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CGD Climate & Global Dynamics

NCAR NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

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

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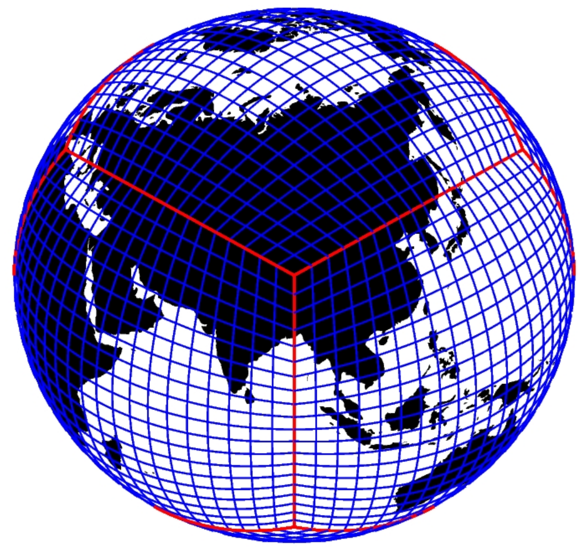

Collaborators:
M.A. Taylor, P.A. Ullrich,
S. Goldhaber, J. Bacmeister

Workshop on Physics-dynamics coupling in geophysical models – bridging the gap
December 2-4, 2014
CICESE, Ensenada, Mexico

Getting away from the lat-lon grid …

CAM=NCAR's Community Atmosphere Model

- Scalability
- Static mesh-refinement capability
- …

CAM-FV (finite volume)

Lin (2004)

CAM-SE (spectral elements)

Dennis et al., (2012)

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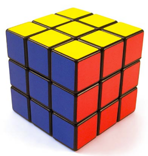
CAM-SE (spectral element dynamical core); (Dennis et al., 2012)

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



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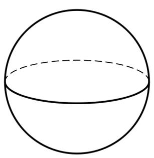

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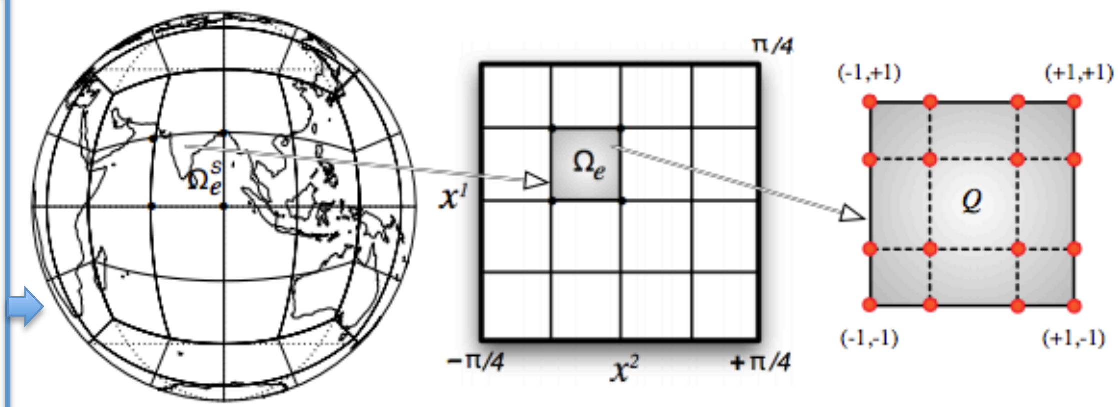
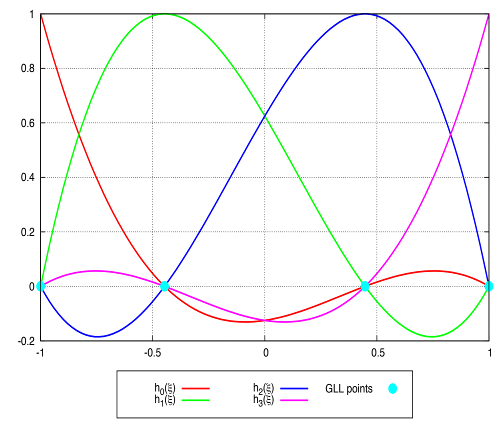


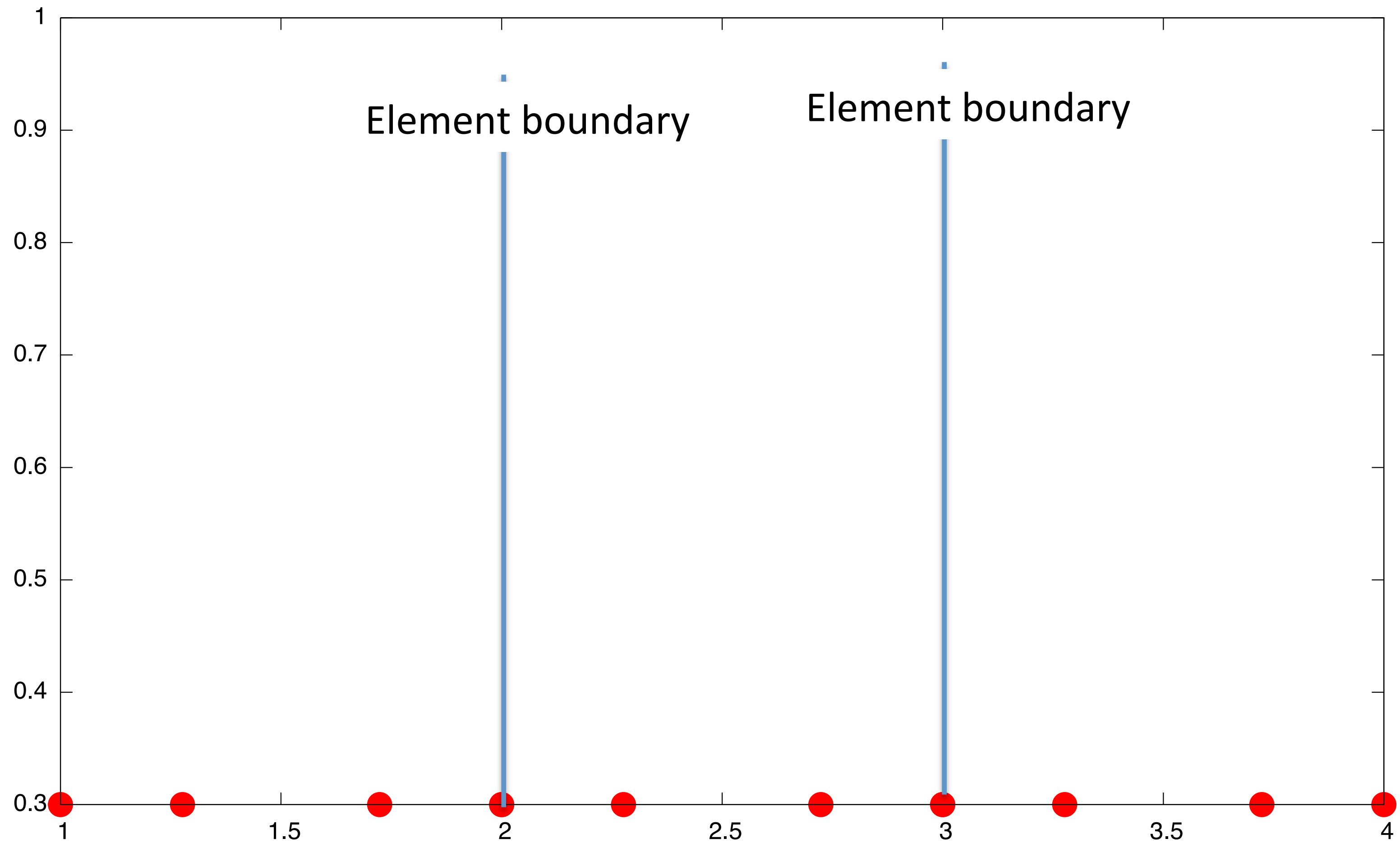
Physical Domain | Computational Domain | GLL Quadrature Grid



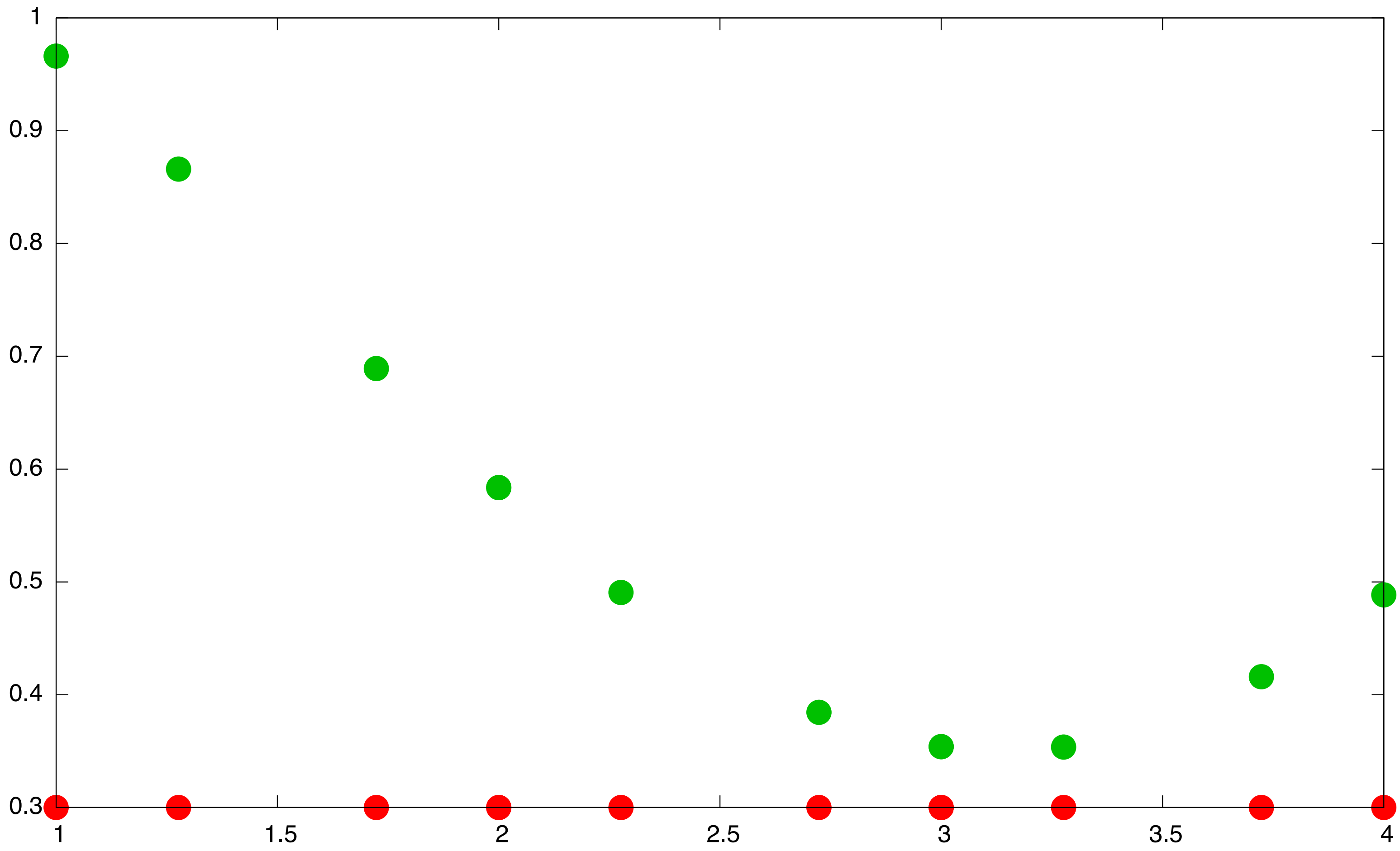
Figures from Nair et al. (2011)

- 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*
  $\rightarrow$ all derivatives inside each element can be computed analytically!

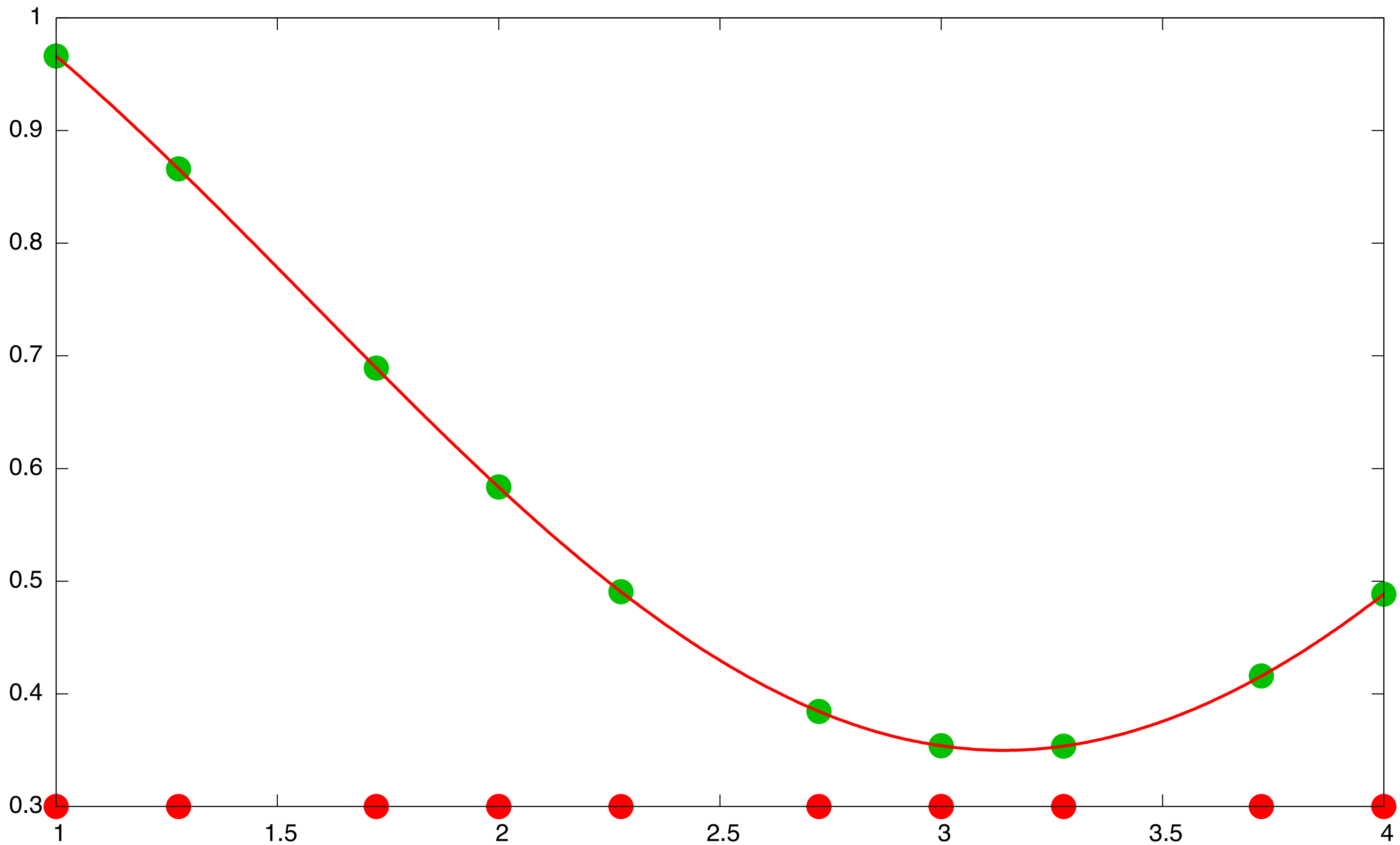
- Computational grid: 3 elements, 4 quadrature points in each element (np=4)
- This quadrature will integrate polynomials of degree 3 exactly
- Note: quadrature points are duplicated on element edges



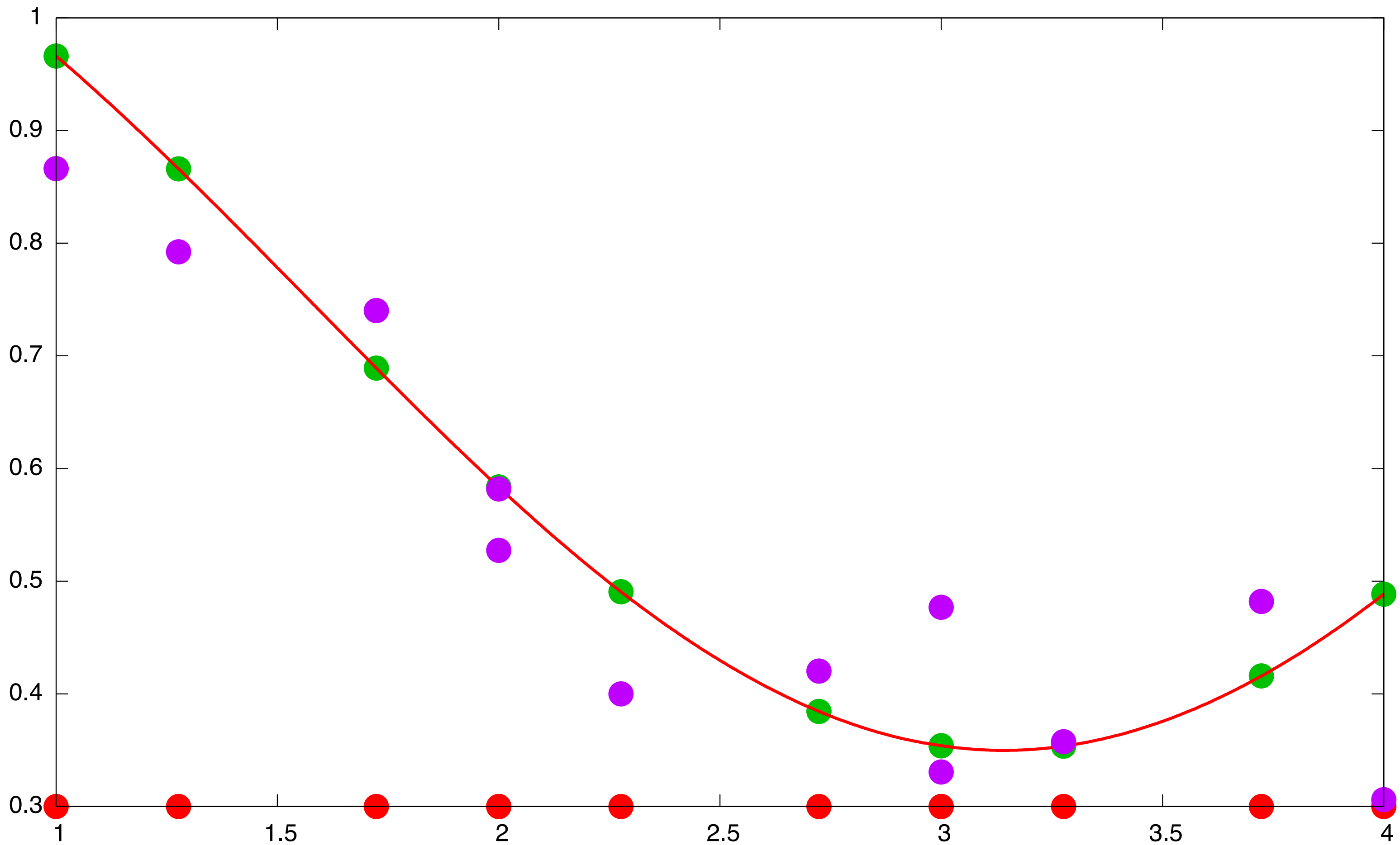
- Let the initial condition for GLL point values be a degree 3 polynomial



- 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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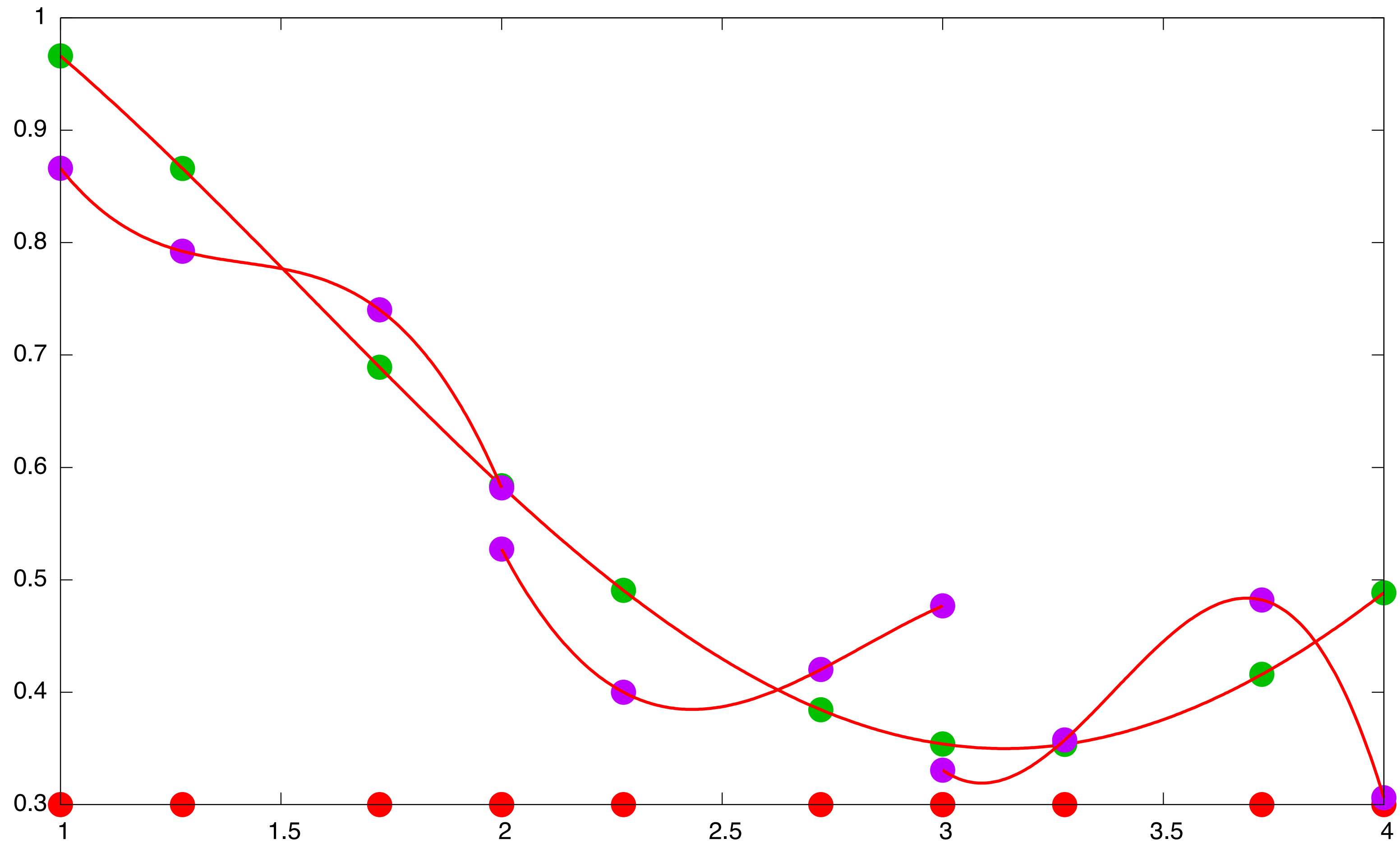
- Within each element the dynamical core advances one Runga-Kutta step
- Note each element advances the solution in time independently
- Discontinuities may develop at element edges



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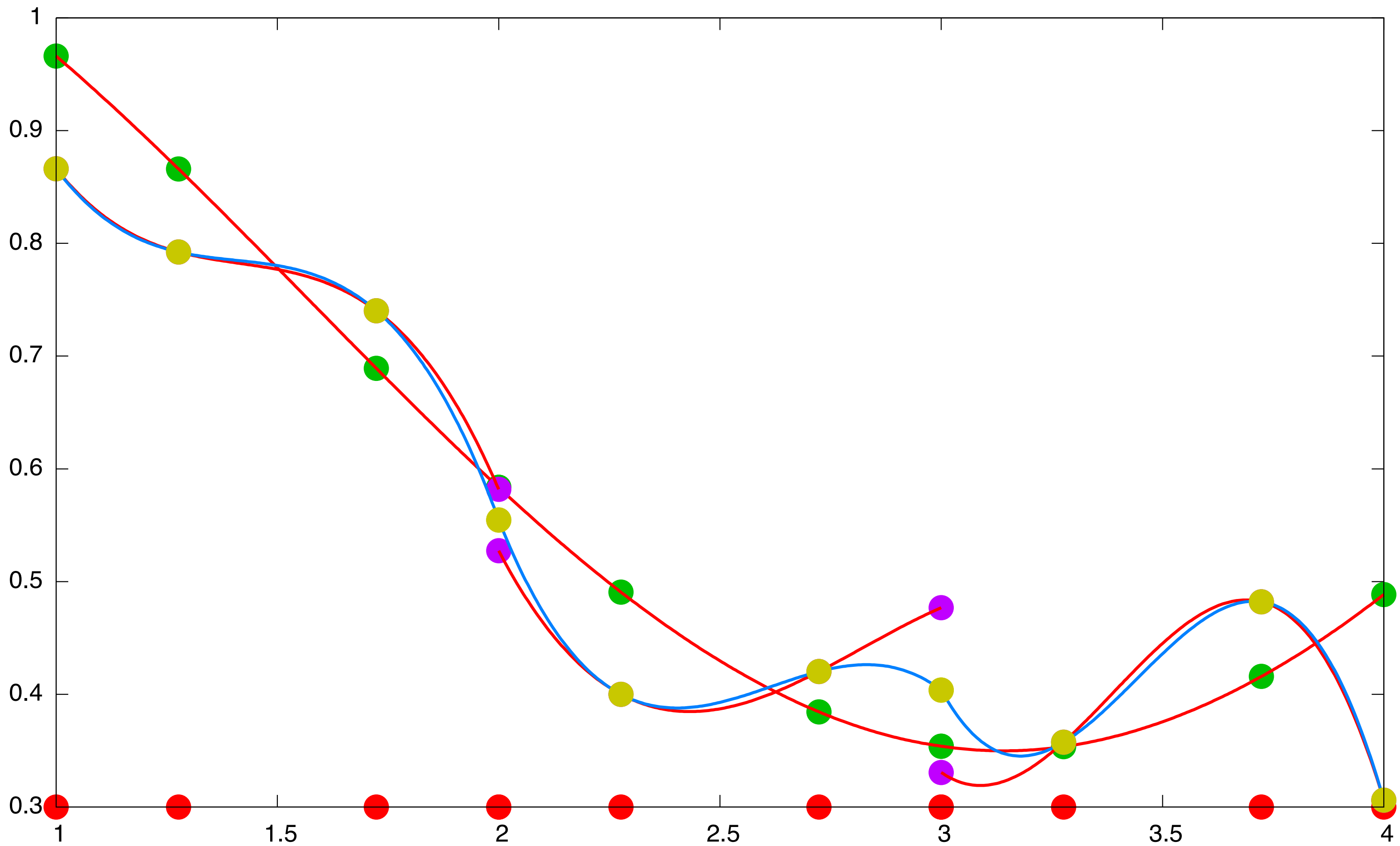
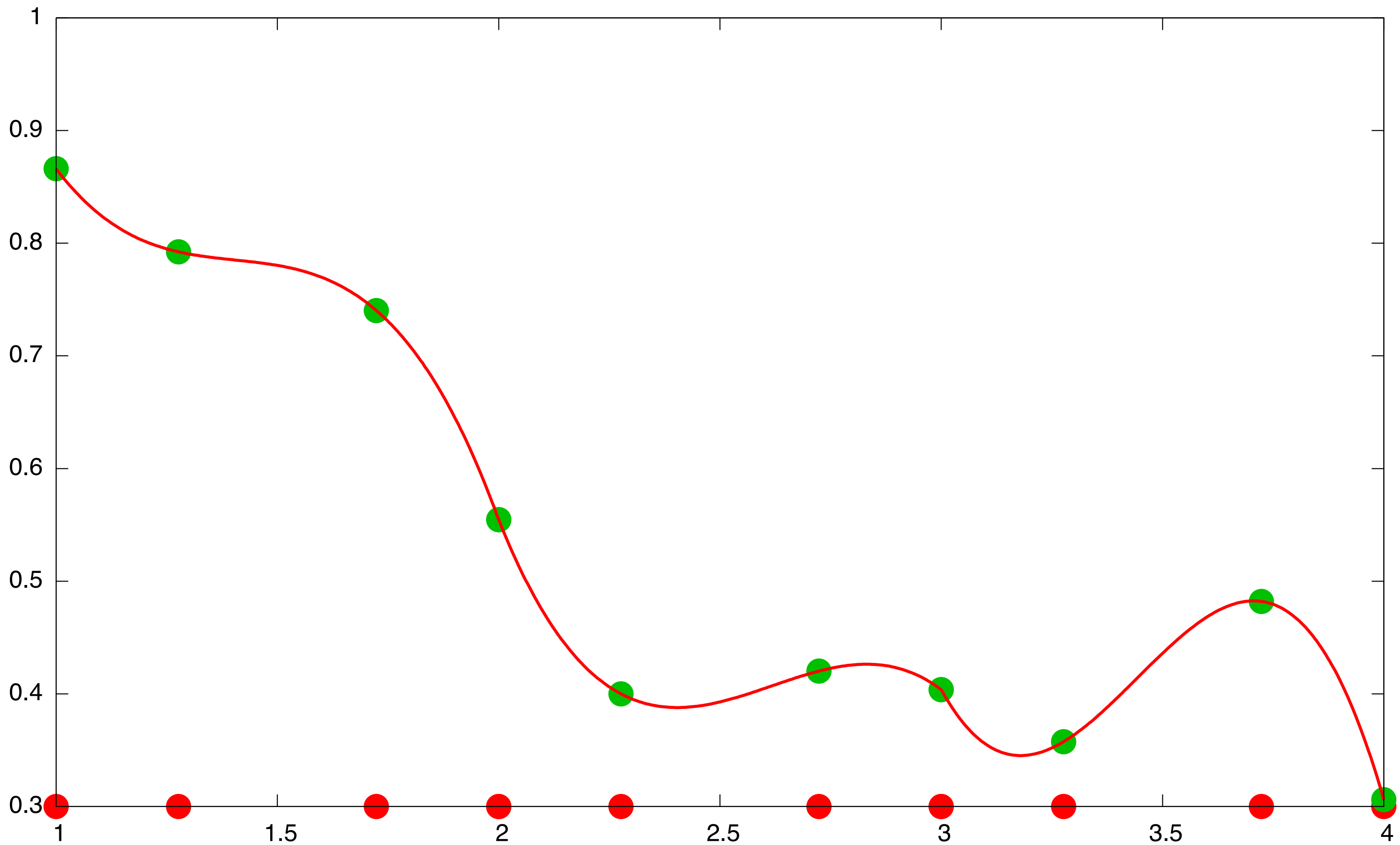
- Within each element the dynamical core advances one Runga-Kutta step
- Note each element advances the solution in time independently
- Discontinuities may develop at element edges **– averaging at element edges**



- This process is repeated for every Runga-Kutta stage (currently 5 times per dynamics time-step)
- **Physics is "run on GLL grid"**



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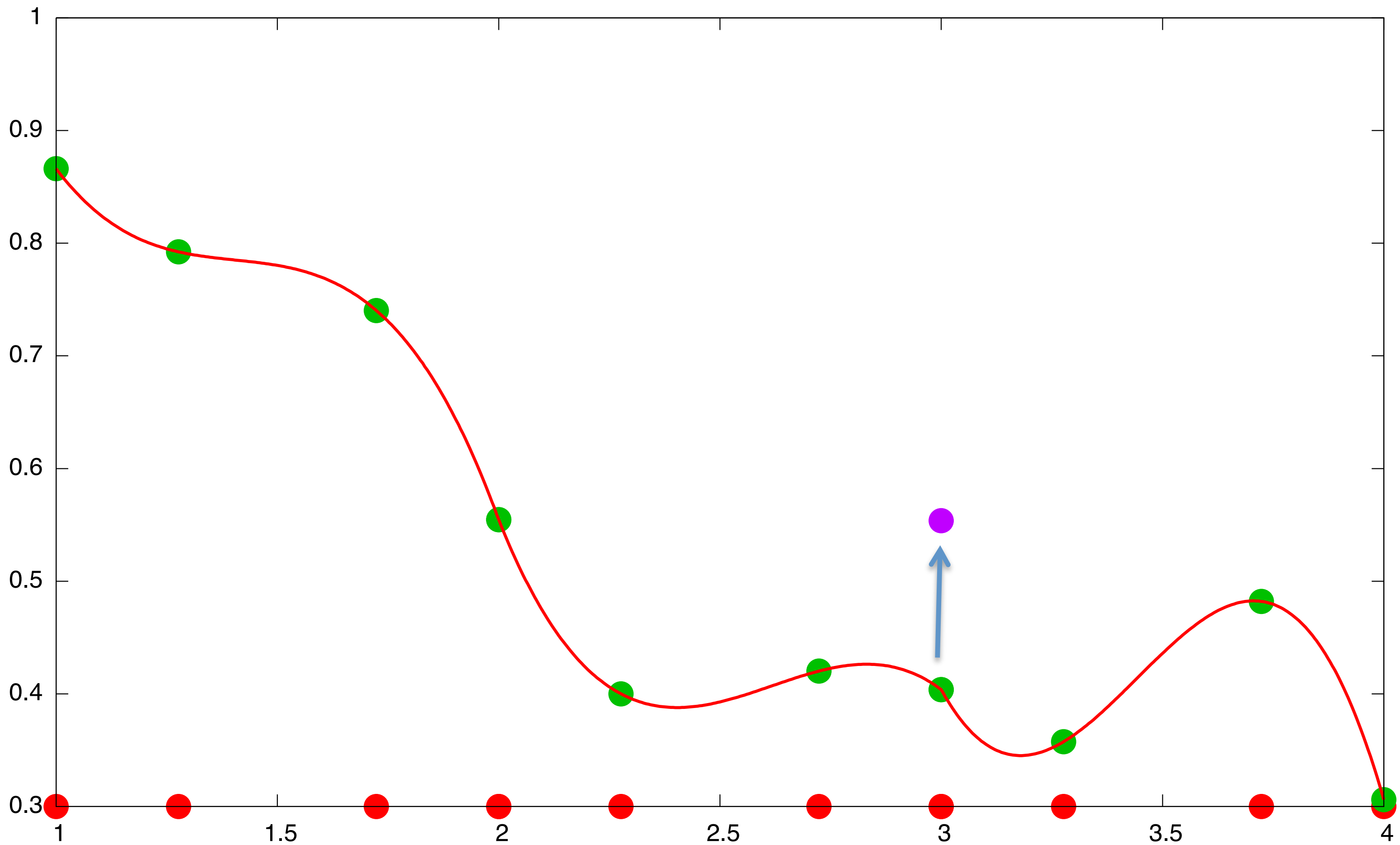
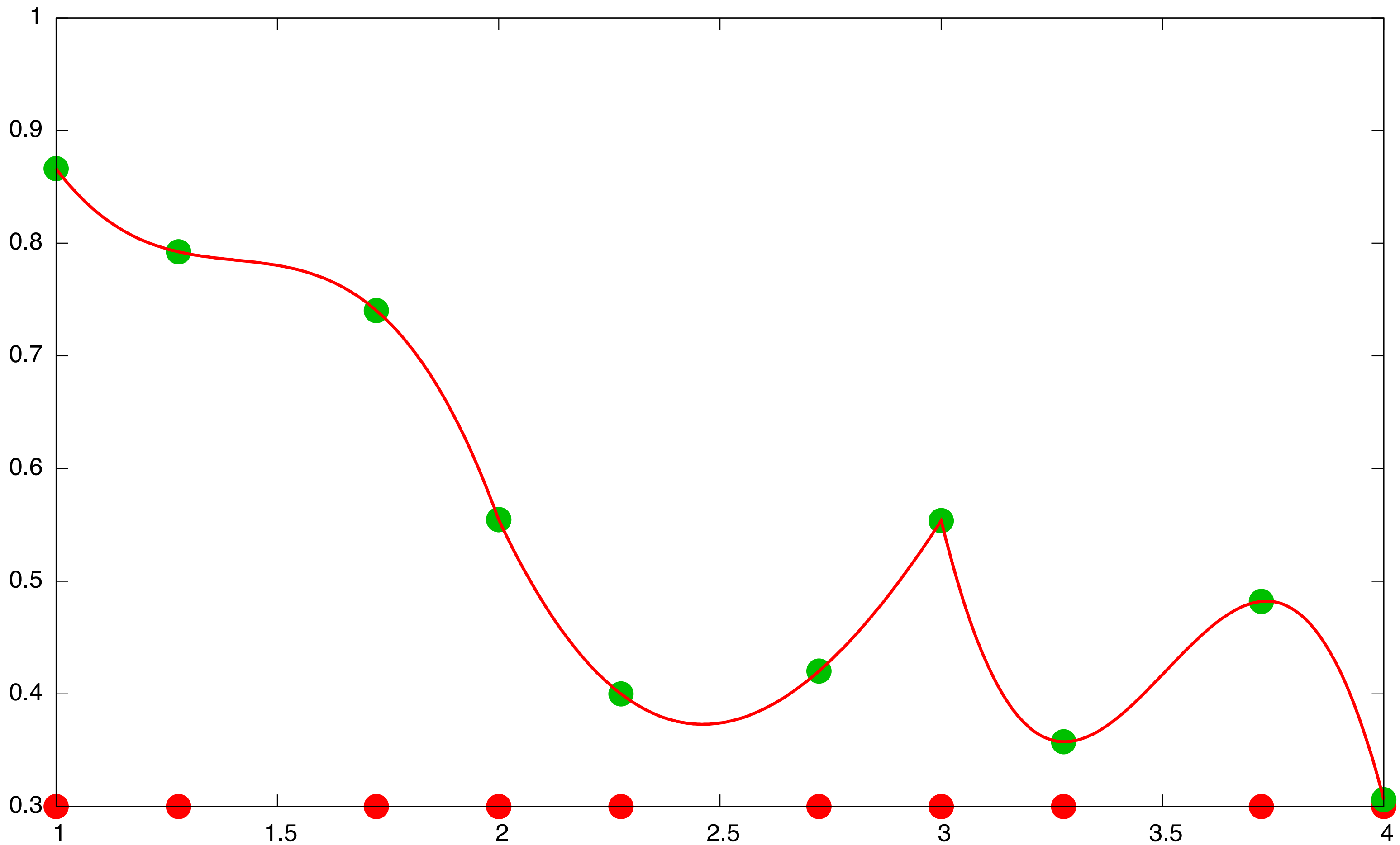
- Physics update: say it perturbs one point value



- Physics update: say it perturbs one point value
- **Polynomial basis changed in element 2**
- **Basis functions only C^0 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

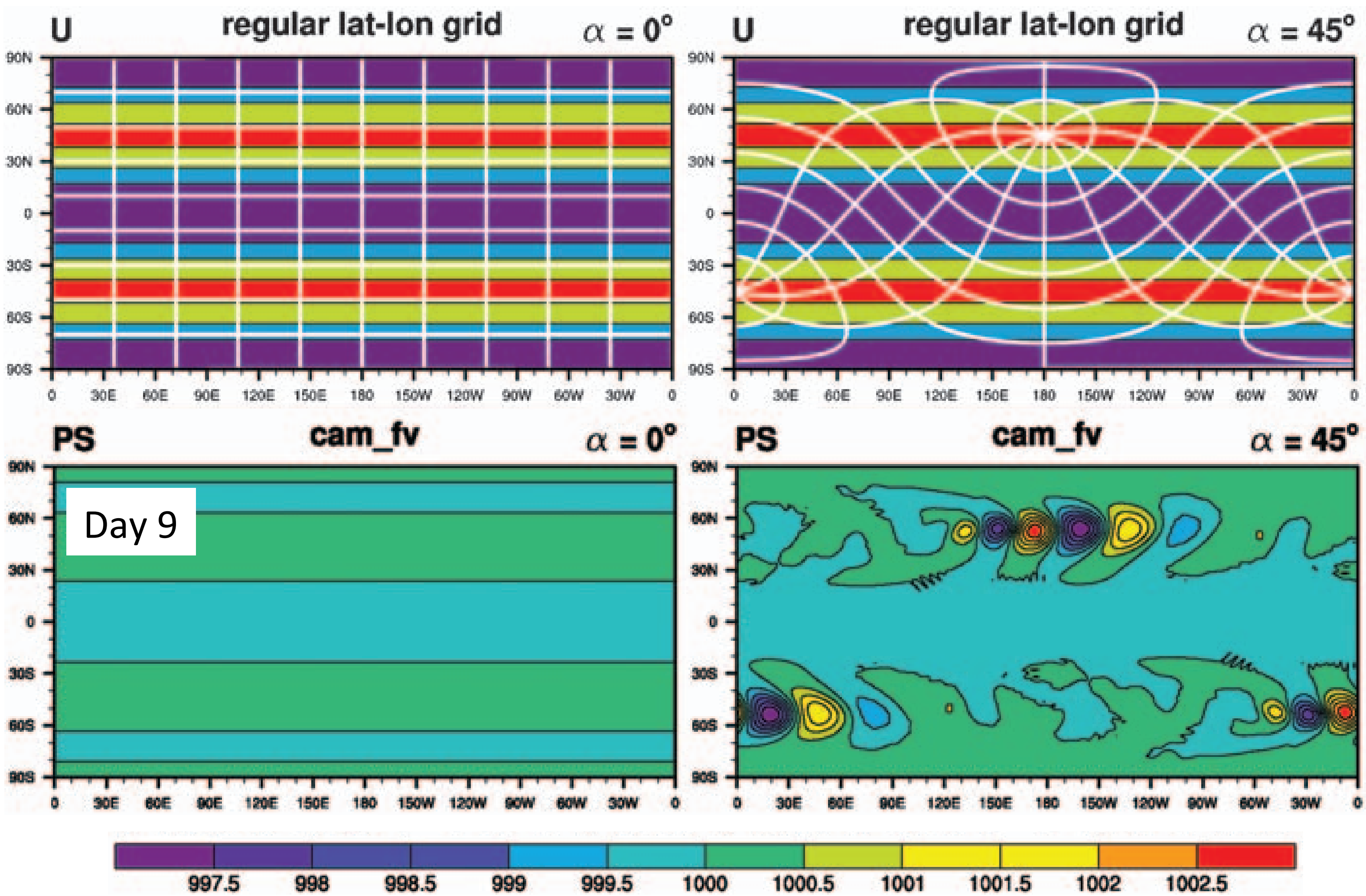
How do we couple the dynamical core with sub-grid scale parameterizations (physics)?

Traditionally physics and dynamics grids are collocated

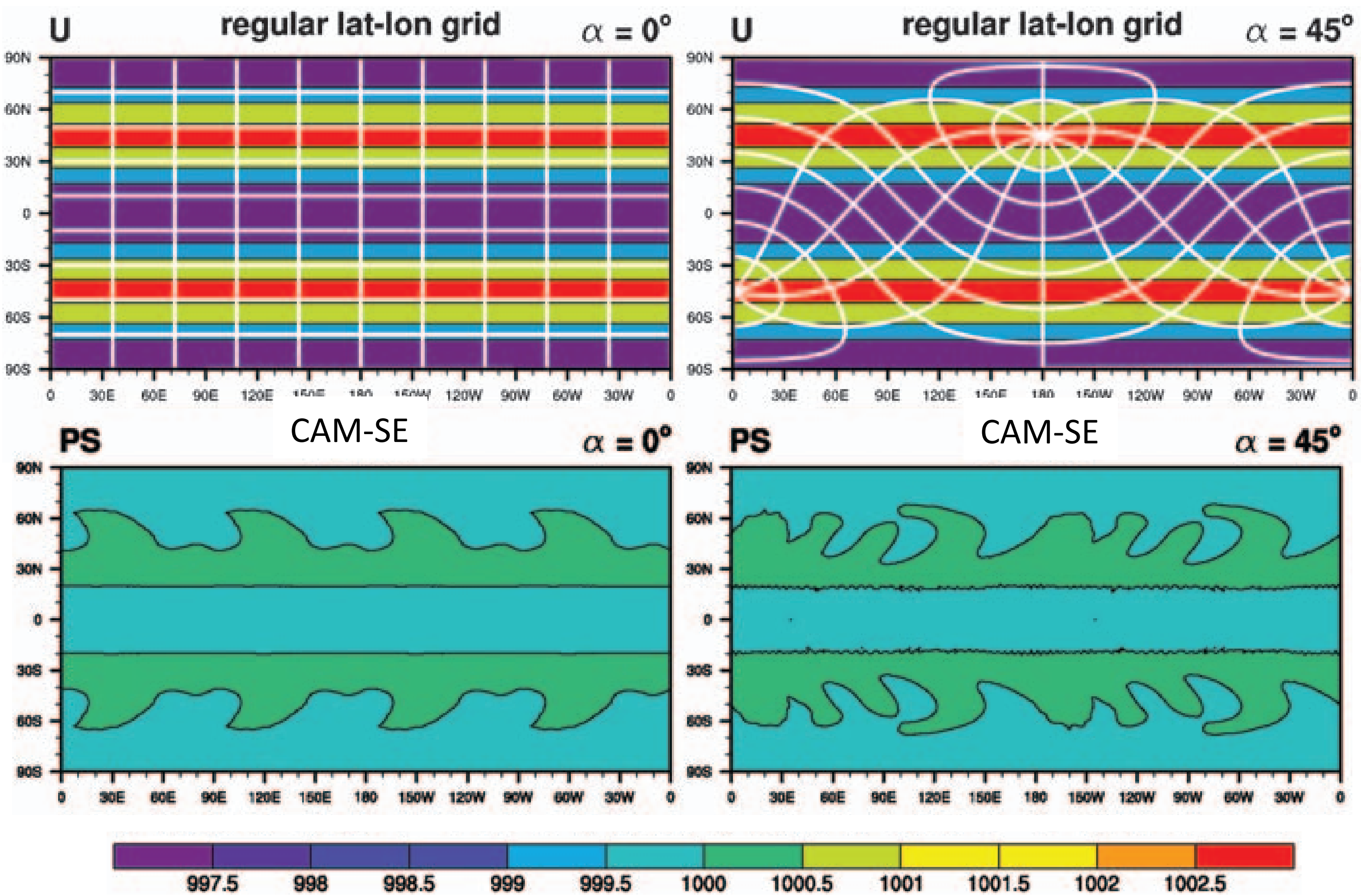
- smoothly varying grid in terms of grid size
- Much higher resolution near poles, however, dynamical core usually has filter in the polar regions to filter out small scales
- Aside: Lat-lon grid is "optimal" for minimizing zonal flow errors! … when grid is no longer aligned errors get rather large ….

Jablonowkski steady-state test case

Lauritzen et al. (2010; JAMES)



Jablonowkski steady-state test case



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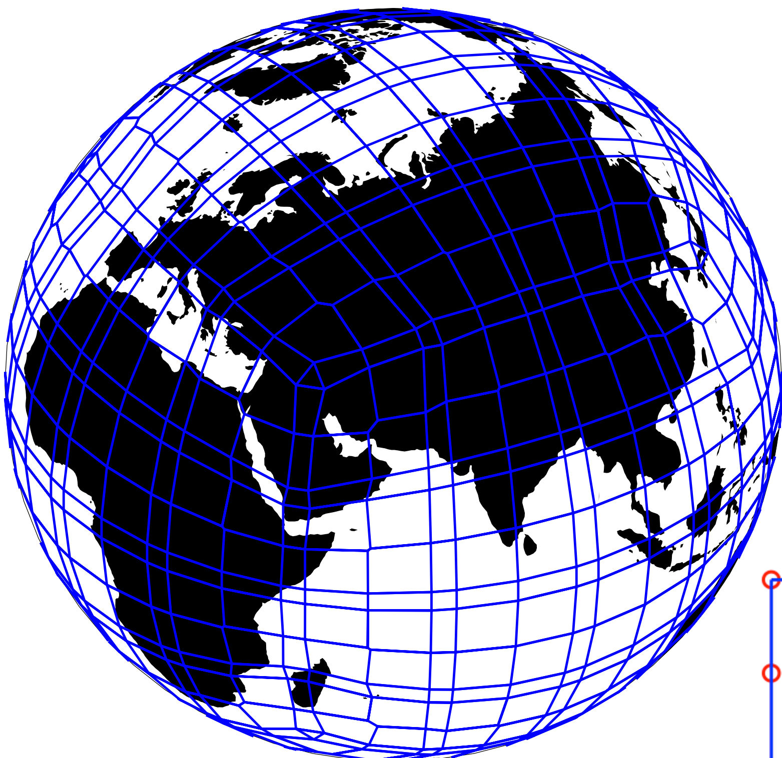
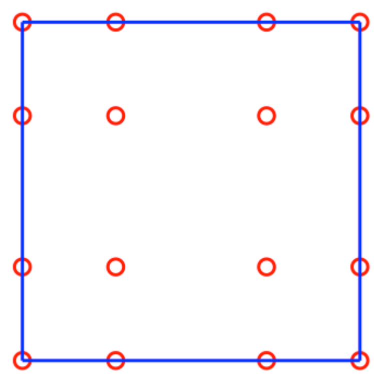


If you construct control volumes around the quadrature points so that the area of the control volumes equals the Gaussian quadrature weight (times metric term) then a very anisotropic grid results

Gets "worse" with:

- mesh-refined grids
- increasing polynomial order

Np=4



np=7

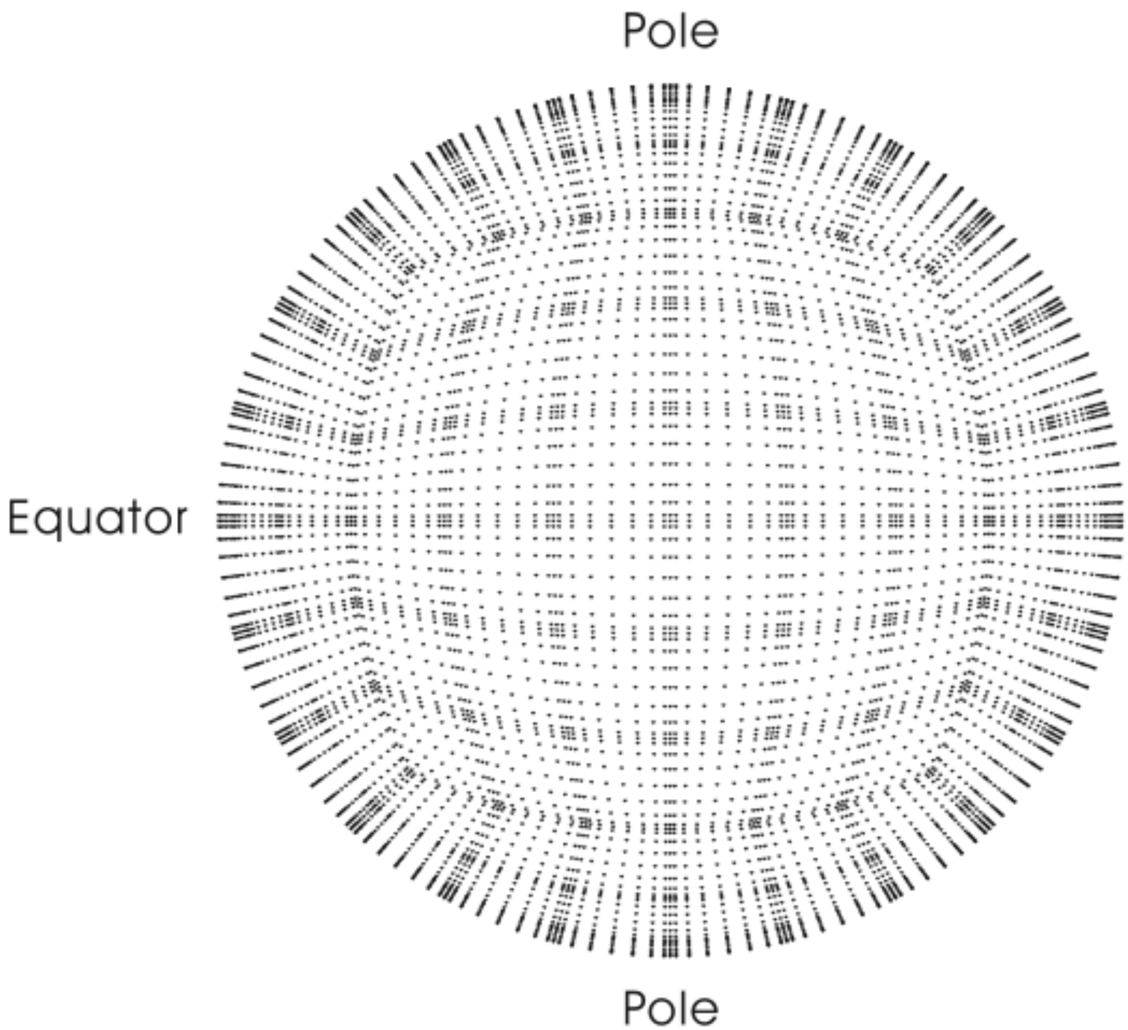
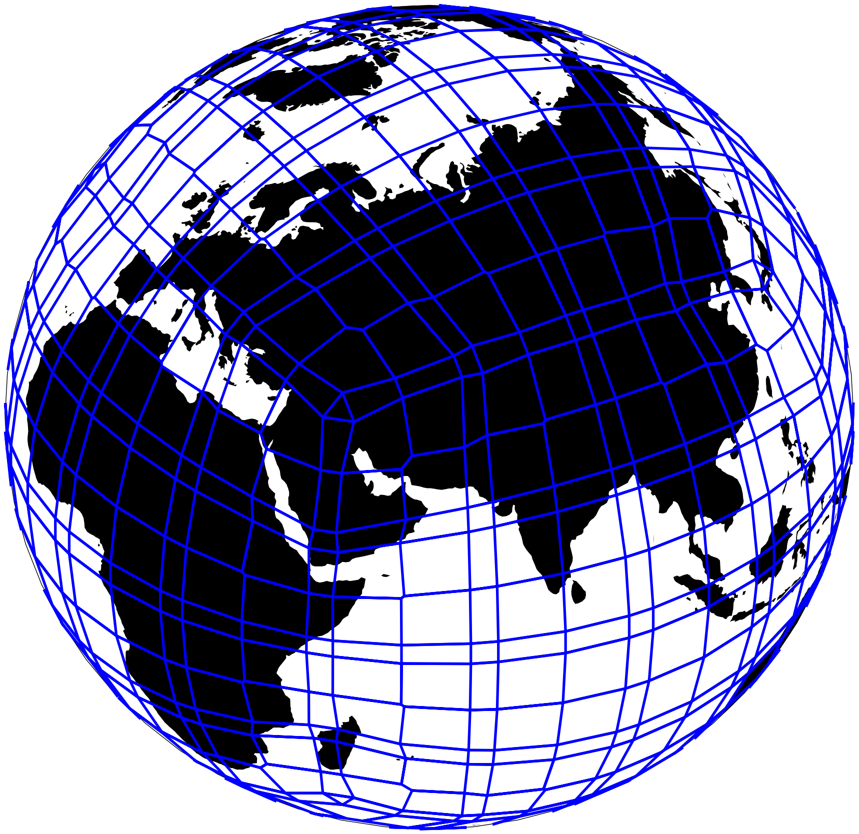


Figure 1. An orthographic view of the hexahedral grid points used in this study for NSEAM. Six elements on one face in one direction and 8th polynomial order of the basis functions are selected for this study. This horizontal

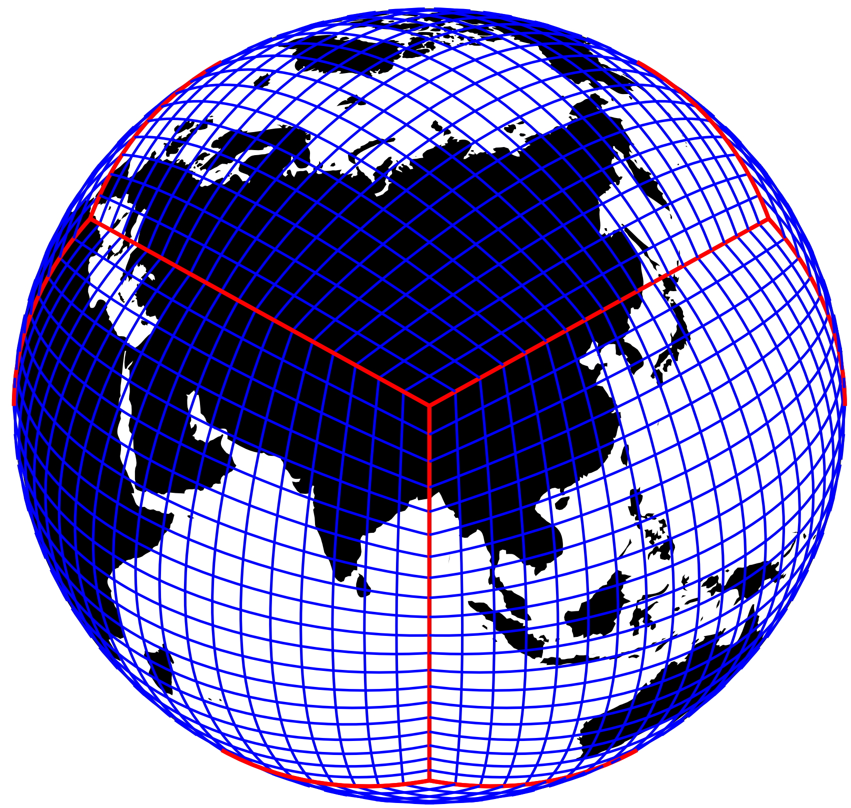
Kim et al. (2008)

Separate physics-dynamics grids?

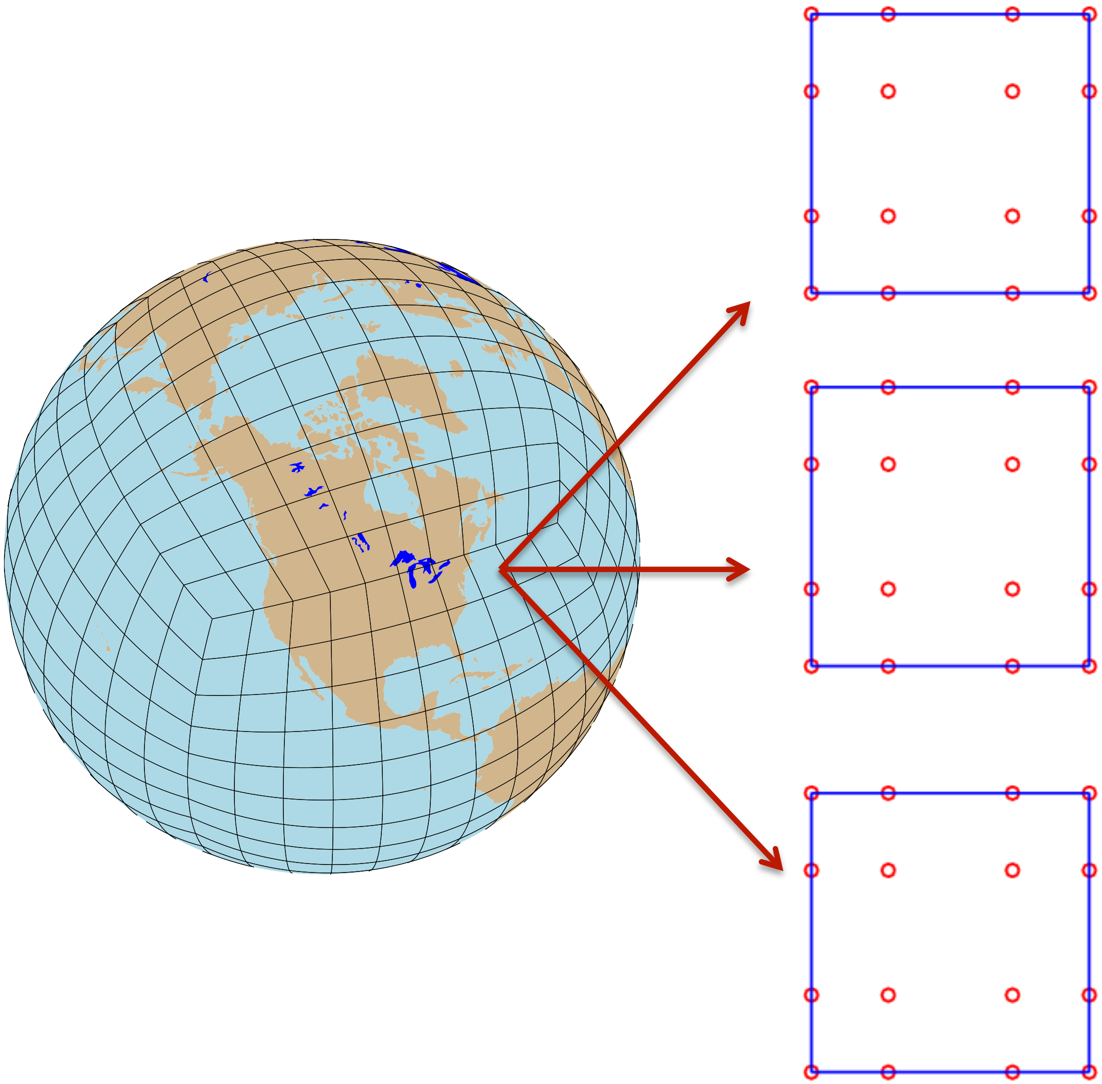
Current physics/"coupler" grid



Finite-volume equi-angular gnomonic grid



CAM-SE "default" NE30NP4 configuration



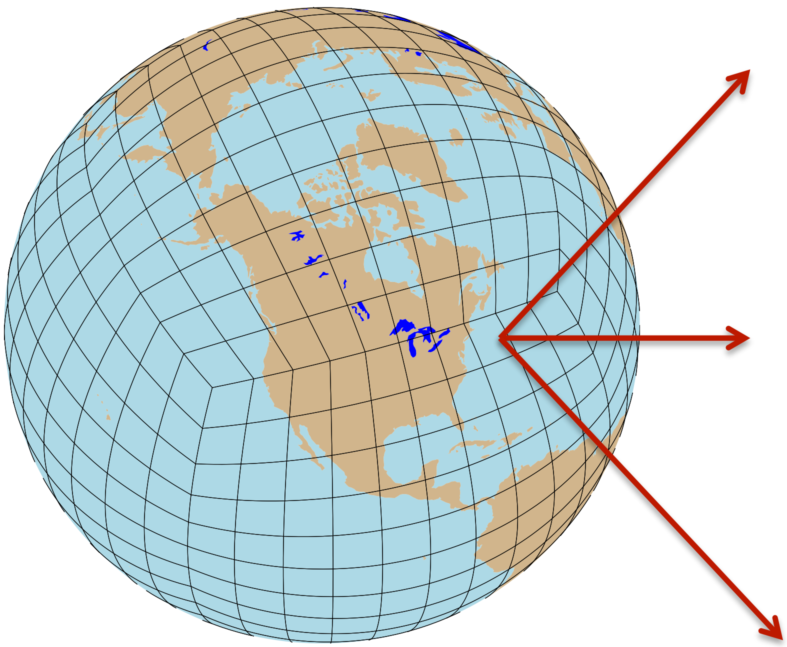
Dynamics: Spectral element dynamics on Gauss-Lobatto nodal values (not quite equally spaced at CAM-SE default 4x4, p=3)

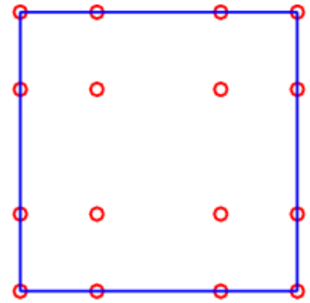
Tracer Advection: Spectral element. Locally conservative and monotone on Gauss-Lobatto nodes

Physics: physics columns computed at Gauss-Lobatto nodal values

Slide courtesy of M. Taylor

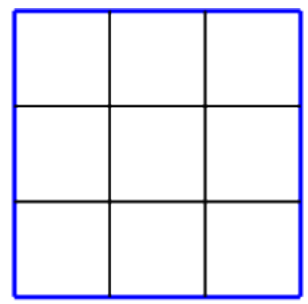
CAM-SE/CSLAM physics grid



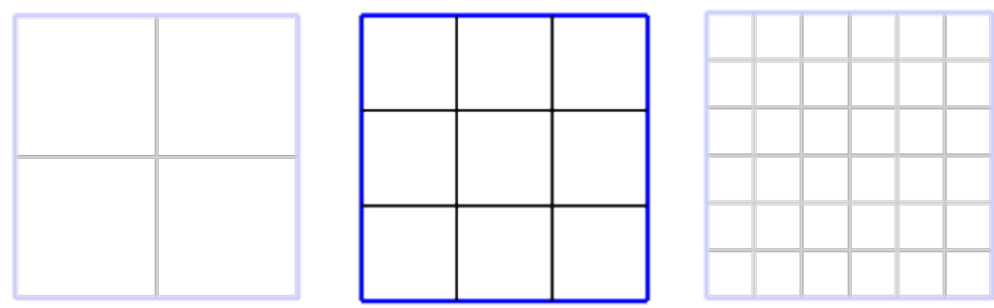


Dynamics: Spectral element

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



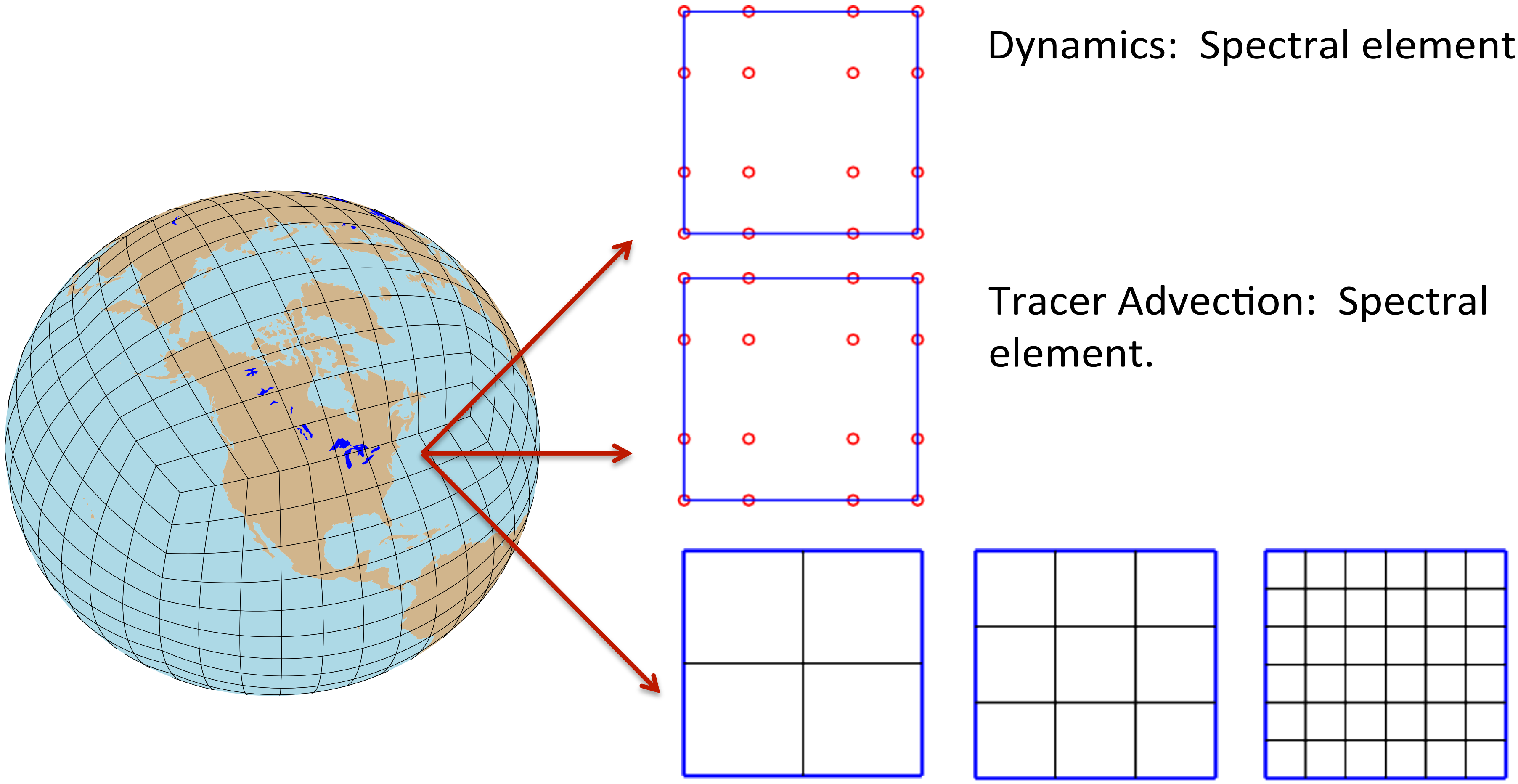
Tracer Advection: CSLAM
Conservative, Semi-Lagrange, multi-tracer efficient algorithm using cell averaged data



Physics: cell averaged data.

Slide courtesy of M. Taylor

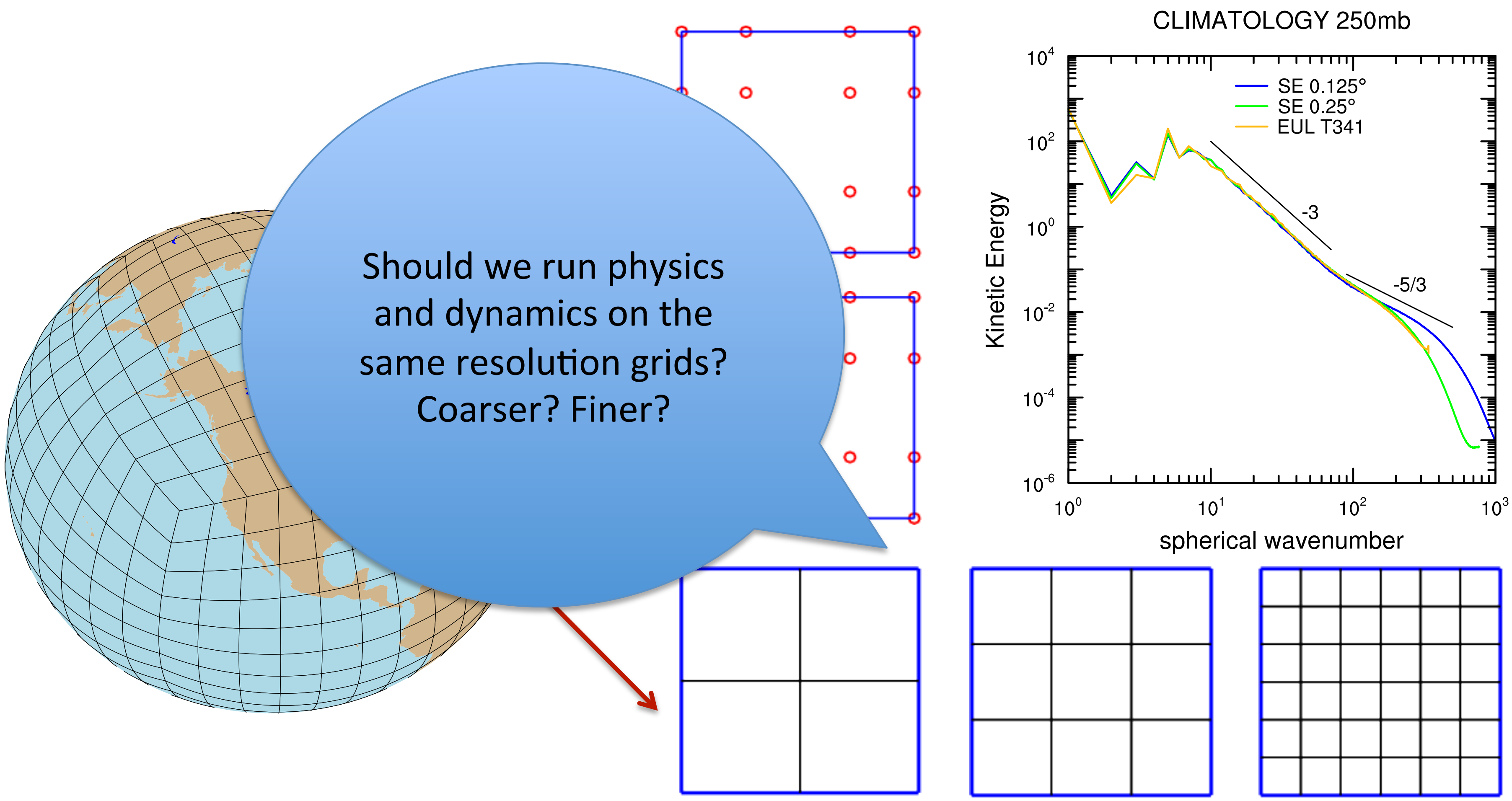
CAM-SE physics grid NE30NP4NC3 configuration



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



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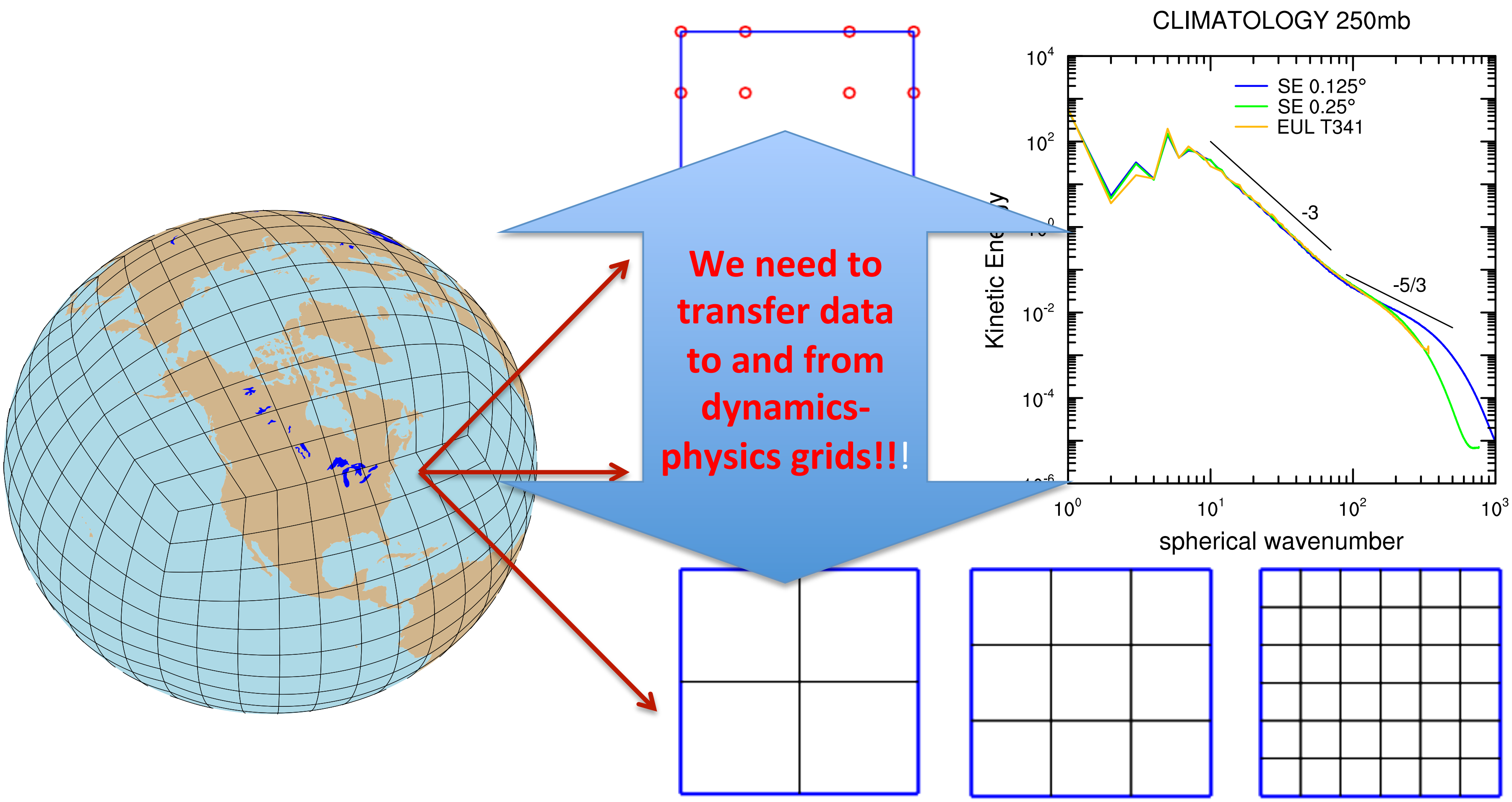

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Slide courtesy of M. Taylor

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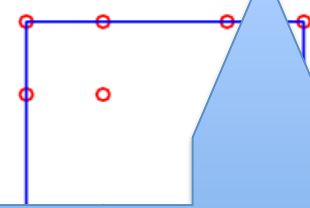
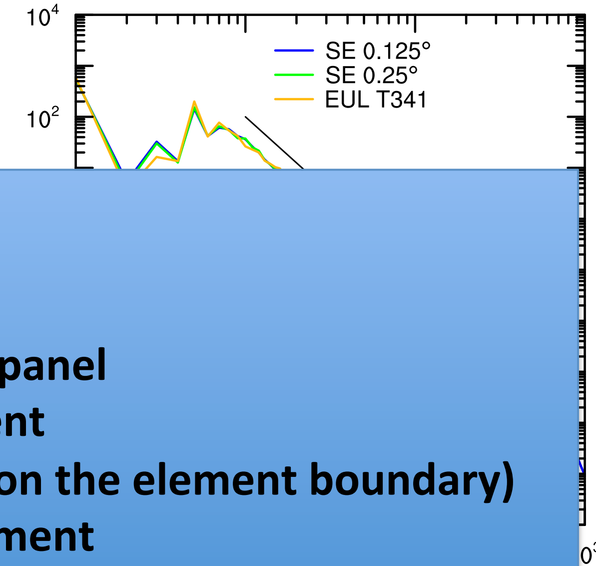
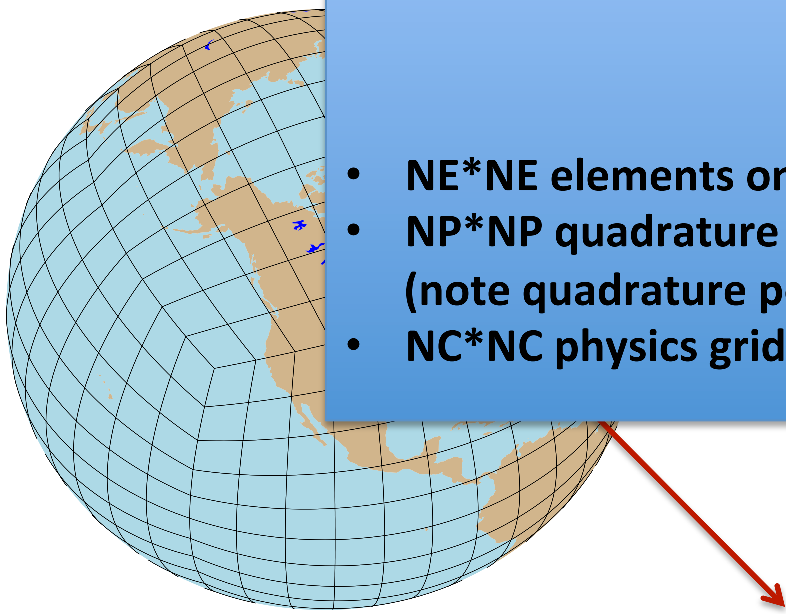
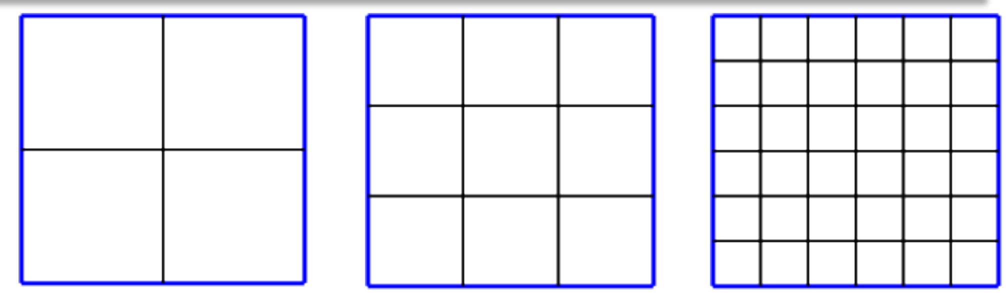




Notation:

- **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**





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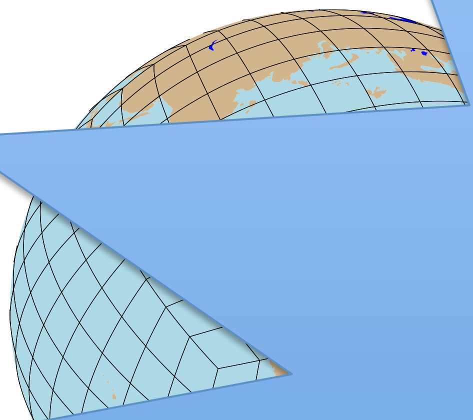
Slide courtesy of M. Taylor

CAM-SE physics grid NE30NP4NC3 c… guration



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

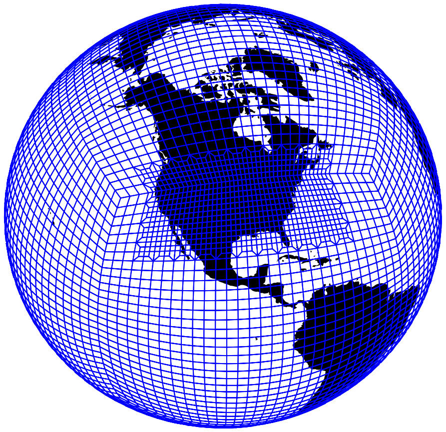
- **history (output)**
- **initialization/restart**
- **Some parameterizations assumed grids were collocated**
- **Initially our results were terrible: it was due to passing updated state from physics to dynamics rather than tendencies (so even if physics did nothing the interpolation truncation errors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

… with cell ave… ed data.
… er, … or finer resolution grid

Slide courtesy of M. T…

Interpolator properties: passing state to physics and returning tendencies to dynamics

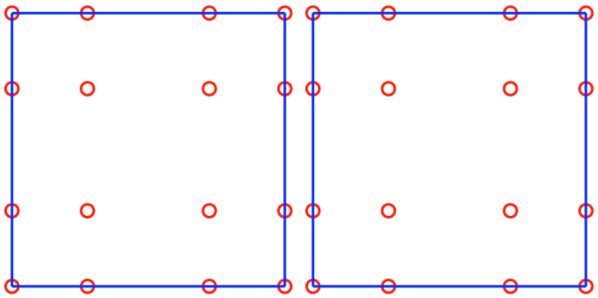
- Conservation (coupled climate modeling)
- Shape-preservation (in particular, no negatives)
- Preserve tracer correlations (important for coupling with chemistry)
- Consistent (preserves a constant)
- Other? Total energy?



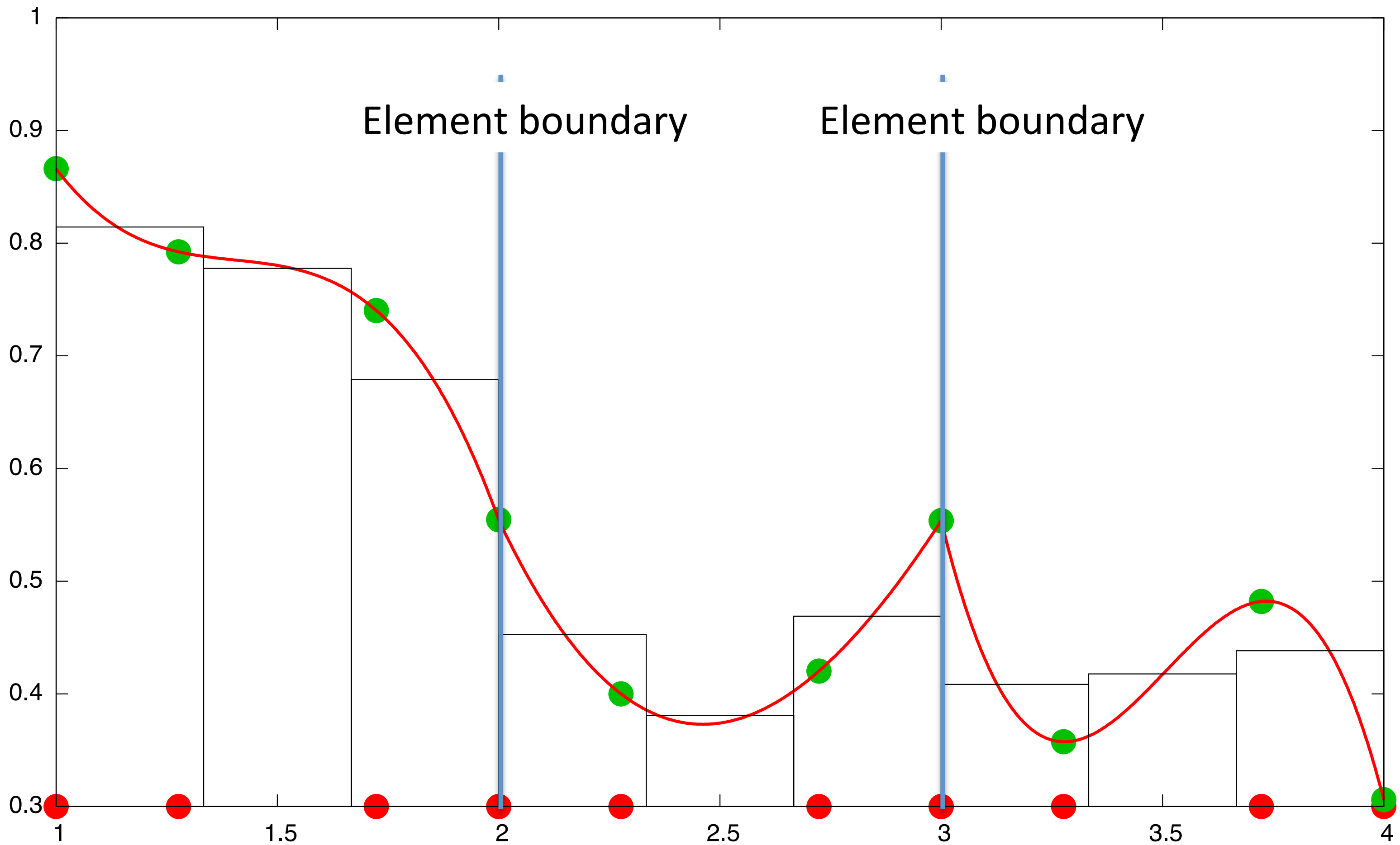
Implementation constraints/limitations (not "physical" limitations):

- 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,…) to physics:
For conservation we interpolate dp*u, dp*T, dp*q



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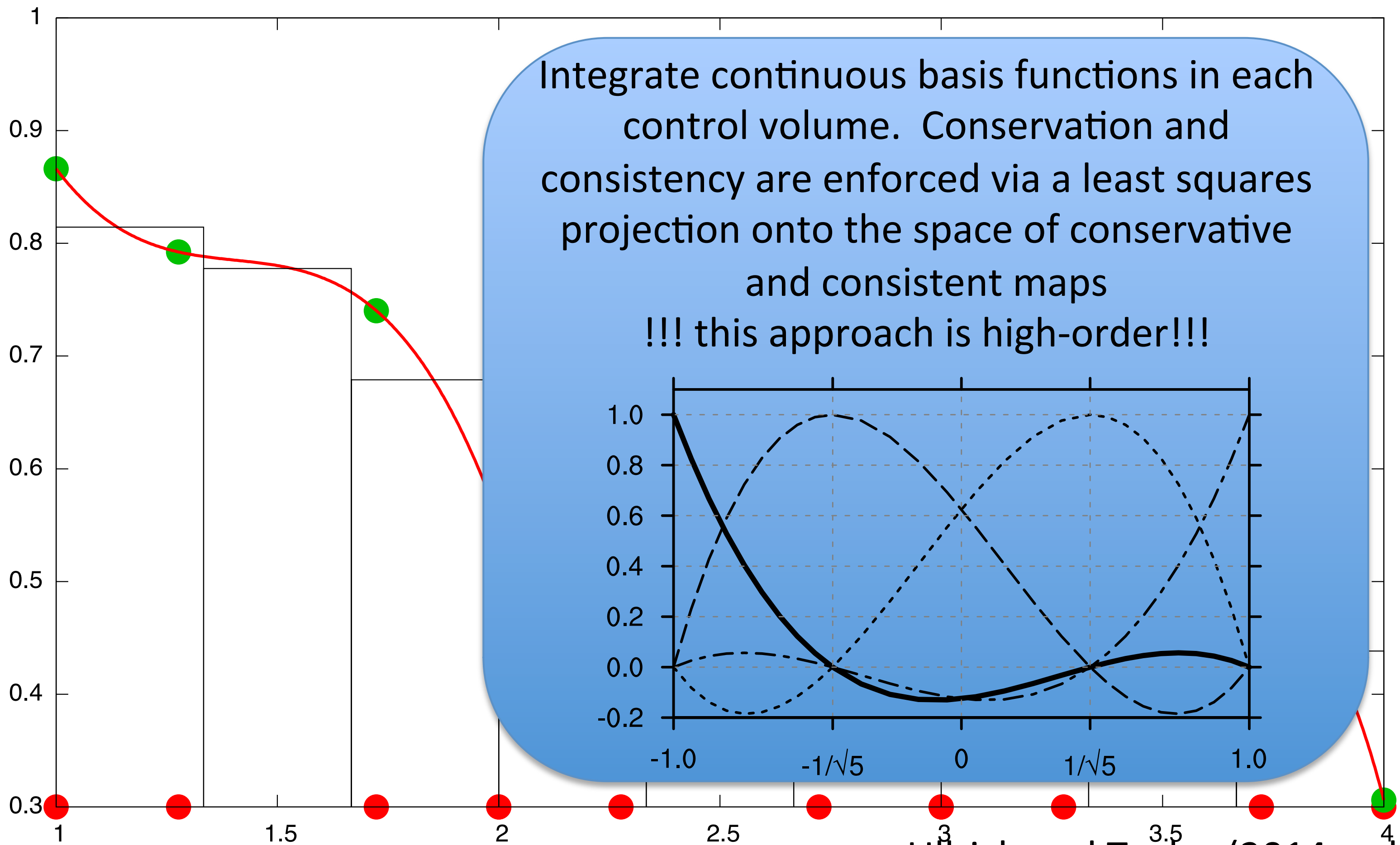
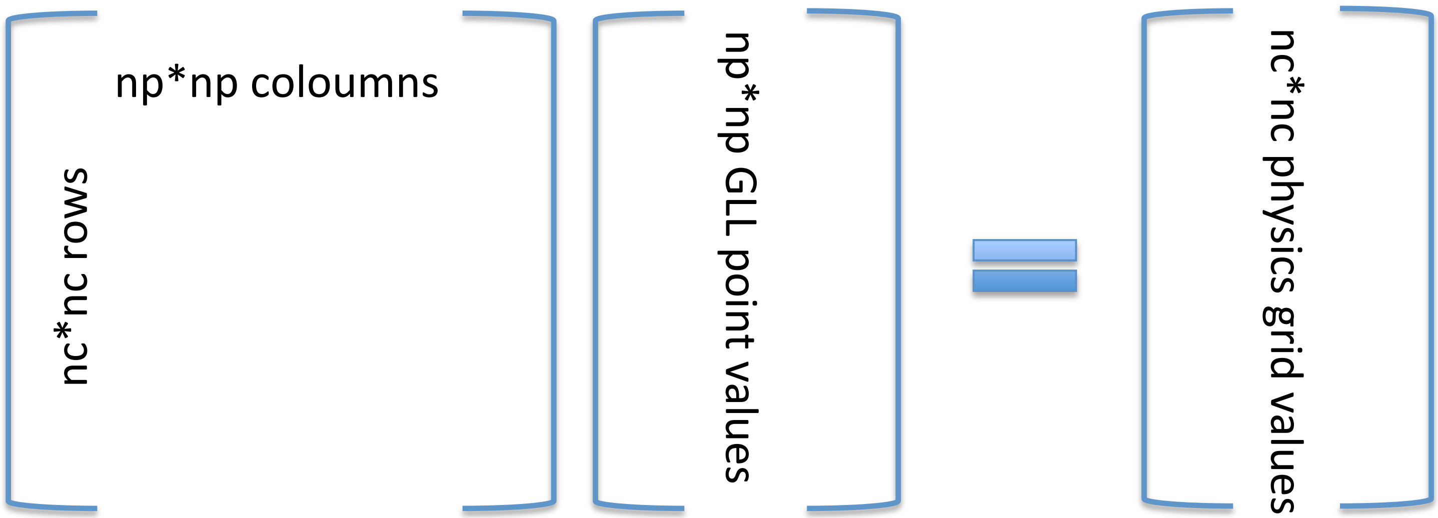


Ullrich and Taylor (2014, submitted)

Passing state (v,T,q,…) to physics: For conservation we interpolate dp*u, dp*T, dp*q

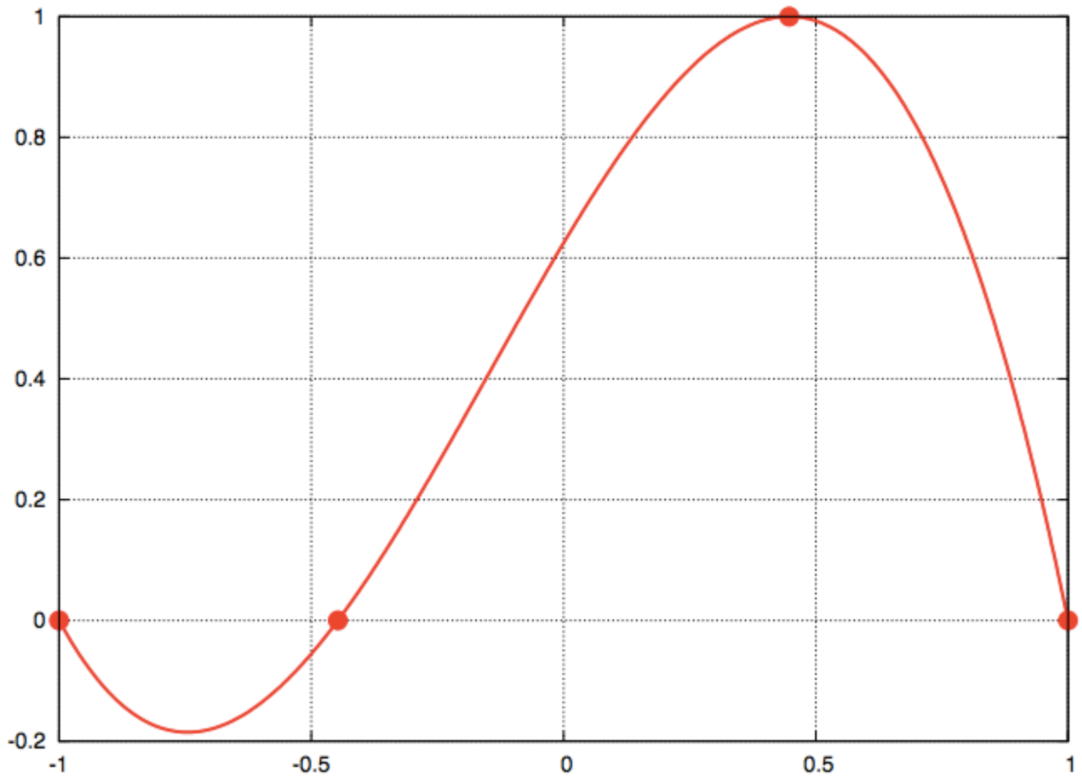


- Interpolation matrix can be pre-computed (it is a linear map)!!!
- After application of interpolation matrix there is a boundary exchange that averages point values on the element boundaries!
- Note: fundamentally different than finite-volume-type remapping where a halo is needed for the reconstruction

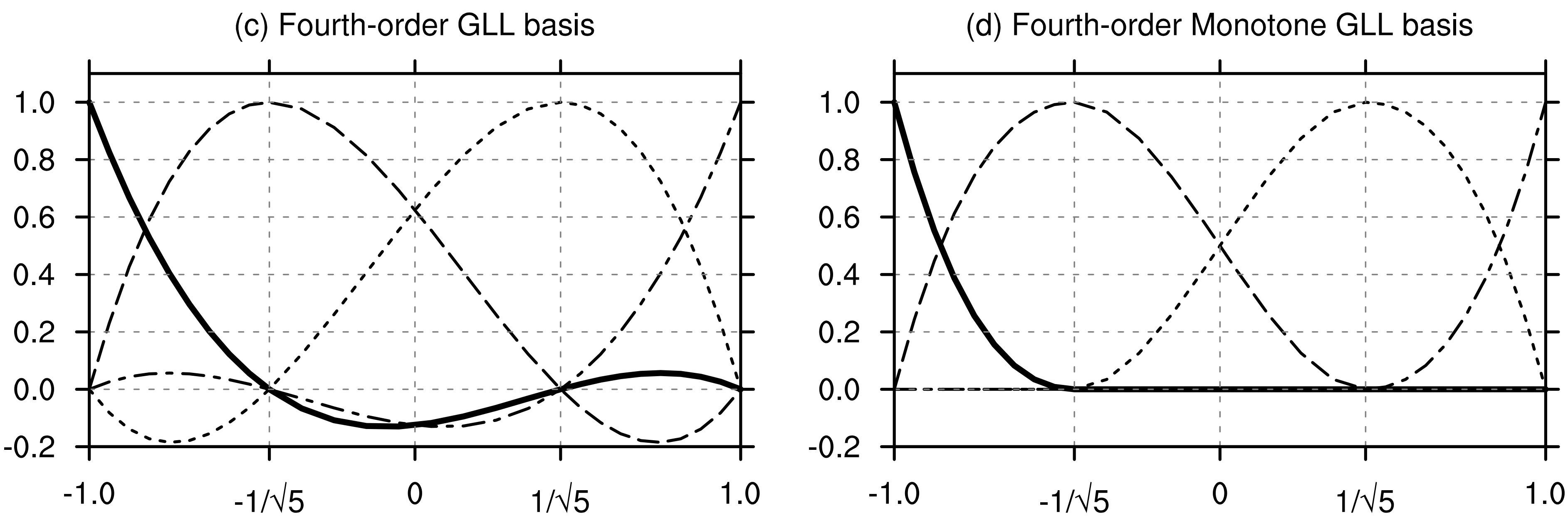
Ullrich and Taylor (2014, submitted)

Passing state (v,T,q,…) to physics: basis functions oscillatory!

Given GLL point values, $U_{j,k}(t) = \{0,0,1,0\}$ for k=0,..,3, the Lagrange "reconstruction" is shown on the Figure below:



Monotone linear map

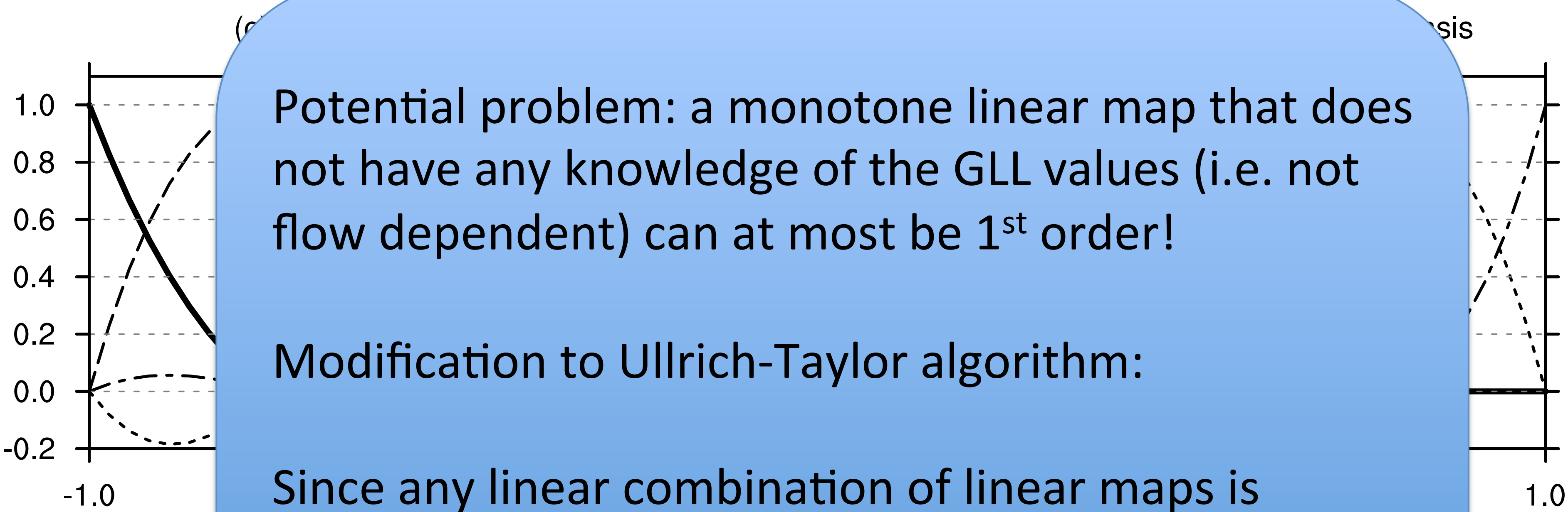


Monotonicity is enforced via a two-step procedure.

- 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 1st order!

Modification to Ullrich-Taylor algorithm:

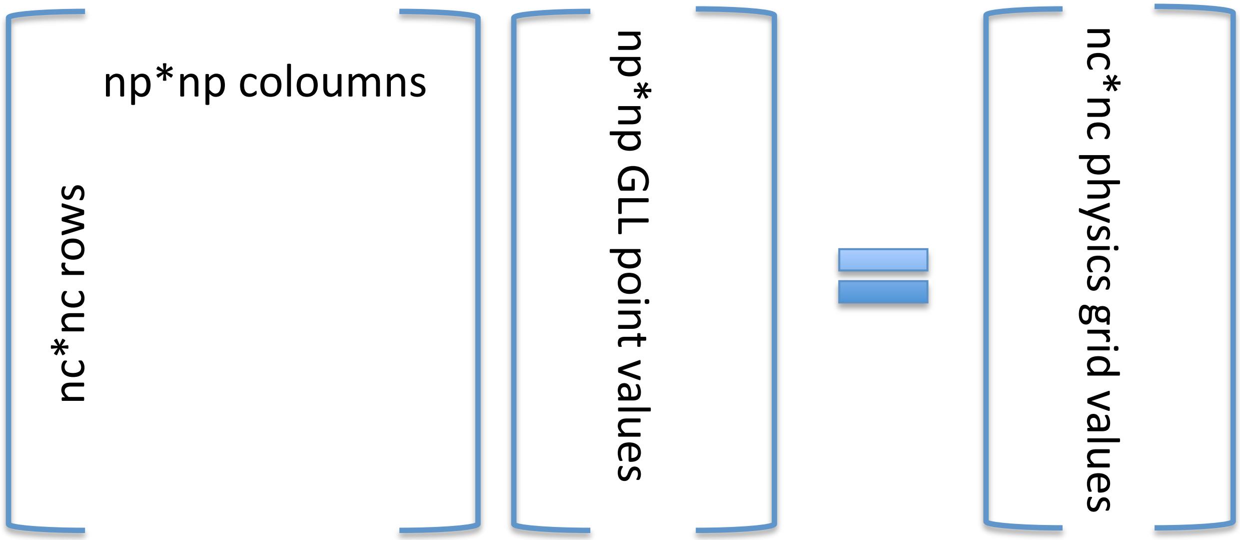
Since any linear combination of linear maps is conservative and consistent one may "optimally" blend the maps for shape-preservation ("FCT-like method")

Monotonic

- instead functio
- This wo conserv mapping 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)

"FCT" version of Ullrich-Taylor algorithm



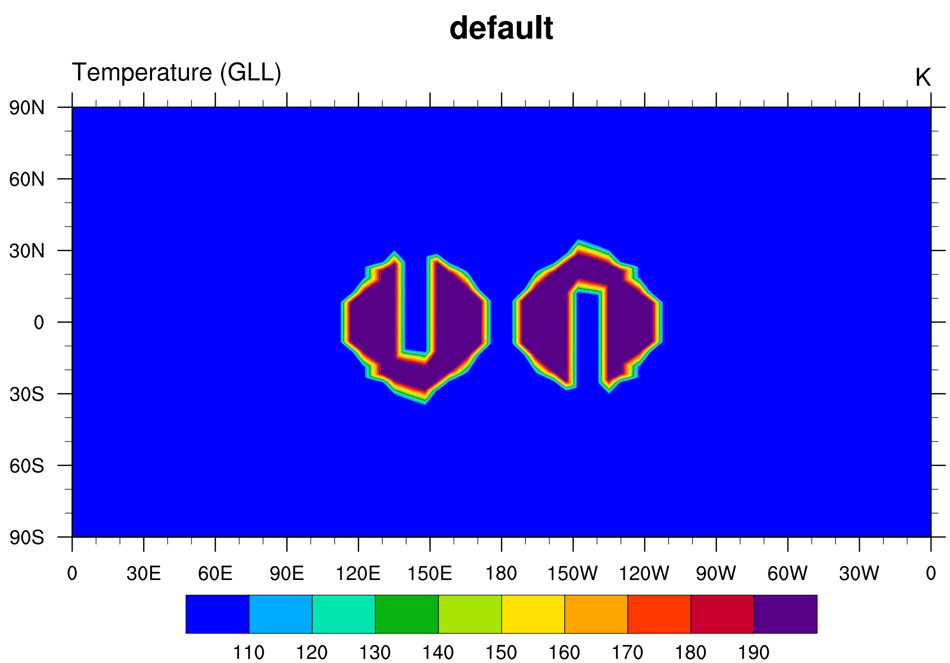
$$A_{non\text{-}mono} * GLL = PHYS_{non\text{-}mono}$$

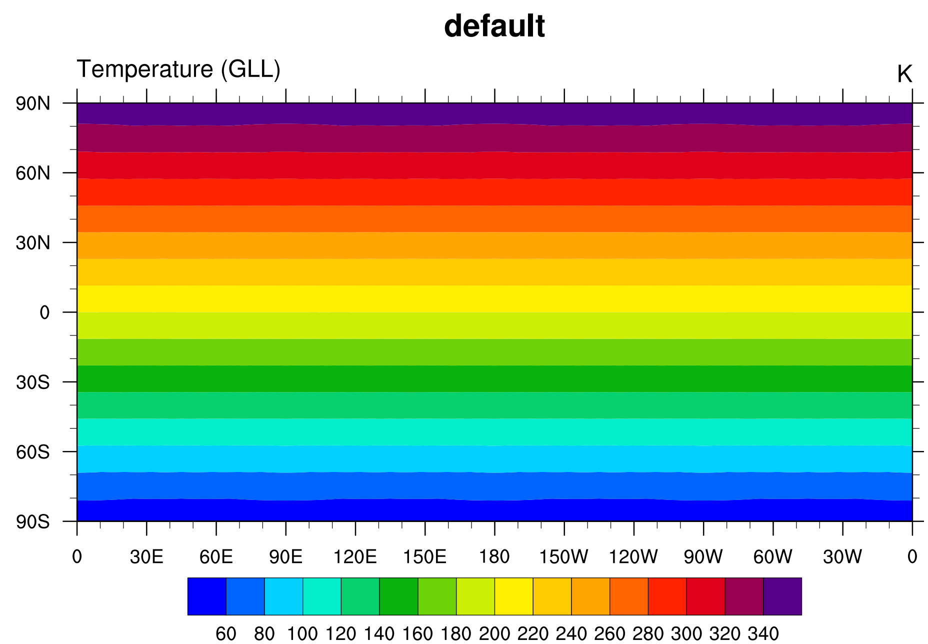
$$A_{mono} * GLL = PHYS_{mono}$$

$$[\alpha\ A_{mono} + (1\text{-}\alpha)\ A_{non\text{-}mono}\ GLL] = PHYS_{mono}$$

where $\alpha = (\max(GLL)\text{-}PHYS_{non\text{-}mono})/(PHYS_{mono} - PHYS_{non\text{-}mono})$ or
$\alpha = (\min(GLL)\text{-}PHYS_{non\text{-}mono})/(PHYS_{mono} - PHYS_{non\text{-}mono})$

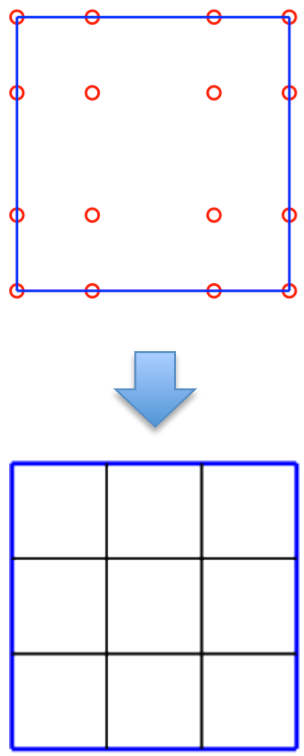
Dynamics to physics grid mapping

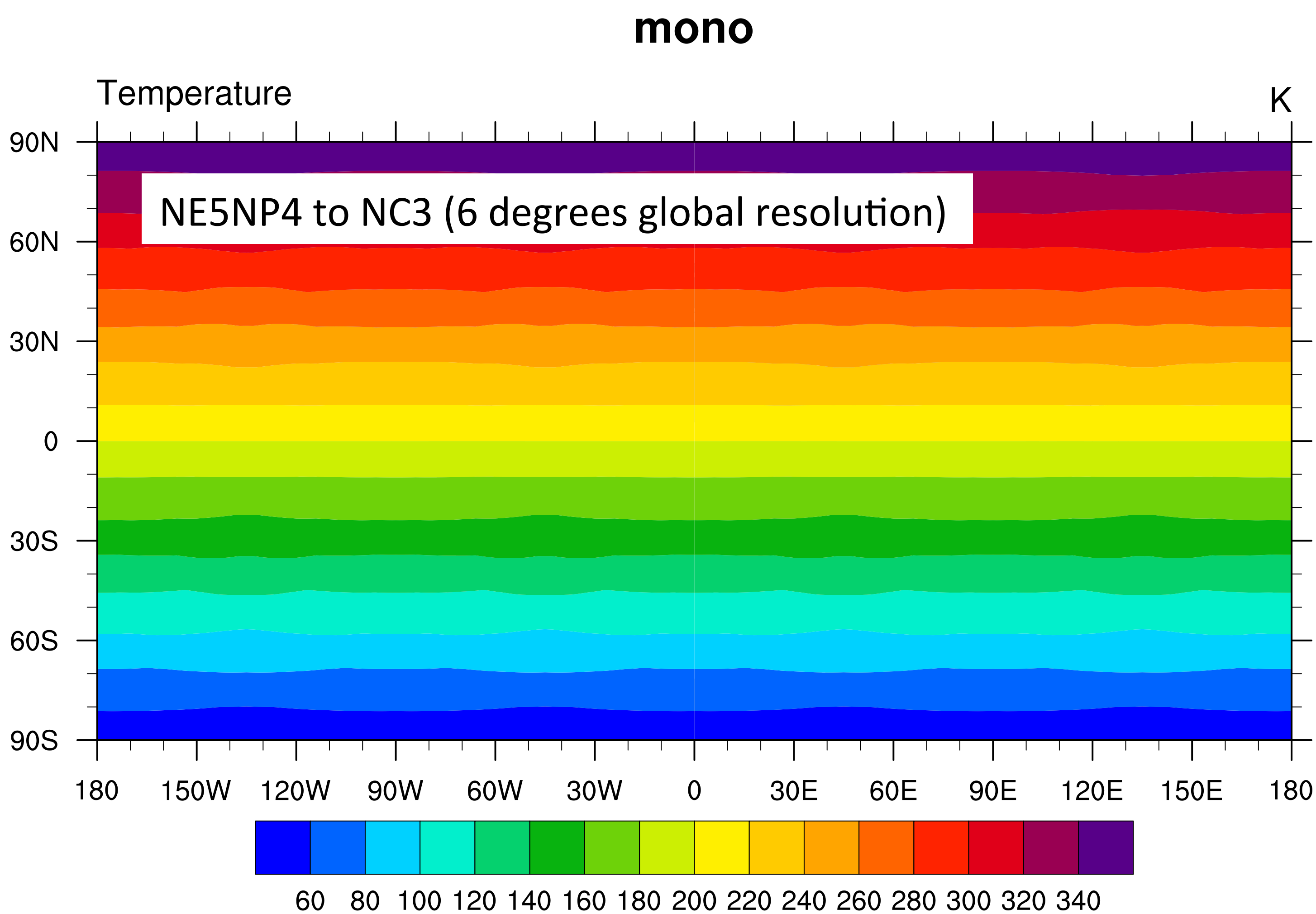




Properties we are looking for: Preserve smooth fields and at the same time not generate new extrema for rough distributions (and be mass-conservative and consistent)

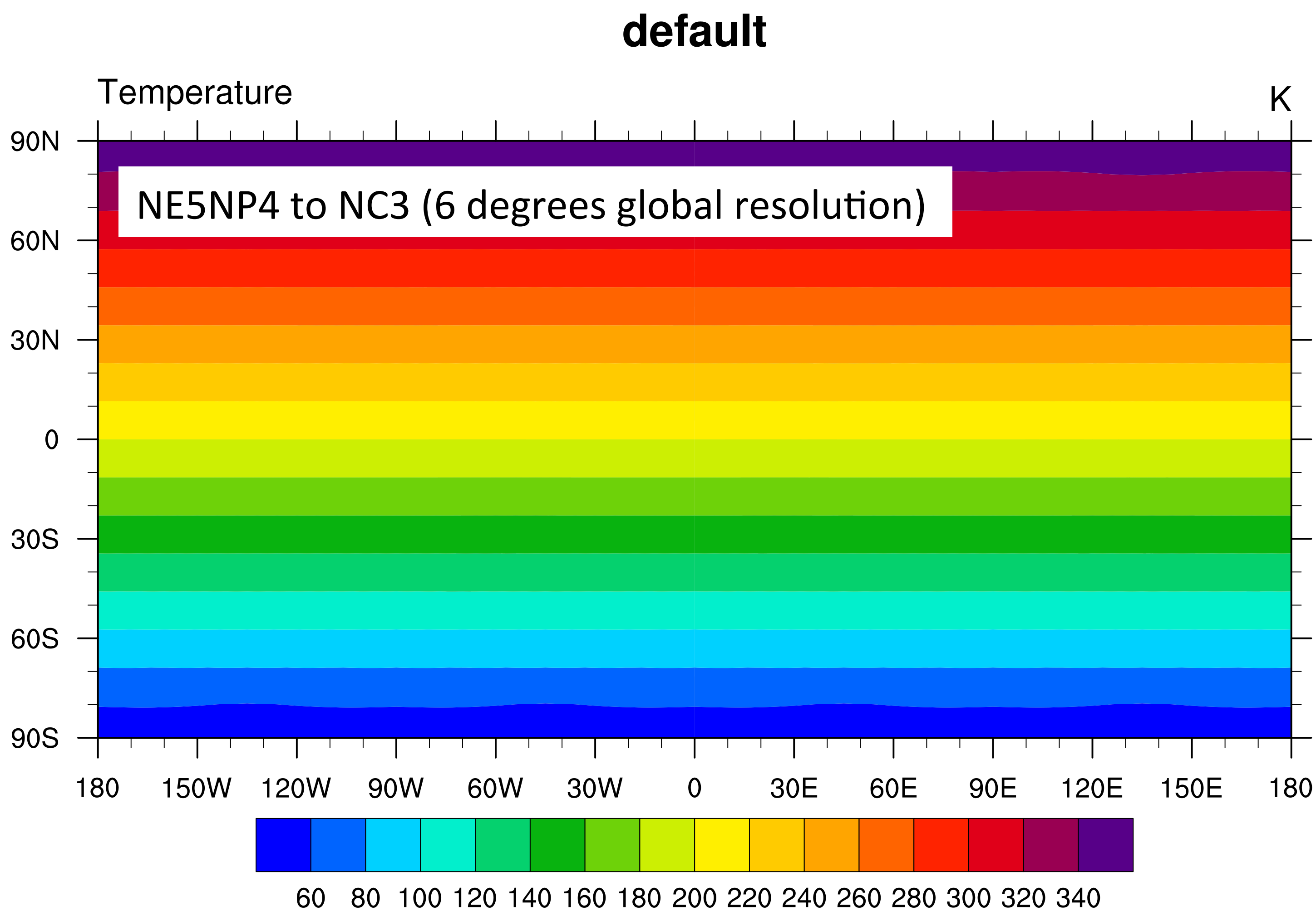
Smooth field ("spherical harmonic")





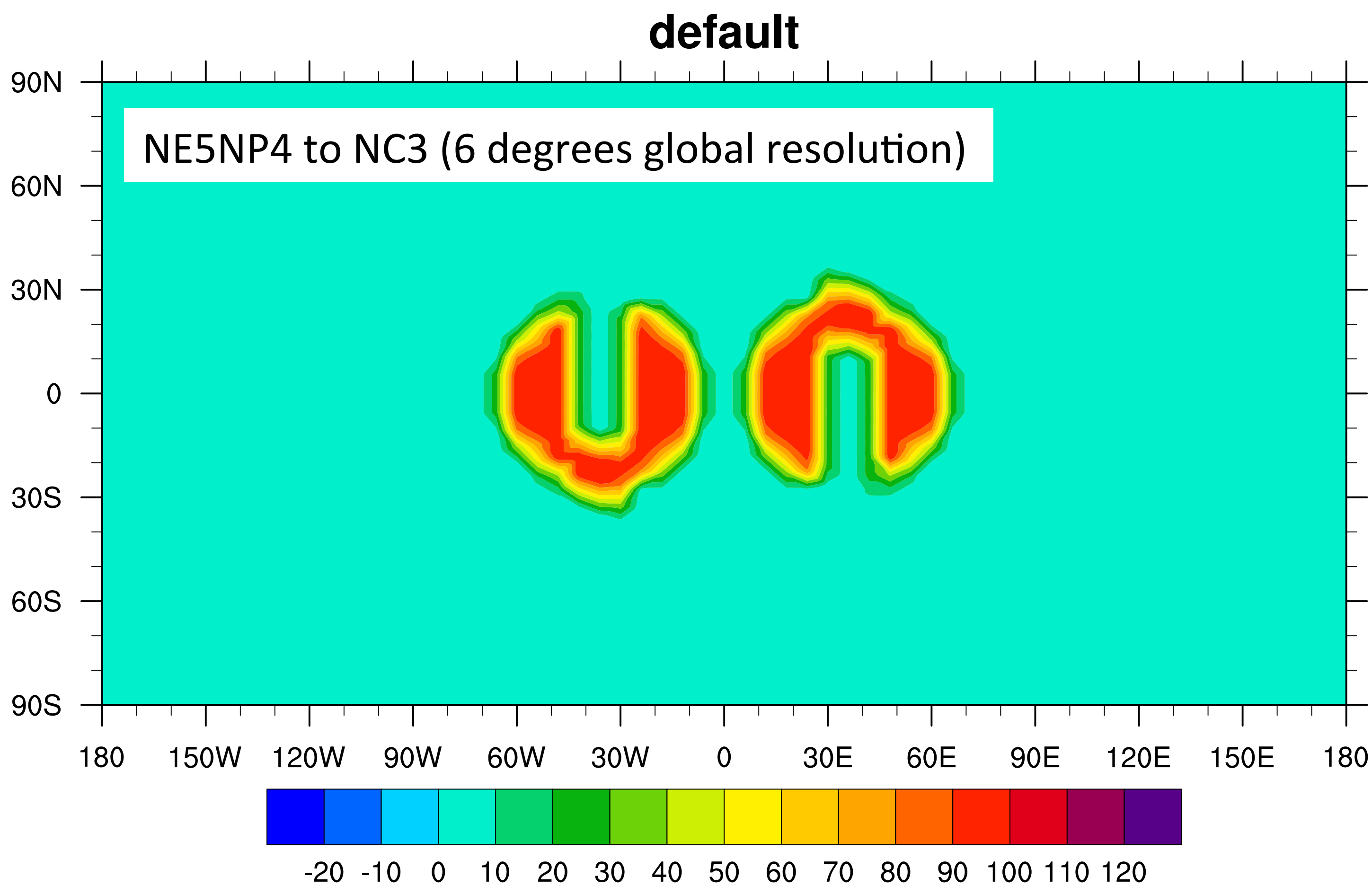
1st order monotone map (not flow dependent): see grid

Smooth field ("spherical harmonic")



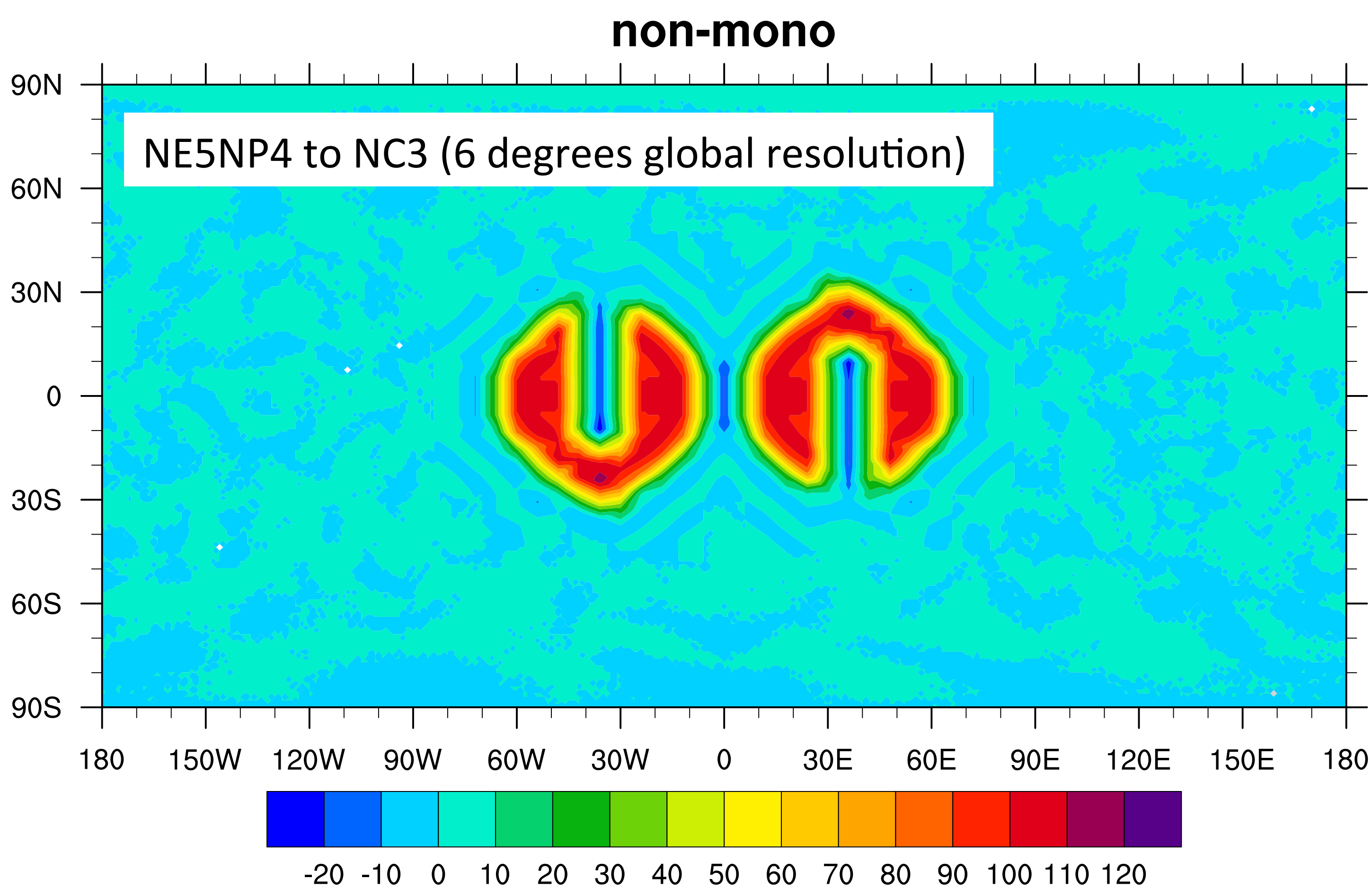
Optimally blend conservative and monotone map

Rough field ("slotted cylinder")



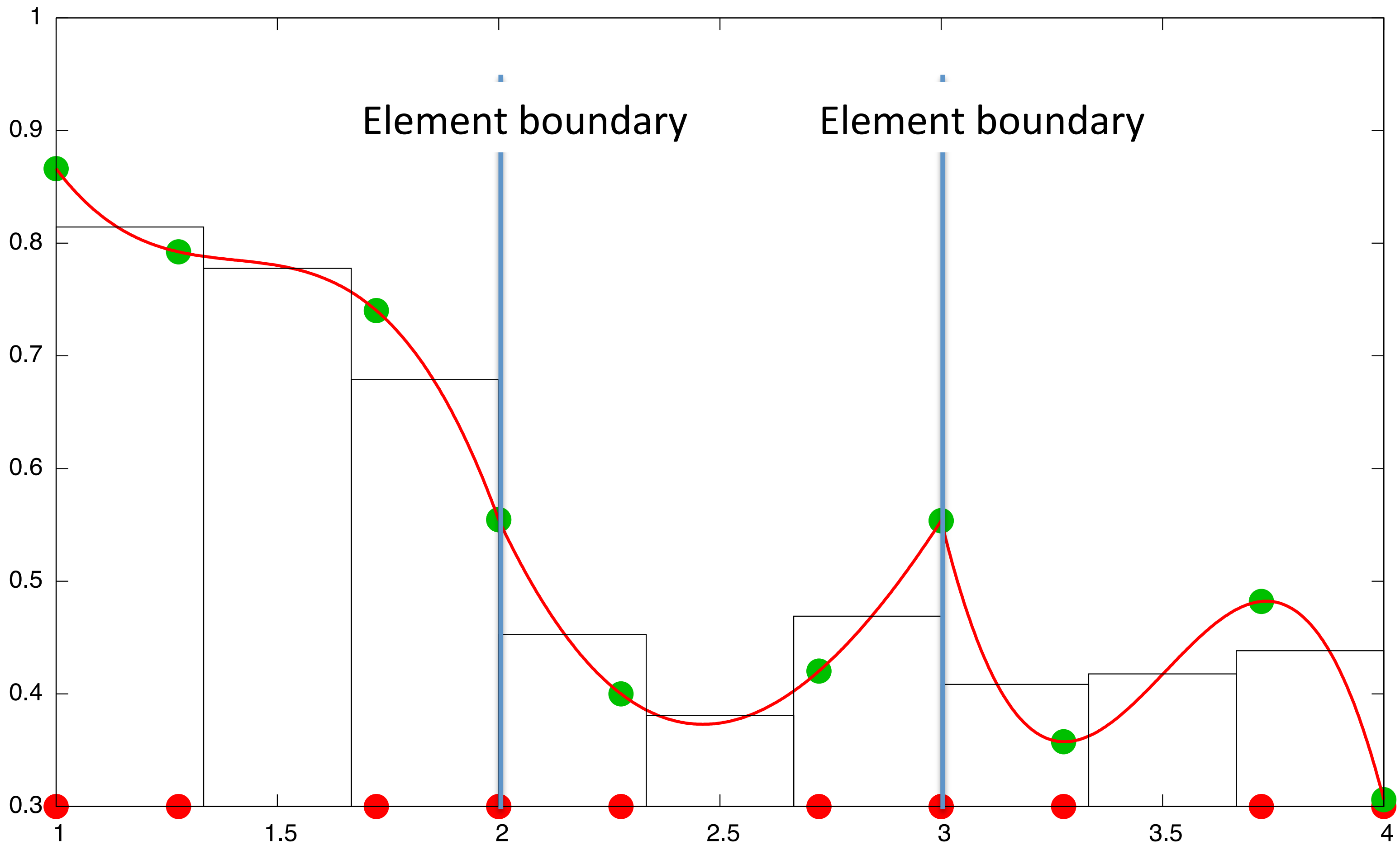
Optimally blend conservative and monotone map

Rough field ("slotted cylinder")



Non-monotone conservative

Passing tendencies (fv,fT,fq,…) to dynamics:
Use a 1st-order, shape-preserving, conservative linear map

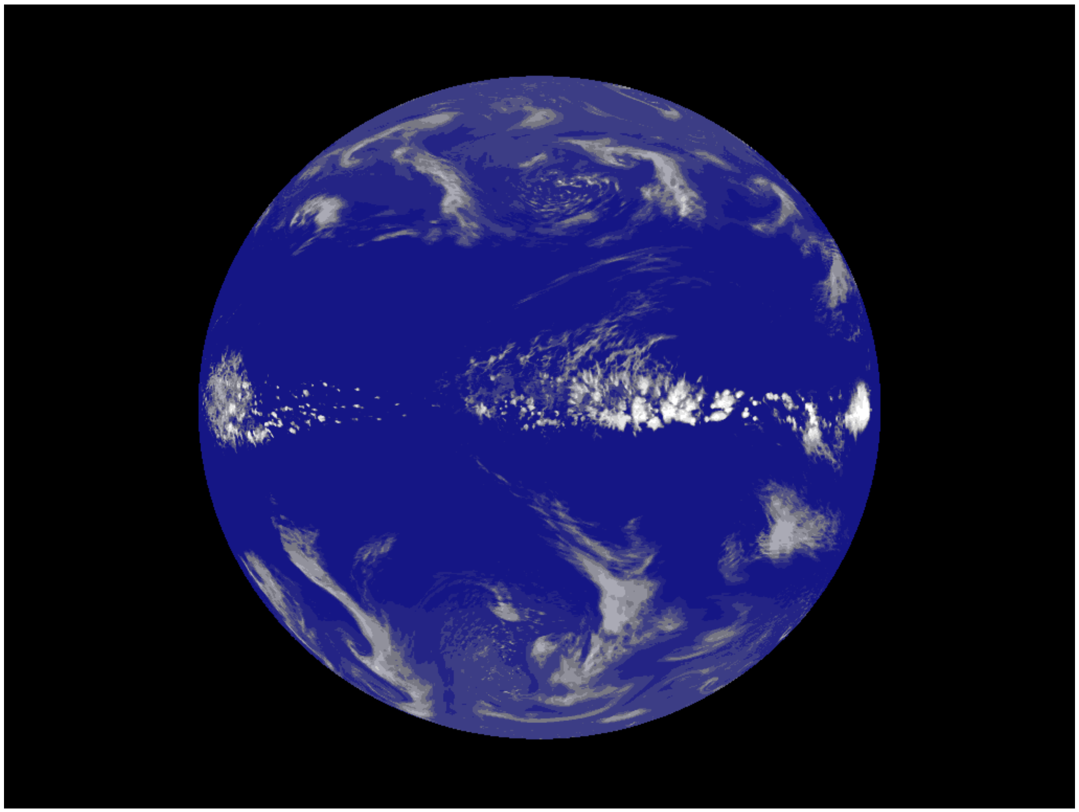


SciDAC
Scientific Discovery through Advanced Computing

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

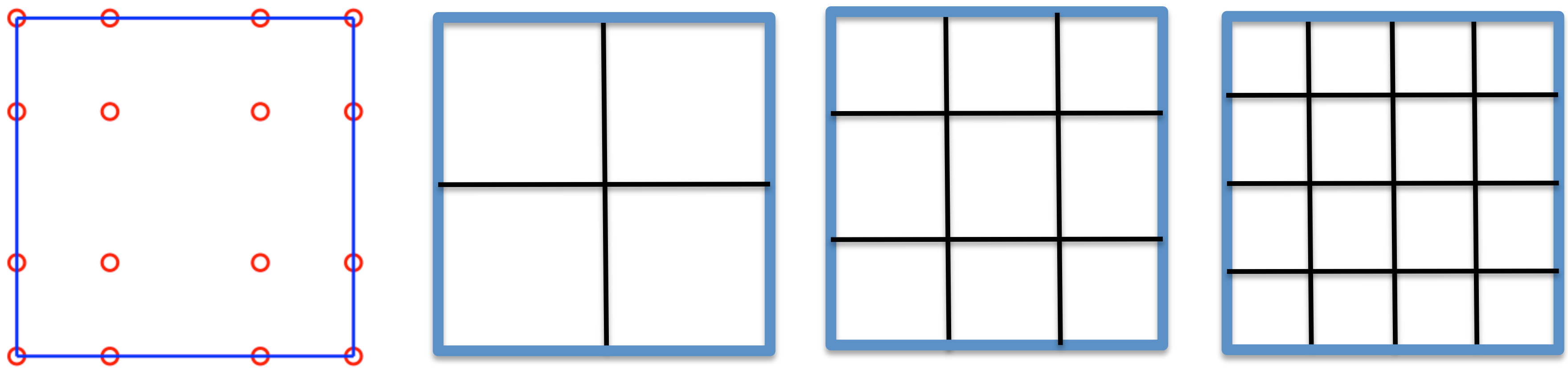
=> Free motions, no forced component



Why CAM4? More resolution sensitivity than CAM5 (and it is cheaper!)

Configurations

NE30NP4	NE30NP4NC2	NE30NP4NC3	NE30NP4NC4



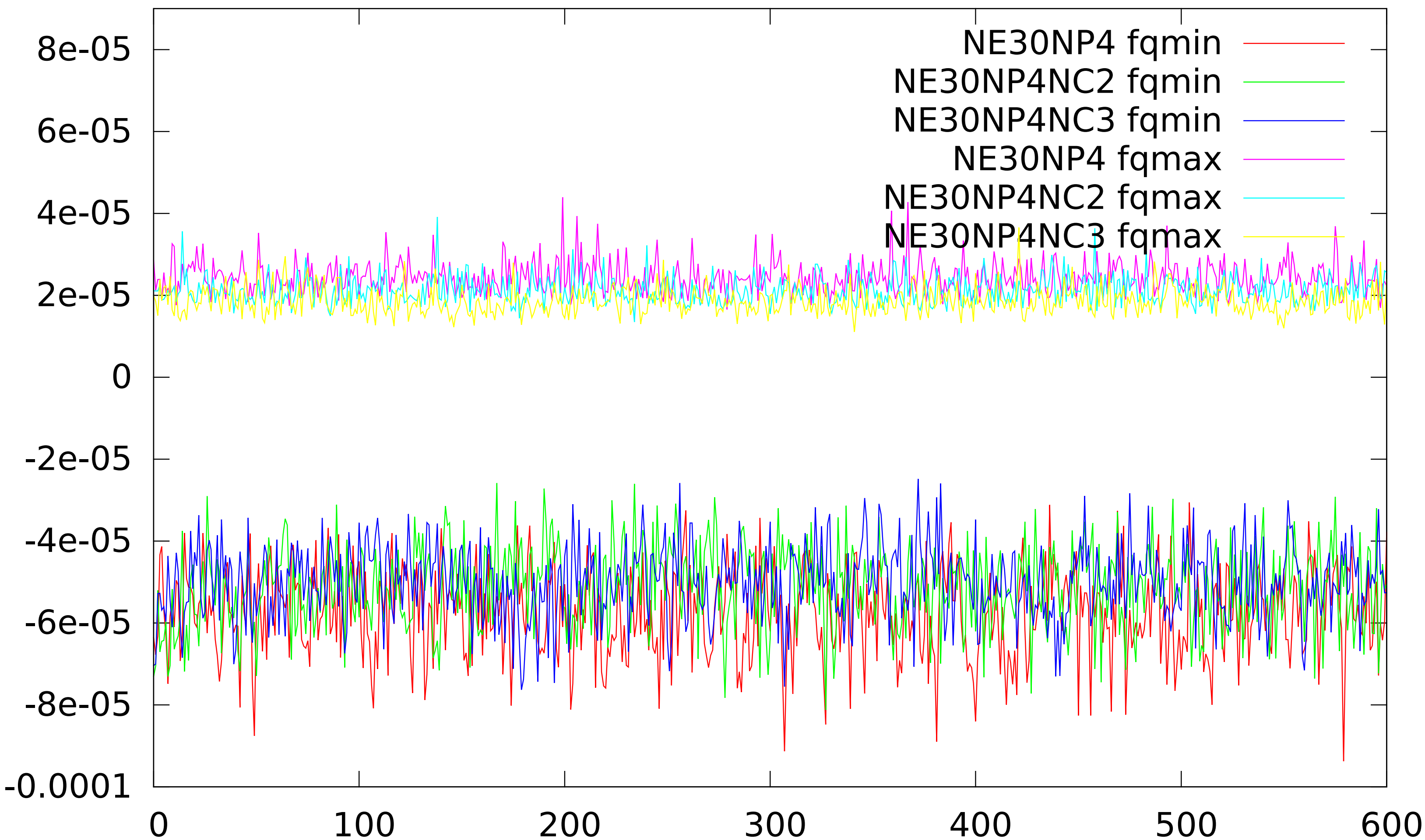
4.154 SYPD	4.913 SYPD	4.281 SYPD	

Efficiency measures in SYPD (= simulated years per day) on 2096 processors with I/O.

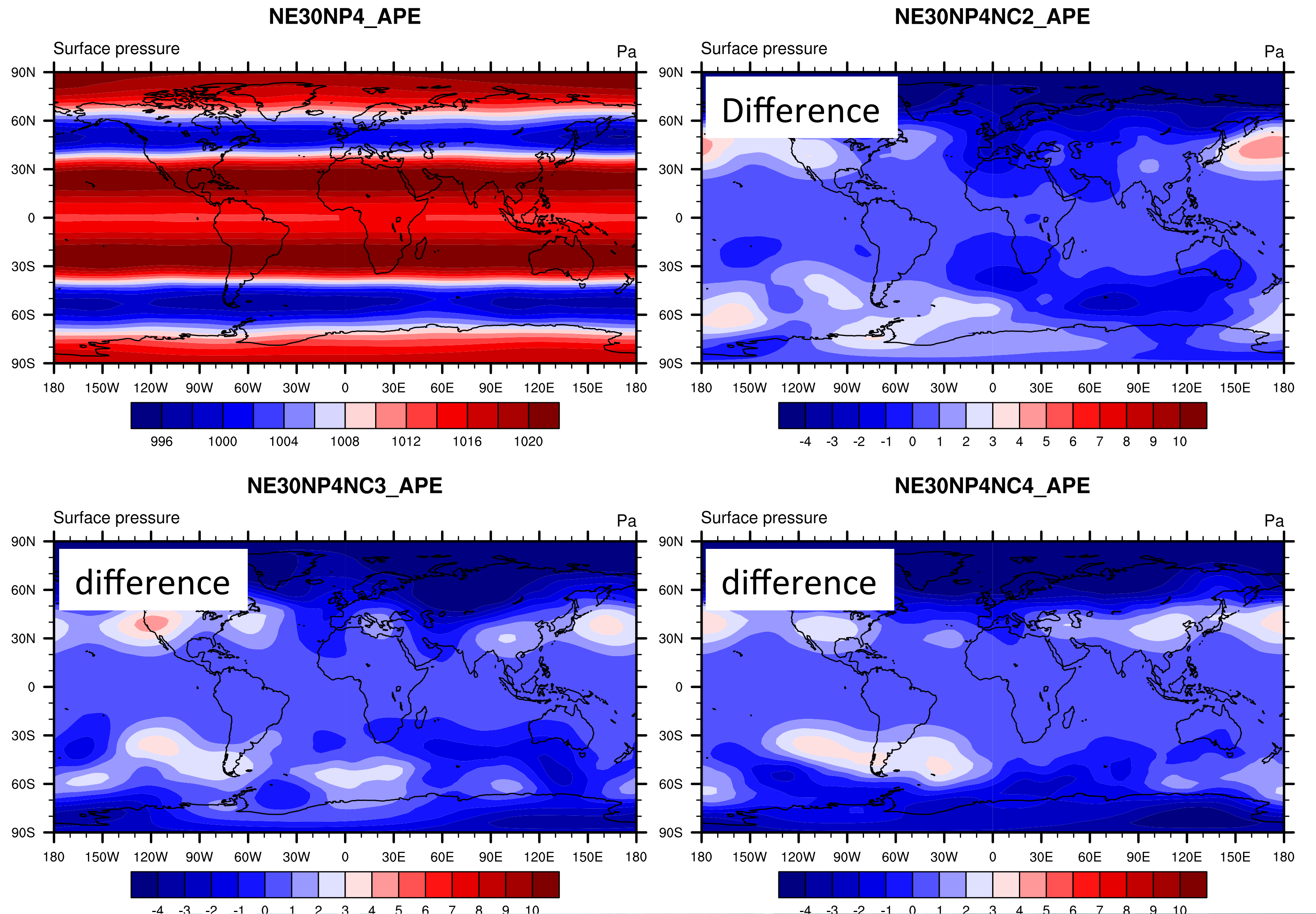
Data mapped to 3° lat-lon grid for analysis

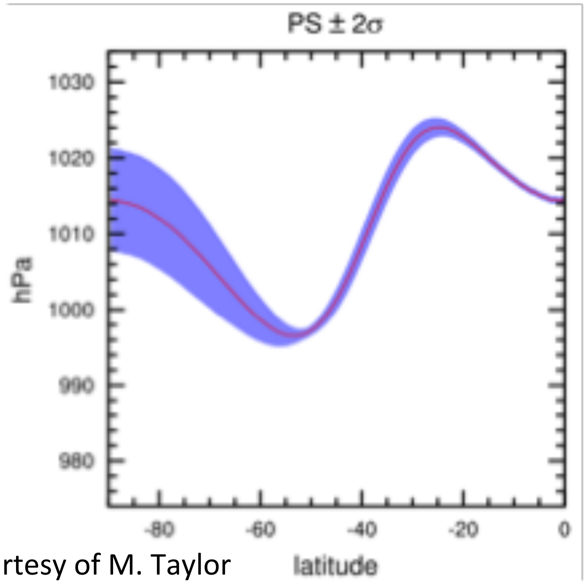
Length of simulations: 30 months

Min/max moisture forcing

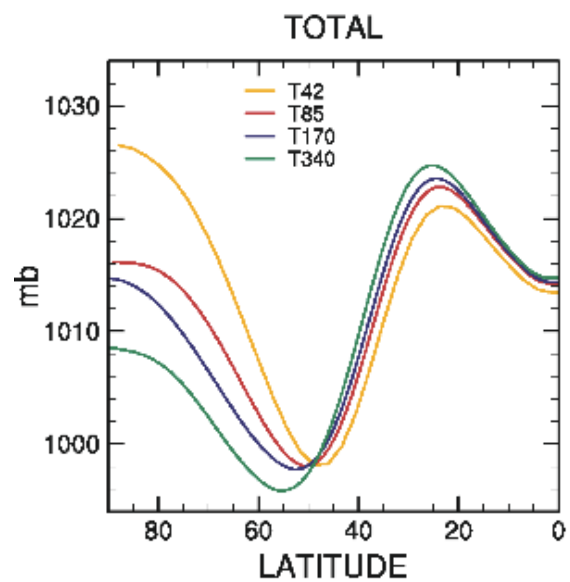


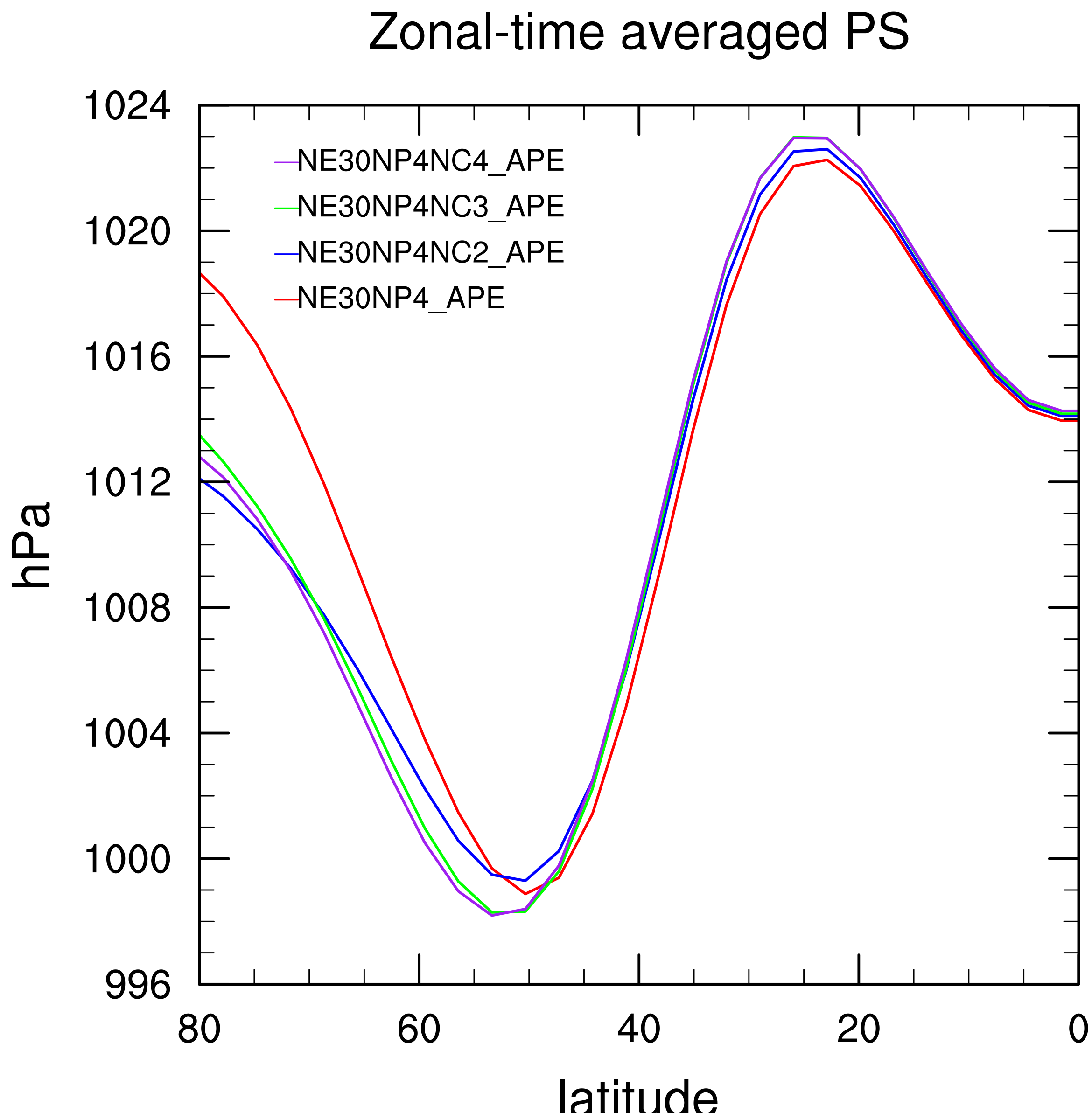
Time averaged PS



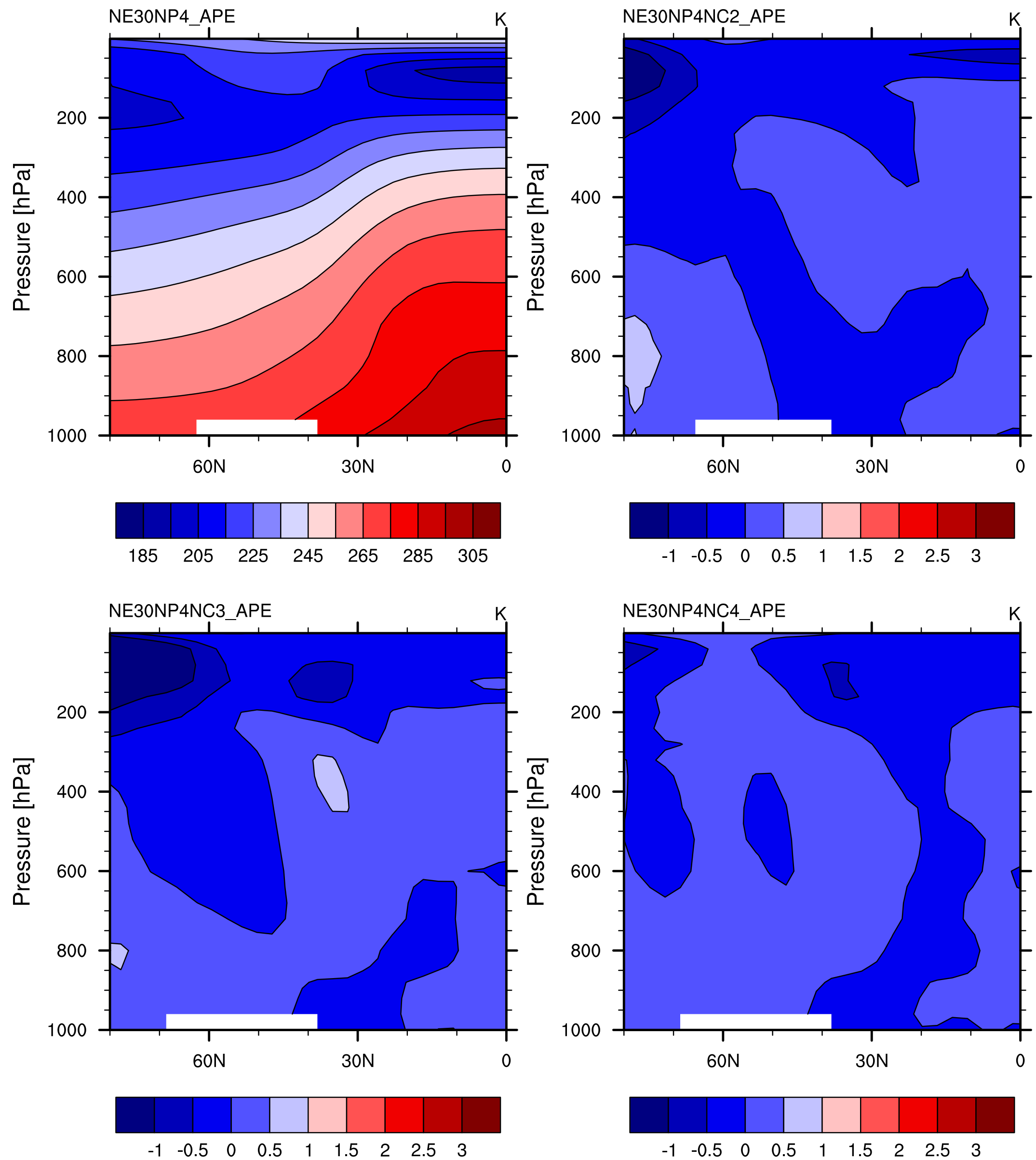


Courtesy of M. Taylor



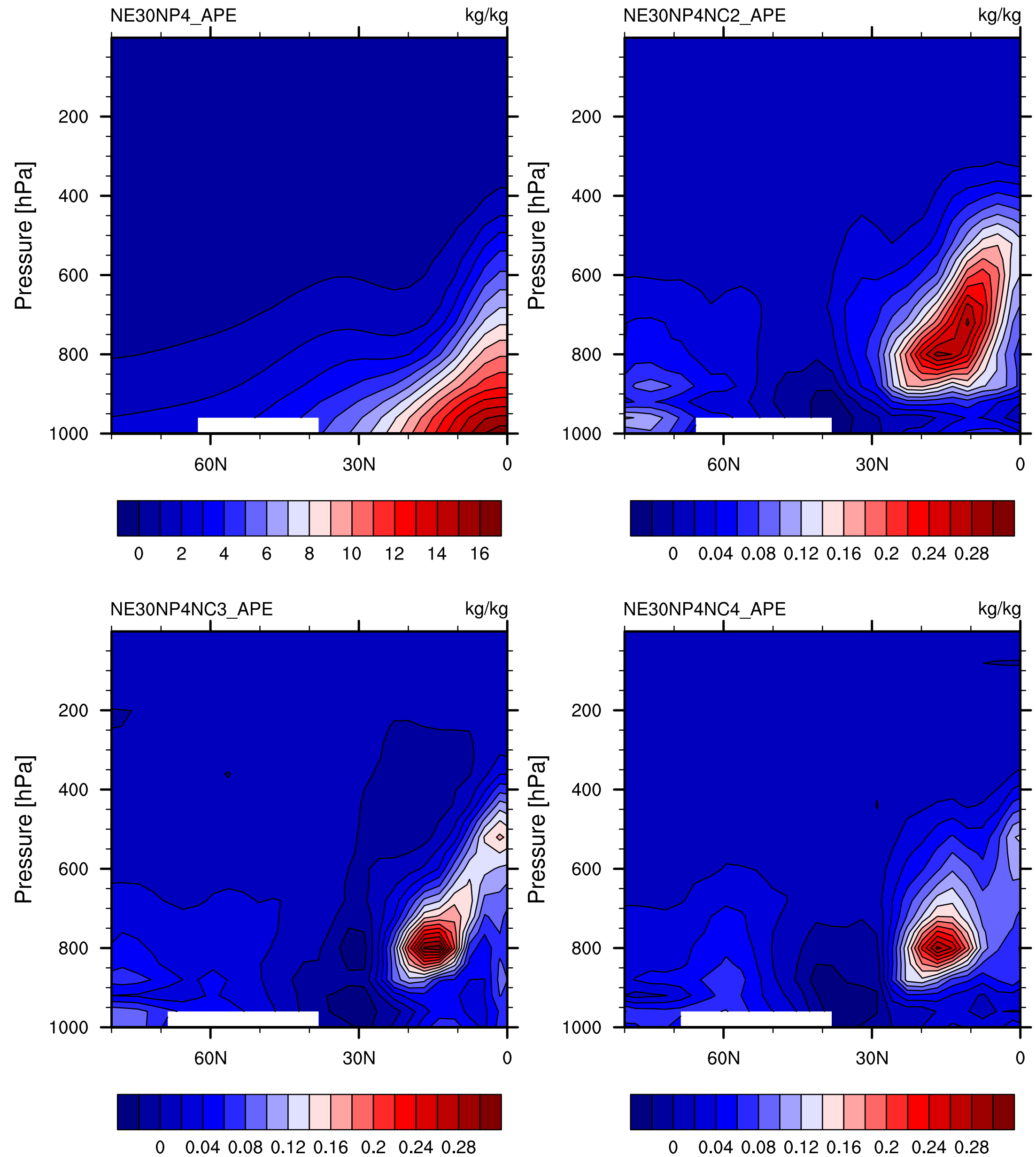


Zonal-time averaged T



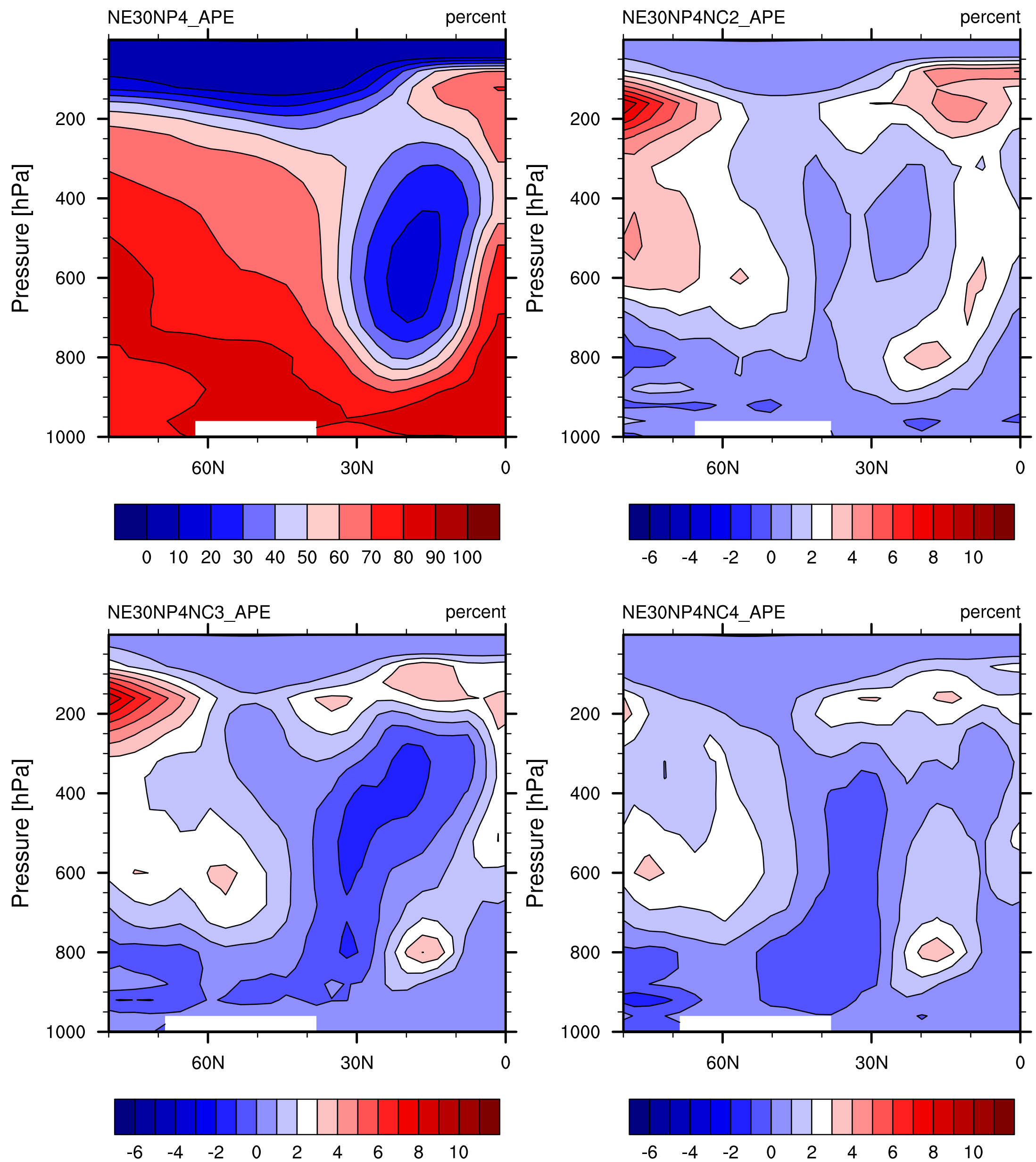
Zonal-time averaged Q

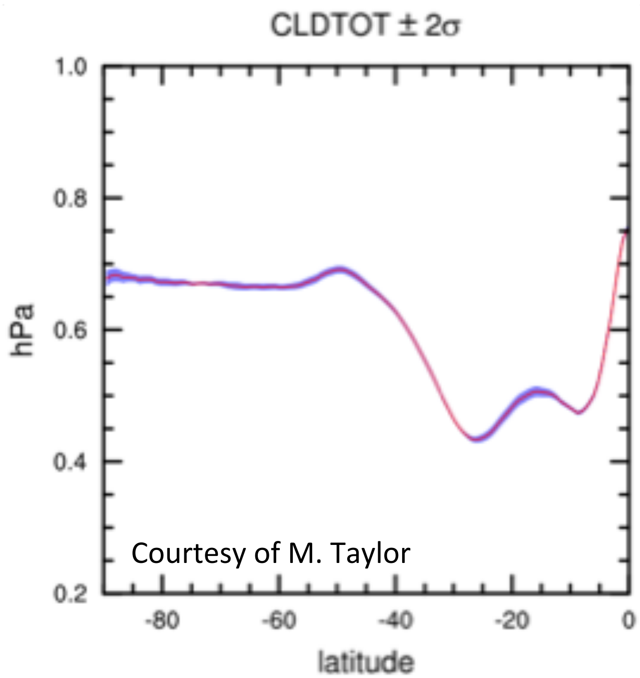
Q = Specific humidity

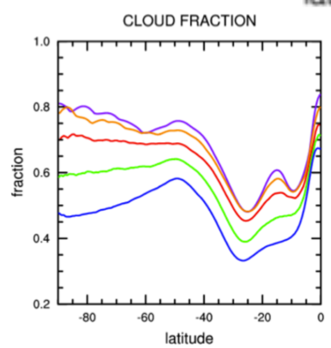


Zonal-time averaged RELHUM

RELHUM = Relative humidity



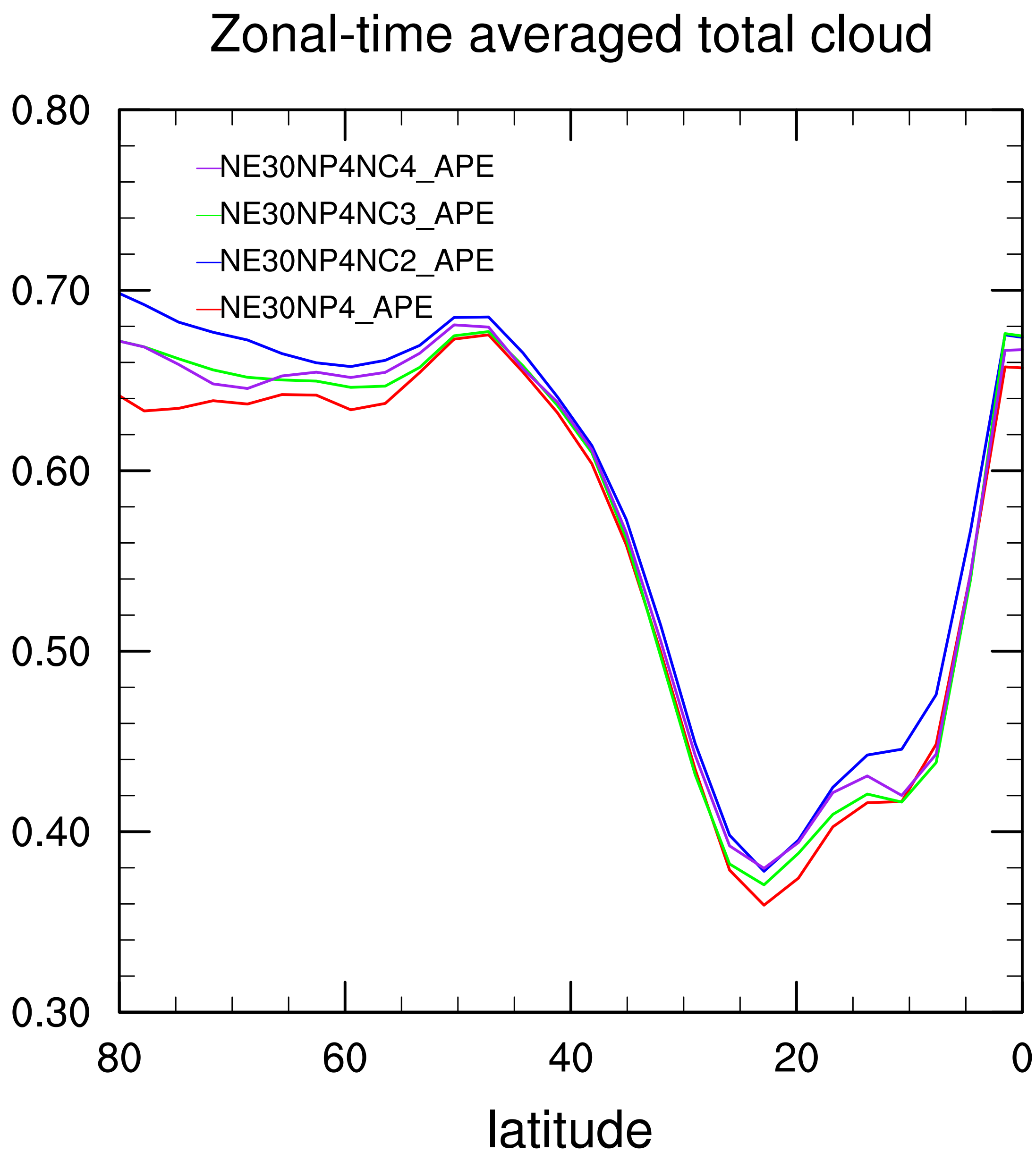




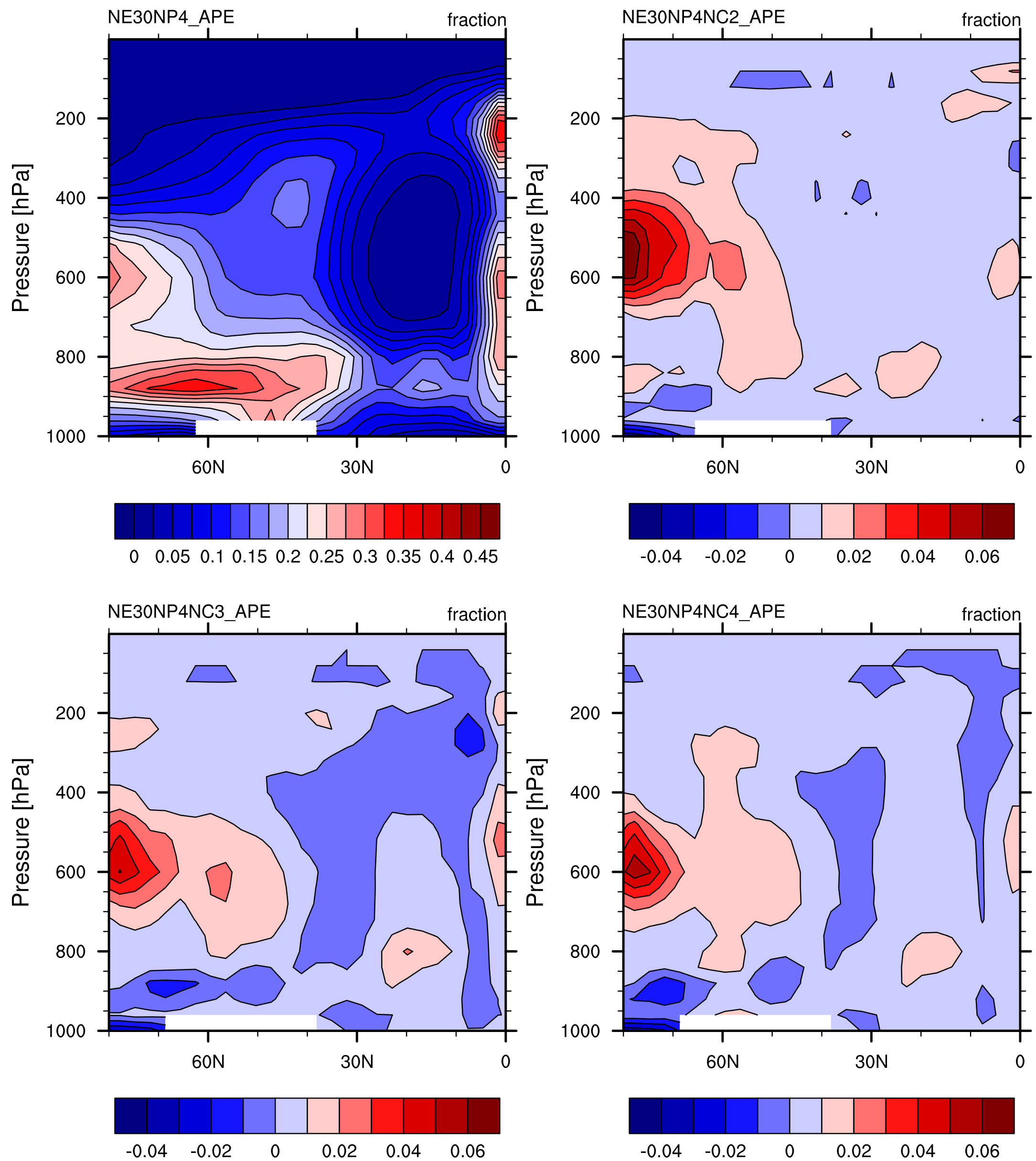
Courtesy of M. Taylor

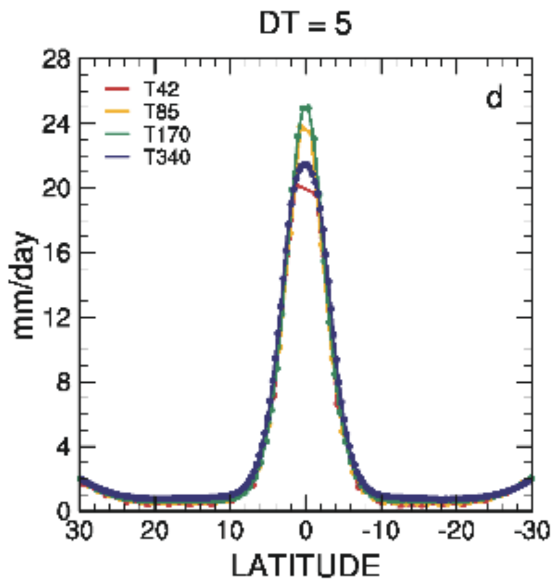
CAM-SE with resolutions:
2.7° 1.9° 1.0° 0.5° 0.25°

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

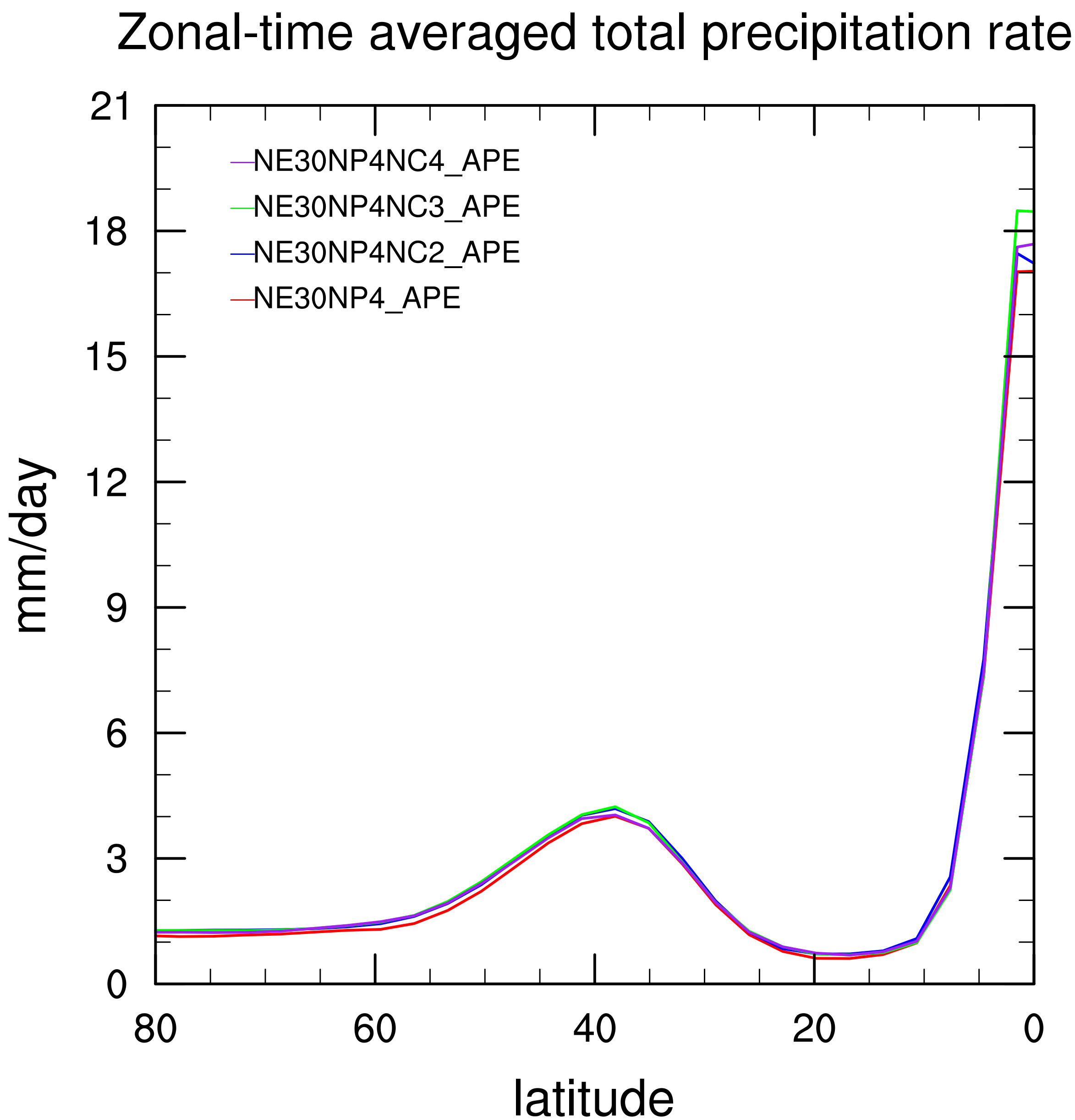


Zonal-time averaged CLOUD





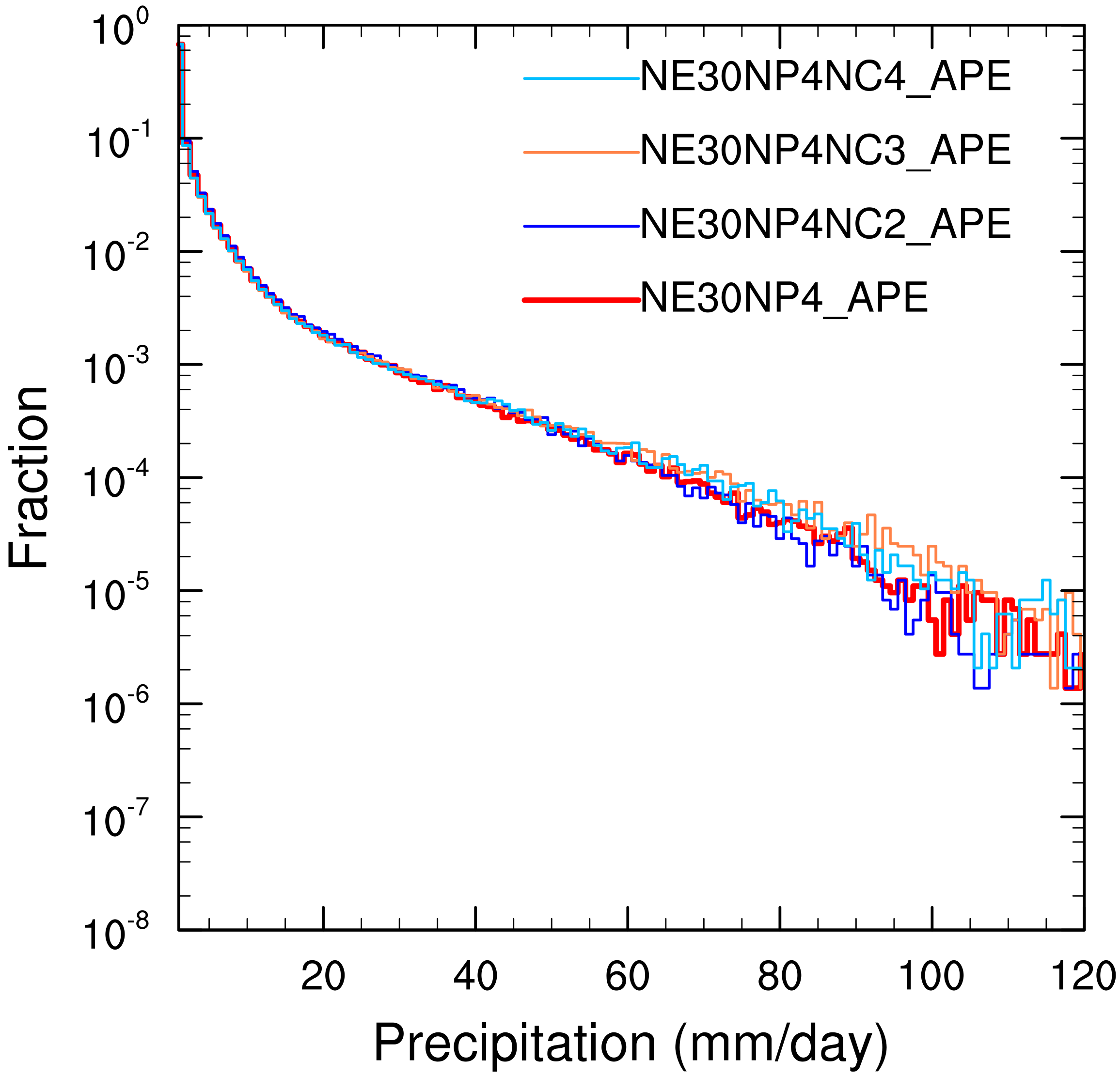
Williamson (2004)



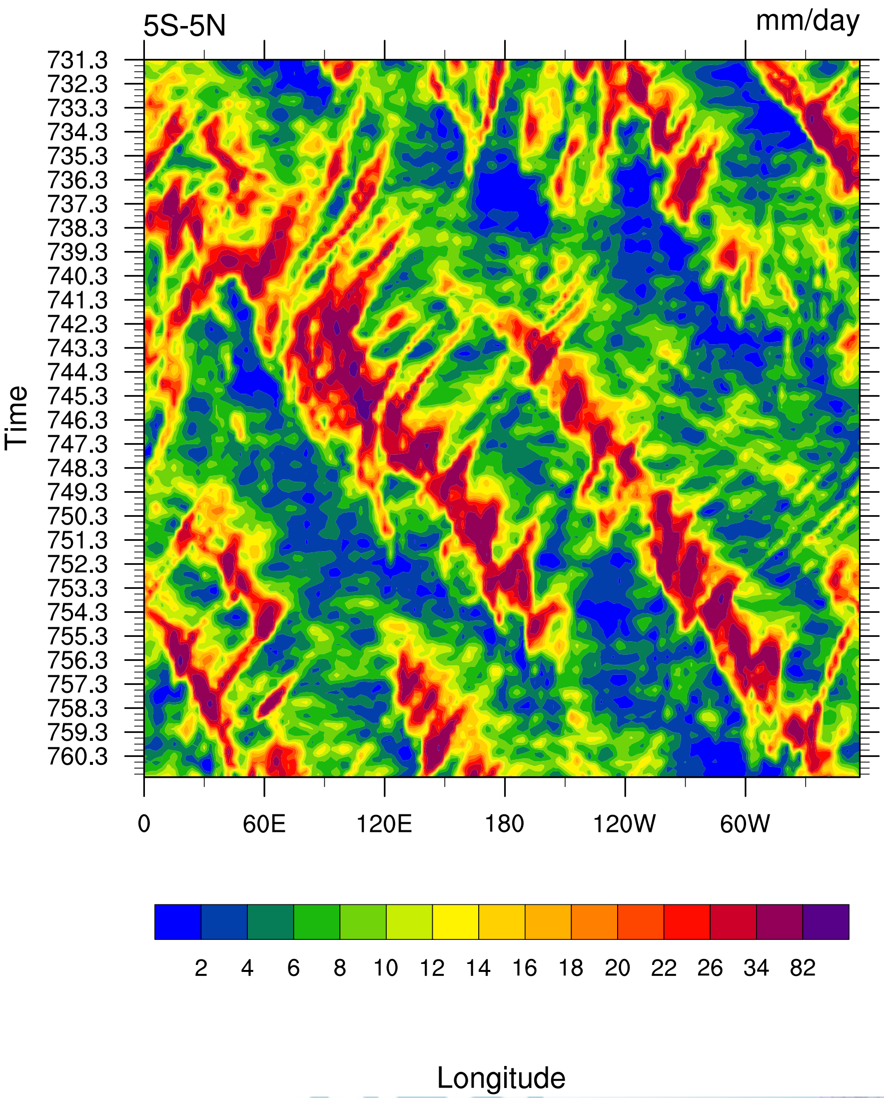
PDF

PRECT (30 month simulation - 6h data)

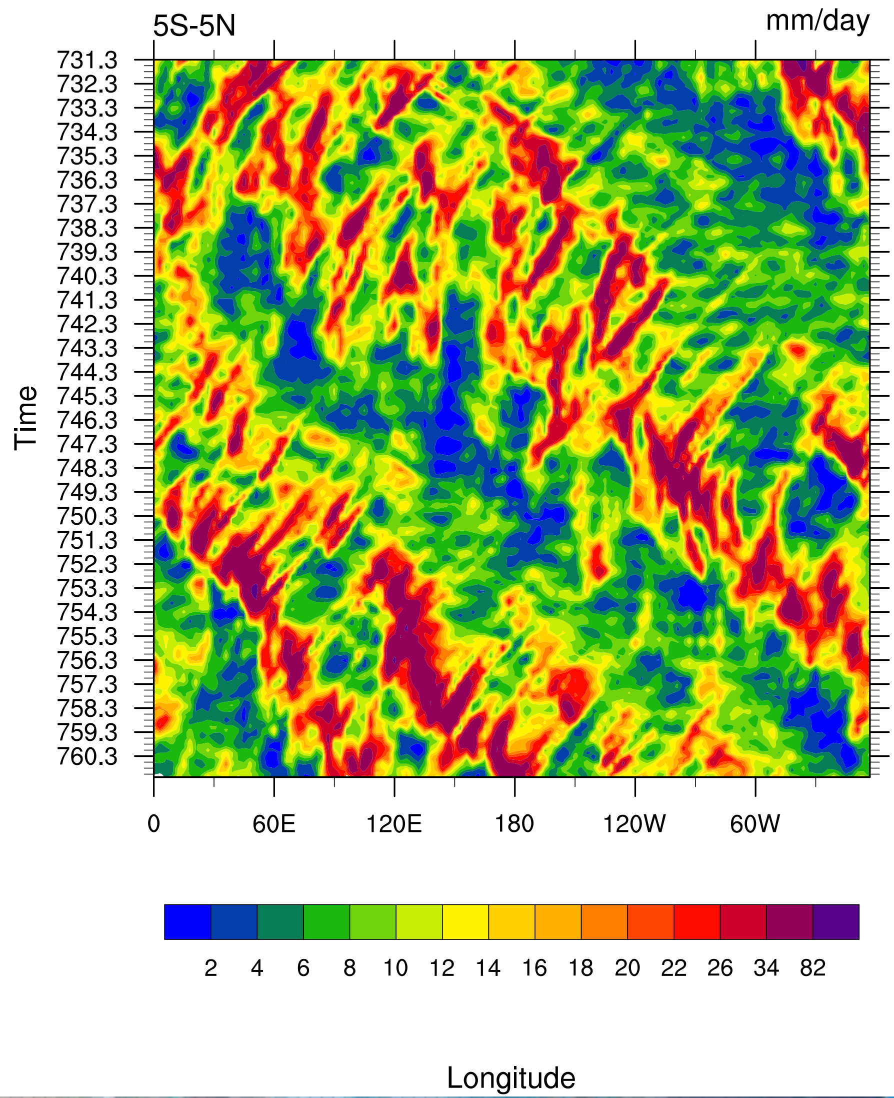
Data mapped to 3° lat-lon grid

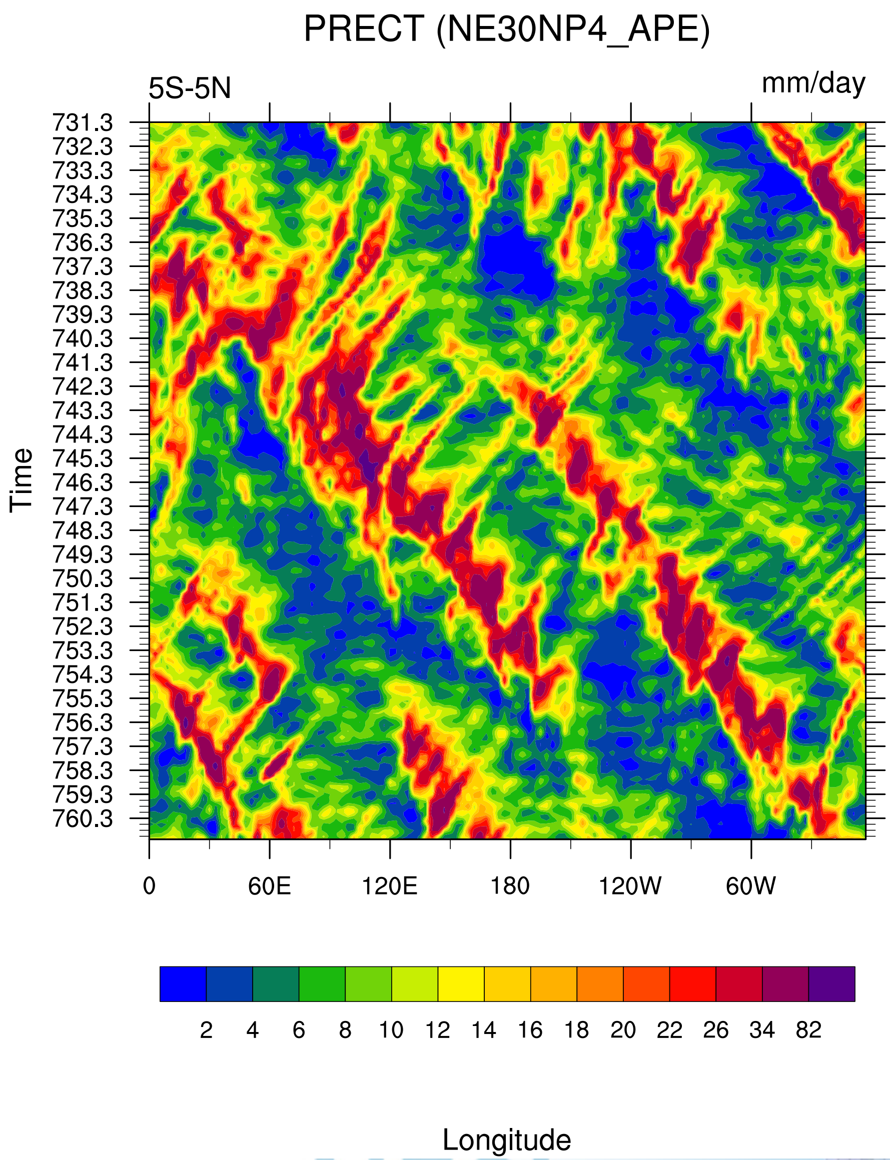


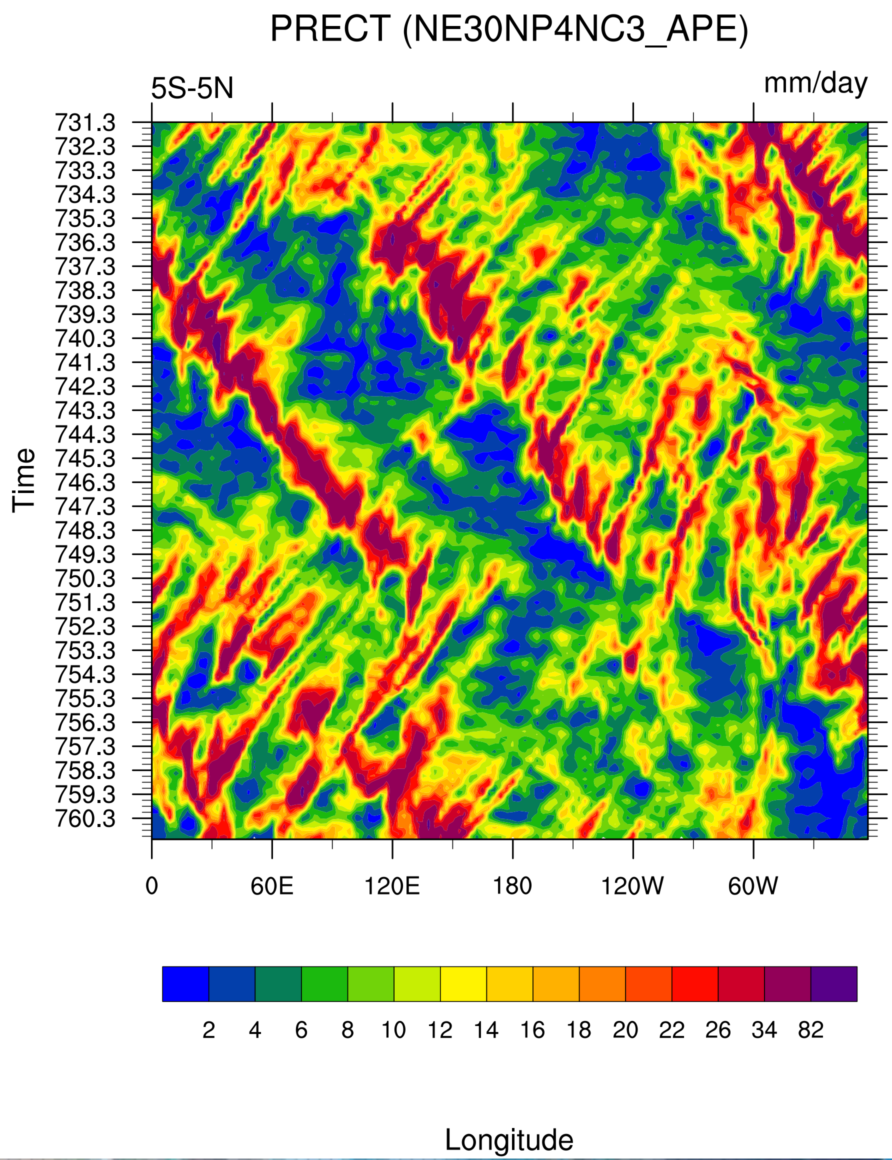
PRECT (NE30NP4_APE)



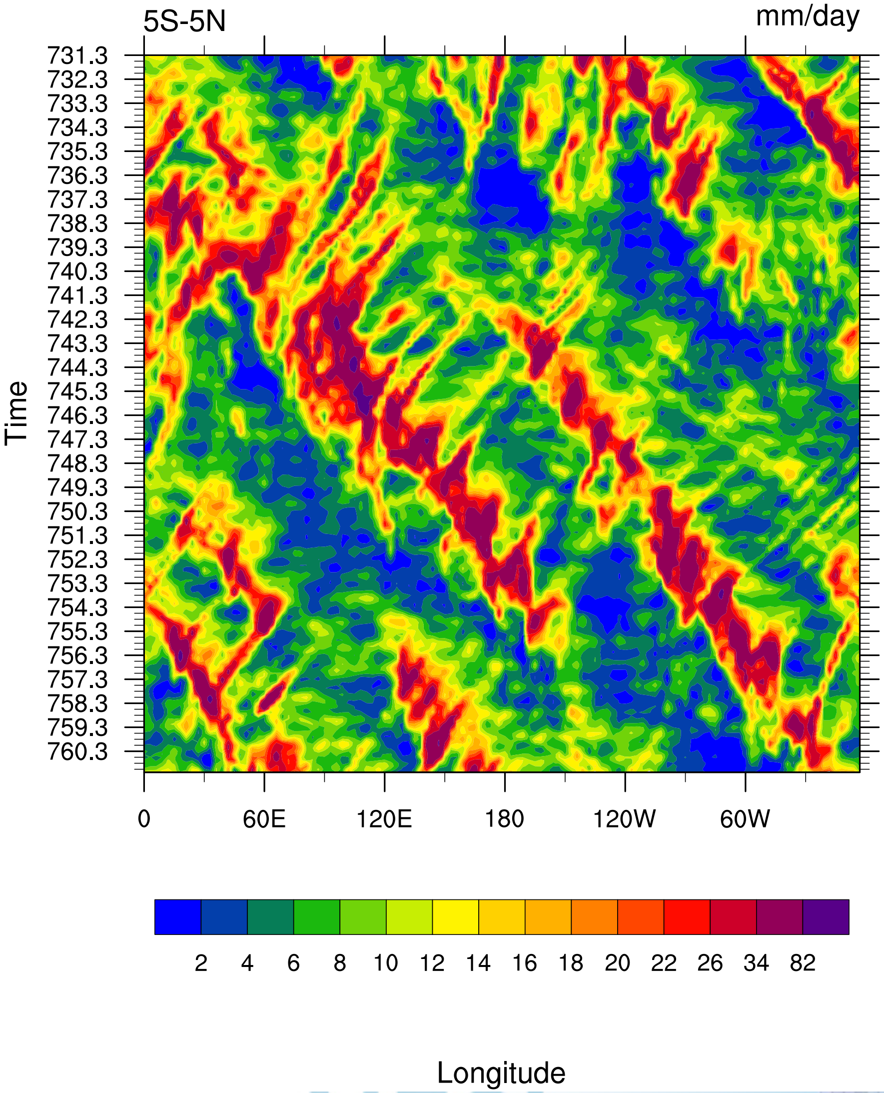
PRECT (NE30NP4NC2_APE)



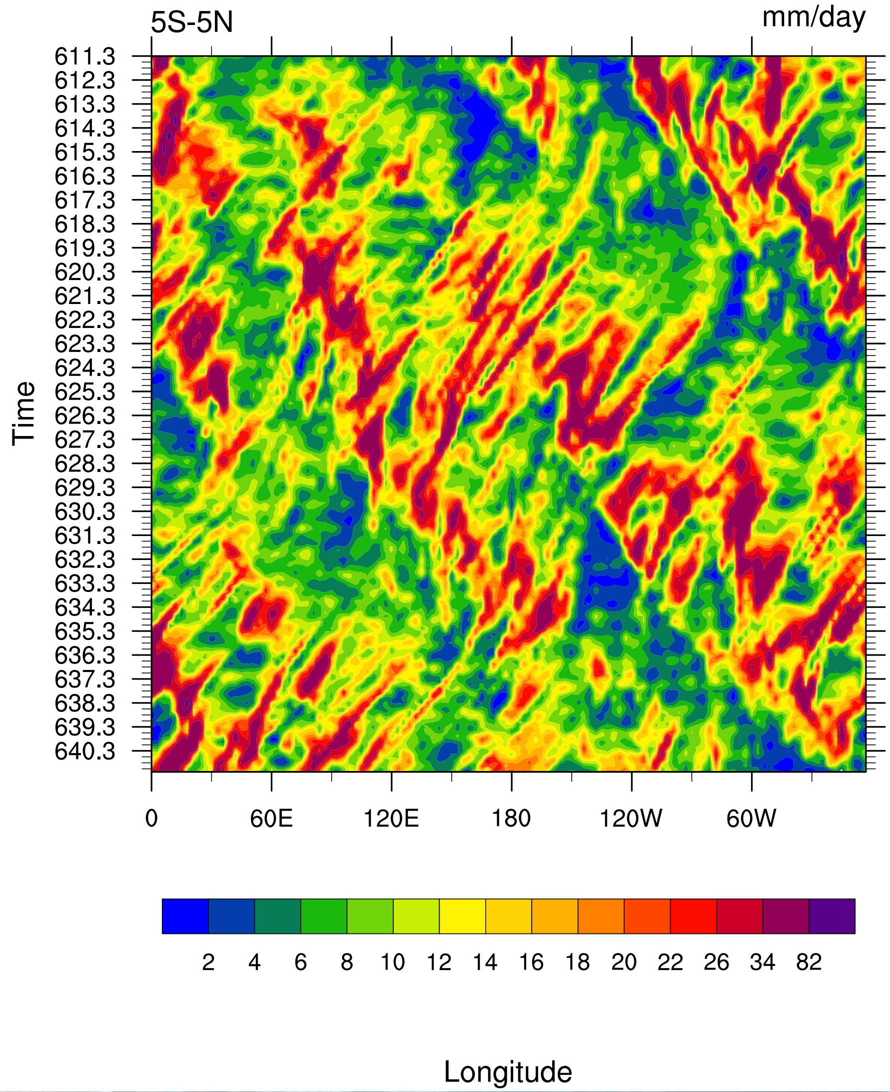

PRECT (NE30NP4_APE)
5S-5N
mm/day
Time
731.3
732.3
733.3
734.3
735.3
736.3
737.3
738.3
739.3
740.3
741.3
742.3
743.3
744.3
745.3
746.3
747.3
748.3
749.3
750.3
751.3
752.3
753.3
754.3
755.3
756.3
757.3
758.3
759.3
760.3
0
60E
120E
180
120W
60W
2 4 6 8 10 12 14 16 18 20 22 26 34 82
Longitude


PRECT (NE30NP4NC3_APE)
5S-5N
mm/day
Time
731.3
732.3
733.3
734.3
735.3
736.3
737.3
738.3
739.3
740.3
741.3
742.3
743.3
744.3
745.3
746.3
747.3
748.3
749.3
750.3
751.3
752.3
753.3
754.3
755.3
756.3
757.3
758.3
759.3
760.3
0
60E
120E
180
120W
60W
2 4 6 8 10 12 14 16 18 20 22 26 34 82
Longitude

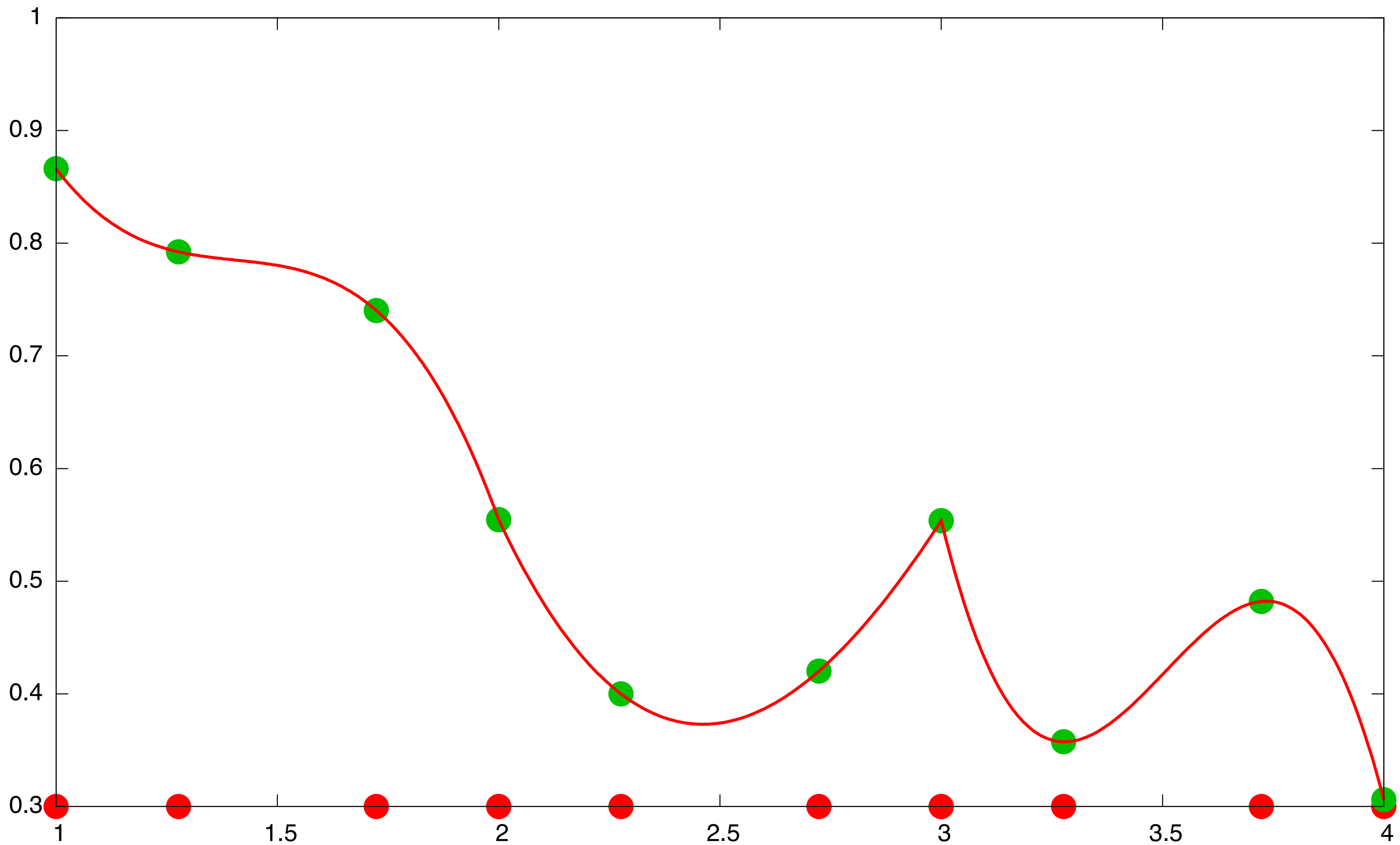
PRECT (NE30NP4_APE)

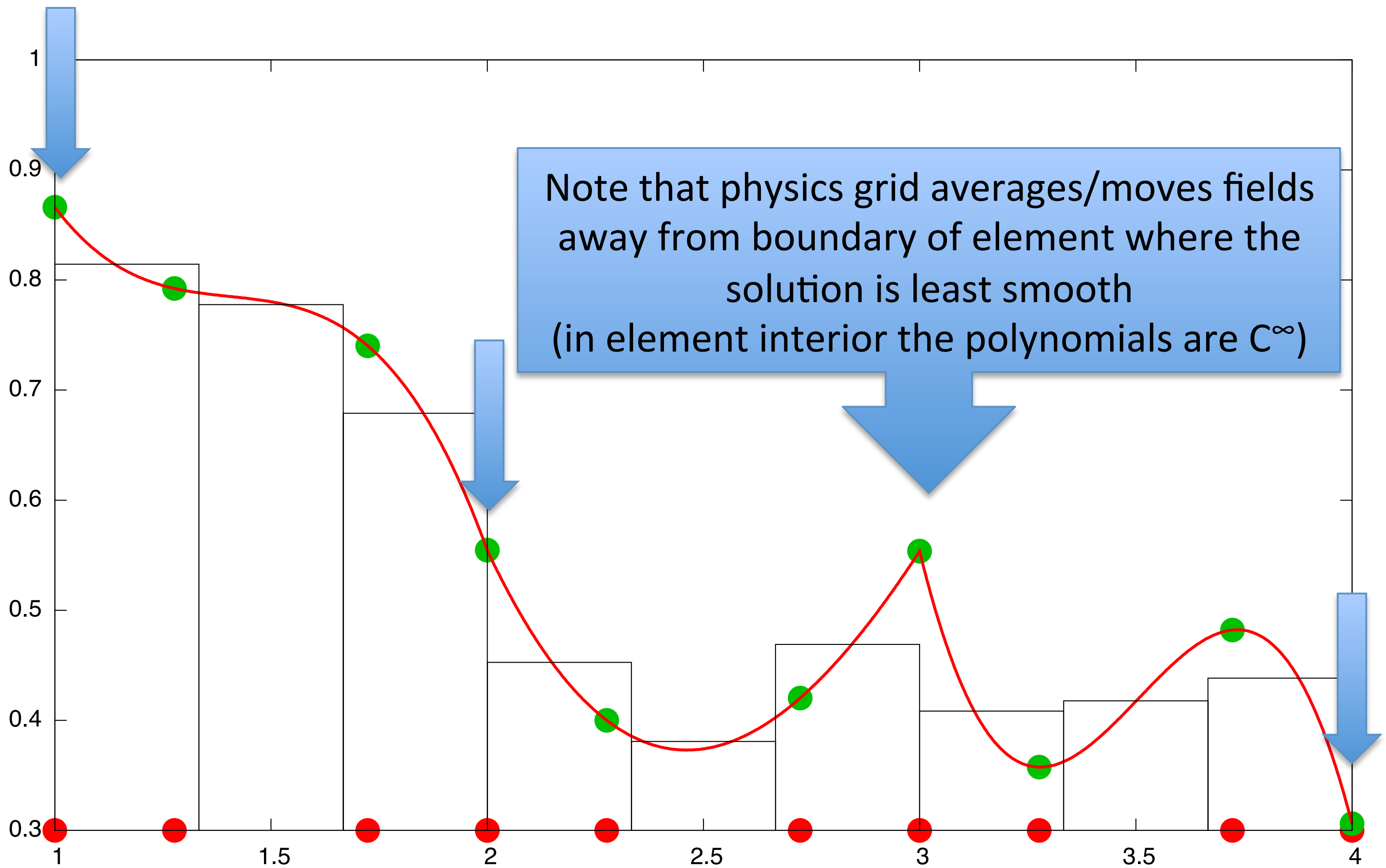


PRECT (NE30NP4NC4_APE)

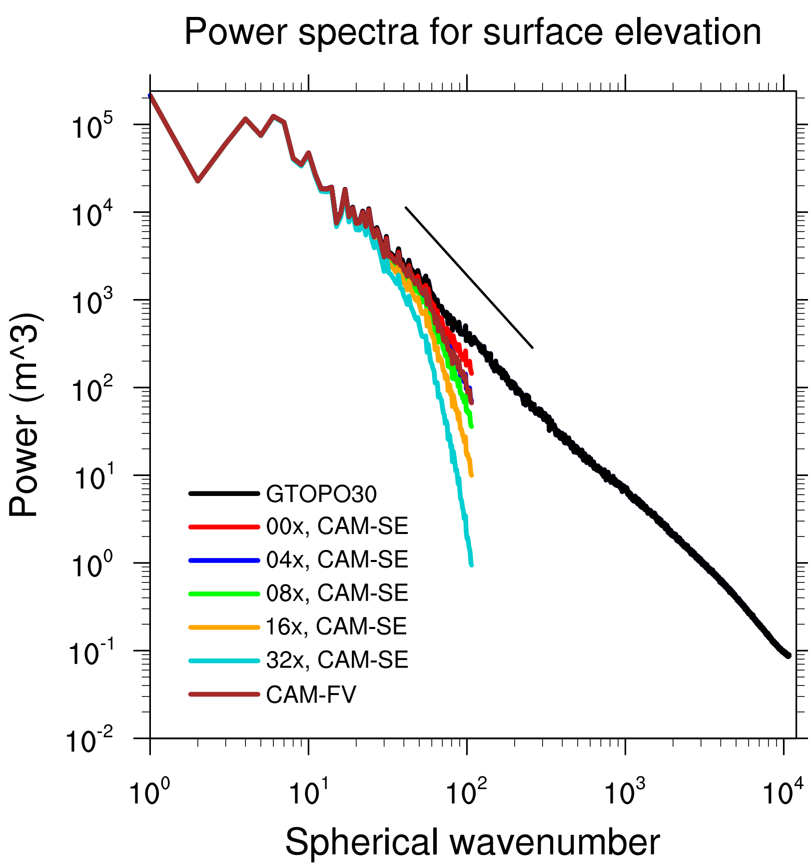


Stationary grid scale forcing


1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
1
1.5
2
2.5
3
3.5
4


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∞)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
1
1.5
2
2.5
3
3.5
4

Topography smoothing in CAM



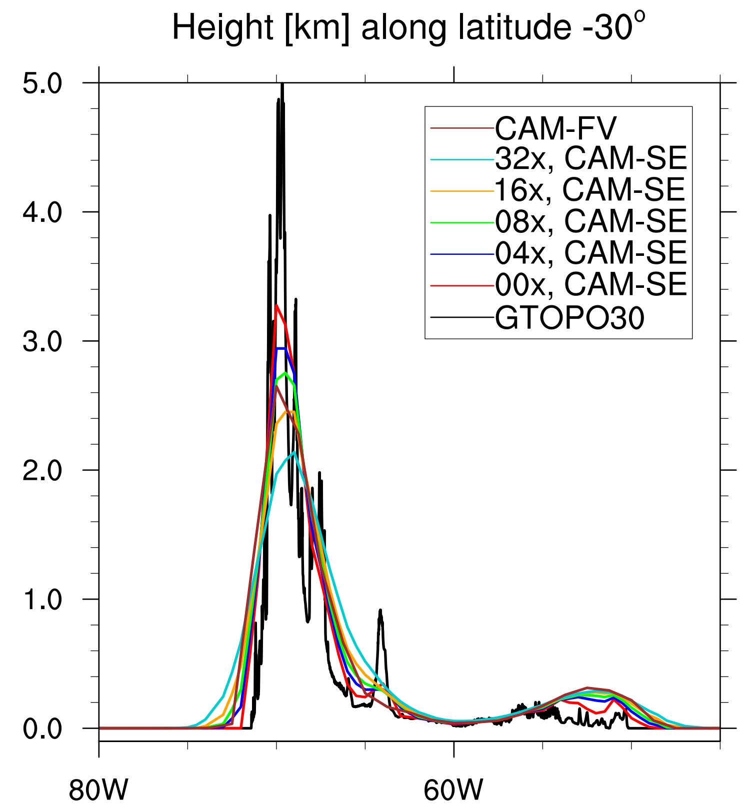


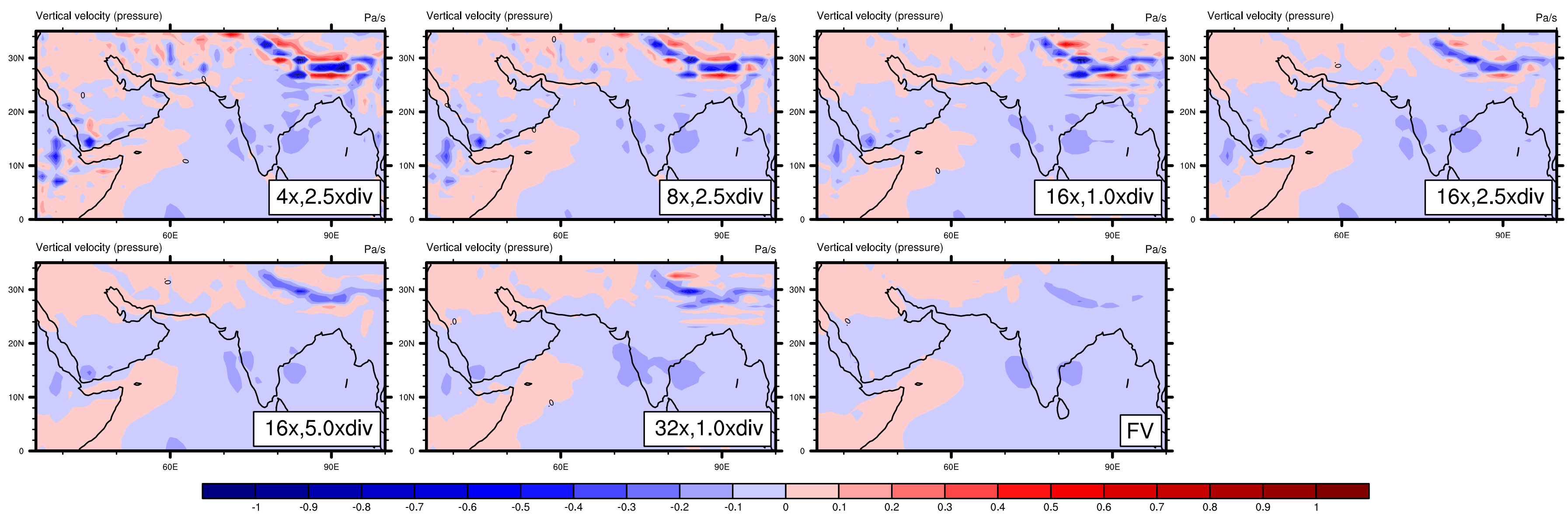
Figure 2. Surface elevation in kilometers for a cross section along latitude 30°S (through Andes mountain range) for different representations of surface elevation. The labeling is the same as in Figure 1.

Lauritzen et al., (2014), in prep: *NCAR Global Model Topography Generation Software for Unstructured Grids*

Topography smoothing in CAM

30 year AMIP simulations

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



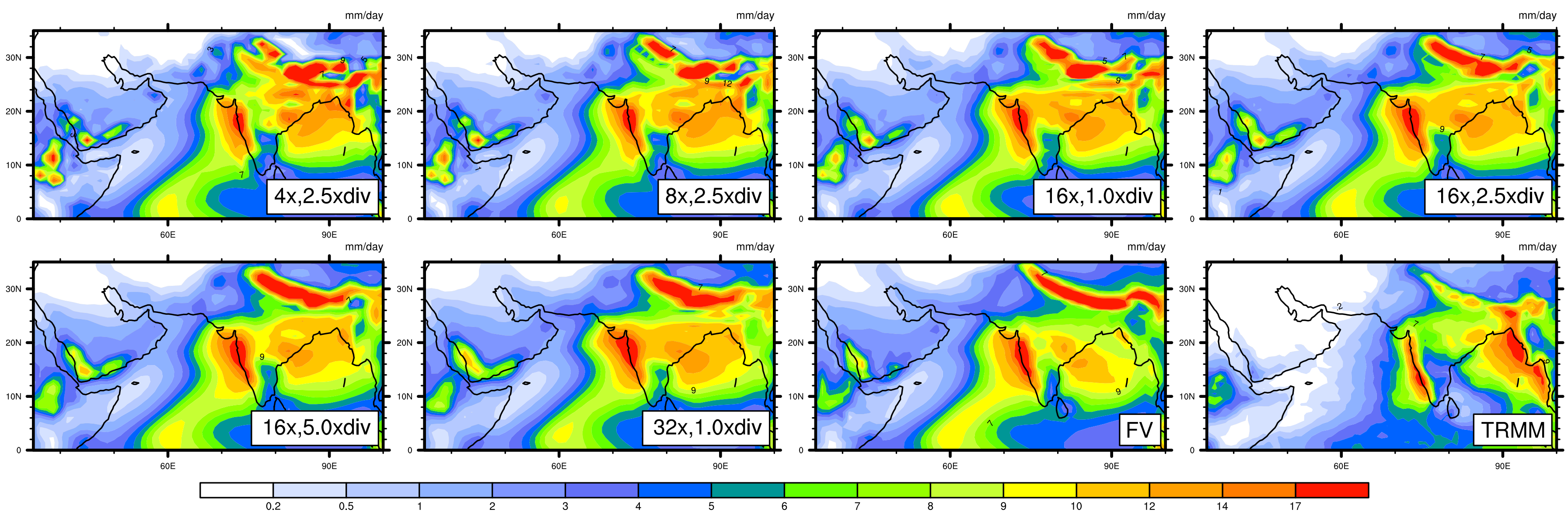
Notation: 2.5xdiv = 2.5 times more divergence damping than vorticity damping

Lauritzen et al., (2014), in prep: *NCAR Global Model Topography Generation Software for Unstructured Grids*

Topography smoothing in CAM

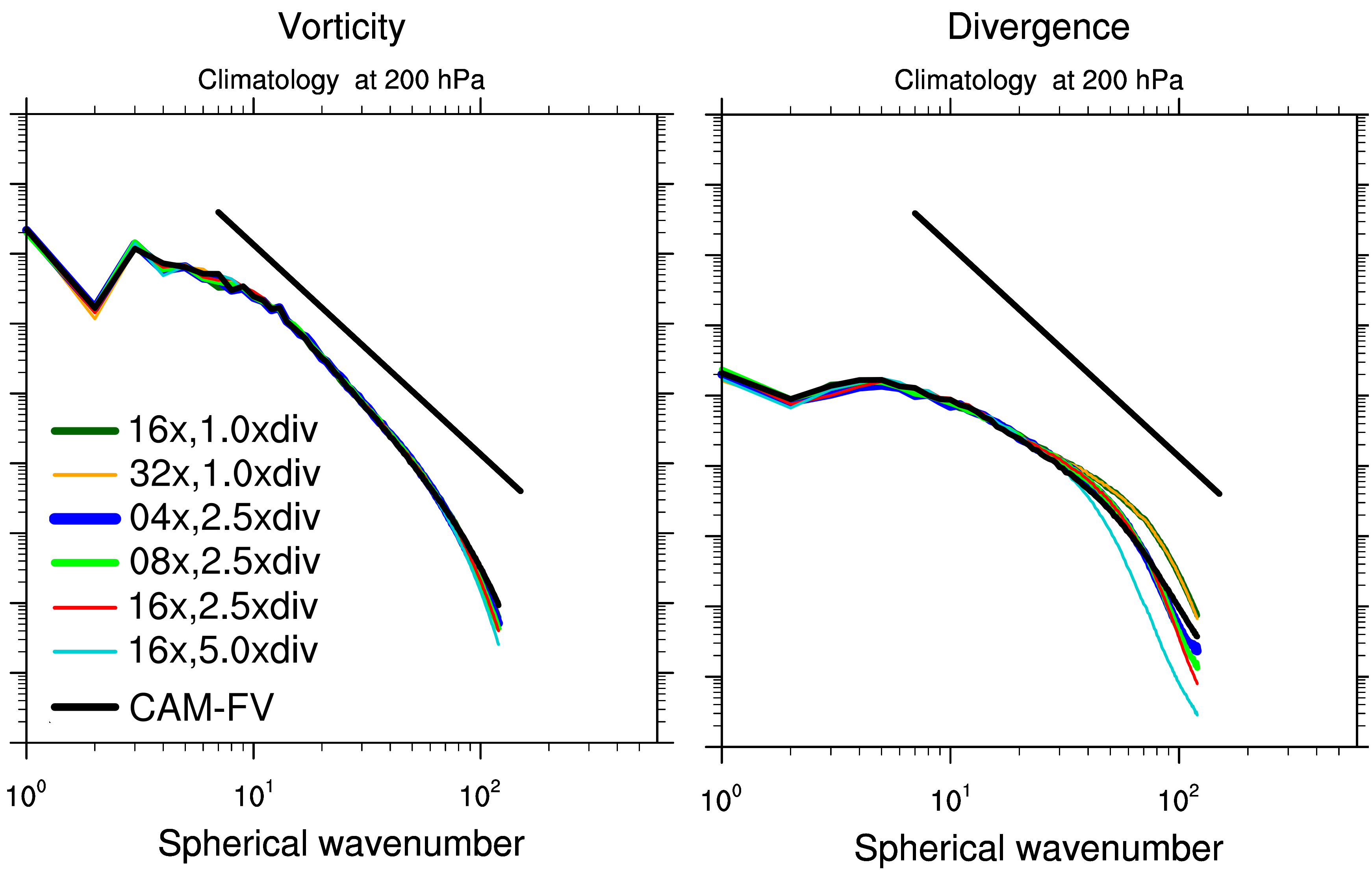
30 year AMIP simulations

Total precipitation rate



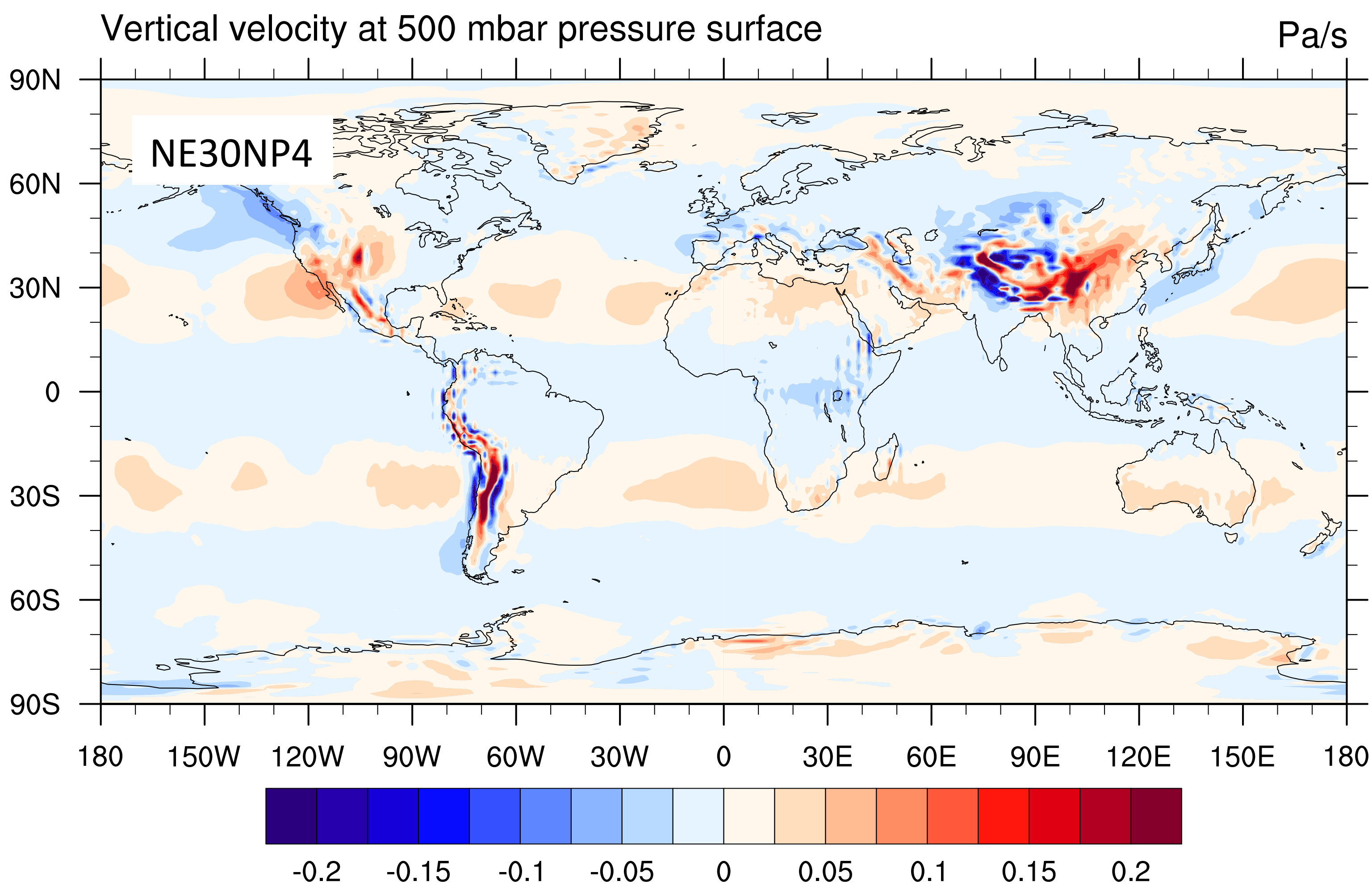
Lauritzen et al., (2014), in prep: *NCAR Global Model Topography Generation Software for Unstructured Grids*

Topography smoothing in CAM

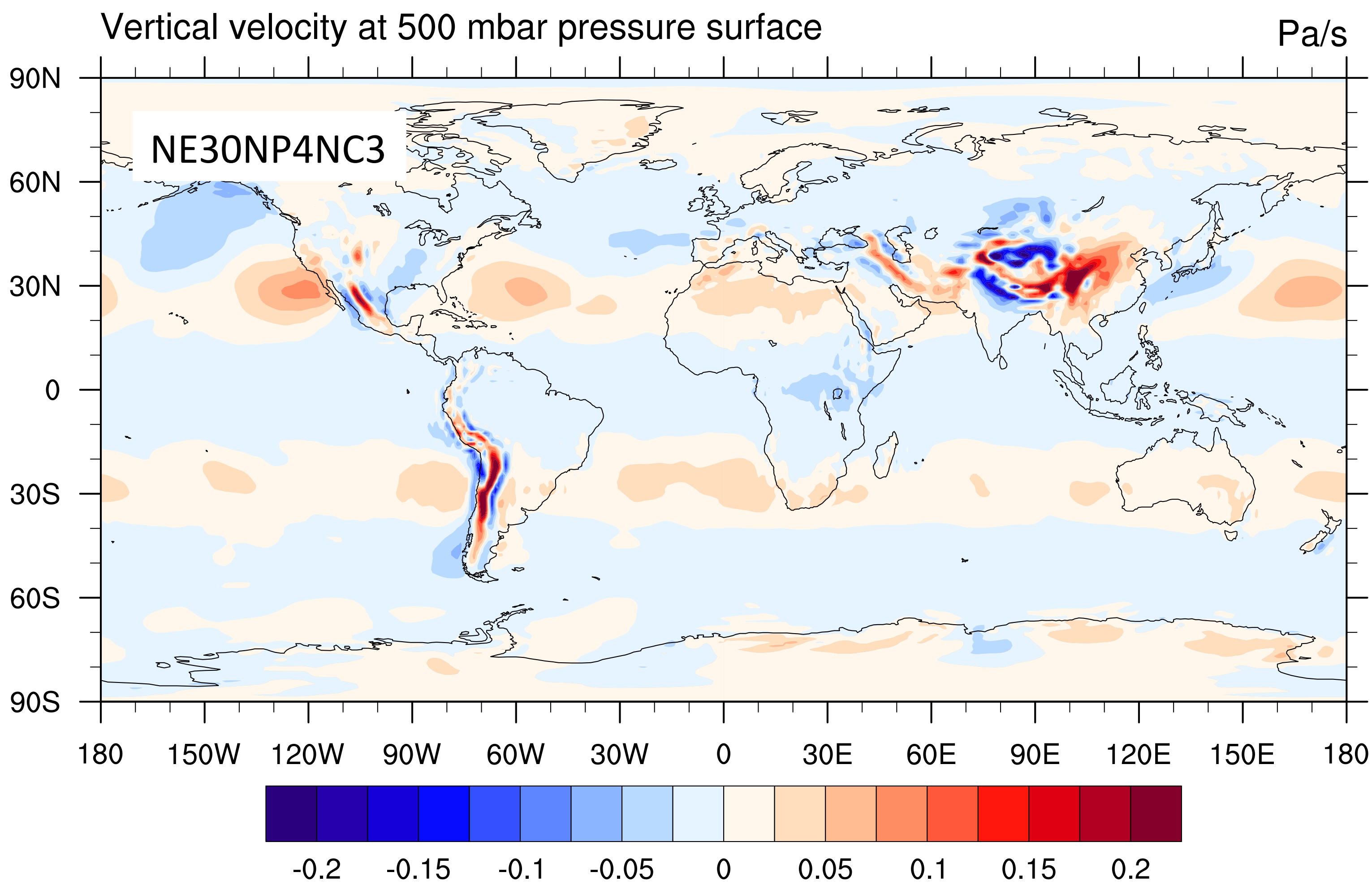


Lauritzen et al., (2014), in prep: *NCAR Global Model Topography Generation Software for Unstructured Grids*

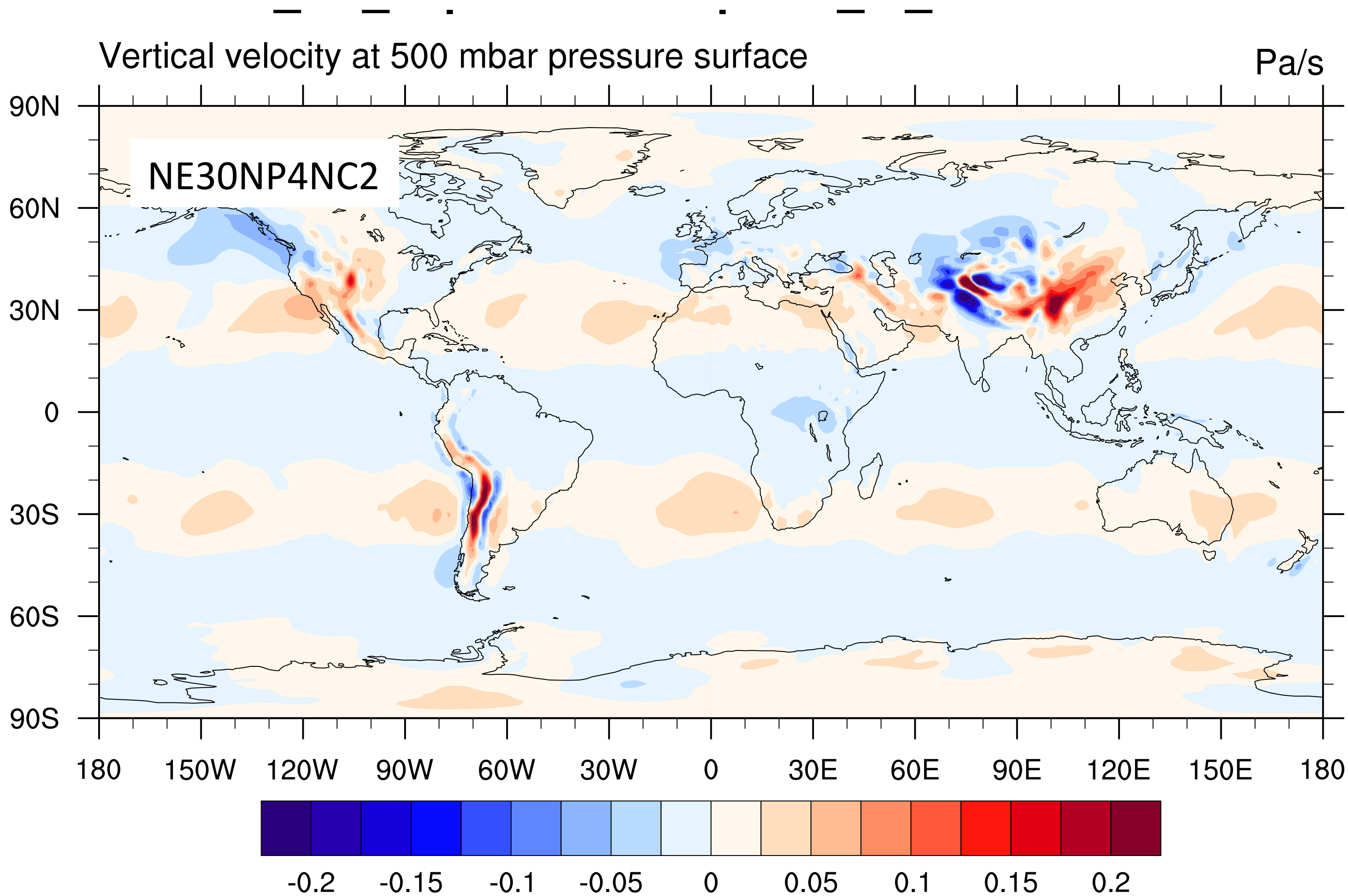
Held-Suarez with topography



Held-Suarez with topography



Held-Suarez with topography



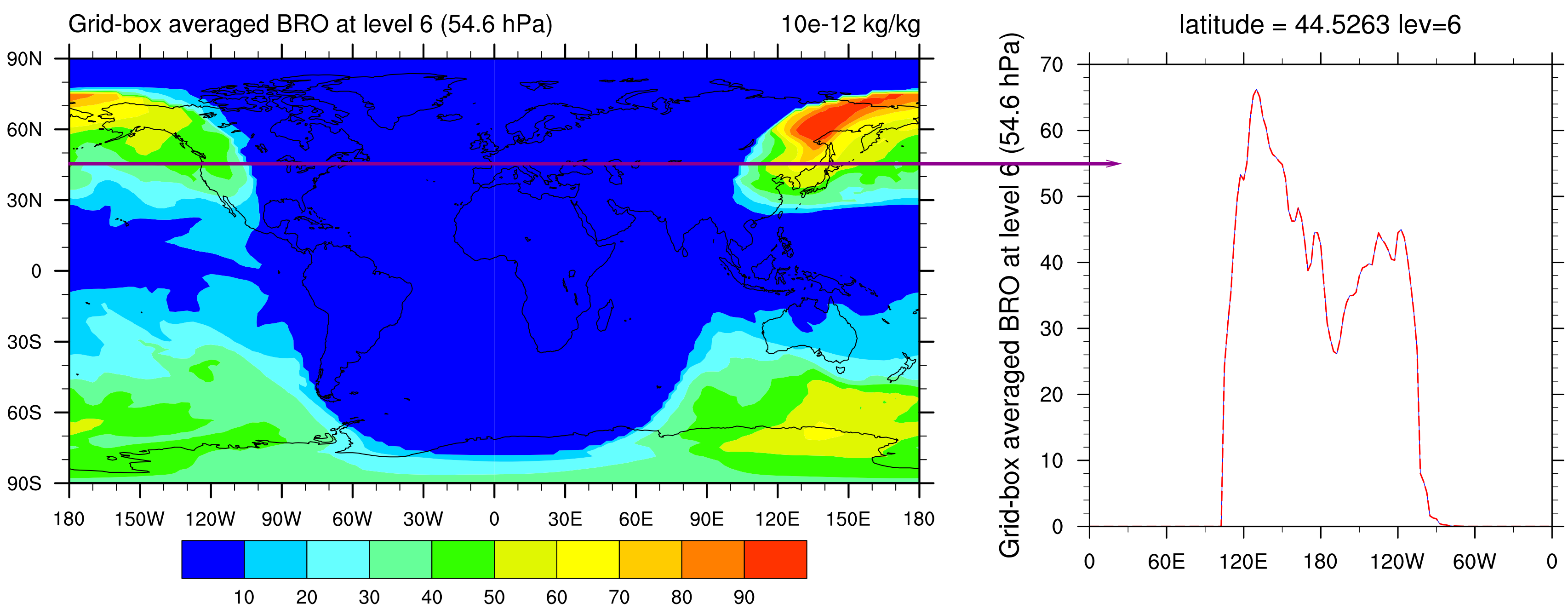
Aside ….

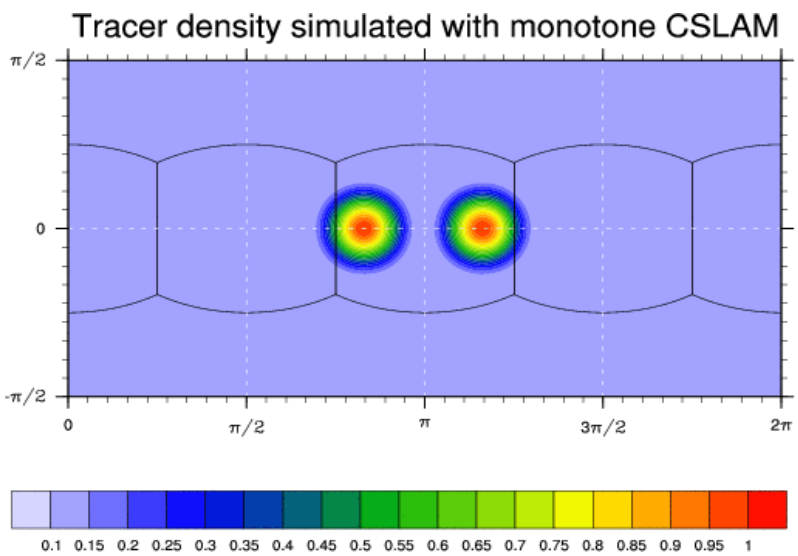
Go a step beyond inert transport testing, that is, add non-linear forcing to idealized flow problem!

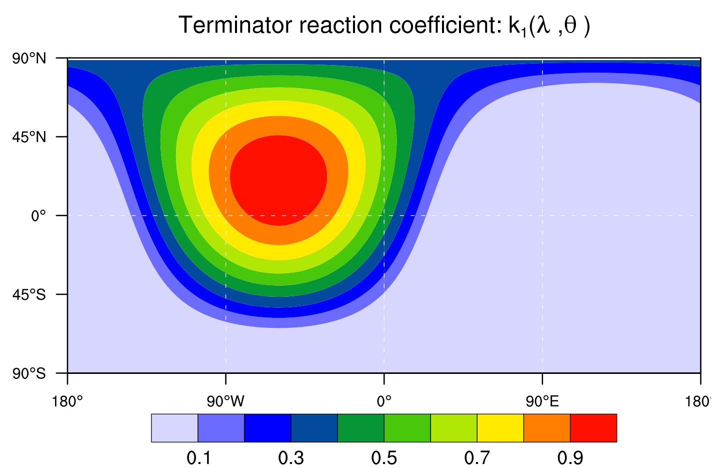
At the same time keep things simple enough to be able determine/understand cause and effect

An option: simplified chemical reactions
(right-hand side is products of mixing ratios)

"Inspiration":
Photolysis driven chemistry







The kinetic equations corresponding to the above system (equations (2) and (1)) are given by

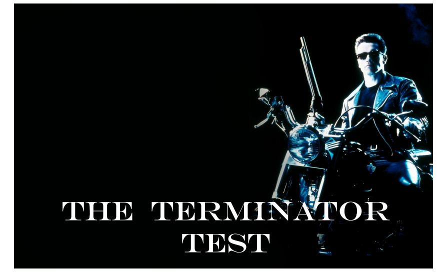
$$\frac{D\mathrm{Cl}}{Dt} = 2k_1\mathrm{Cl}_2 - 2k_2\mathrm{Cl}\,\mathrm{Cl}, \tag{4}$$

$$\frac{D\mathrm{Cl}_2}{Dt} = -k_1\mathrm{Cl}_2 + k_2\mathrm{Cl}\,\mathrm{Cl}, \tag{5}$$

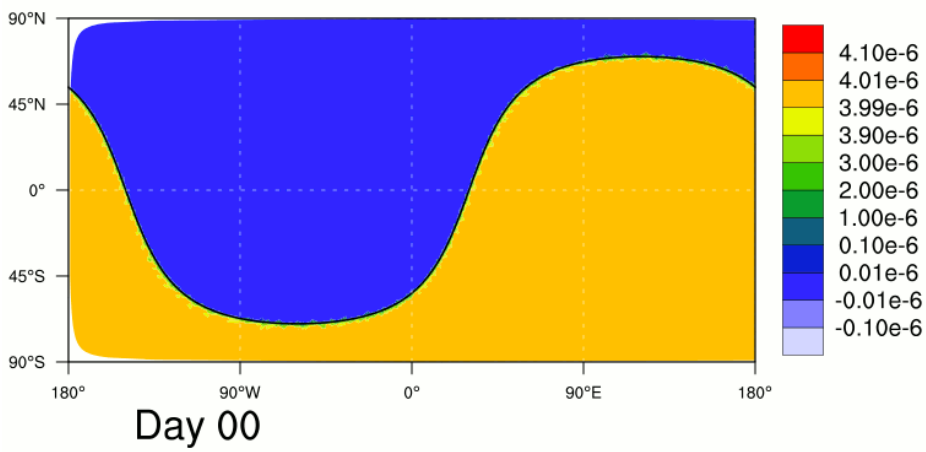
where D/Dt is the material (or total) derivative $D/Dt = \partial/\partial t + \boldsymbol{v}\cdot\nabla$ and $\boldsymbol{v}$ is the wind vector. It is easily verified that the weighted sum of Cl and Cl_2 is conserved along characteristics of the flow

$$\frac{D\mathrm{Cl}_y}{Dt} = \frac{D}{Dt}\left[\mathrm{Cl} + 2\mathrm{Cl}_2\right] = 0. \tag{6}$$

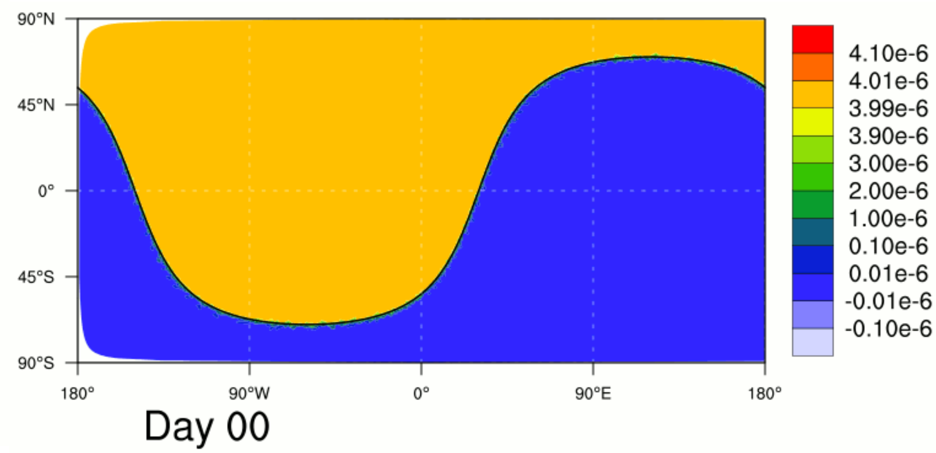
The terminator 'toy'-chemistry test: A simple tool to assess errors in transport schemes (Lauritzen et al, 2014, submitted to GMDD)



CL2



Cl

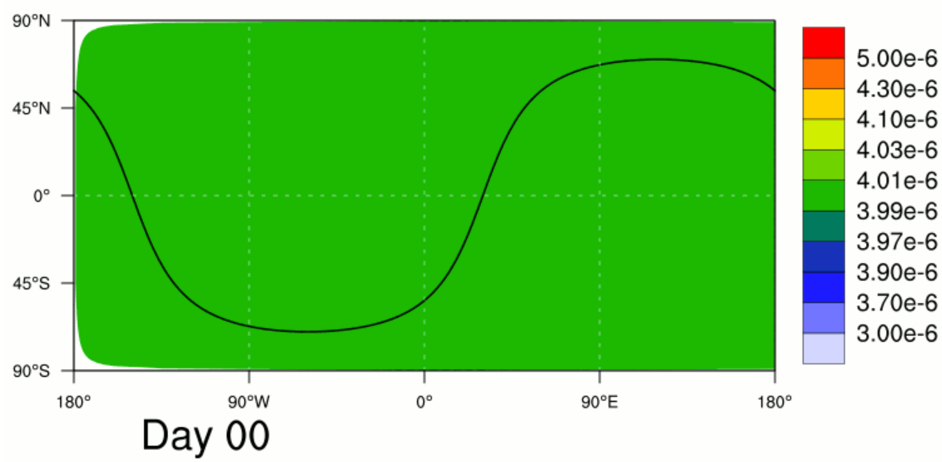


Non-linear "terminator-toy" chemistry:

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

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

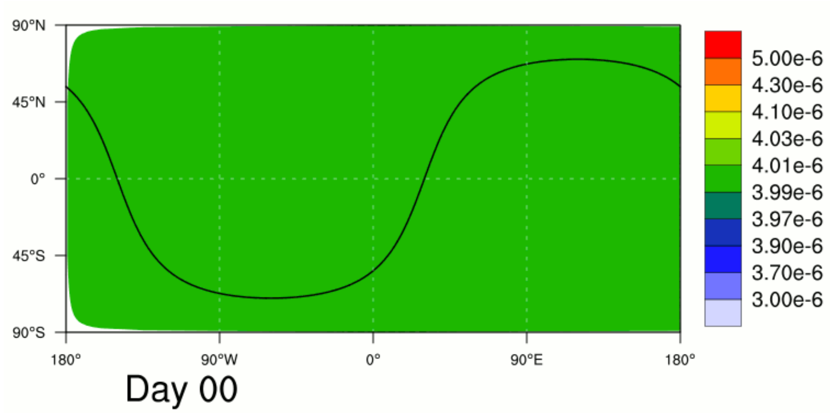
Exact solution: $Cl+2*Cl_2$ = constant



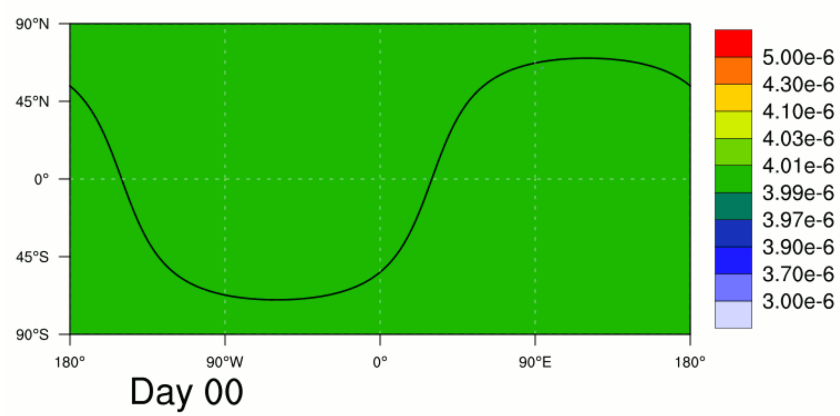
Cly

Wind field: Nair and Lauritzen deformational flow

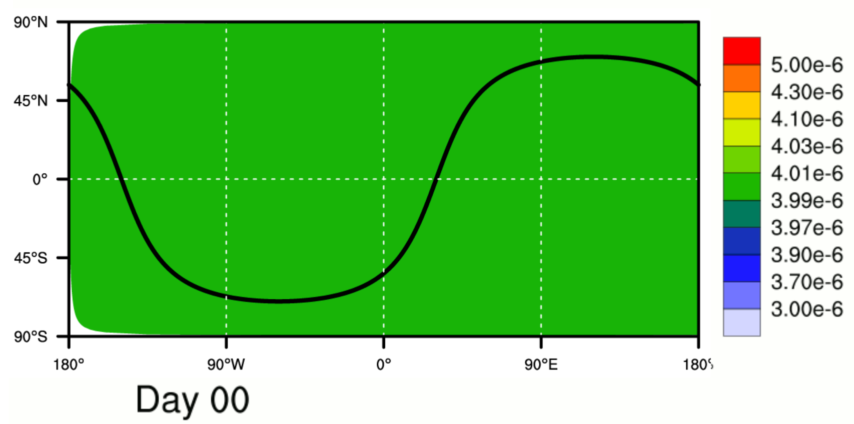
Errors are due to non-conservation of linear correlations by the limiter (and physics-dynamics coupling)



CAM-SE

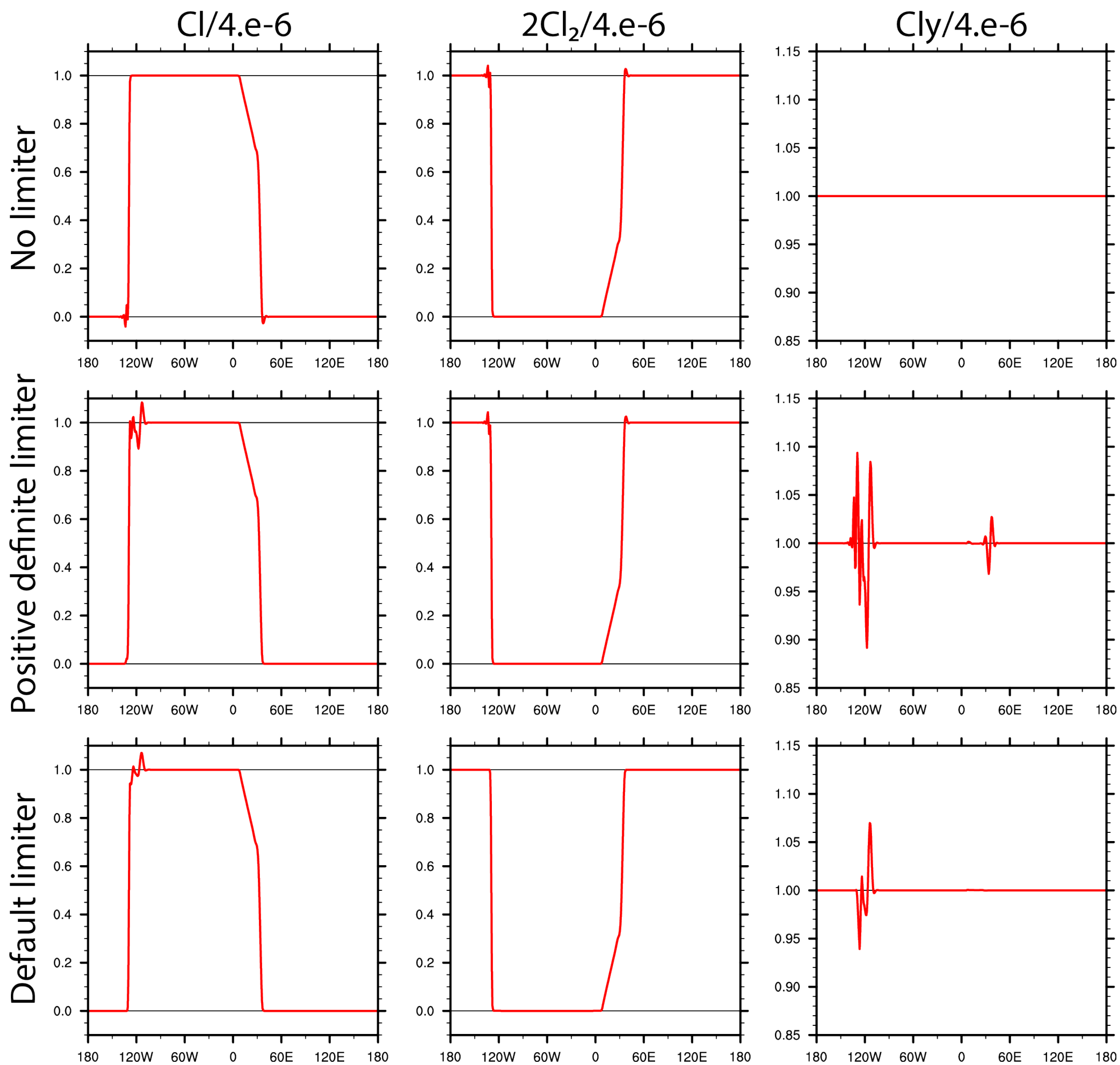


CAM-FV



CSLAM
(Conservative Semi-Lagrangian
Multi-tracer scheme)
Lauritzen et al. (2010)

Testing limiters (with CAM-SE)



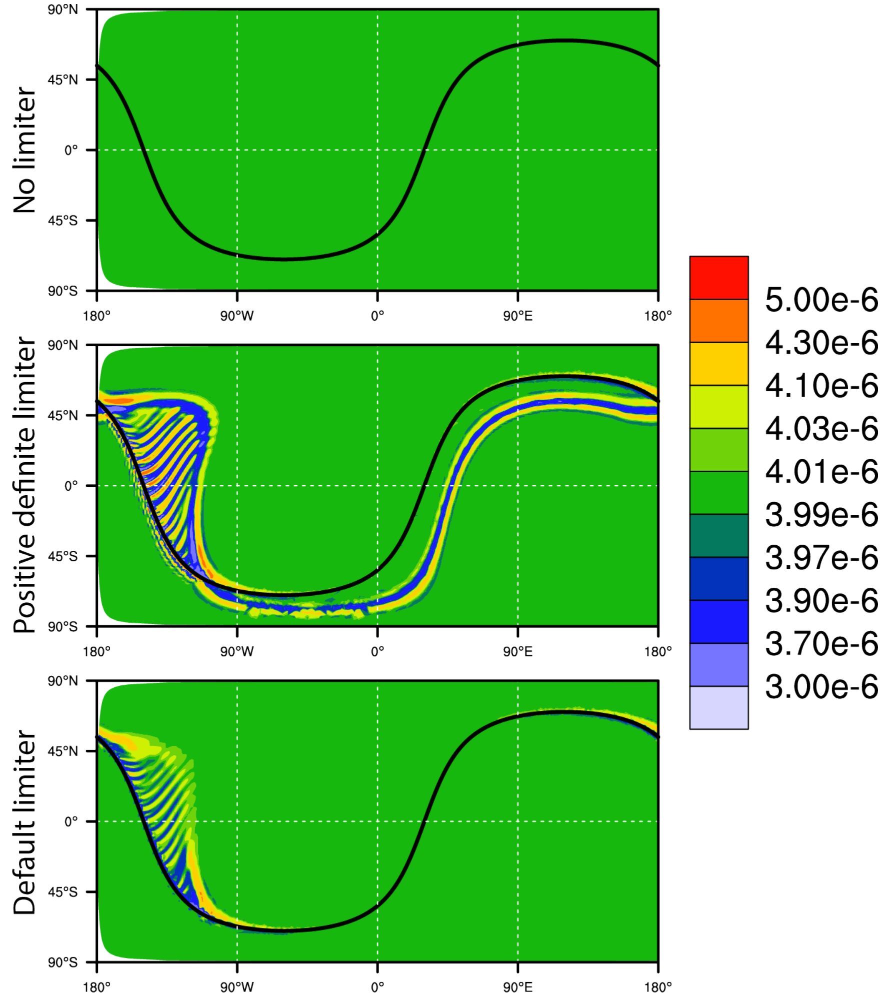


Figure 4. Contour plot of Cl_y at day 1 using CAM-SE in $ftype = 1$ configuration where (upper) no limiter, (middle) positive definite limiter, and the default CAM-SE limiter is applied, respectively. The solid black line depicts the location of the terminator line. Note that the contour levels are not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

Simplified framework to test physics dynamics coupling

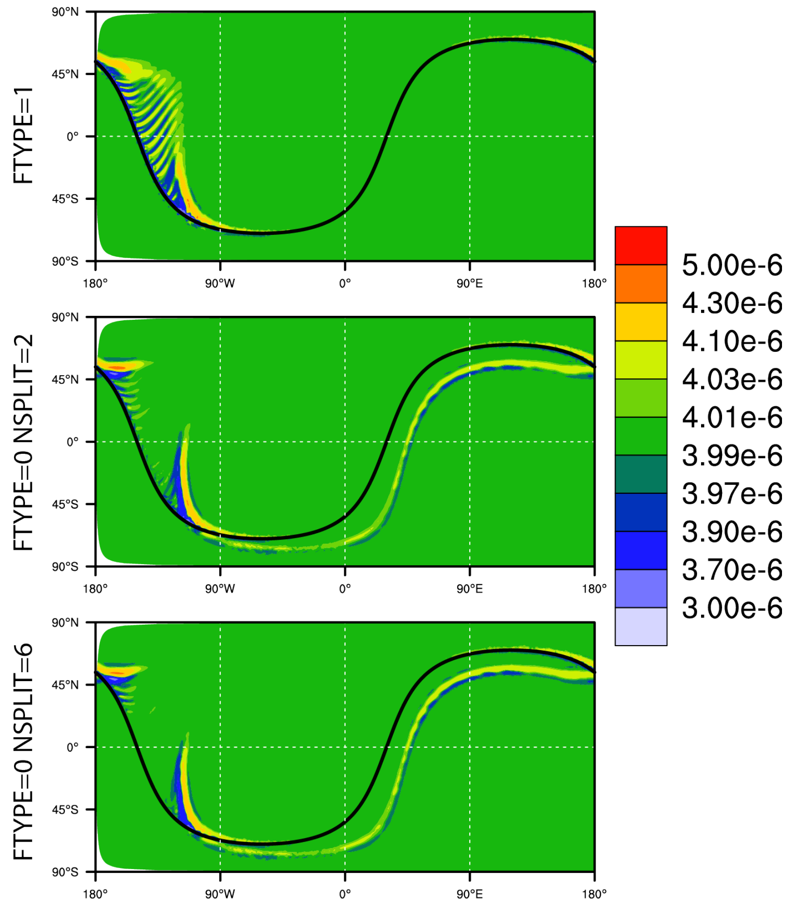
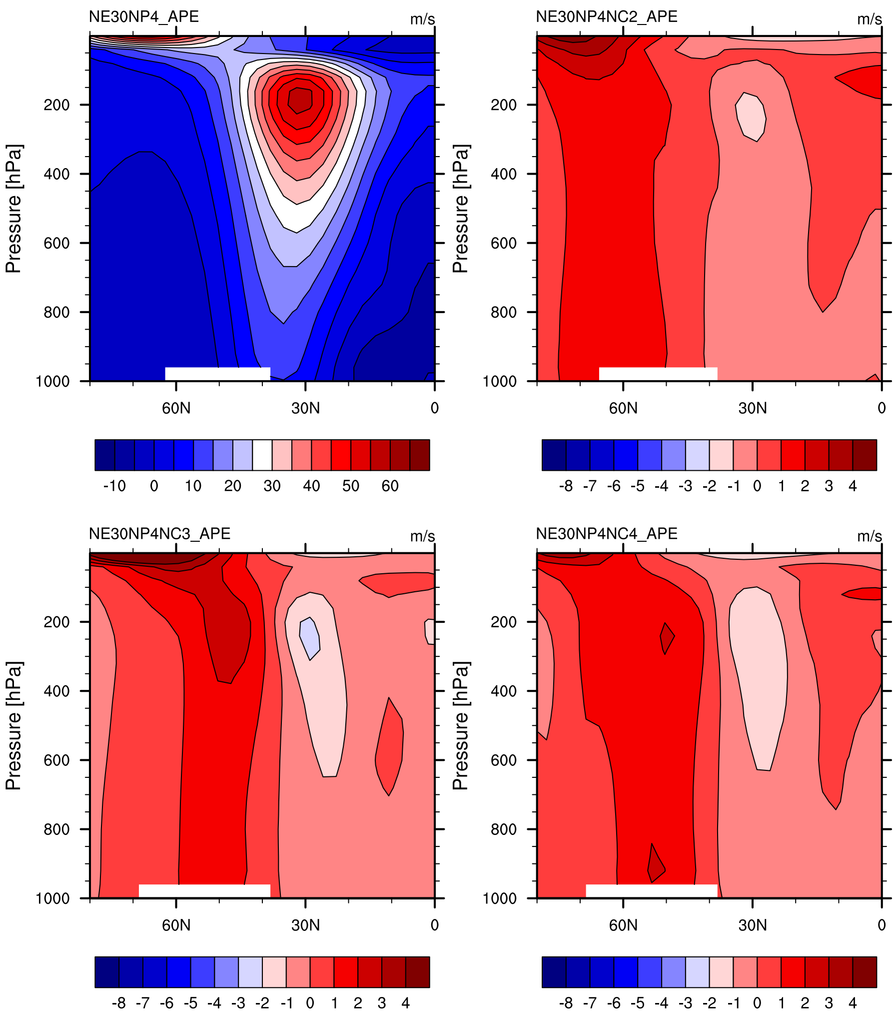


Figure 6. Contour plots of Cl_y at day 1 using CAM-SE based on (upper) $ftype = 1$, (middle) $ftype = 0$ and $nsplit = 3$, and (lower) $ftype = 0$ and $nsplit = 6$, respectively. In all simulations the tracer time-step is constant $\Delta t_{tracer} = 300s$.

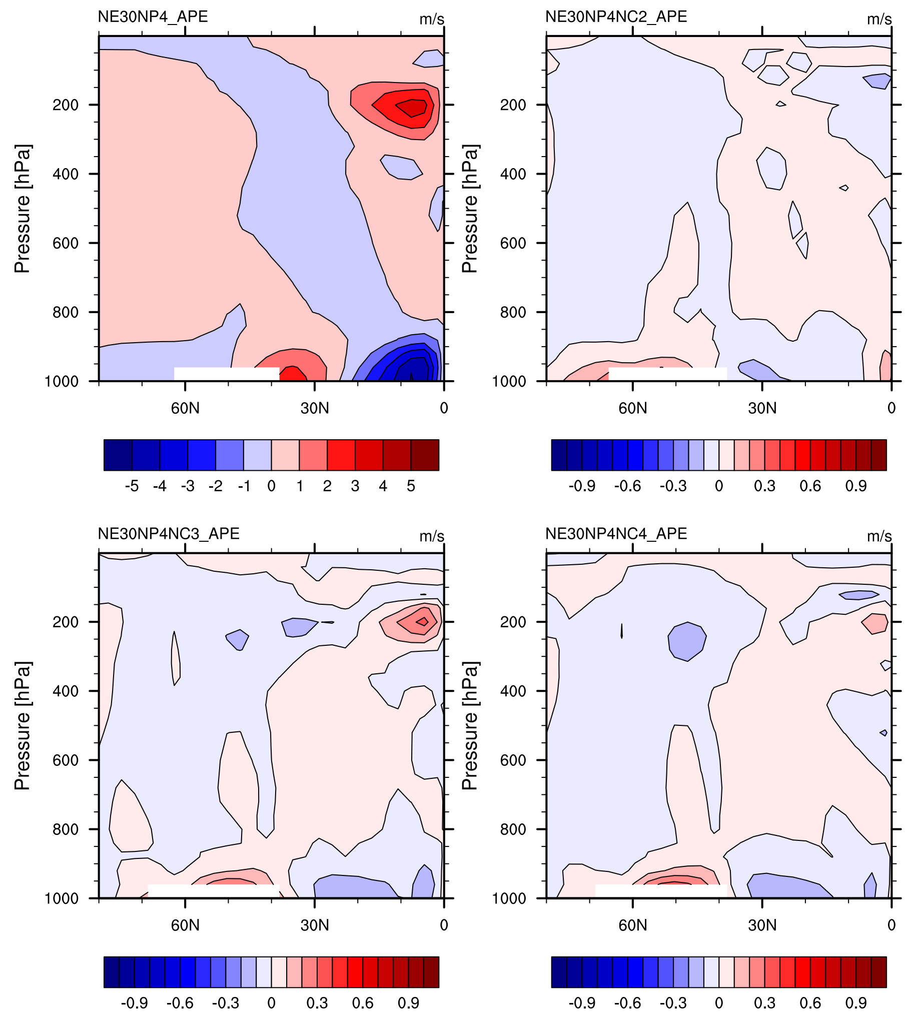
Algorithm 1 Pseudo-code explaining the different levels of subcycling and physics-dynamics coupling used in CAM-SE.

Outer loop advances solution Δt in time:
for $t = 1, 2, \ldots$ **do**
  Compute physics tendencies F_i, $i = \mathrm{Cl}, \mathrm{Cl}_2$
  for $ns = 1, 2, \ldots, nsplit$ **do**
    Update state with chemistry/physics tendencies:
    $C_i = C_i + \frac{\Delta t}{nsplit} F_i$, $i = \mathrm{Cl}, \mathrm{Cl}_2$
    for $rs = 1, 2, \ldots, rsplit$ **do**
      subcycling of tracer advection:
      $C_i = C_i + \frac{\Delta t}{nsplit \times rsplit} \mathcal{T}(C_i)$, $i = \mathrm{Cl}, \mathrm{Cl}_2$
    end for
  end for
end for

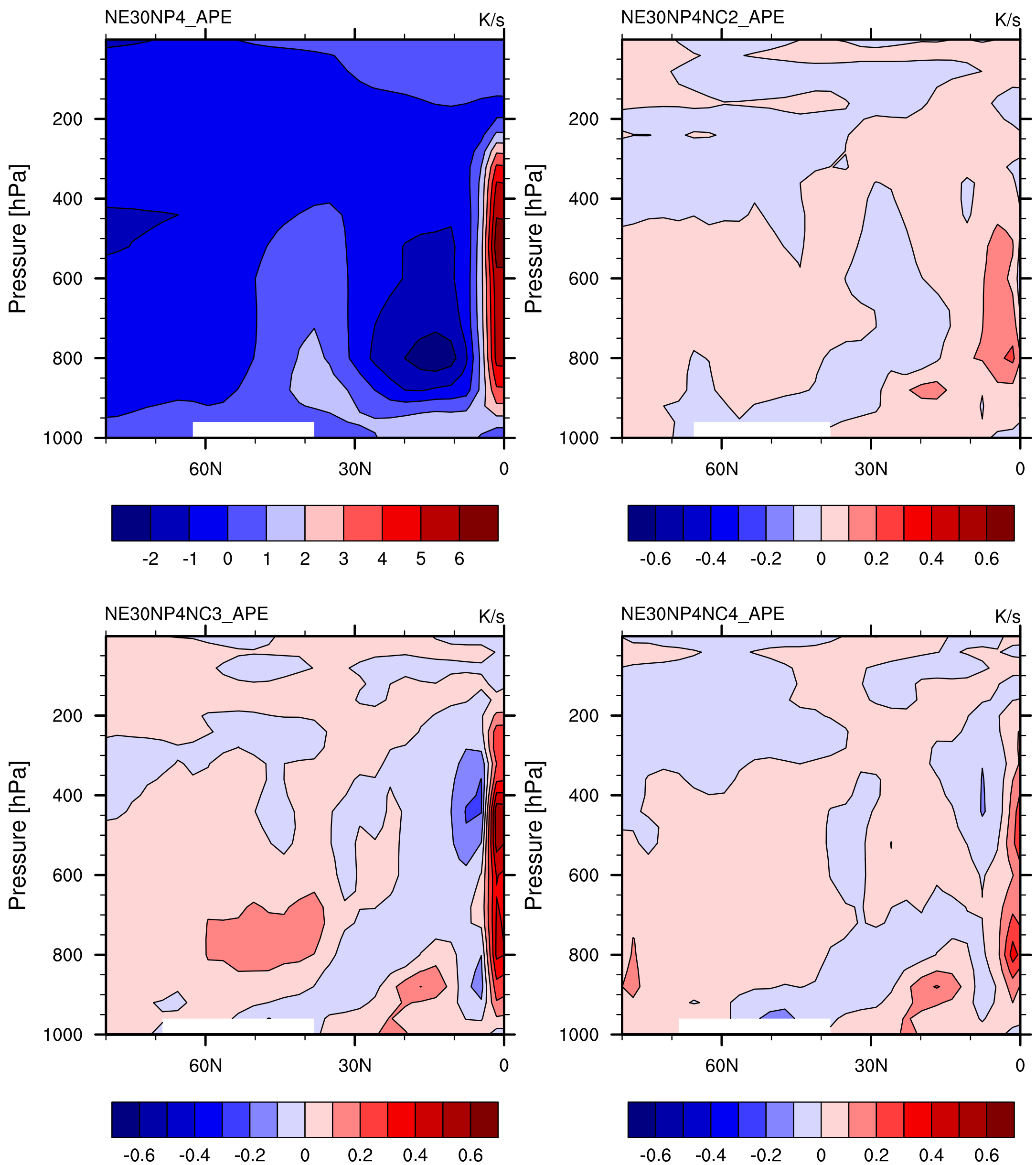
Zonal-time averaged U

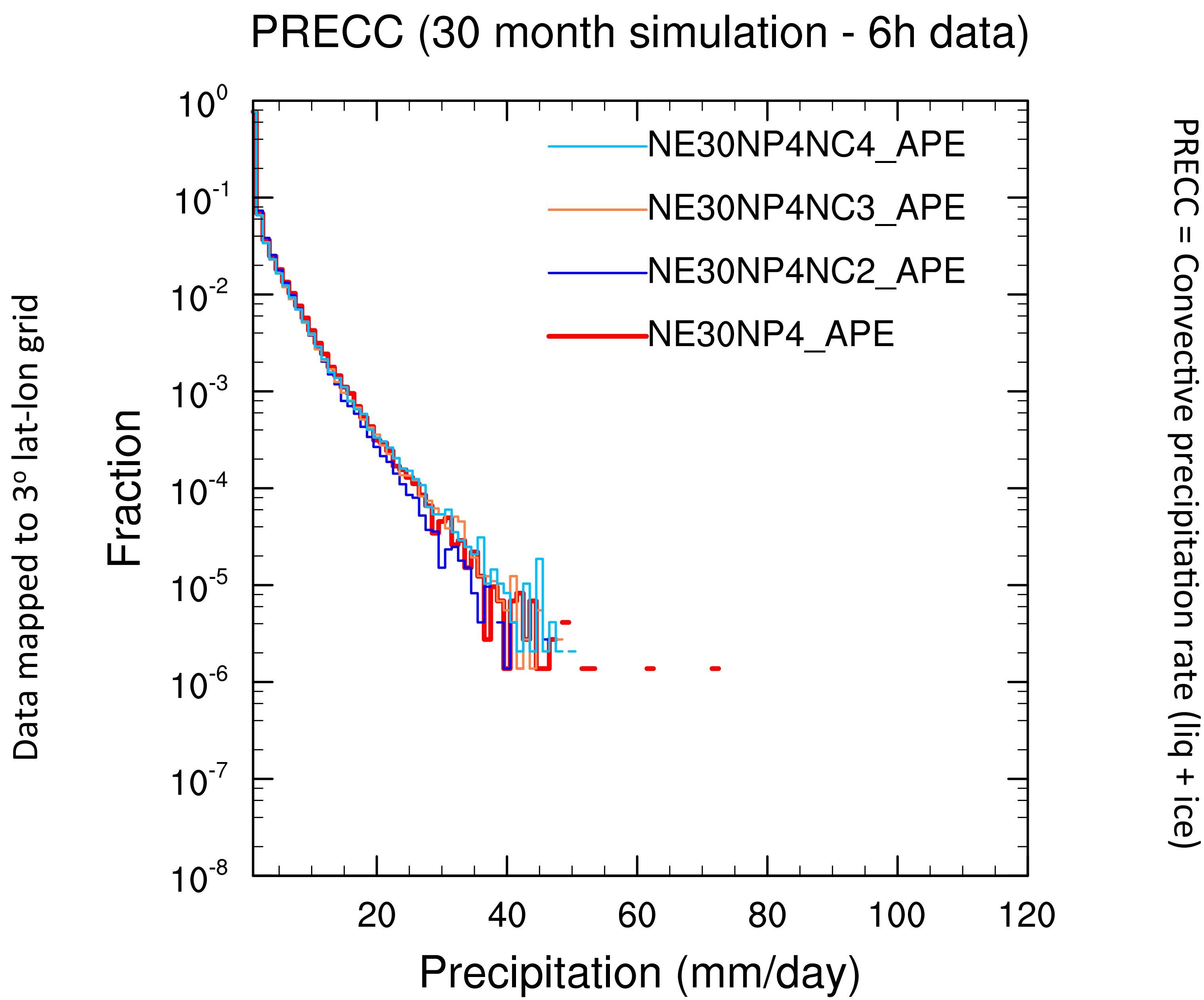


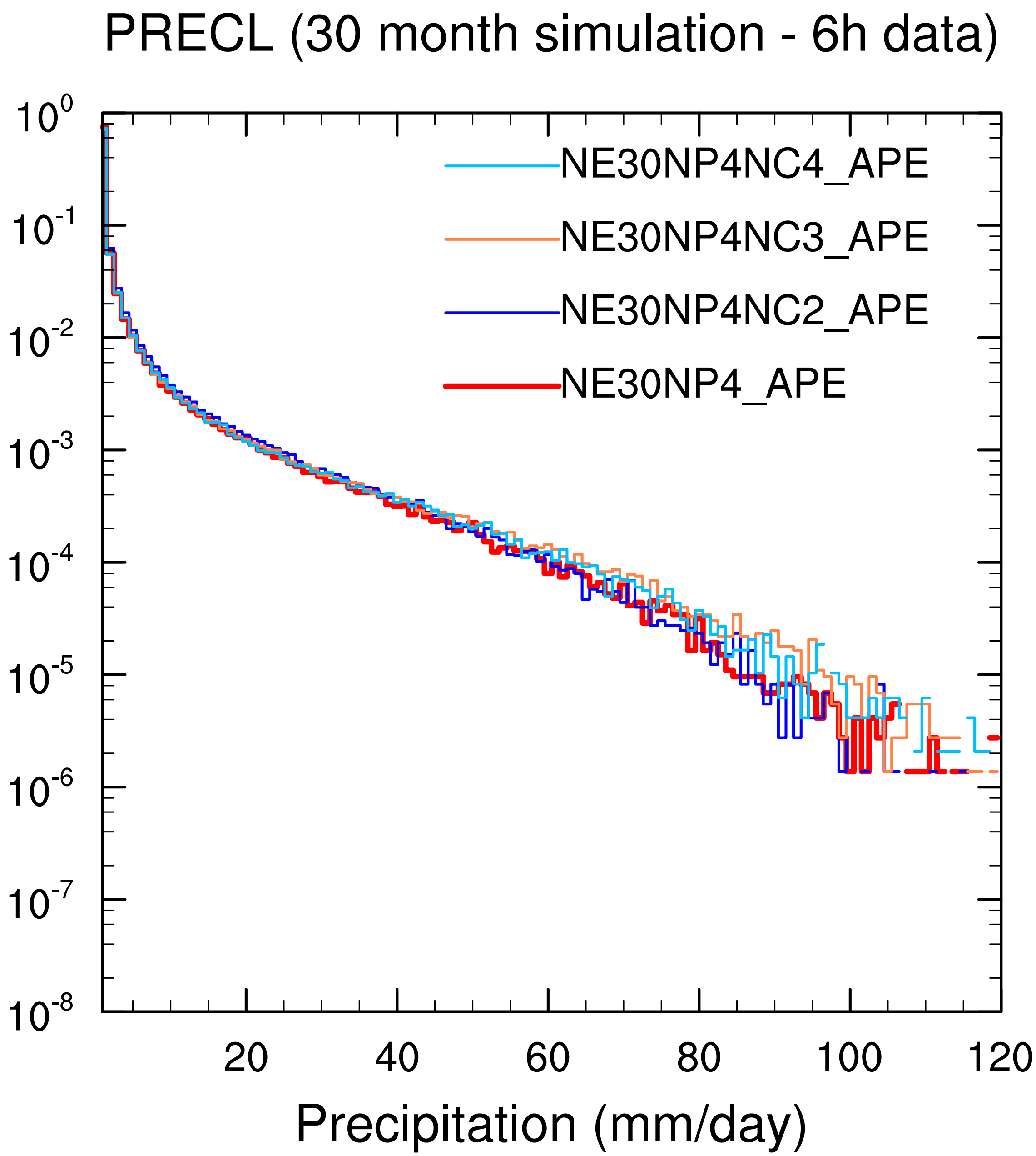
Zonal-time averaged V



Zonal-time averaged PTTEND




PRECC (30 month simulation - 6h data)
NE30NP4NC4_APE
NE30NP4NC3_APE
NE30NP4NC2_APE
NE30NP4_APE
Fraction
Precipitation (mm/day)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
20
40
60
80
100
120
Data mapped to 3° lat-lon grid
PRECC = Convective precipitation rate (liq + ice)



Data mapped to 3° lat-lon grid

PRECL = Large-scale (stable) precipitation rate (liq + ice)