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

Peter Hjort Lauritzen (pel@ucar.edu)
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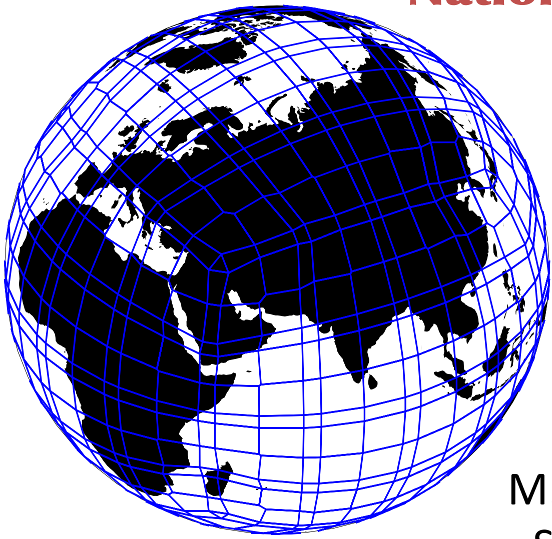
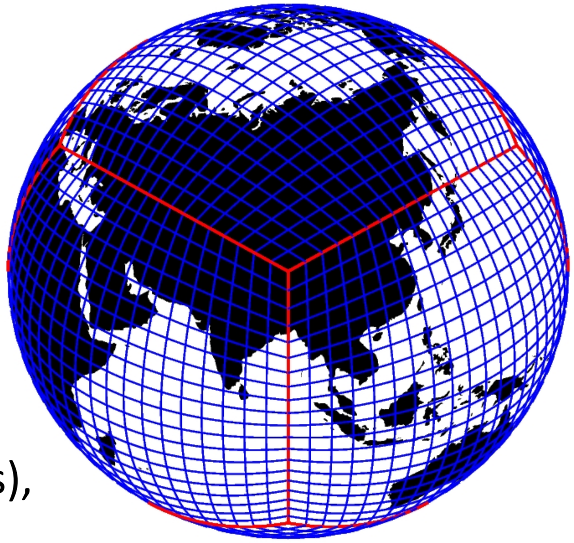
Boulder, Colorado, USA





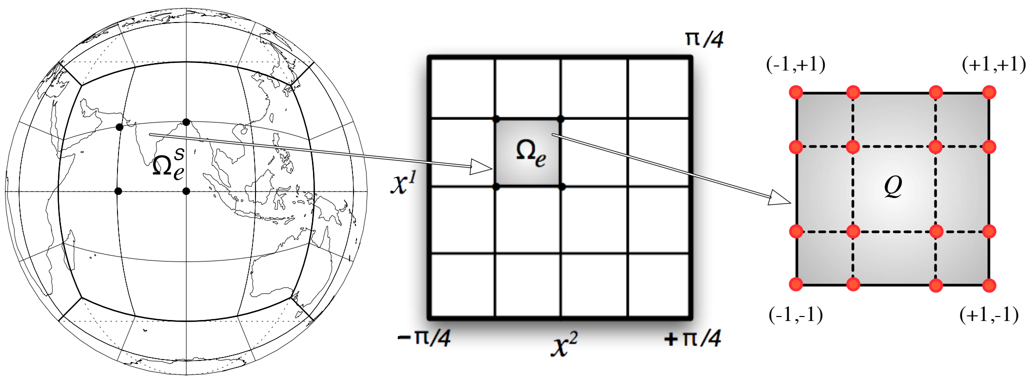
M.A. Taylor (SNL), P.A. Ullrich (UC Davis),
S. Goldhaber (NCAR), J. Overfelt (SNL),
J. Bacmeister (NCAR)

CESM Atmosphere Model Working Group (AMWG) Meeting, NCAR, Boulder, Colorado
18 – 20 February, 2015

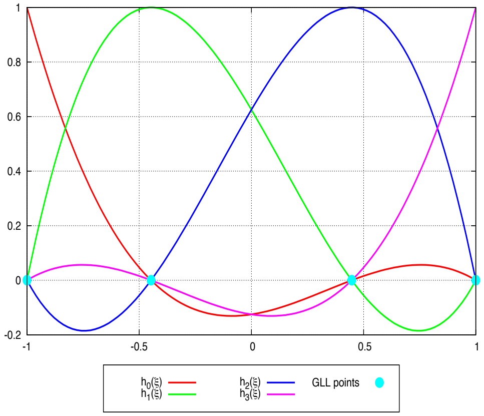
CAM-SE: NCAR-DOE Community Atmosphere Model with Spectral Elements dynamical core

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

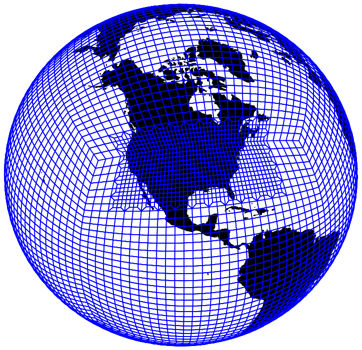
Nair et al., 2011



Physical Domain **Computational Domain** **GLL Quadrature Grid**



- 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?)**



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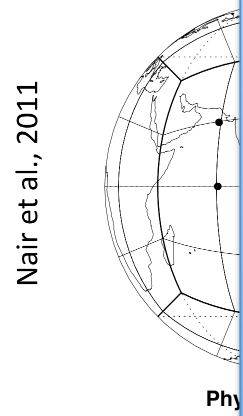
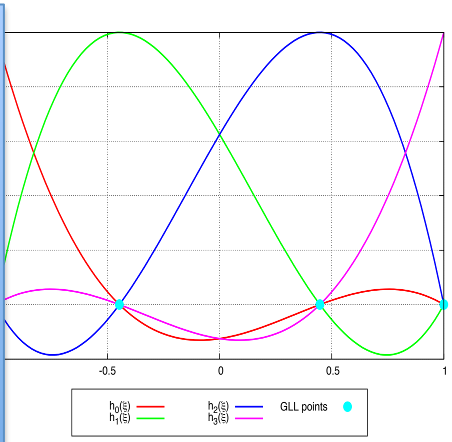


- On Yellowstone, CAM-SE is faster than CAM-FV when more than approximately 2100 processors are used
- Users do not necessarily use many processors & it may be hard to get large jobs through the queue on high performance computing systems
  (“cultural” change needed?)



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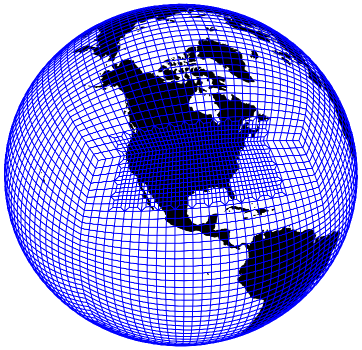
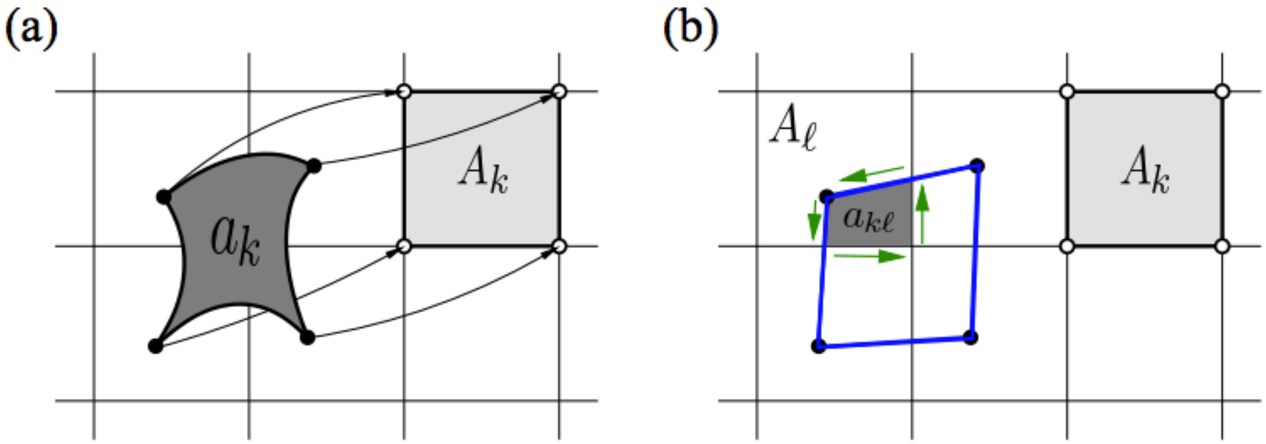


A way to accelerate tracer transport:

CSLaM scheme (Conservative Semi-Lagrangian Multi-tracer)



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

$$\int_{A_k} \psi_k^{n+1}\,dx\,dy = \int_{a_k} \psi_k^{n}\,dx\,dy \quad = \quad \sum_{\ell=1}^{L_k}\left[\sum_{i+j\leqslant 2} c_\ell^{(i,j)}\, w_{k\ell}^{(i,j)}\right],$$

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

- $w_{k\ell}^{(i,j)}$ 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)

Lauritzen, Nair and Ullrich (*J. Comput. Phys.*, 2010)

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SciDAC
Scientific Discovery through
Advanced Computing

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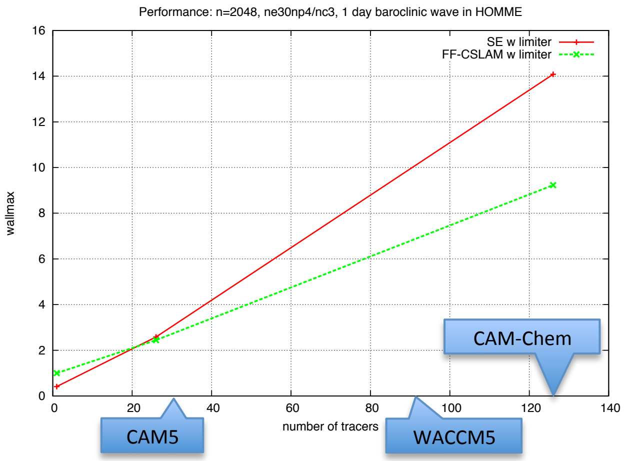


MPI communication

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**

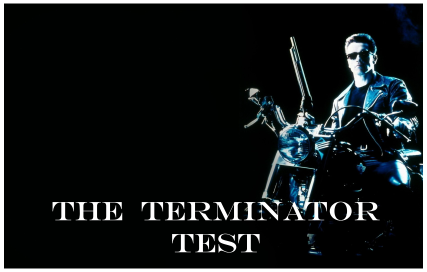
That said, CSLAM needs a larger halo than SE.

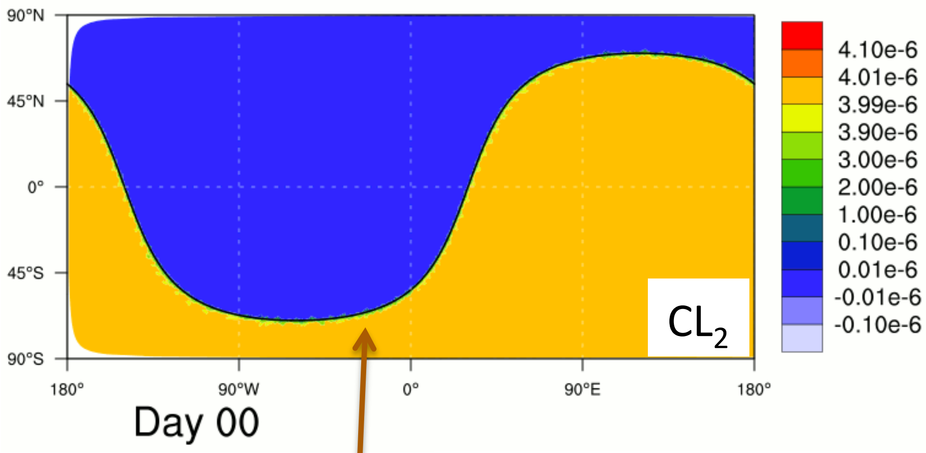
CSLAM implemented in NCAR-DOE HOMME (High-Order Methods Modeling Environment) by Erath et al., (2012); CAM-SE “pulls” SE dynamical core from HOMME

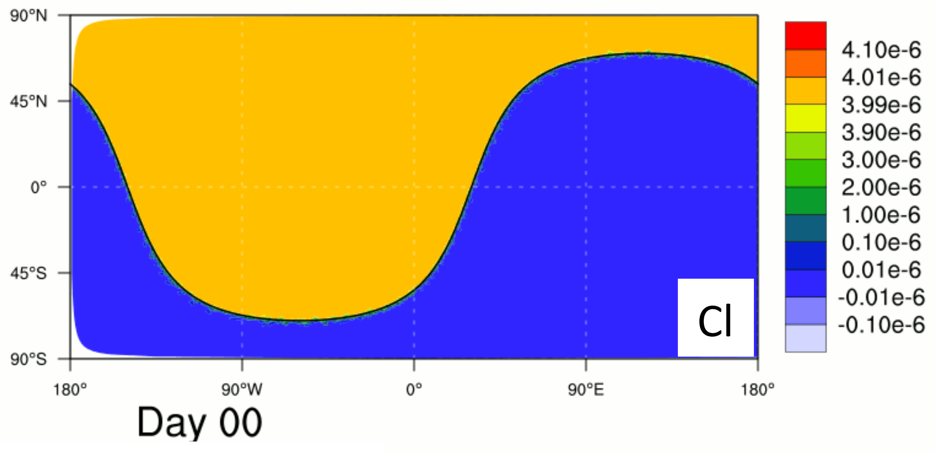
The terminator ‘toy’-chemistry test: A simple tool to assess errors in transport schemes

(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:

$Cl+2*Cl_2$ = constant

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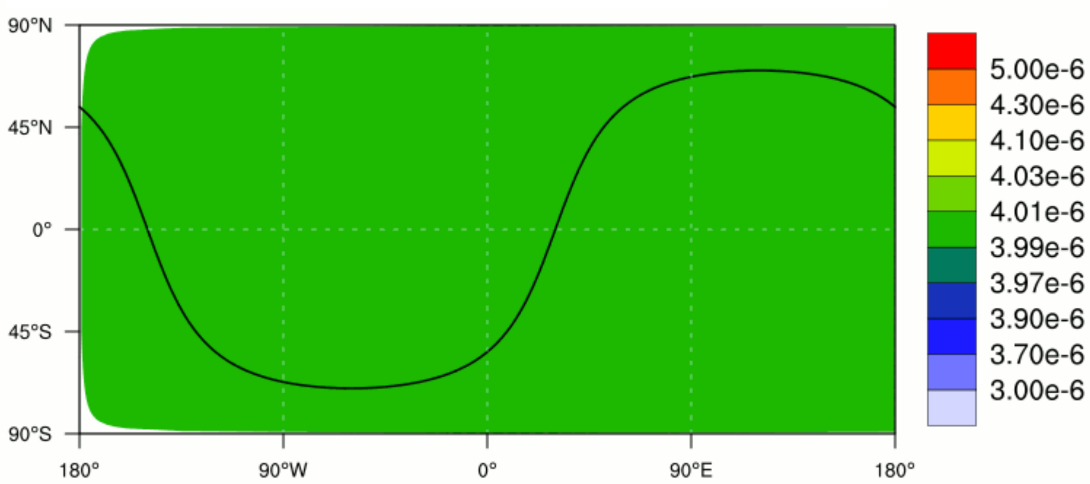

Wind field:
Nair and Lauritzen deformational flow

Errors are due to non-conservation of linear correlations usually caused by the limiter and/or physics-dynamics coupling!

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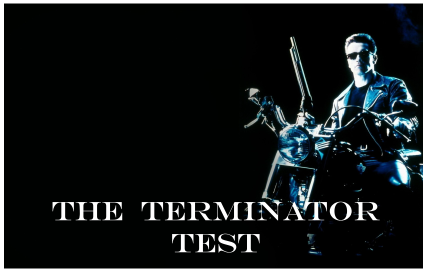
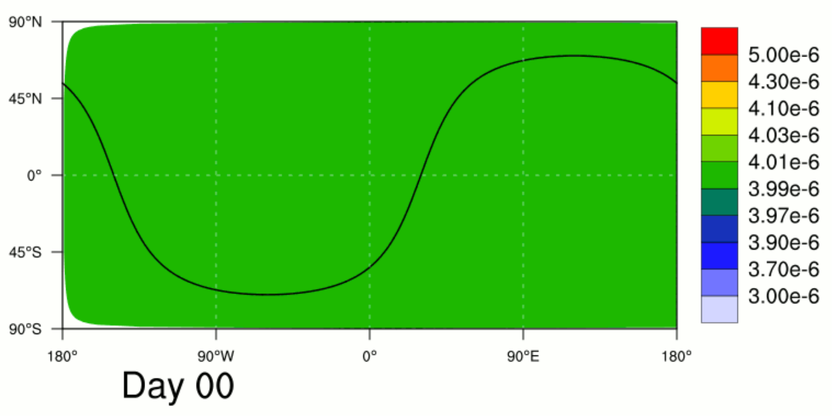
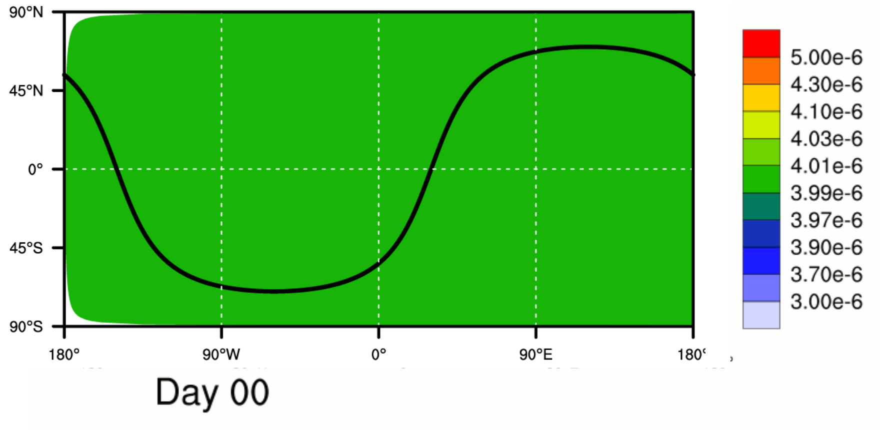


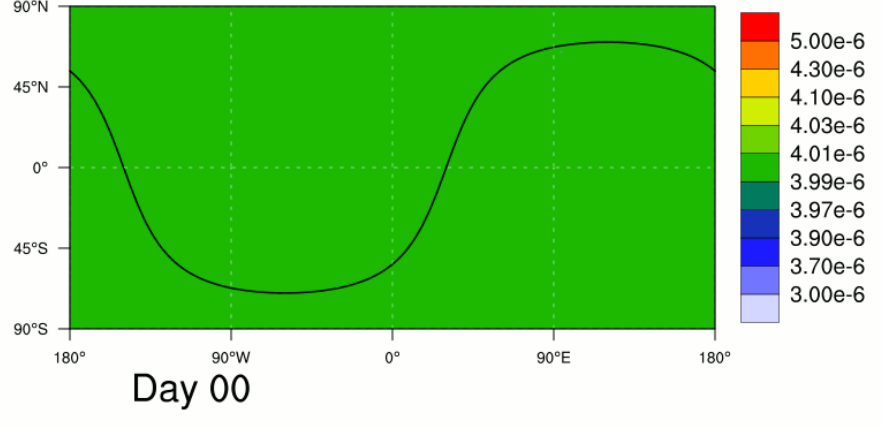
CAM-SE



CSLAM



CAM-FV (Lin 2004)



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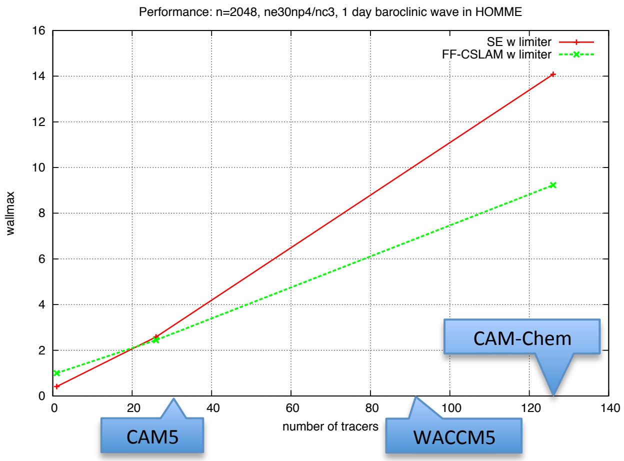

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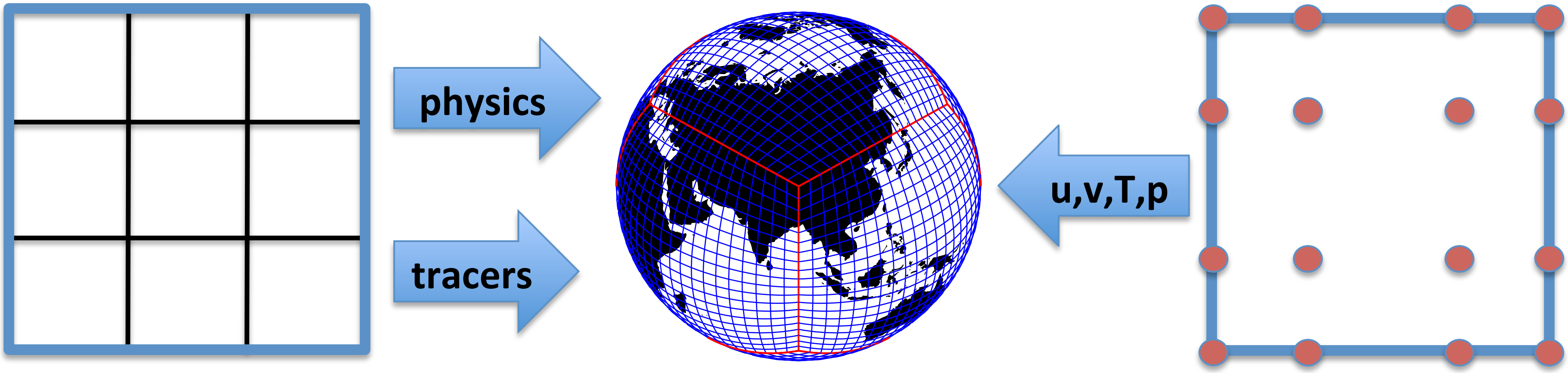
- 👍 Multi-tracer efficient (high start-up cost but “cheap” for each additional tracer)
- 👎 CSLAM uses a “finite-volume”-type grid and SE uses a quadrature grid



physics

tracers

u,v,T,p

A way to accele te t transport:

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  -> accurat
  al, ...)
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- Prese e!
- Current v
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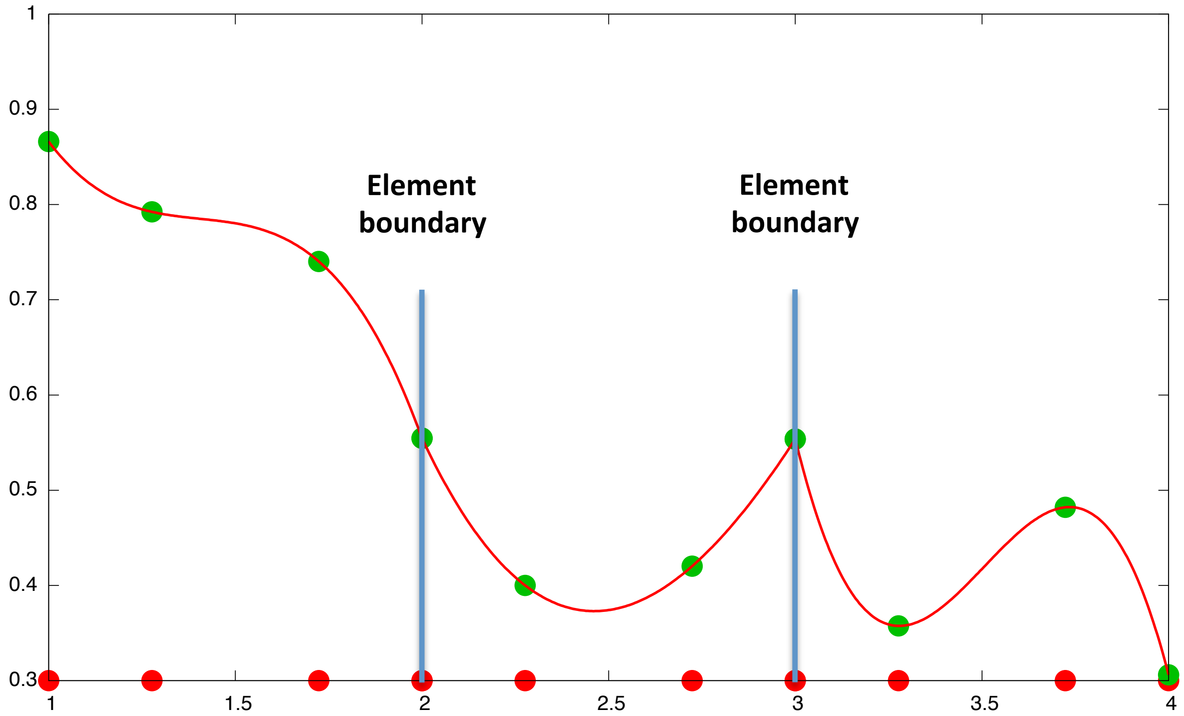
  l tracer)

Separating physics and dynamics grids in models based on Galerkin methods may not be a “bad” thing!

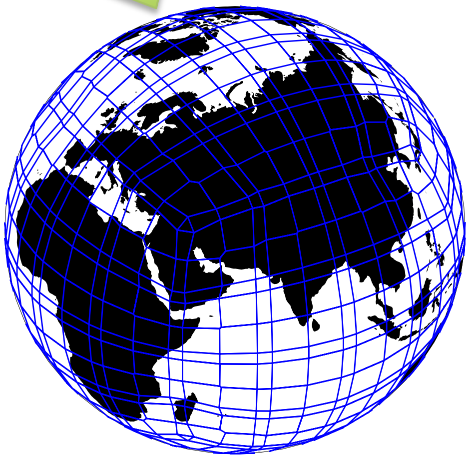
Current physics-dynamics coupling

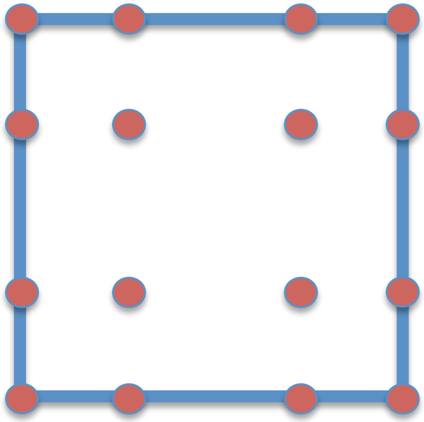
Atmospheric state passed to physics is at quadrature points:

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



Coupler grid





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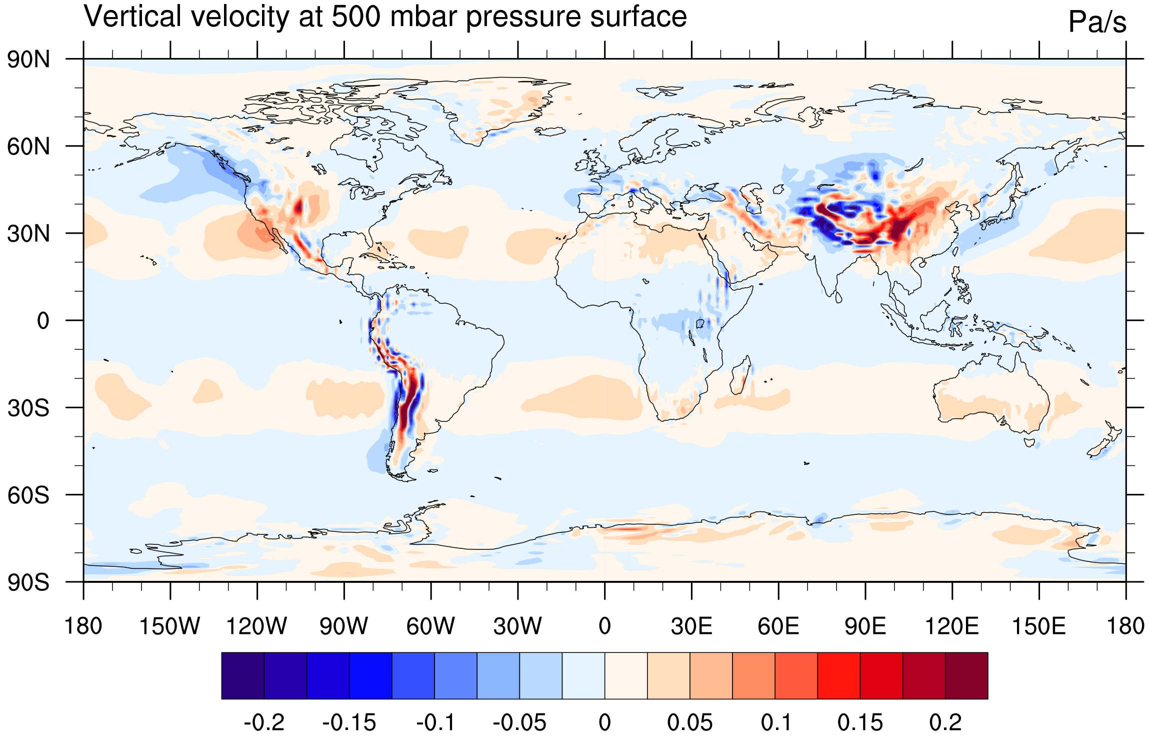
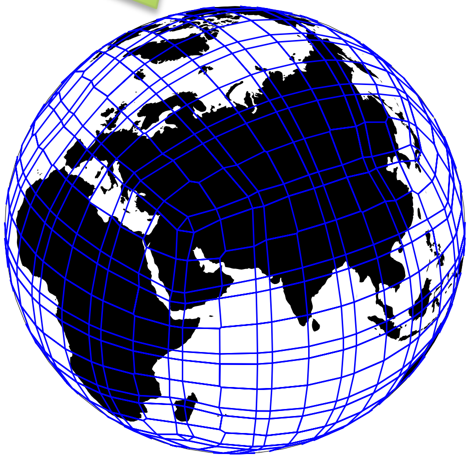
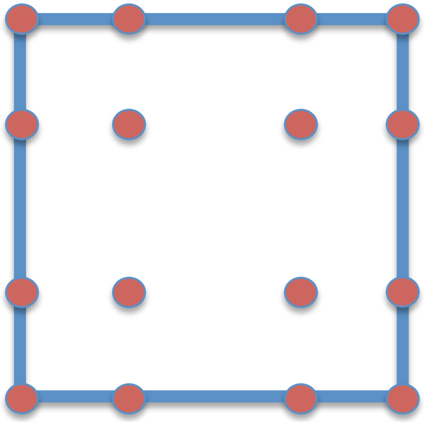
Held-Suarez with topography



Coupler grid



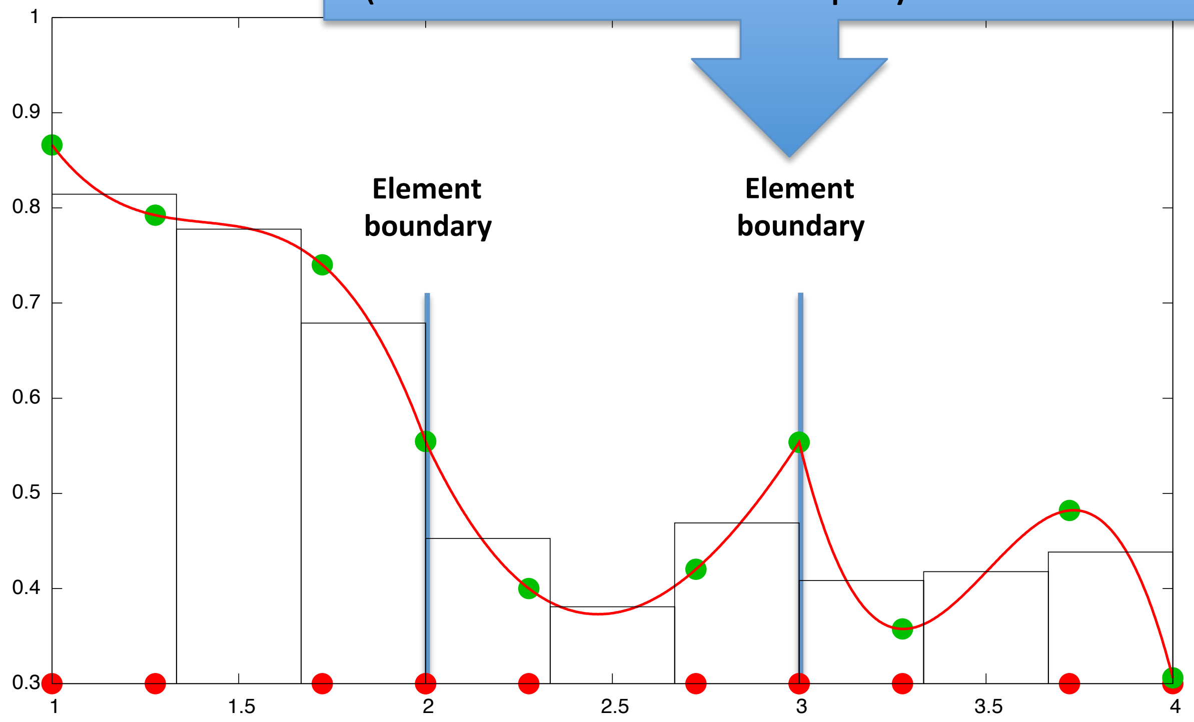


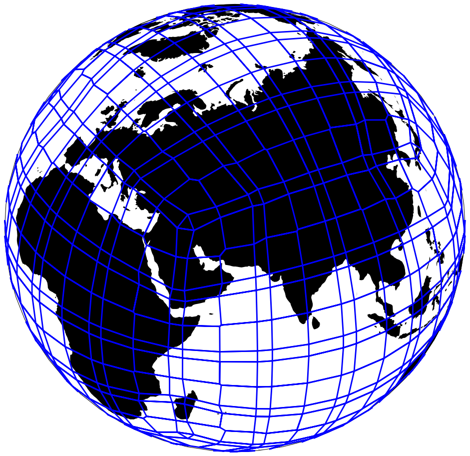
"Equal-area" physics grid

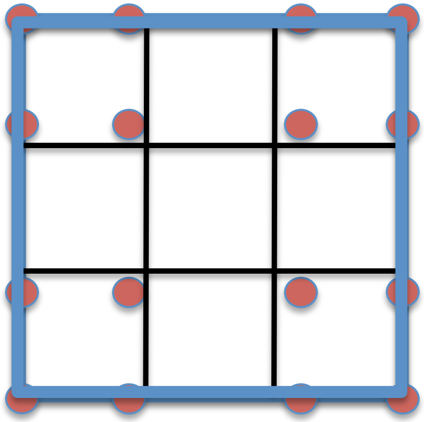
Atmospheric state passed to physics is at quadrature points:

- Leads to an-isotropic "sampling" of atmospheric state
- High-order basis
  least smooth nea

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^{∞})

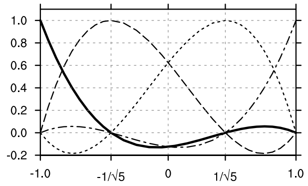






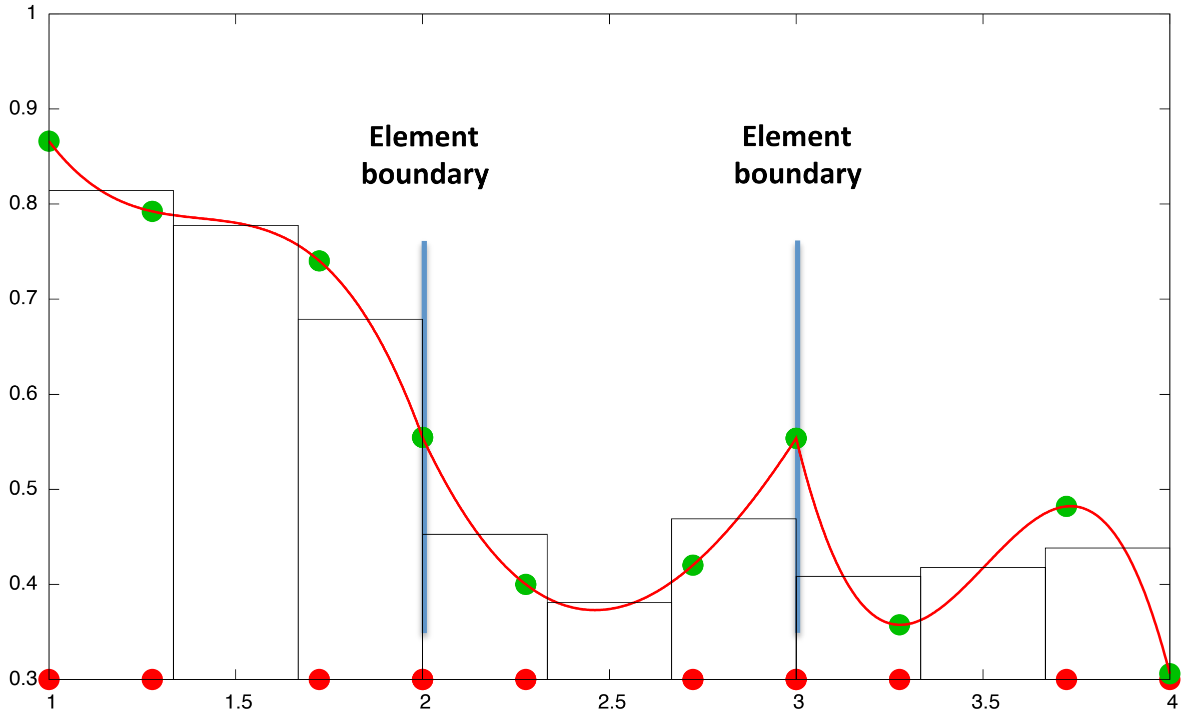
Mapping variables from dynamics to physics:

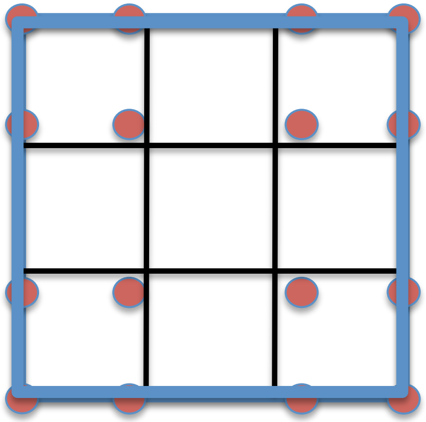
Integrate atmospheric state (basis functions) over control volumes: **Conservation** and **consistency** (=preservation of a constant) is enforced via a least squares projection onto the space of conservative and consistent maps. *Ullrich and Taylor* (2015)



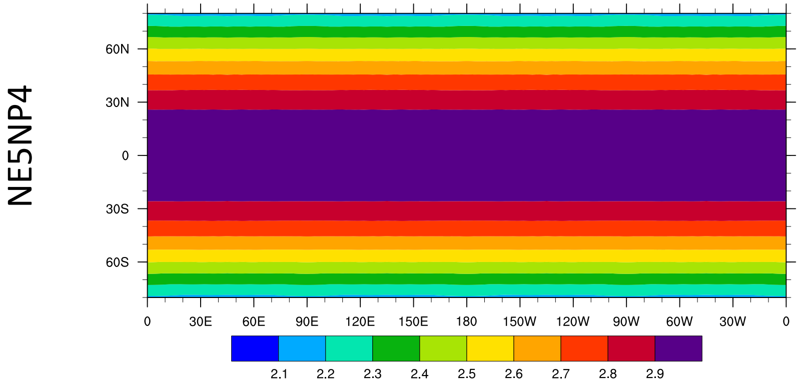
Interpolation matrix can be pre-computed

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

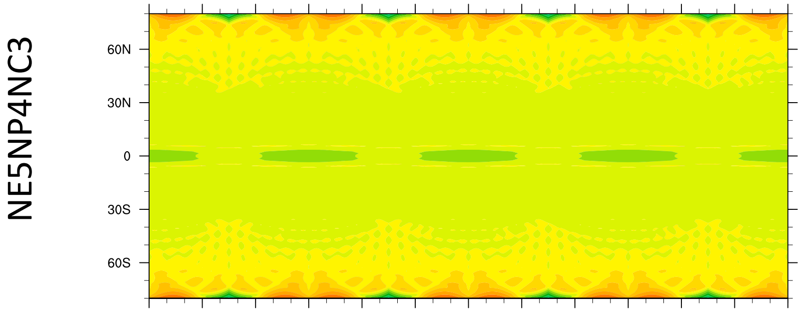




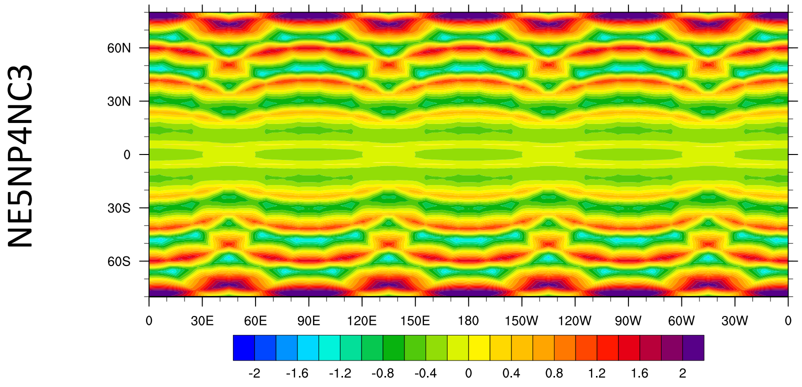
(a) 2+cos(lat)



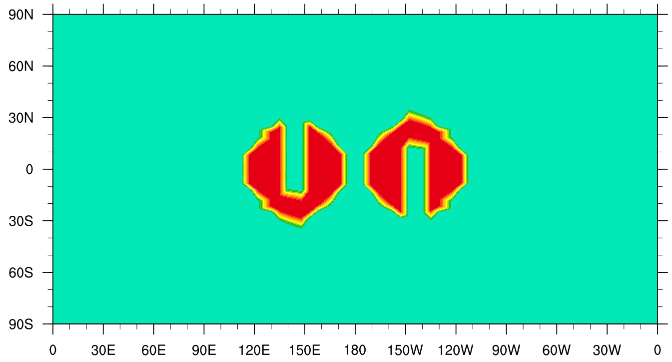
(b) Default map: difference



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



(a) Slotted cylinder



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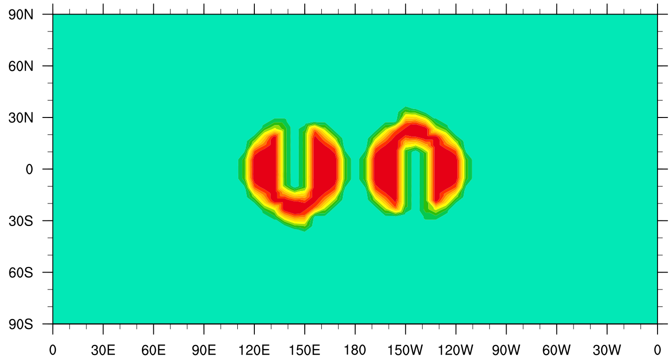
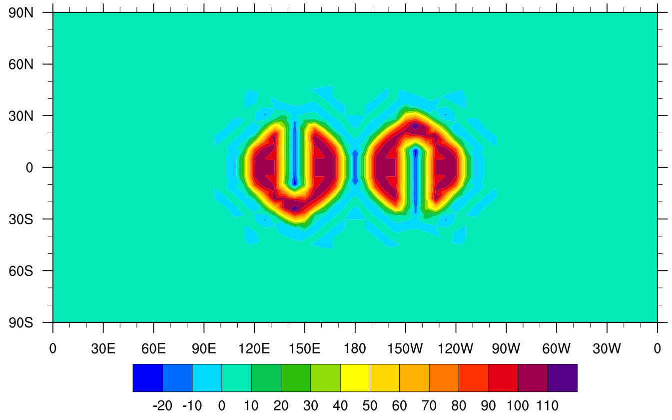
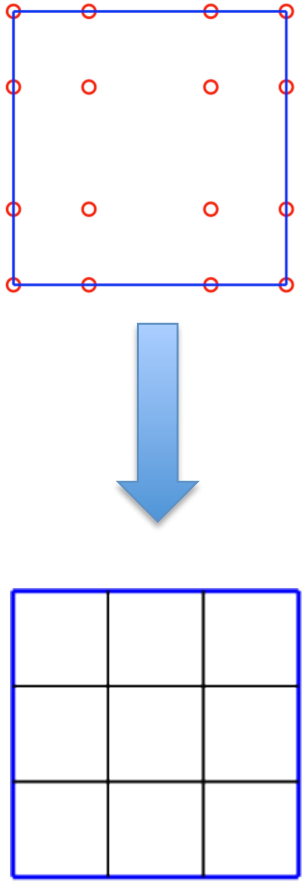


(c) Non-monotone map



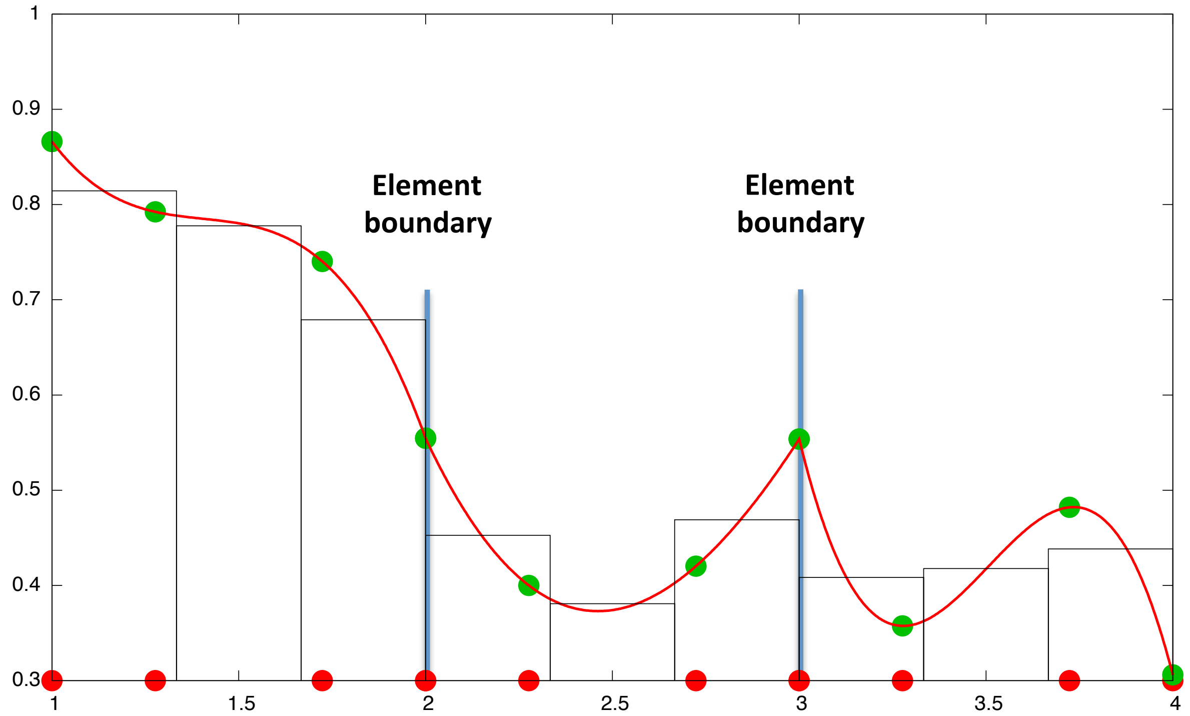
Resolution: 6 degrees

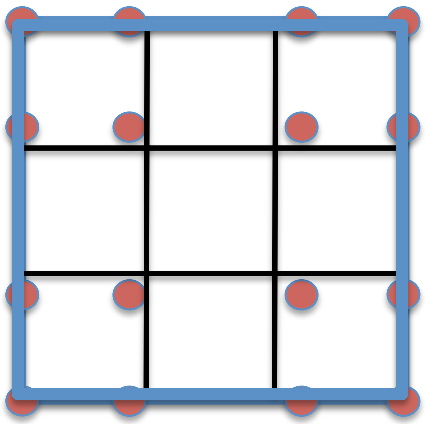


Mapping tendencies from physics to dynamics

Similar method: first-order map that is **shape-preserving, conservative** and **consistent**.

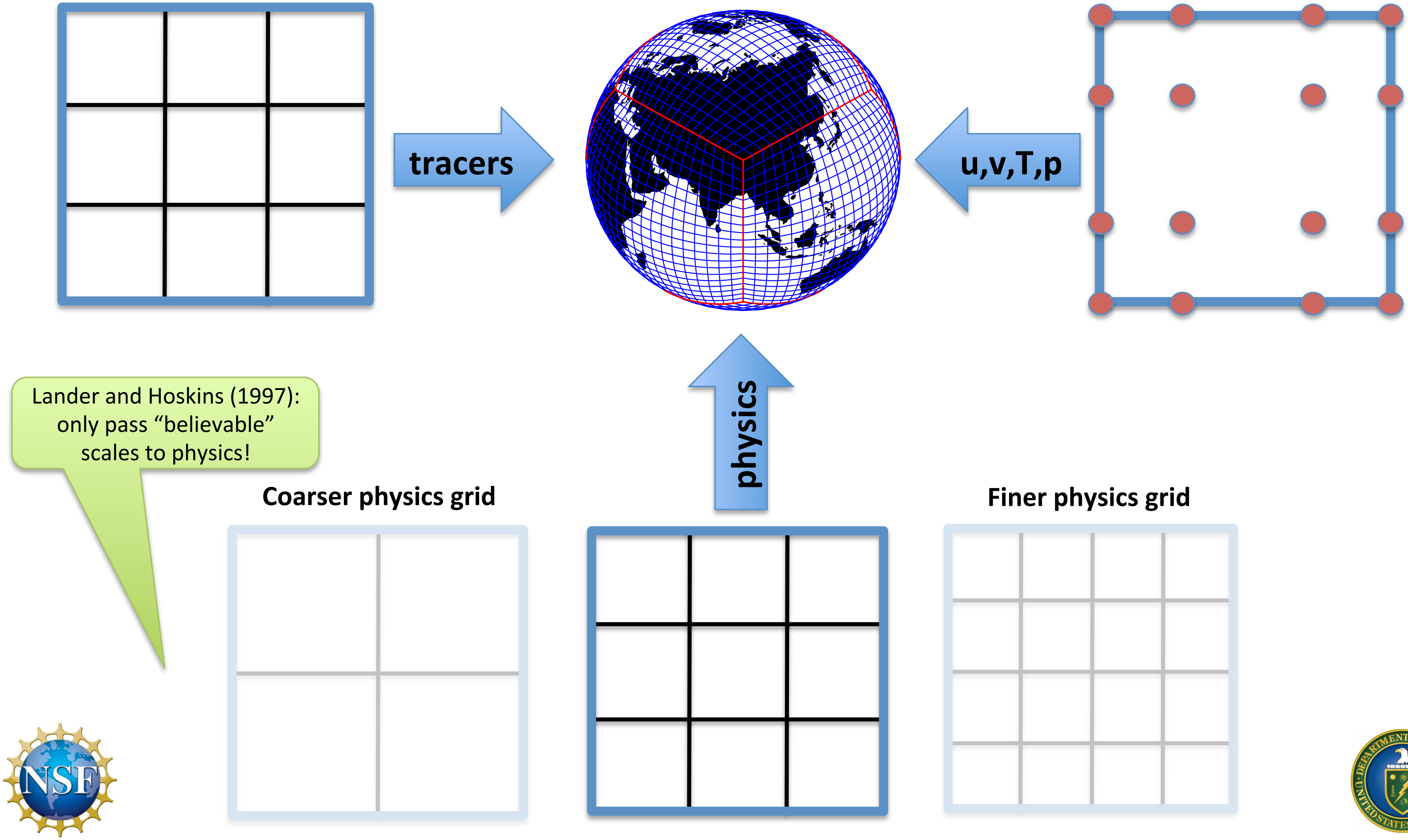
Ullrich and Taylor (2015)





CAM-SE-CSLAM

combining the best of two worlds: high-order spectral dynamics & finite-volume transport



tracers

u,v,T,p

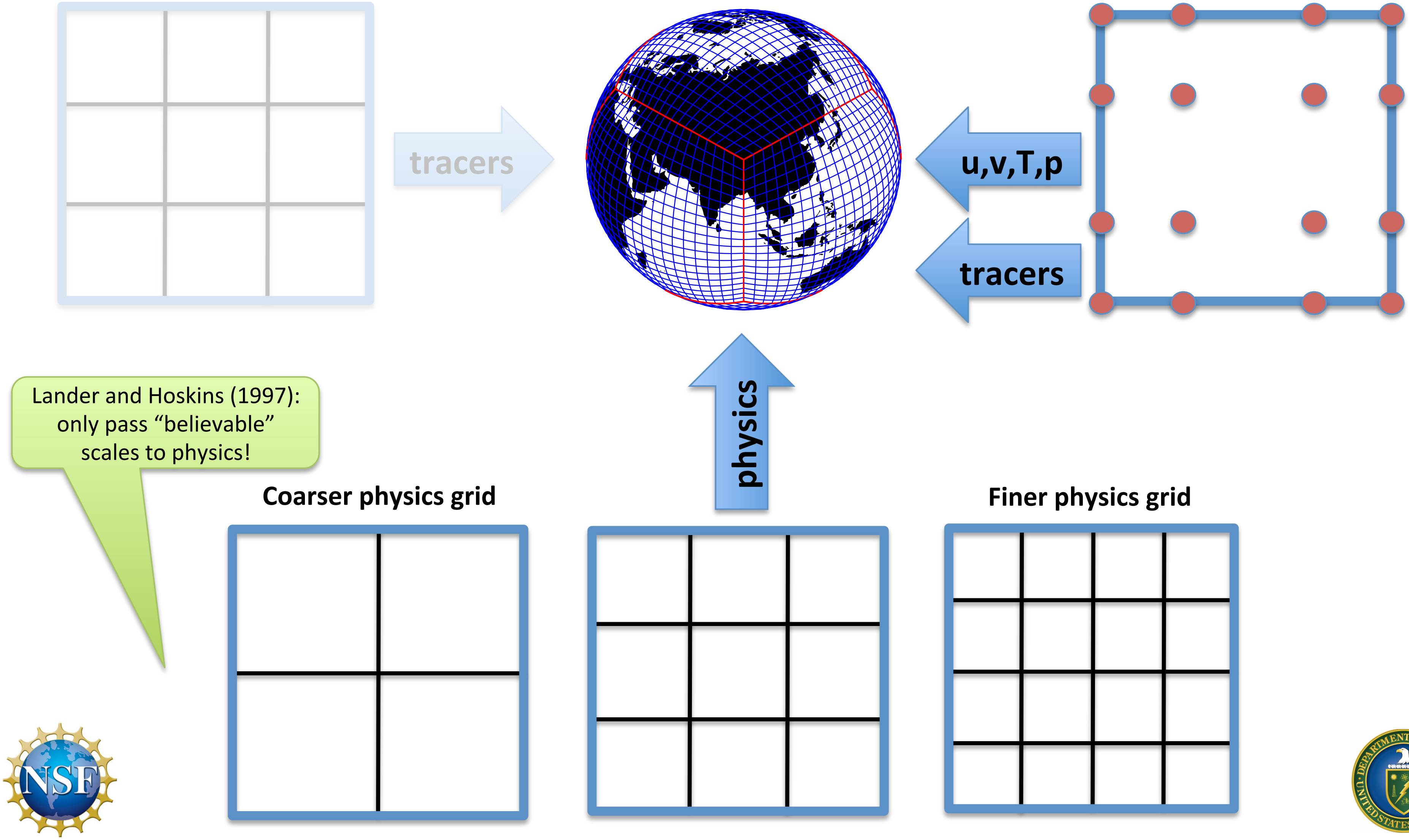
physics

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

Coarser physics grid

Finer physics grid

CAM-SE-physgrid



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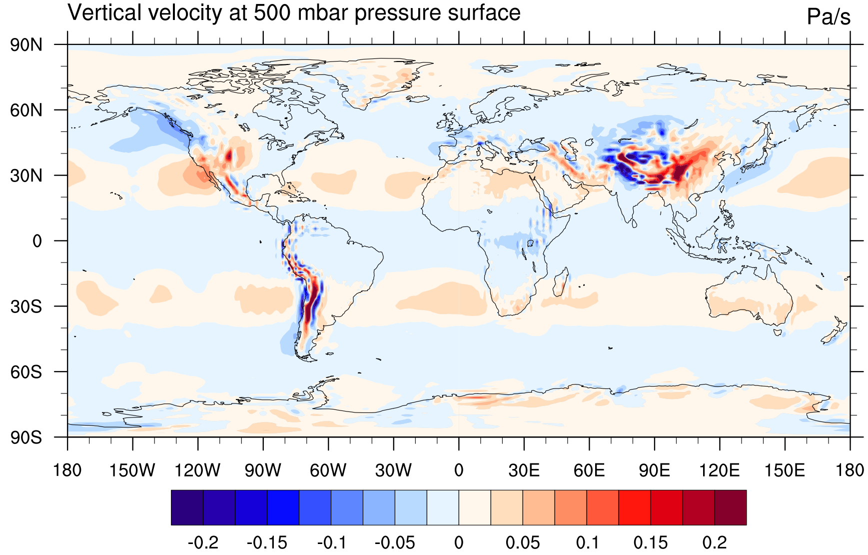
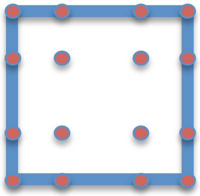
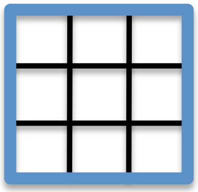
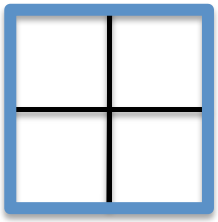
Held-Suarez with topography

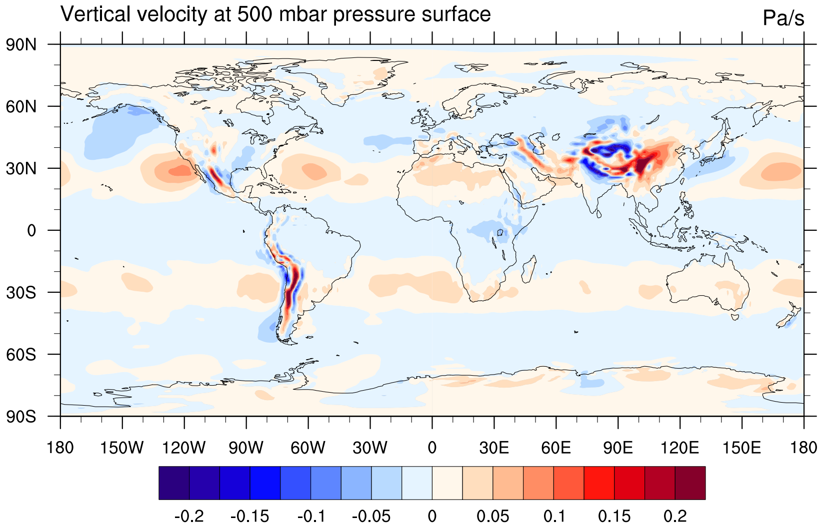
Dry dynamics test case: physics package replaced with simple boundary friction and relaxation of T towards zonally symmetric profile


Vertical velocity at 500 mbar pressure surface





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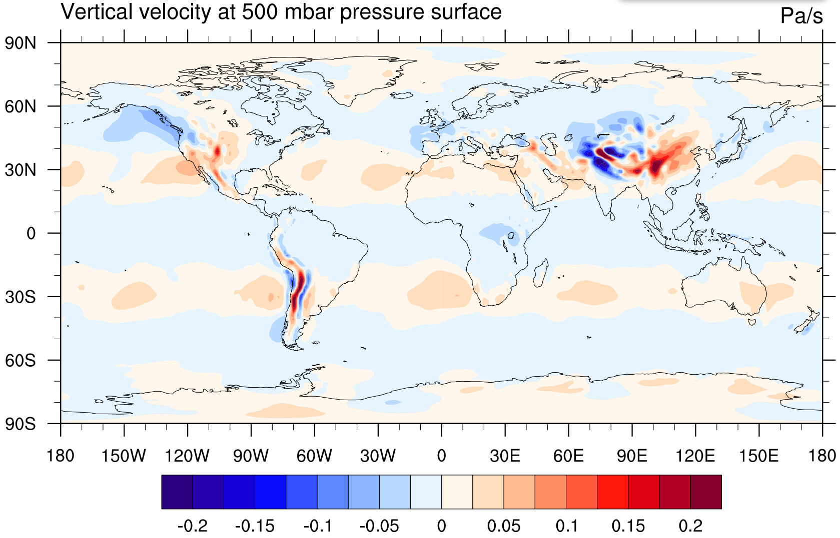
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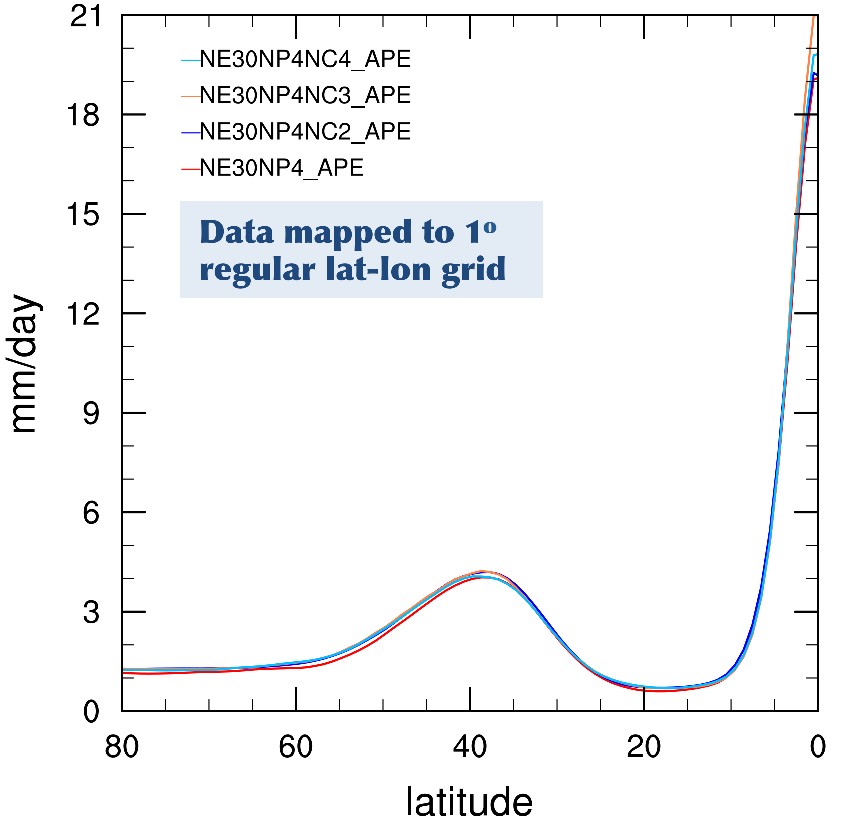
CAM4 Aqua-planet simulations

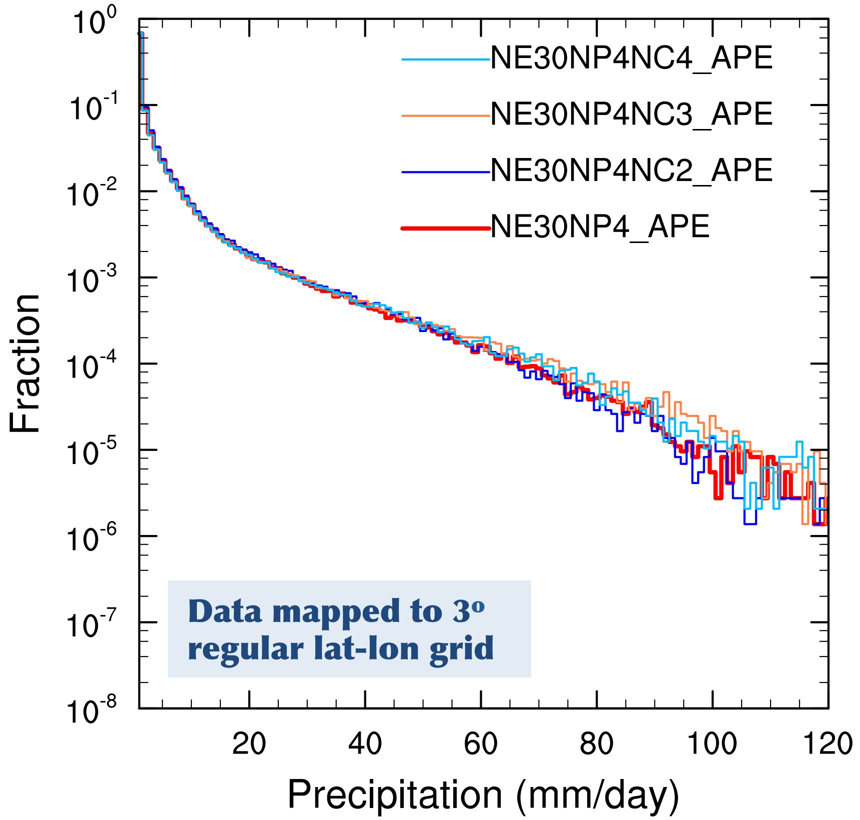
Idealized surface: no land (or mountains) + specified zonally symmetric sea surface temperatures => **free motions, no forced component**

Zonal-time averaged total precipitation rate

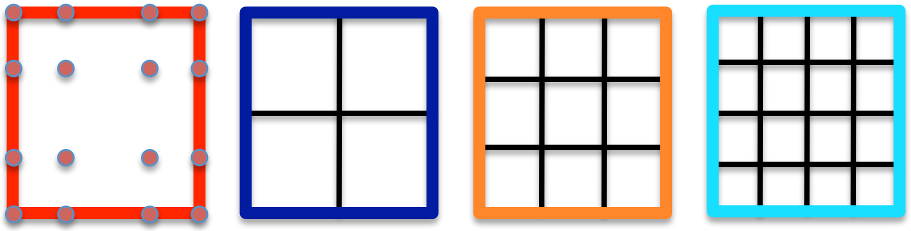


Data mapped to 1° regular lat-lon grid

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)

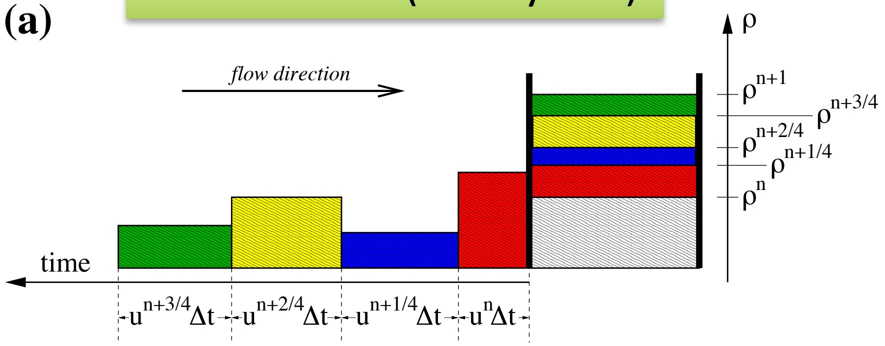
Last step(s) towards CAM-SE-CSLAM: coupling mass

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

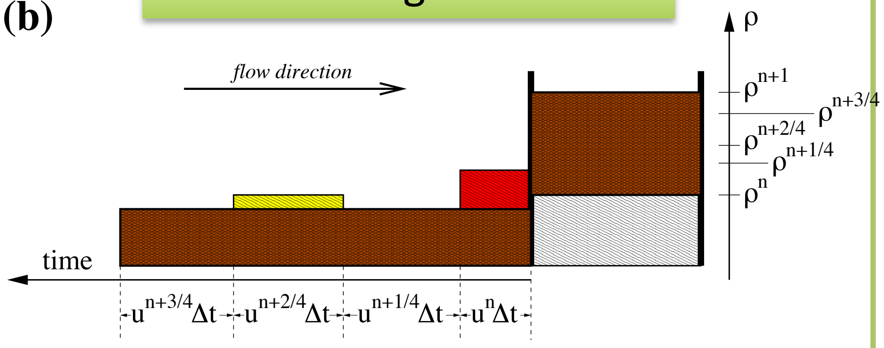
- Mass-conservation and shape-preservation
- Consistency: when mixing ratio is =1 the tracer mass must reduce to the SE mass

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, …):

Air mass flux (sub-cycled)



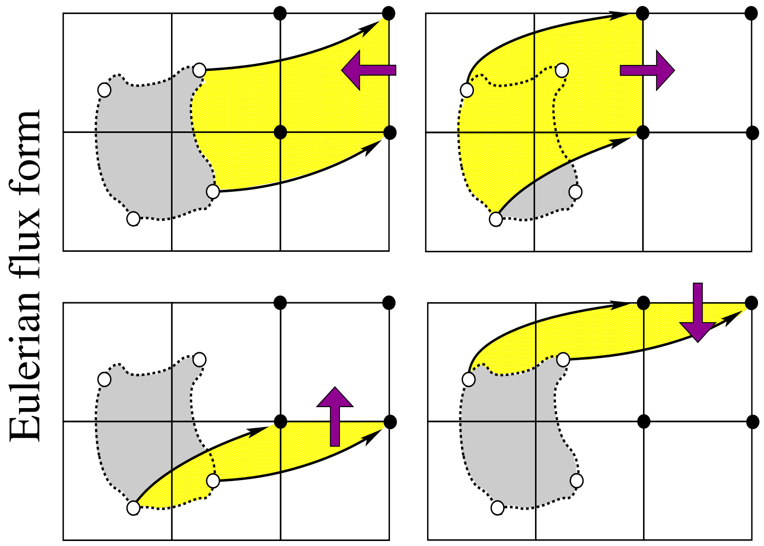
Tracer mixing ratio “flux”



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

Last step(s) towards CAM-SE-CSLAM: coupling mass

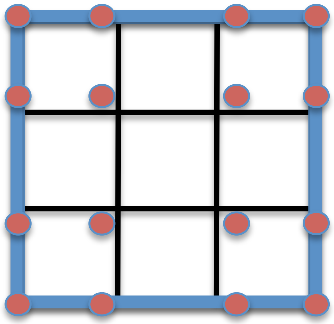
Flux-coupling with CAM-SE-CSLAM:



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.

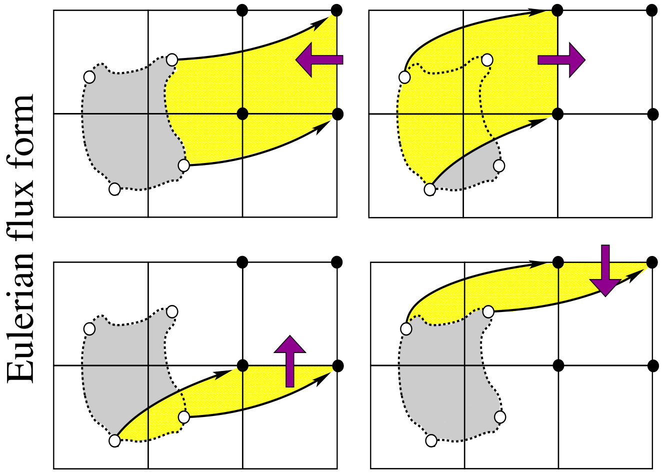


Unforeseen issue:

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”!

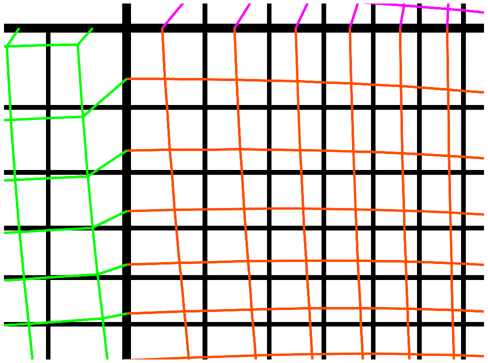


Straight forward for dimensionally split schemes
but not for fully 2D schemes such as CSLAM.

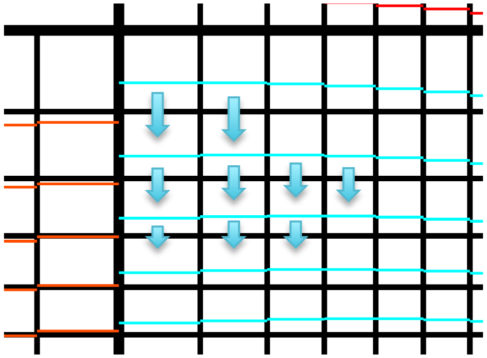
Problem:

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.

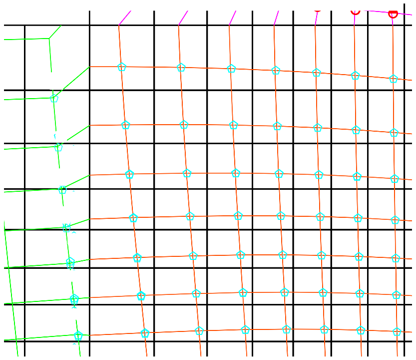
Analytical upstream grid



Equivalent perpendicular y-flux



Departure grid based on fluxes



More information: http://www.cgd.ucar.edu/cms/pel

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