SciDAC Scientific Discovery through Advanced Computing

NSF

CGD Climate & Global Dynamics

NCAR NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

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

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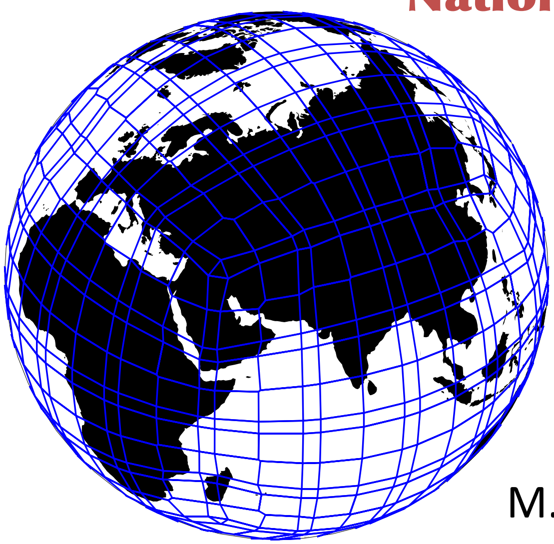
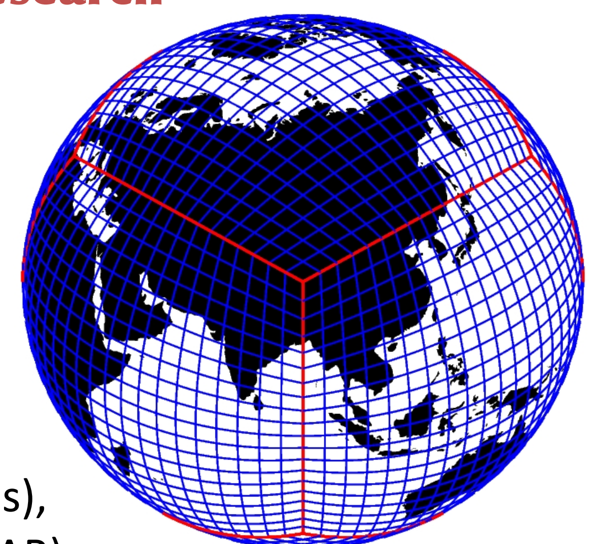
Boulder, Colorado, USA





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

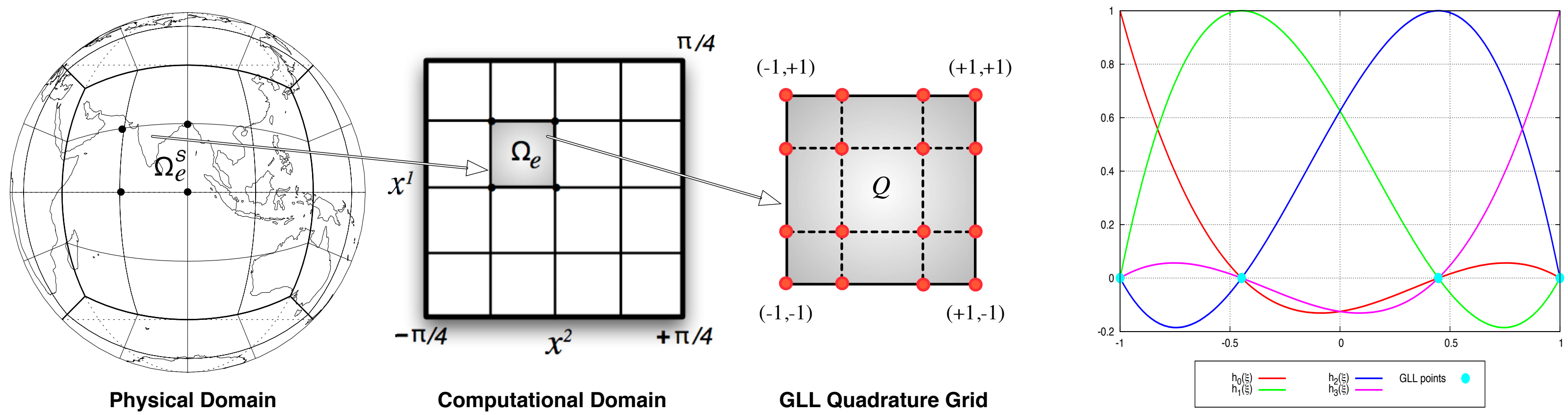
AGU Fall Meeting
Session: Climatology and Trends of Extreme Events in Climate Models Capable of Resolving Regional-Scale Processes I
December 17, 2014, San Francisco

NCAR Earth System Laboratory

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:

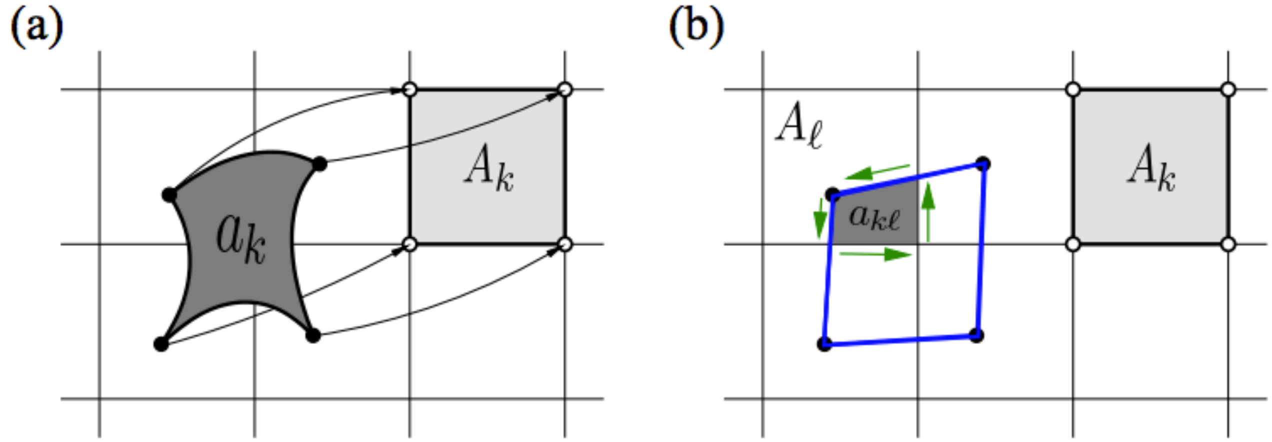
Nair et al., 2011



- 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 $\psi = \rho, \rho\,\phi$:

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

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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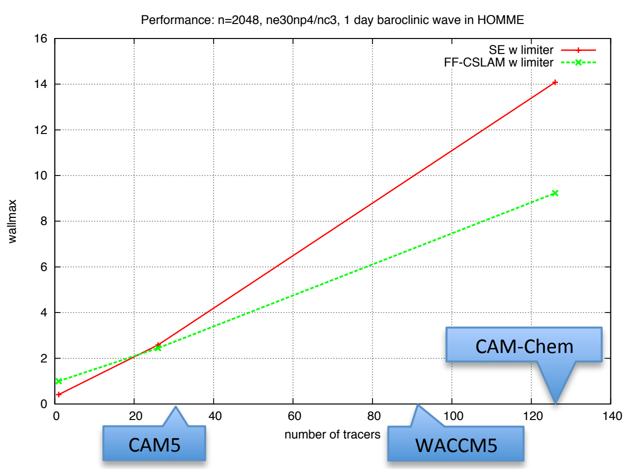
- Fully two-dimensional
  - -> accurate treatment of weak singularities, e.g., cube corners
  - -> can be implemented on various spherical grids (cubed-sphere, icosahedral, …)
- Shape-preserving (no negatives, no spurious grid-scale oscillations)
- Preserves linear correlations (even with shape-preservation) – 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):



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**

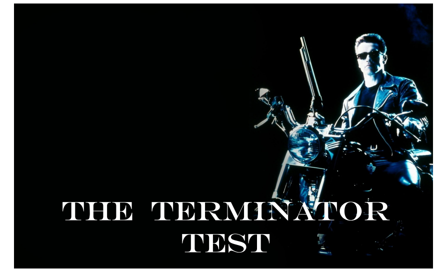
That said, CSLAM needs a larger halo than SE.

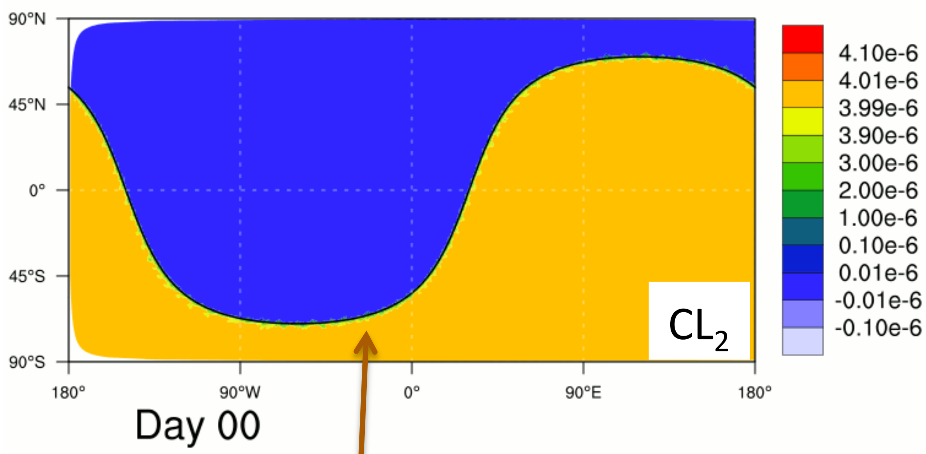
CSLAM implemented in NCAR-DOE HOMME (High-Order Methods Modeling Environment) by Erath et al., (2012); CAM-SE "pulls" SE dynamical core from HOMME

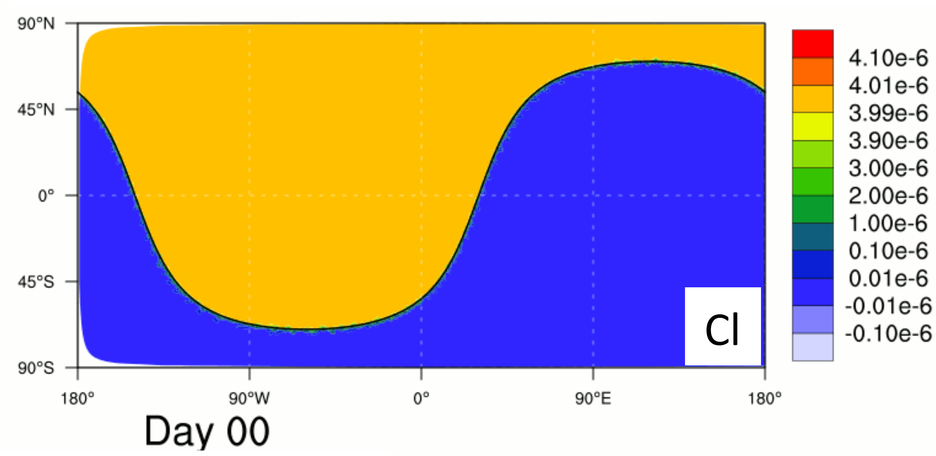
The terminator 'toy'-chemistry test: A simple tool to assess errors in transport schemes

(Lauritzen et al, 2014, GMDD)

See: http://www.cgd.ucar.edu/cms/pel/terminator.html







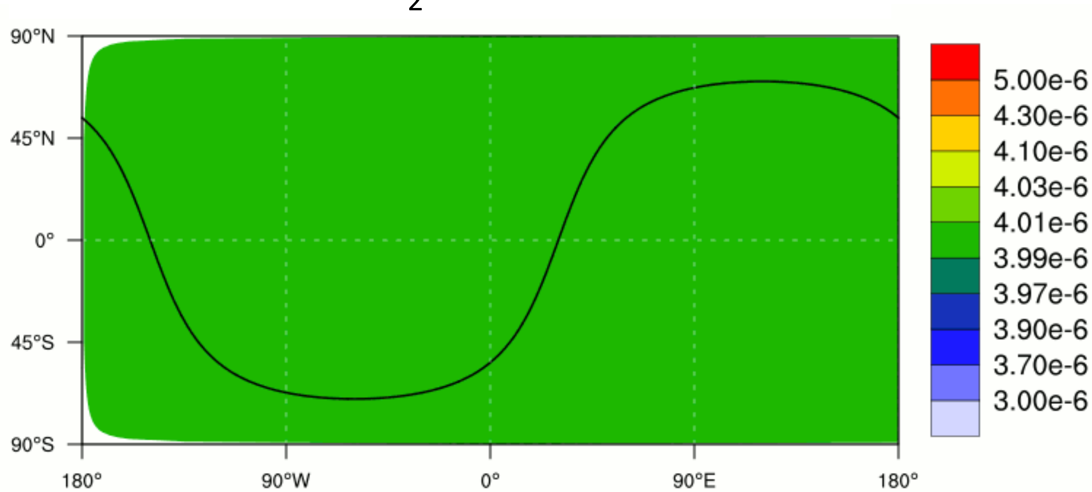
Non-linear Terminator 'toy' chemistry:

$$Cl_2 \rightarrow Cl + Cl : k_1$$

$$Cl + Cl \rightarrow Cl_2 : k_2$$

Exact solution: $Cl+2*Cl_2$ = constant

$Cl+2*Cl_2$ = 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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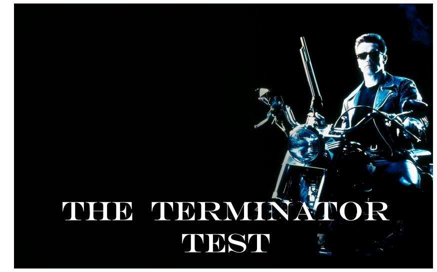
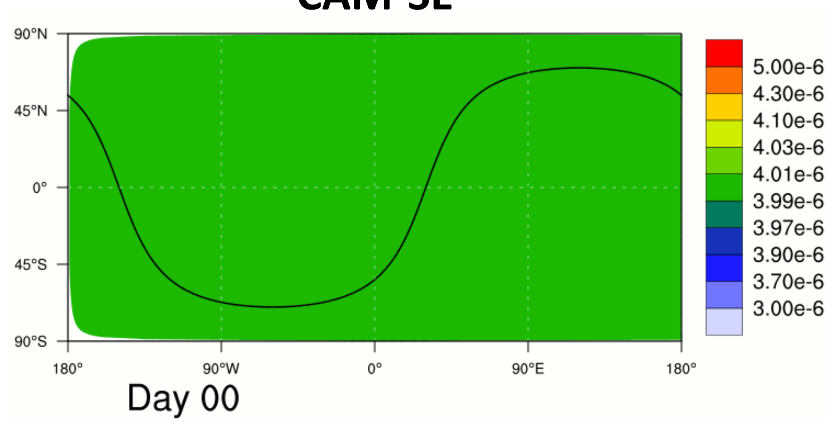
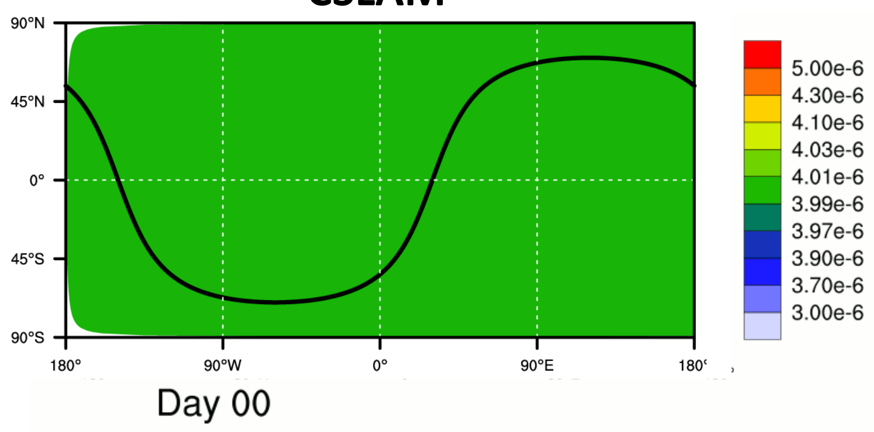


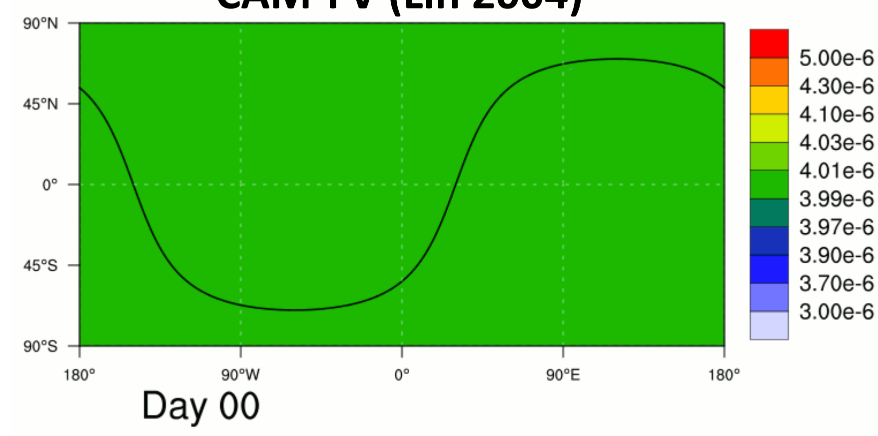
CAM-SE



CSLAM



CAM-FV (Lin 2004)



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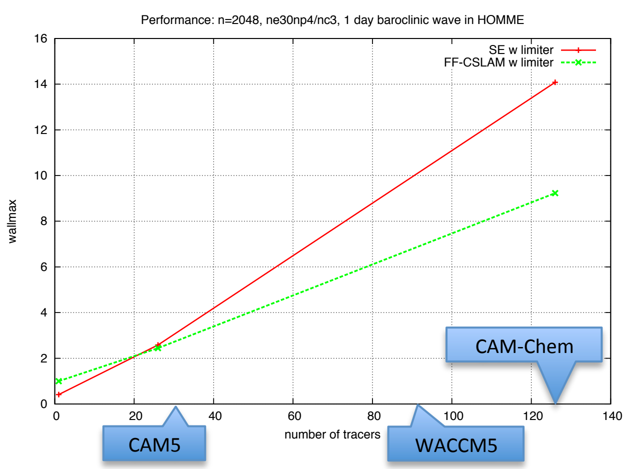

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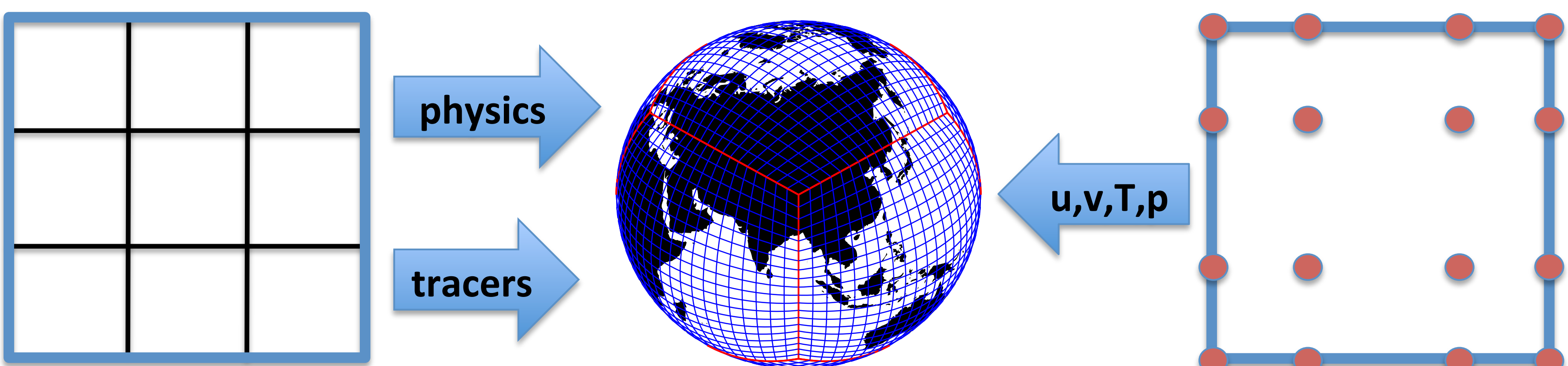
- Multi-tracer efficient (high start-up cost but "cheap" for each additional tracer)
- CSLAM uses a "finite-volume"-type grid and SE uses a quadrature grid



A way to accel… ate … er transport:

CSLaM sch…e (Conser… …gran…n Multi-tracer)

SciDAC

- Highly scalable … 20…
- Inherently mas…
- Fully two-dimer…
  -> accur…
  …edral, …)
- Sh…
- Prese… …t slide!
- Current …
- Allows f… …number)
  …tional tracer)
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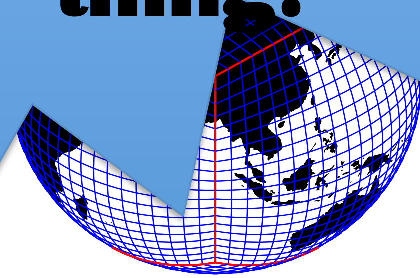
Separating physics/tracer and dynamics grids with Galerkin methods may not be a "bad" thing!

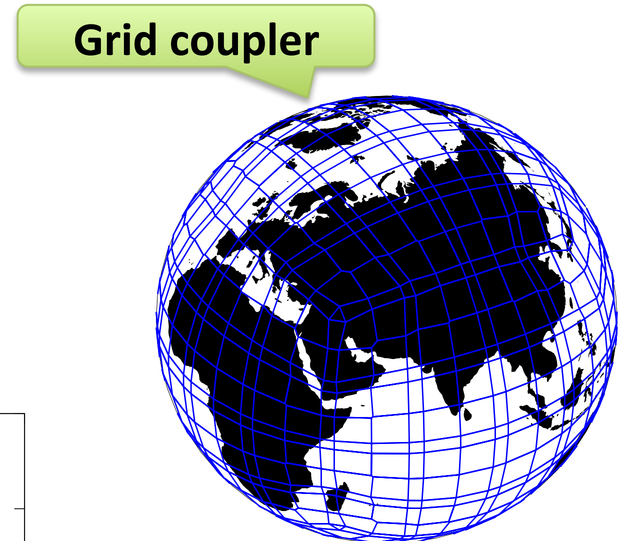


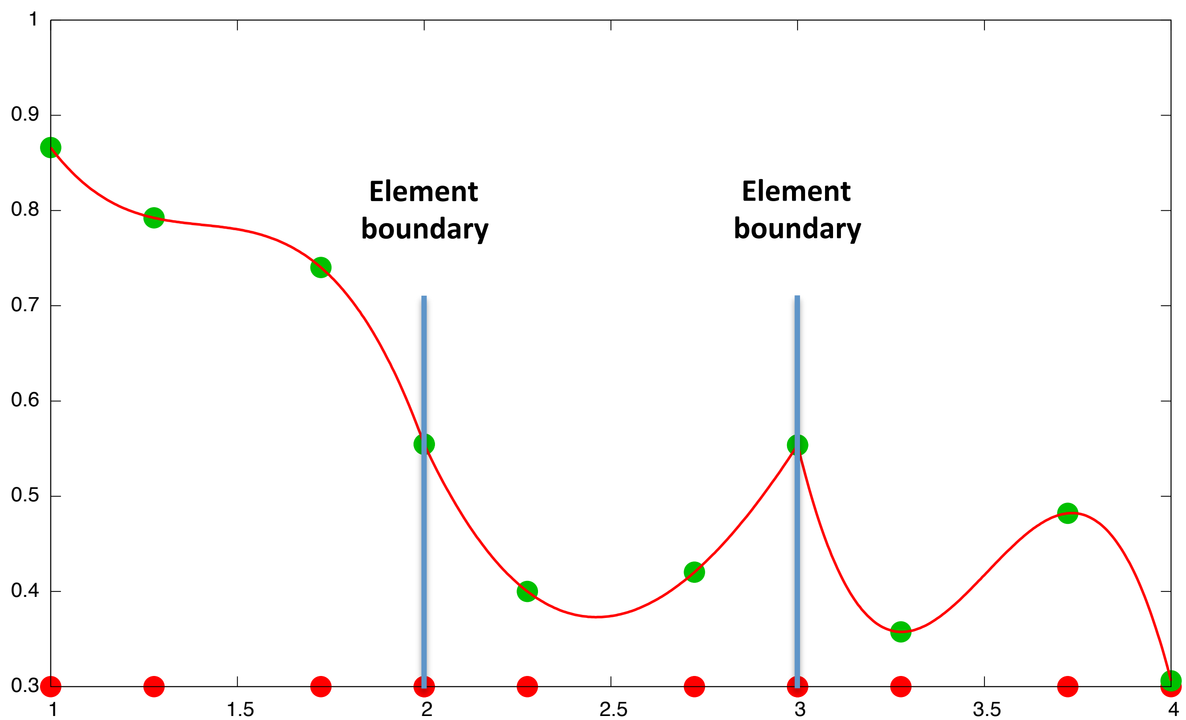
u,v,T,p

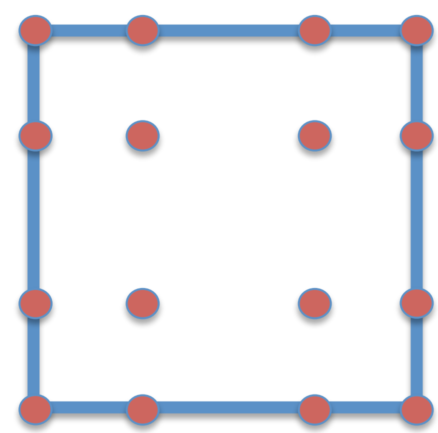
Current physics-dynamics coupling

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:







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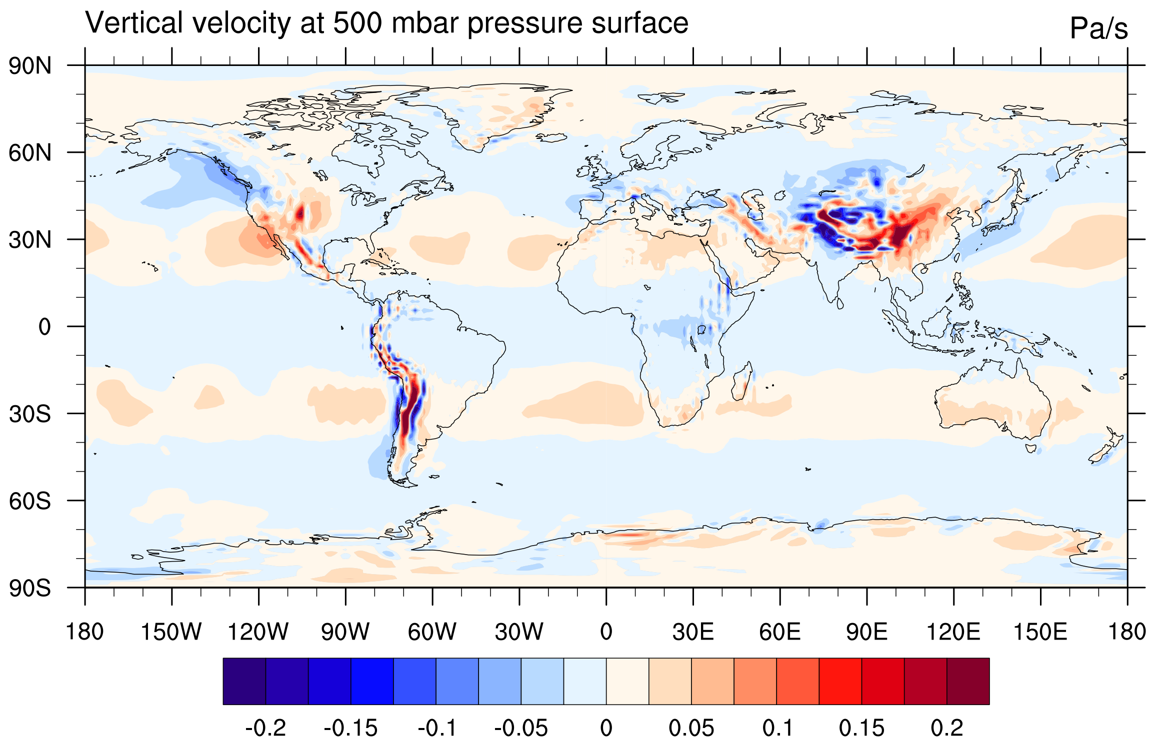
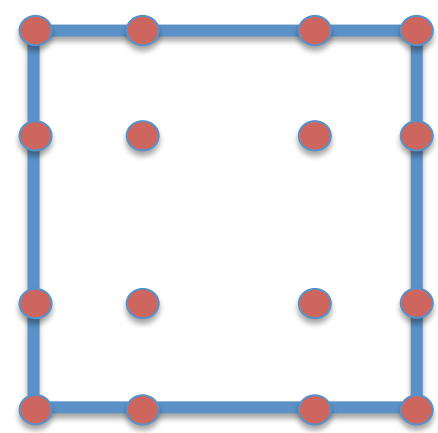
Held-Suarez with topography



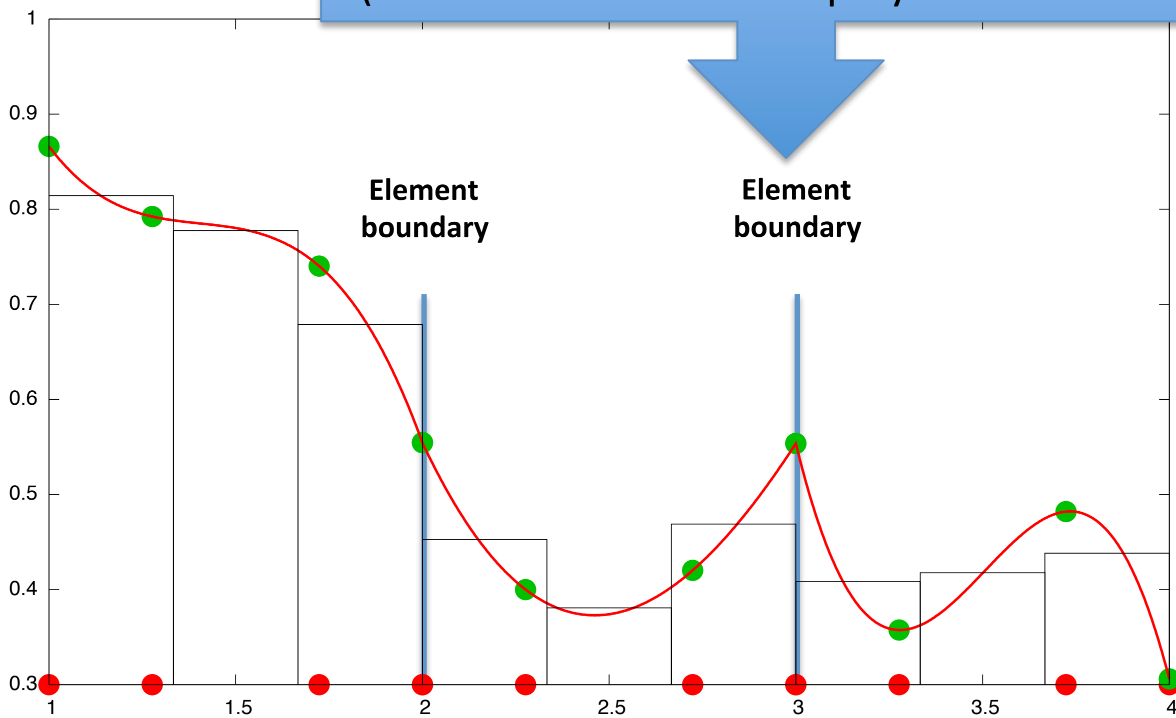
Grid coupler

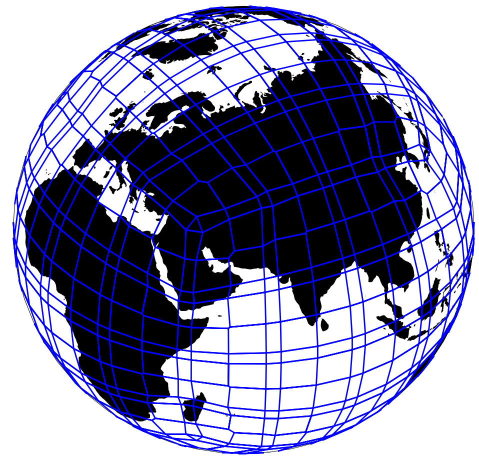


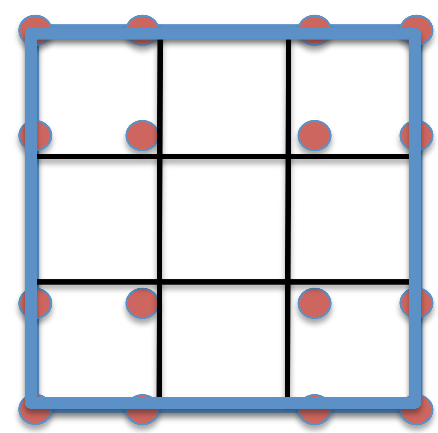
"Equal-area" physics grid

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^{∞})

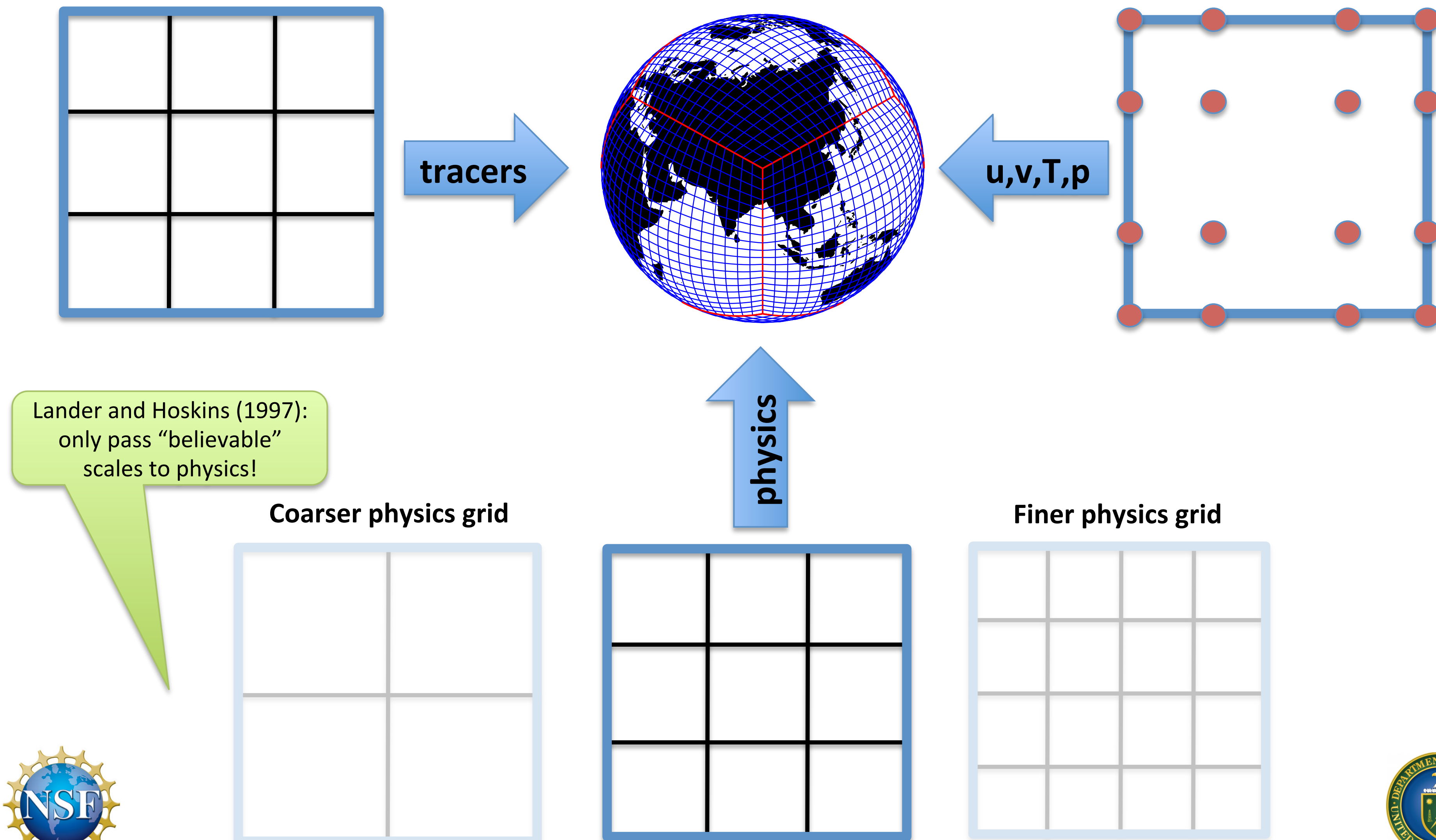




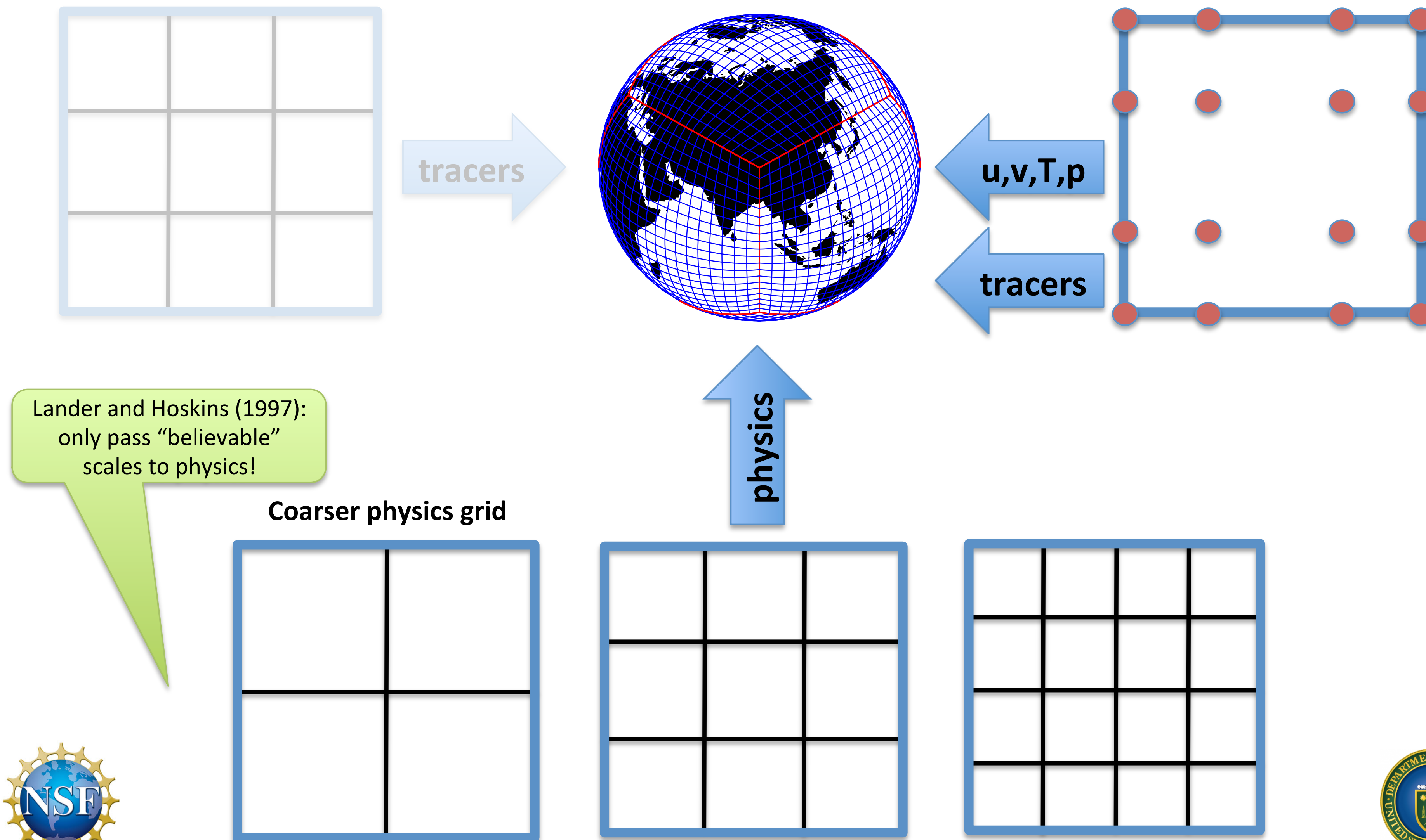


CAM-SE-CSLAM

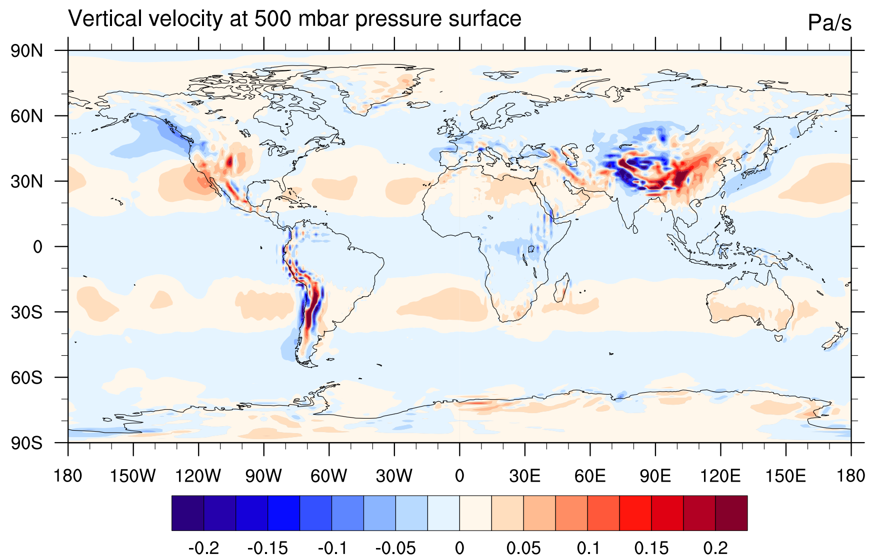
combining the best of two worlds: high-order spectral dynamics & finite-volume transport

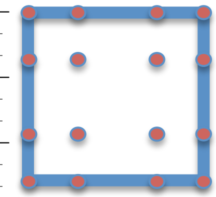


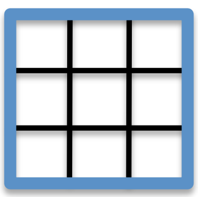
CAM-SE-physgrid

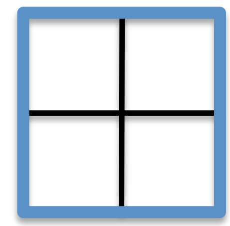


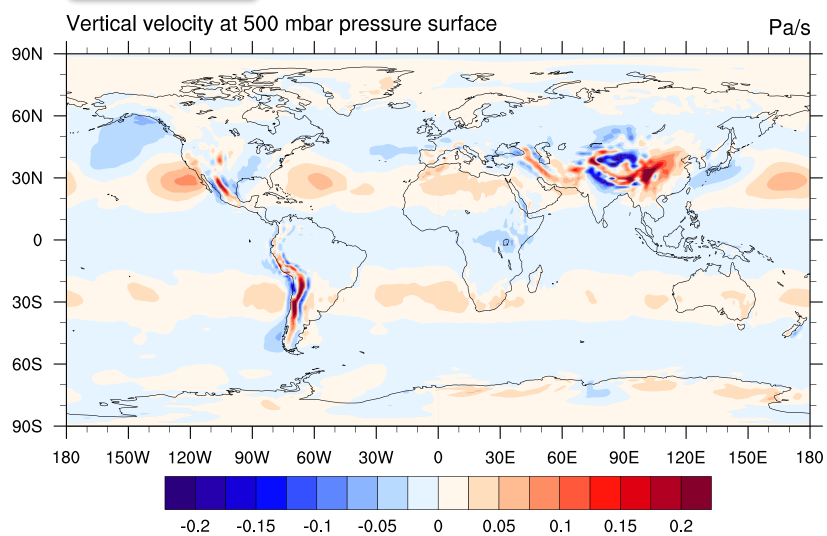
Held-Suarez with topography

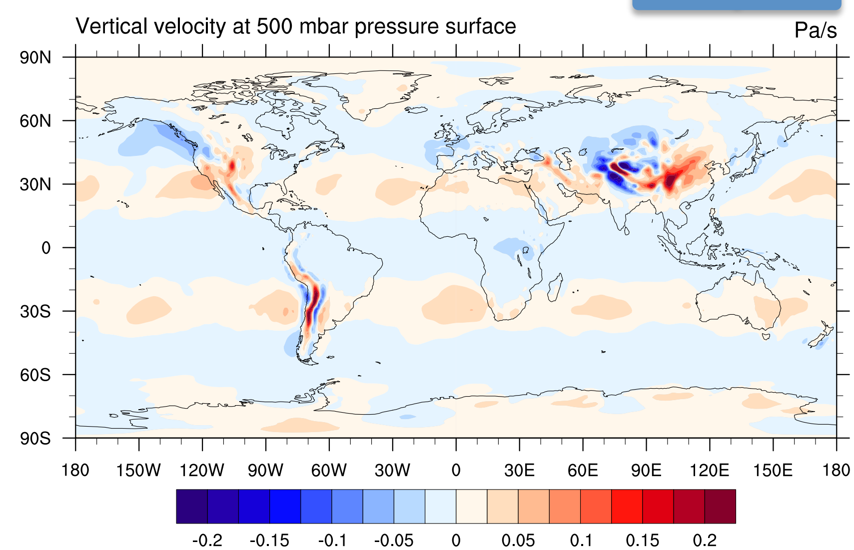








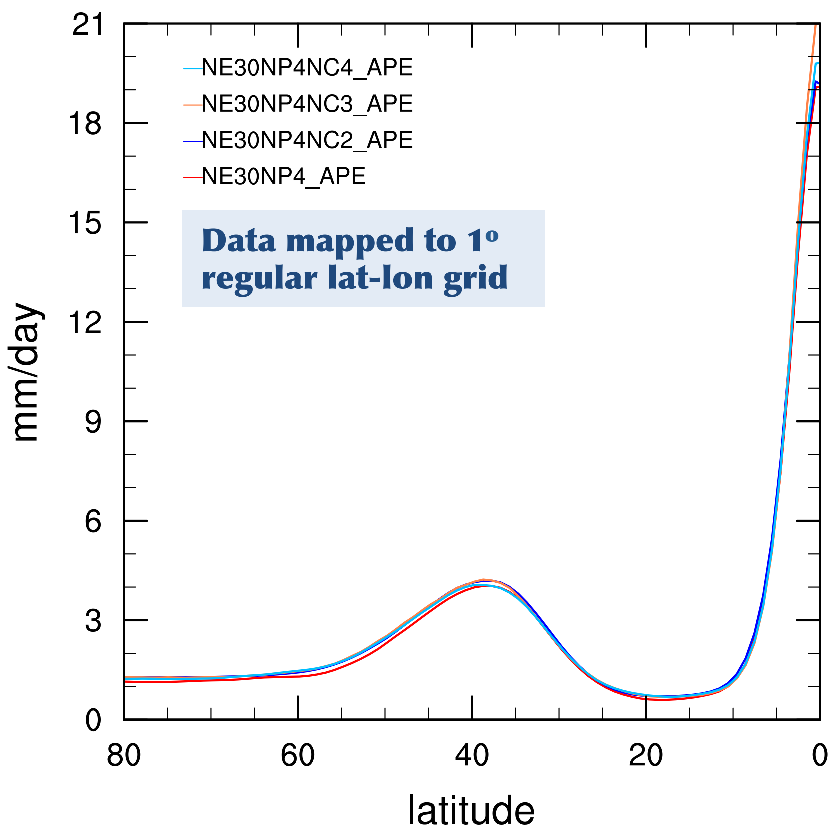




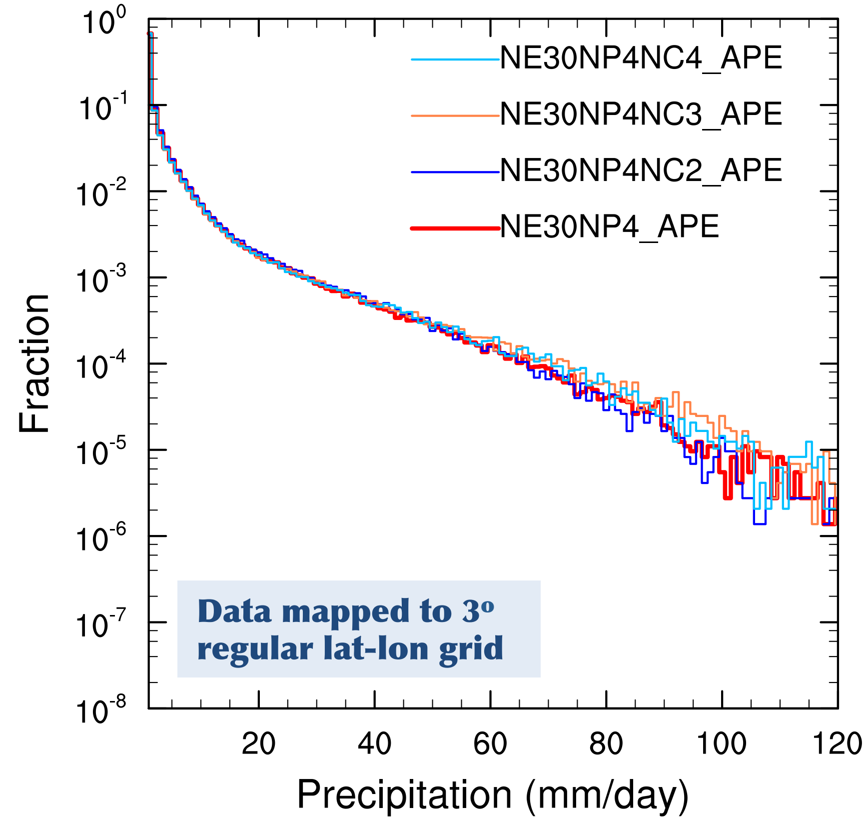
CAM4 Aqua-planet simulations

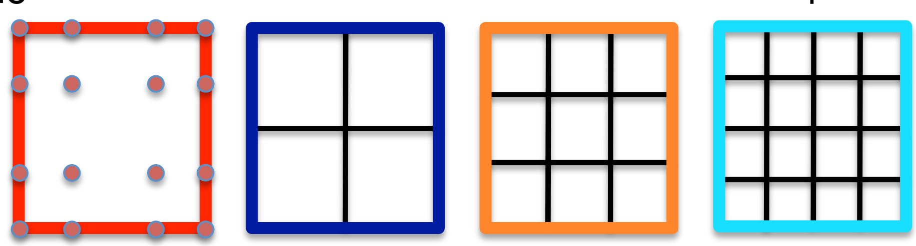
Idealized surface: no land (or mountains) + specified zonally symmetric sea surface temperatures => **free motions, no forced component**

Zonal-time averaged total precipitation rate



PRECT (30 month simulation - 6h data)



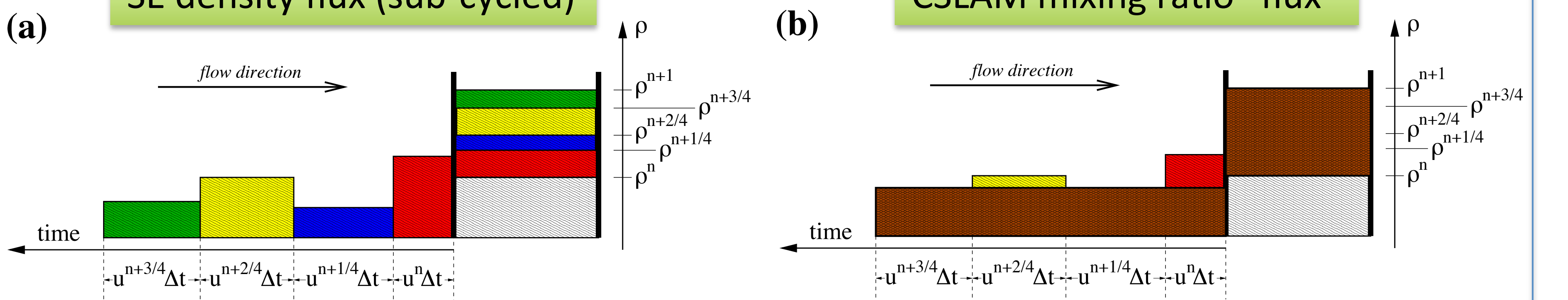


Last step towards CAM-SE-CSLAM: coupling mass

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

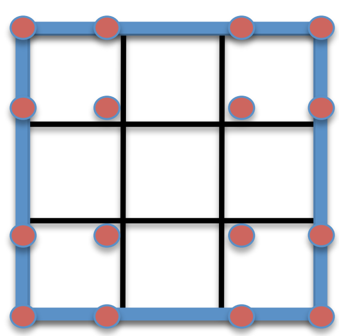
SE density flux (sub-cycled)

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.

Implementation almost done … (James Overfelt,SNL,DOE)

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