressure surface

Pa/s

NE30NP4NC3
Held-Suarez with topography

Vertical velocity at 500 mbar pressure surface

NE30NP4NC2
Aside ....
Go a step beyond inert transport testing, that is, add non-linear forcing to idealized flow problem!

At the same time keep things simple enough to be able determine/understand cause and effect

An option: simplified chemical reactions (right-hand side is products of mixing ratios)
"Inspiration": Photolysis driven chemistry

How much 'real mixing' is appropriate for climate applications? How much 'unmixing' can we tolerate?

Add 'toy' chemistry to new idealized test case: Two tracers that react with each other but should always add up to a constant.

Emulate, e.g., Br: Strong diurnal cycle (produced by photolysis).

- test development in progress (collaboration with NCAR-ACD)

Peter Hjort Lauritzen (NCAR)
The reactions are designed to conserve the total number of particles, where \( Cl \) and \( Cl_2 \) are the rates of production of \( Cl \) and \( Cl_2 \), respectively.

Lauritzen et al.: Terminator test

The non-linear 'toy' chemistry equations for \( Cl \) and \( Cl_2 \) are:

\[
\frac{DCl}{Dt} = 2k_1 Cl_2 - 2k_2 Cl Cl, \tag{4}
\]

\[
\frac{DCl_2}{Dt} = -k_1 Cl_2 + k_2 Cl Cl, \tag{5}
\]

where \( D/Dt \) is the material (or total) derivative \( D/Dt = \partial/\partial t + v \cdot \nabla \) and \( v \) is the wind vector. It is easily verified that the weighted sum of \( Cl \) and \( Cl_2 \) is conserved along characteristics of the flow:

\[
\frac{DCl_y}{Dt} = \frac{D}{Dt} [Cl + 2Cl_2] = 0. \tag{6}
\]
The terminator ‘toy’-chemistry test: A simple tool to assess errors in transport schemes (Lauritzen et al, 2014, submitted to GMDD)

Non-linear “terminator-toy” chemistry:

\[ Cl_2 \rightarrow Cl + Cl : k_1 \]
\[ Cl + Cl \rightarrow Cl_2 : k_2 \]

Exact solution: \( Cl + 2*Cl_2 = \text{constant} \)

Errors are due to non-conservation of linear correlations by the limiter (and physics-dynamics coupling)
CAM-SE

CAM-FV

CSLAM (Conservative Semi-Lagrangian Multi-tracer scheme)
Lauritzen et al. (2010)
Testing limiters (with CAM-SE)

Figure 5. Cross sections of day 1 (left column) Cl, (middle column) $2\text{Cl}_2$, and (right column) $\text{Cl}_y$ at 45° based on CAM-SE with (top row) no limiter, (middle row) positive definite limiter, (lower row) and default limiter, respectively. Results are normalized by $4 \times 10^6$ (the initial value of $\text{Cl}_y$).

5.5 Quantification of $\text{Cl}_y$ errors
To quantify the errors introduced in the terminator test, we suggest to compute standard error norms for $\text{Cl}_y$. The global normalized error norms used are $\| \cdot \|^2(t)$ and $\| \cdot \|^1(t)$ (e.g., Williamson et al., 1992):

$$\| \cdot \|^2(t) = \frac{\int [\text{Cl}_y(t) - \text{Cl}_y(0)]^2}{\int [\text{Cl}_y(0)]^2},$$
$$\| \cdot \|^1(t) = \max \left[ \frac{\text{Cl}_y(t)}{\text{Cl}_y(0)}, \frac{\text{Cl}_y(0)}{\text{Cl}_y(t)} \right],$$

where $\text{Cl}_y(0) = 4 \times 10^6$ is the globally-uniform initial condition and the global integral $I$ is defined as follows:

$$I([\cdot]) = \frac{1}{4\pi^2} \int_{\frac{\pi}{2}}^{\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} ([\cdot], \theta, t) \cos \theta \, d\theta \, dt.$$

As a reference we show the time-evolution of $\| \cdot \|^2(t)$ and $\| \cdot \|^1(t)$ for CAM-FV and CAM-SE on Figure 7.

6 Conclusions
A simple idealized 'toy' chemistry test case is proposed. It consists of advecting two reactive species (Cl and $\text{Cl}_2$) in the Nair and Lauritzen (2010) flow field. The simplified non-linear chemistry creates strong gradients in the species similar to what is observed for photolysis driven species in the stratosphere. The forcing terms for the continuity equations for Cl and $\text{Cl}_2$ are computed analytically over one time-step (assuming no advection) and Fortran codes for computing the forcing terms are provided as supplemental material. Hence, model developers who have already setup the standard test case suite of Lauritzen et al. (2012) can with modest efforts setup the terminator test by adding the forcing terms to their codes. As the test case of Nair and Lauritzen (2010) this forced advection problem has an analytic solution. The 'toy' chemistry by design does not disrupt preexisting linear relations between the species. So the only source of error is from the transport scheme and/or the physics-dynamics coupling. The terminator test is setup so that $\text{Cl}_y$ is a constant so any deviation from constancy is an error in preserving linear correlations. Many transport testing limiters (with CAM-SE)
5.4 CAM-SE: Physics-dynamics coupling experiments

As explained in section 4 the dynamics (tracer transport) and physical parameterizations (terminator chemistry) can be coupled in various ways. Here we discuss results based on two coupling methods available in CAM-SE referred to as $ftype=1$ and $ftype=0$. In $ftype=1$ the tendencies from physics are added to the atmospheric state at the beginning of dynamics. For $ftype=0$ the tendencies are split into $nsplit$ equal-sized adjustments. On Figure 6 the total Chlorine $Cl_y$ is shown using the $ftype=1$ configuration, $ftype=0$ using $nsplit=2$ and $nsplit=6$, respectively. In all experiments the tracer time-step is held fixed so in the latter two configurations $rsplit=3$ and $rsplit=1$, respectively.

Near the western edge of the terminator (located at approximately 130°W on Figure 5) where the gradients are steepest, the errors in $Cl_y$ are largest for $ftype=1$. The physics adjustments that steepen the gradients are largest at the western edge and consequently produces states that challenges the limiters more. When the physics tendency is added gradually throughout the tracer transport the errors are reduced as $nsplit$ is increased.

At the eastern edge of the terminator (located at approximately 30°E on Figure 5) the gradients are less steep compared to the western edge. In fact, the location of the gradient near the eastern edge propagates (see animation in supplemental material) whereas the gradients at the western edge of the terminator are static in space. The physics tendencies in this area are not stationary in space and are weaker so the transport signal is larger. This means that for any given point in the eastern area, the state used for computing the physics tendencies changes during the tracer subcycling. As a result the gradients will have propagated during the transport step but the physics tendencies will steepen gradients in the 'old' location. This 'inconsistency' is present with $ftype=0$. For $ftype=1$ the physics update is based on the 'correct' in time state. The temporal inconsistency in the state used for computing physics tendencies for $ftype=0$ produces an increase in errors near the eastern edge of the terminator compared to $ftype=1$.

Physical parameterization packages may contain code that sets negative mixing ratios to zero. Or similarly there may be code that prevent tendencies to be added to the state if it is zero or negative. The terminator test may be a useful tool to diagnose such alternations in large complicated codes.

Figure 4. Contour plot of $Cl_y$ at day 1 using CAM-SE in $ftype=1$ configuration where (upper) no limiter, (middle) positive definite limiter, and the default CAM-SE limiter is applied, respectively. The solid black line depicts the location of the terminator line. Note that the contour levels are not linear.
Simplified framework to test physics dynamics coupling

Figure 6. Contour plots of Cl$_y$ at day 1 using CAM-SE based on (upper) ftype = 1, (middle) ftype = 0 and nsplit = 3, and (lower) ftype = 0 and nsplit = 6, respectively. In all simulations the tracer time-step is constant $\Delta t_{tracer} = 300s$.

Algorithm 1 Pseudo-code explaining the different levels of subcycling and physics-dynamics coupling used in CAM-SE.

Outer loop advances solution $\Delta t$ in time:

for $t = 1, 2, \ldots$ do

Compute physics tendencies $F_t$, $i = $ Cl, Cl$_2$

for $ns = 1, 2, \ldots, nsplit$ do

Update state with chemistry/physics tendencies:

$C_i = C_i + \frac{\Delta t}{nsplit} F_t$, $i = $ Cl, Cl$_2$

for $rs = 1, 2, \ldots, rsplit$ do

subcycling of tracer advection:

$C_i = C_i + \frac{\Delta t}{nsplit \times rsplit} T(C_i)$, $i = $ Cl, Cl$_2$

end for

end for

end for
Zonal-time averaged PTTEND

NE30NP4_APE

NE30NP4NC2_APE

NE30NP4NC3_APE

NE30NP4NC4_APE
PRECC $= \text{Convective precipitation rate (liq + ice)}$

Data mapped to 3° lat-lon grid

**PRECC (30 month simulation - 6h data)**

- NE30NP4NC4_APE
- NE30NP4NC3_APE
- NE30NP4NC2_APE
- NE30NP4_APE

Fraction vs. Precipitation (mm/day)
PRECL = Large-scale (stable) precipitation rate (lq + ice)

PRECL (30 month simulation - 6h data)

Data mapped to 3º lat-lon grid

Precipitation (mm/day)

Fraction