Separating dynamics, physics and tracer transport grids in a global climate model

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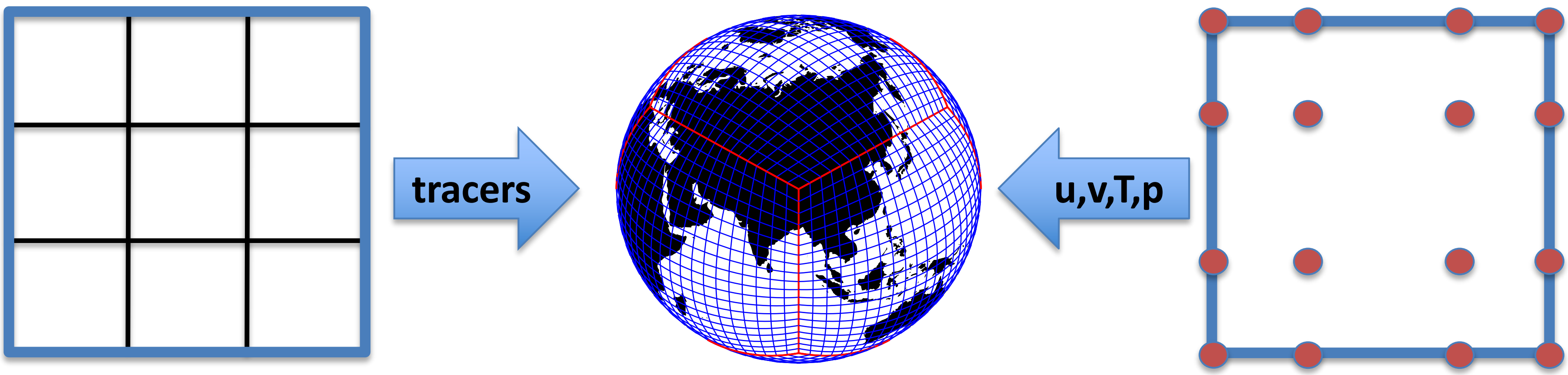
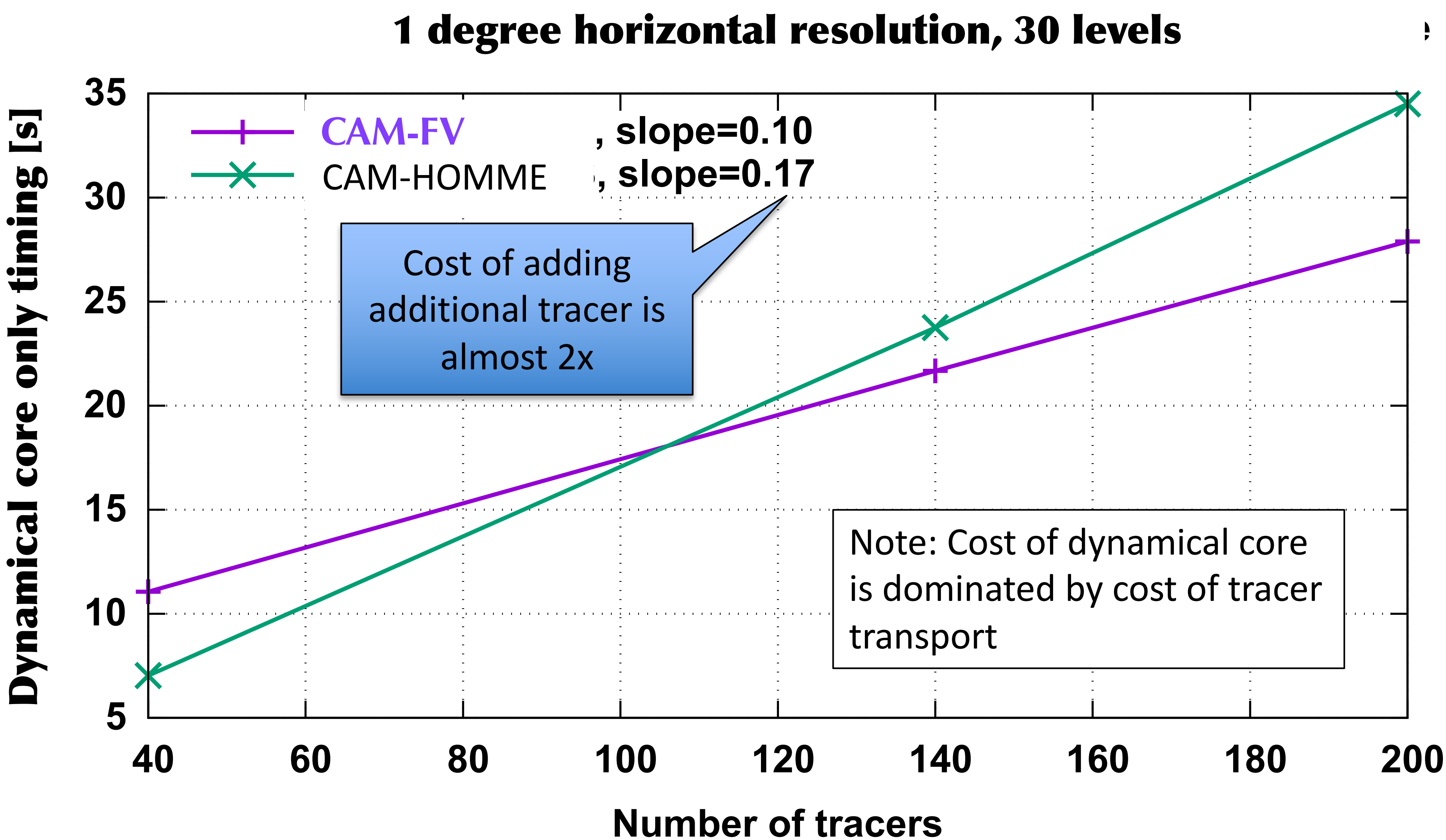
Part I: separating transport and dynamics grids/methods in CAM-SE



Why?

Cost per additional tracer (dynamical core timings using 1728 tasks)

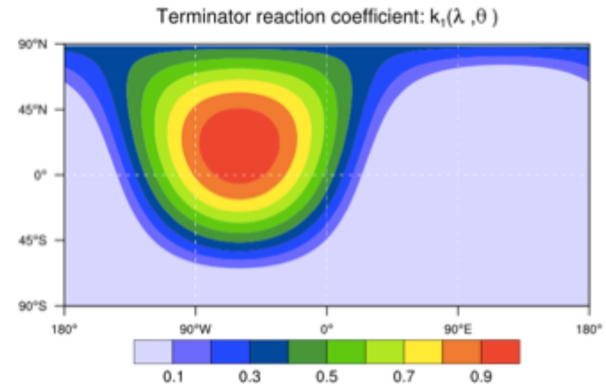


The terminator 'toy'-chemistry test: A simple tool to assess errors in transport schemes

(Lauritzen et al., 2015)

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

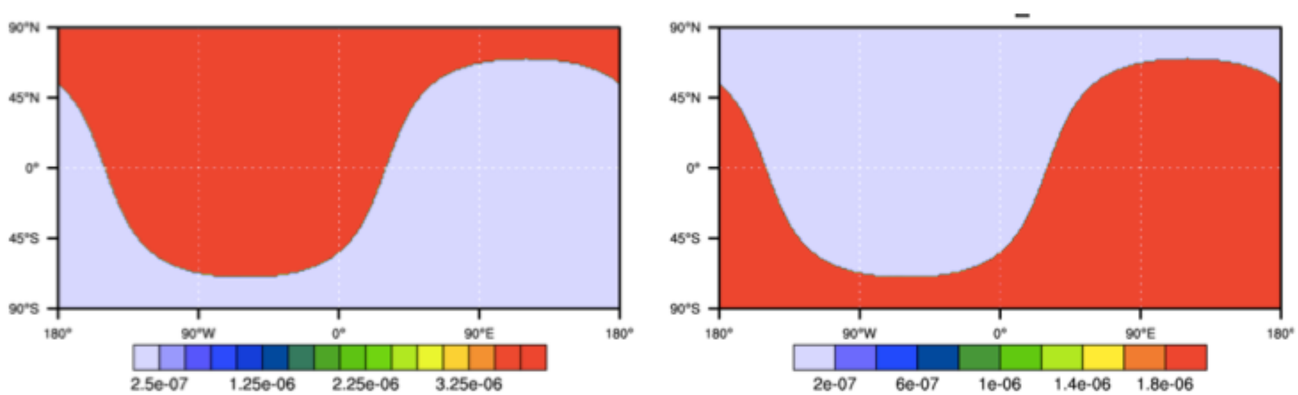
- Consider 2 reactive chemical species, Cl and Cl_2 :



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

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

- Steady-state solution (no flow):



- In any flow-field Cl_y=Cl+2*Cl_2 should be constant at all times (correlation preservation)

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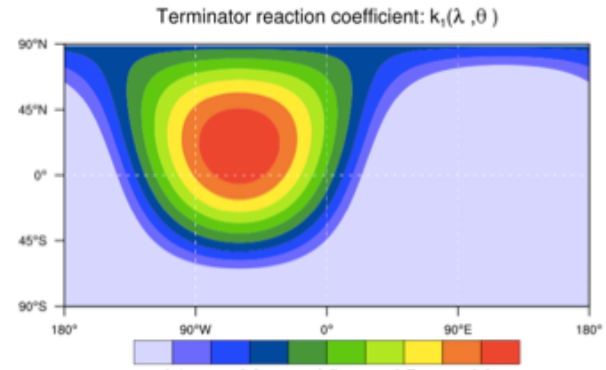

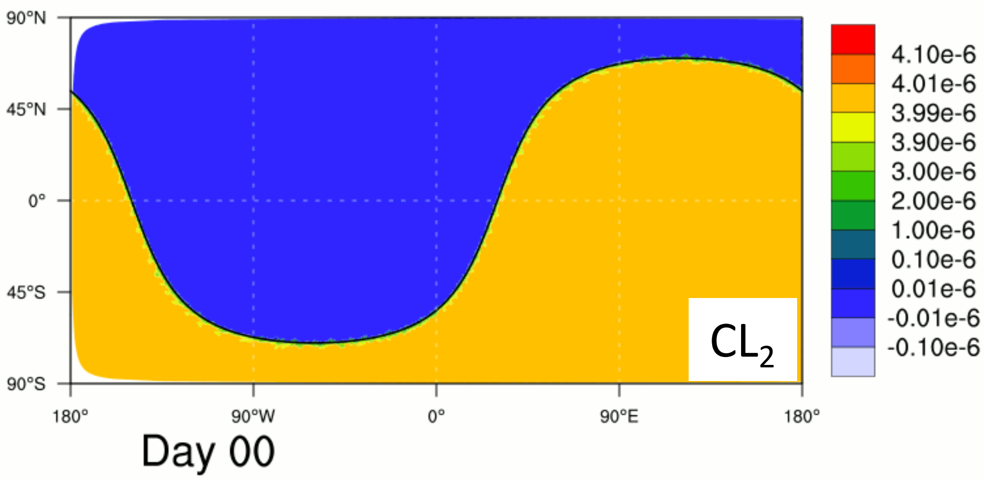

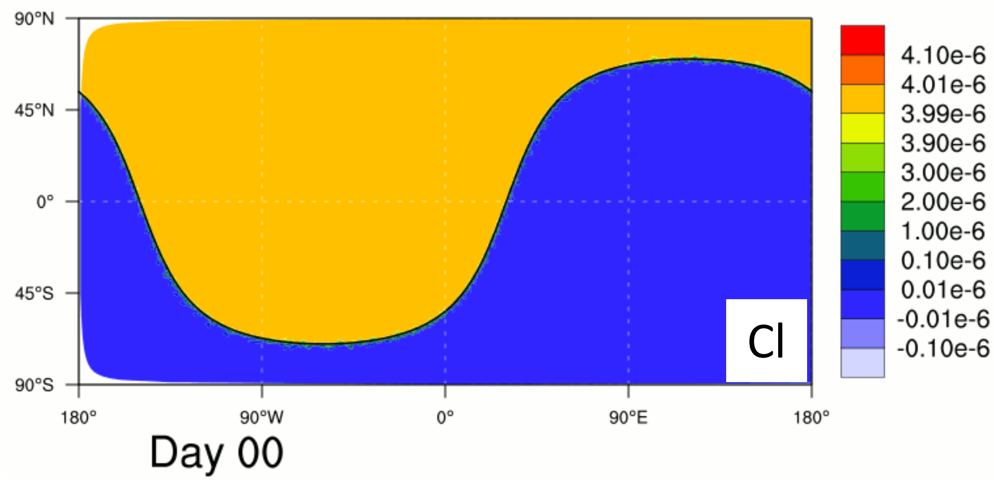

- In any flow-field Cl_y=Cl+2*Cl_2 should be constant at all times (correlation preservation).

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

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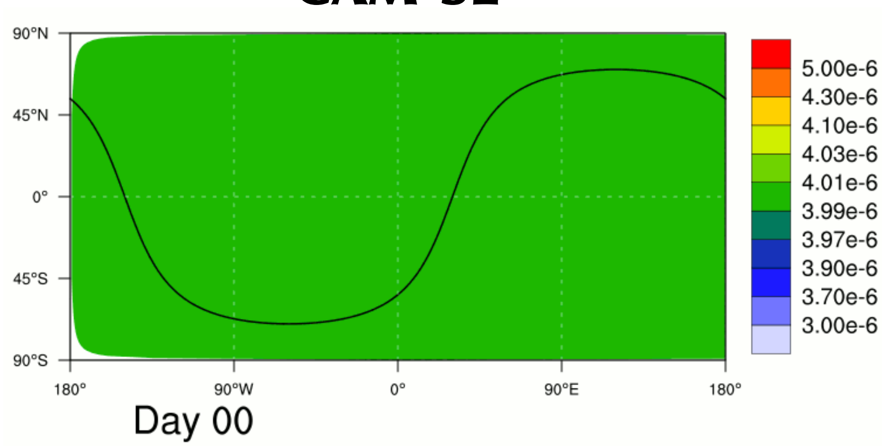
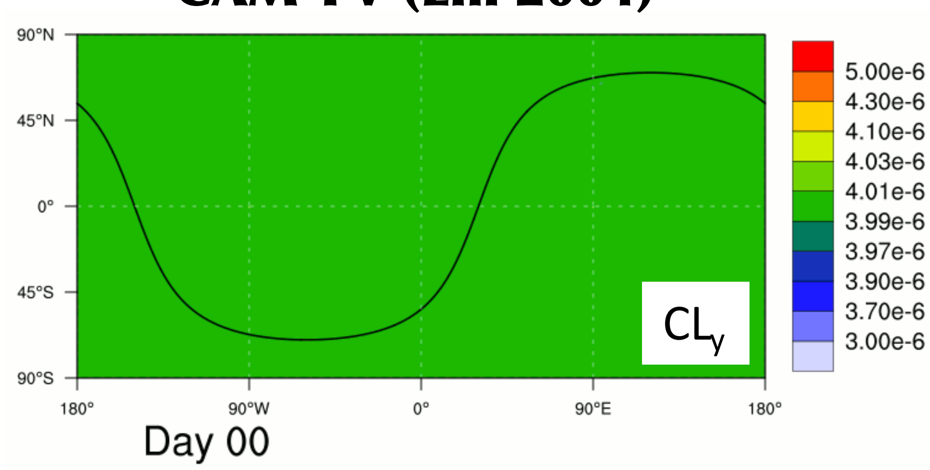
Errors are due to non-conservation of linear correlations in tracer transport scheme and/or physics-dynamics coupling

CAM-SE



CAM-FV (Lin 2004)



- **In any flow-field $Cl_y = Cl + 2*Cl_2$ should be constant at all times (correlation preservation).**

SciDAC Scientific Discovery through Advanced Computing

National Center for Atmospheric Research Atmospheric Chemistry Observations & Modeling

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Problem formulation

Improve the efficiency and accuracy of tracer transport in CAM-SE

Solution?

Note: It is easy to make an efficient model that is inaccurate or an accurate model that is inefficient (at least for smooth problems) …

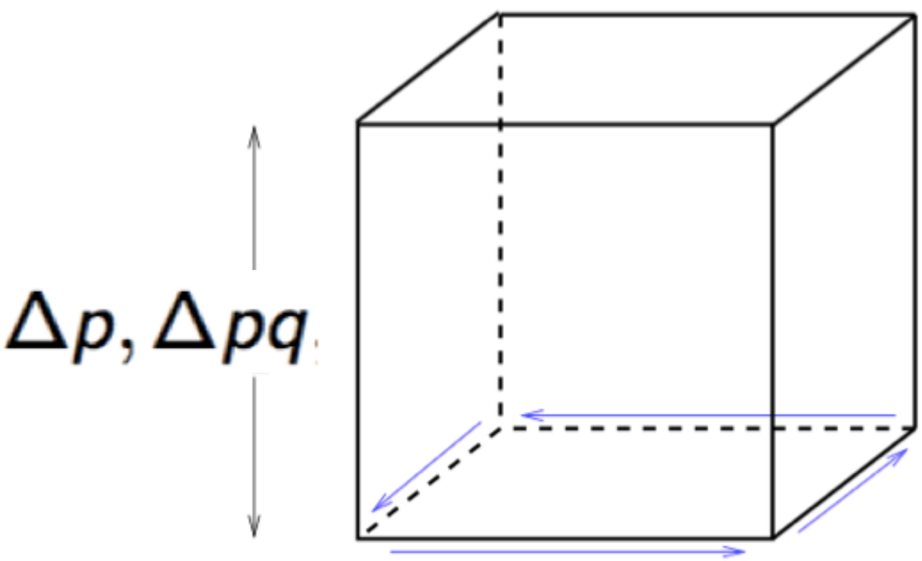
Tracer transport: Continuity equation

Consider the continuity equation of air mass (pressure level thickness Δp), and tracer mass (Δpq, where q mixing ratio)

$$\frac{\partial \psi}{\partial t} + \nabla \cdot (\psi \vec{v}) = 0, \qquad \psi = \Delta p, \Delta pq,$$

respectively, where $\vec{v}$ wind vector.

No sources/sinks



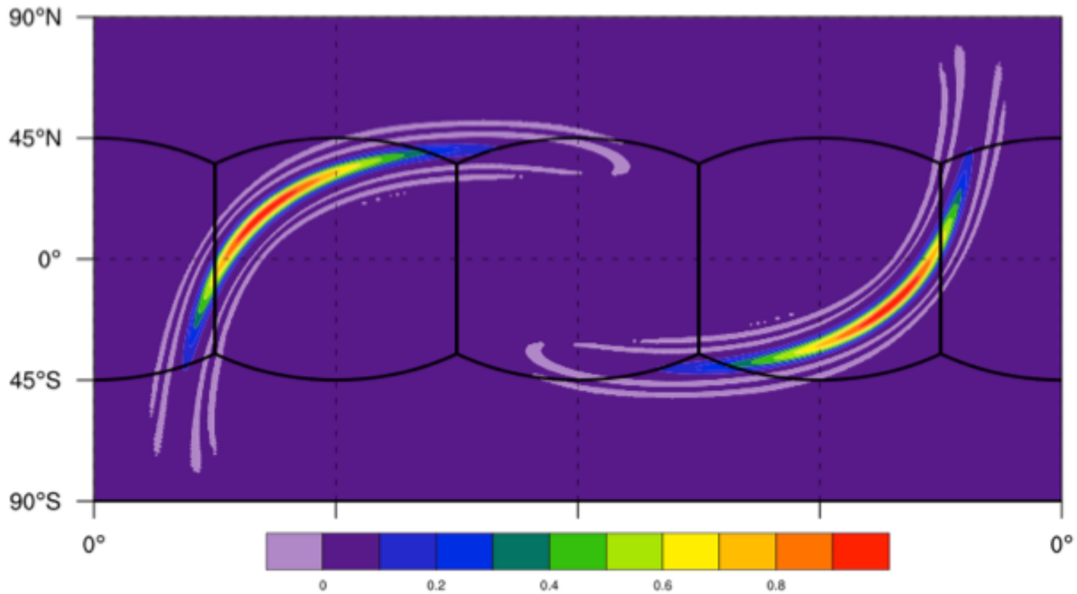
Requirements for transport schemes intended for global climate/climate-chemistry applications:

1. Global (and local) Mass-conservation

The solution to the continuity equation without sources/sinks must conserve mass. Very important!

2. Physical realizable solutions (shape-preservation)

Scheme must not produce new extrema (in particular negatives) in q

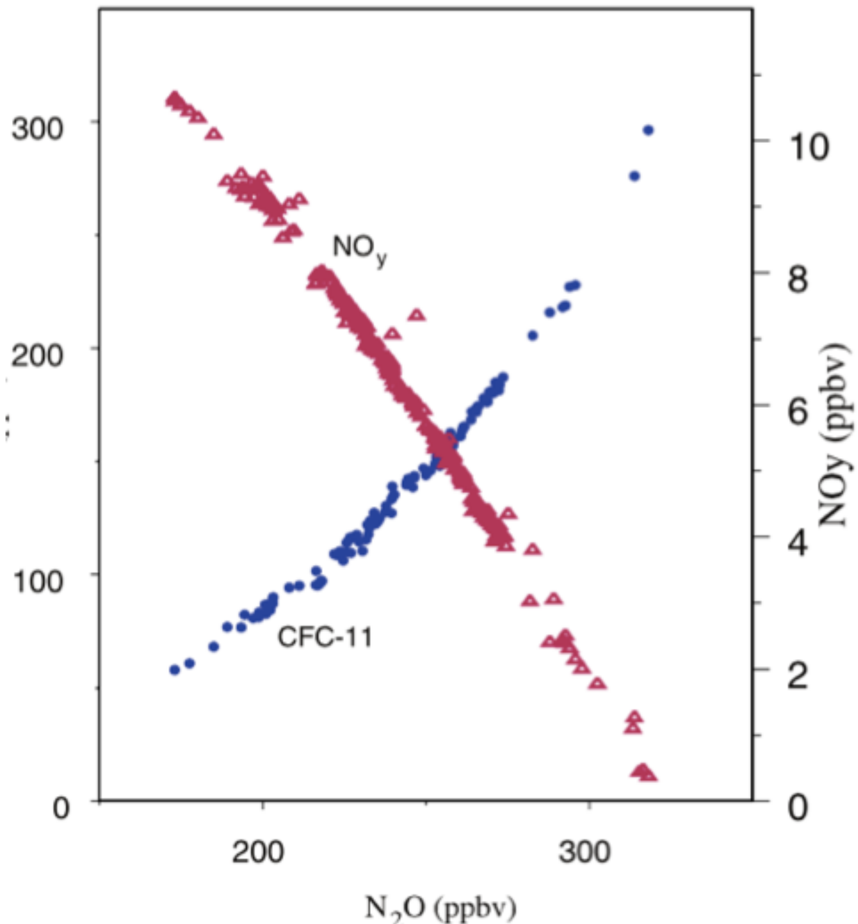


Example of unphysical solution

Requirements for transport schemes intended for global climate/climate-chemistry applications:

3. Preservation of functional relations between tracers

Transport scheme preserves $q_2 = f(q_1)$



Plumb (2007)

Figure: Aircraft observations of long-lived species in the stratosphere

Tracer transport scheme should not unphysically perturb these relations between tracers

Requirements for transport schemes intended for global climate/climate-chemistry applications:

4. Consistency (tracer and air mass are coupled!)

Continuity equations for air mass and tracer mass:

$$\frac{\partial(\Delta p)}{\partial t} + \nabla \cdot (\Delta p \vec{v}) = 0, \quad (1)$$

$$\frac{\partial(\Delta p q)}{\partial t} + \nabla \cdot (\Delta p q \vec{v}) = 0, \quad (2)$$

If $q = 1$ then the transport scheme should reduce to the continuity equation for air.

In model consistency is non-trivial if:

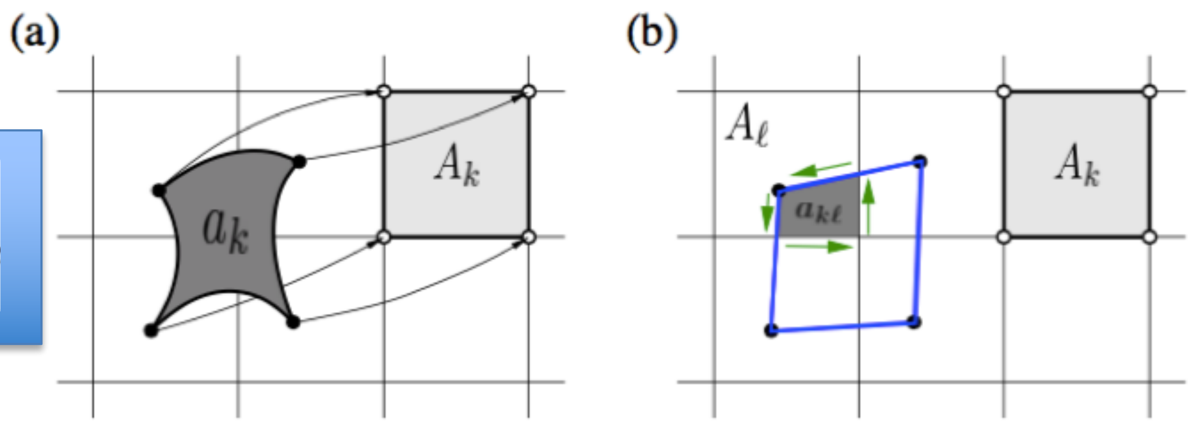
- **Using prescribed wind and mass fields from , e.g., re-analysis.**
- **(2) is solved with a different numerical method than (1)**

A way to accelerate tracer transport:

Basic formulation | Lauritzen et al. (2010)

Conservative Semi-LAgrangian Multi-tracer (CSLAM)

$$\frac{\partial \psi}{\partial t} + \nabla \cdot (\psi \vec{v}) = 0$$



Finite-volume Lagrangian form of continuity equation for air (pressure level thickness, Δp), and tracer (mixing ratio, q):

$$\int_{A_k} \psi_k^{n+1}\, dA = \int_{a_k} \psi_k^n\, dA \;=\; \sum_{\ell=1}^{L_k} \left[\int_{a_{k\ell}} \psi_{k\ell}^n(x,y)\, dA \right], \quad \psi = \Delta p,\, \Delta p\, q,$$

where n time-level, $a_{k\ell}$ overlap areas, L_k #overlap areas, and $\psi_{k\ell}^n(x,y)$ reconstruction function in cell $k\ell$.

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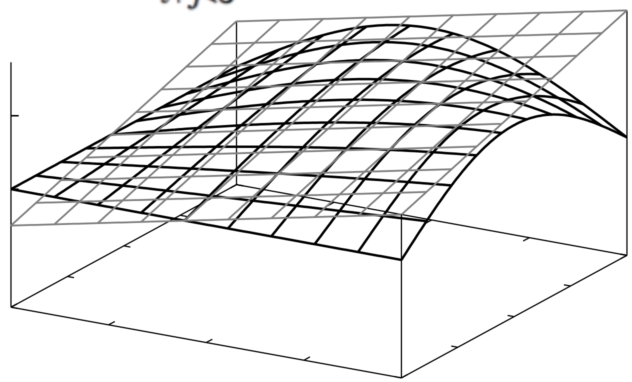
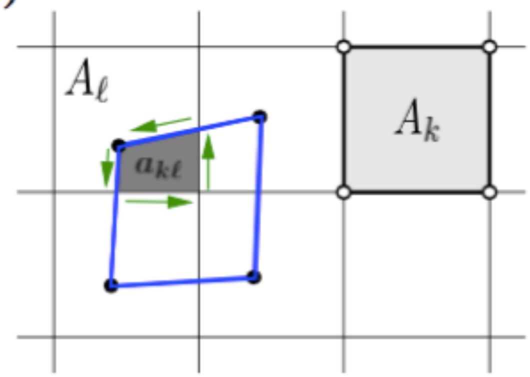
$$\psi^n_{k\ell}(x,y) = \sum_{i+j<3} c^{(i,j)} x^i y^j$$

3rd order



(b)



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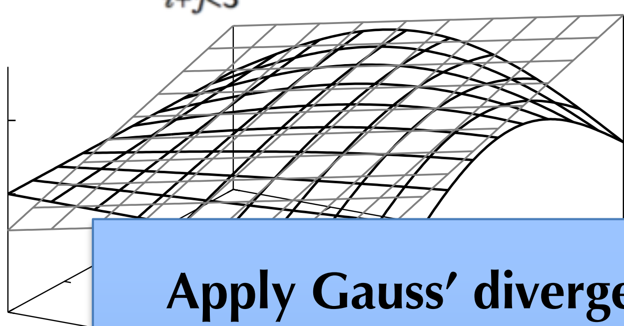

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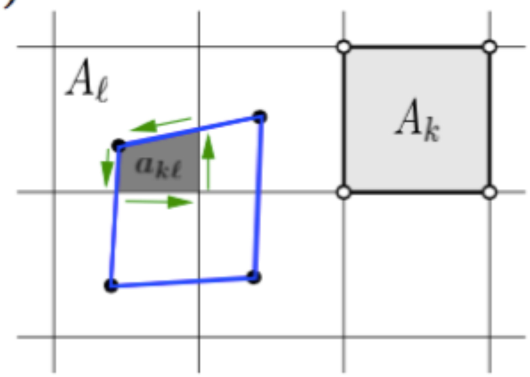

Apply Gauss′ divergence theorem to convert area integrals into line-integrals

Finite-volume Lagrangian … of continuity equation for air (pressure level thickness, Δp), and tracer (mix… ratio, q):

$$\int_{A_k} \psi_k^{n+1}\, dA = \int_{a_k} \psi_k^n\, dA \quad = \quad \sum_{\ell=1}^{L_k} \left[\int_{a_{k\ell}} \psi^n_{k\ell}(x,y)\, dA \right], \quad \psi = \Delta p,\ \Delta p\, q,$$

where n time-level, $a_{k\ell}$ overlap areas, L_k #overlap areas, and $\psi^n_{k\ell}(x,y)$ reconstruction function in cell $k\ell$.

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Basic formulation | Lauritzen et al. (2010)

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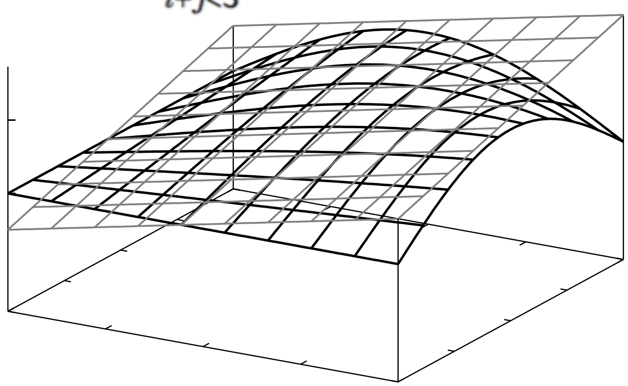
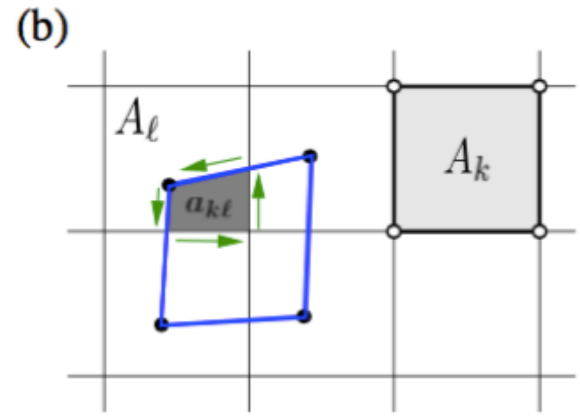
$$\psi^{n}_{k\ell}(x,y) = \sum_{i+j<3} c^{(i,j)} x^{i} y^{j};$$





$$\int_{A_k} \psi_k^{n+1}\, dA = \int_{a_k} \psi_k^{n}\, dA = \sum_{\ell=1}^{L_k} \left[\sum_{i+j\leq 2} c_\ell^{(i,j)} w_{k\ell}^{(i,j)} \right], \quad \psi = \Delta p,\ \Delta p\, q,$$

- Multi-tracer efficient: $w_{k\ell}^{(i,j)}$ re-used for each additional tracer (Dukowicz and Baumgardner, 2000).
- Scheme allows for large time-steps (flow deformation limited).
- Conserves mass, shape, linear correlations (Lauritzen et al., 2014).

A way to accelerate tracer transport:

Basic formulation | Lauritzen et al. (2010)

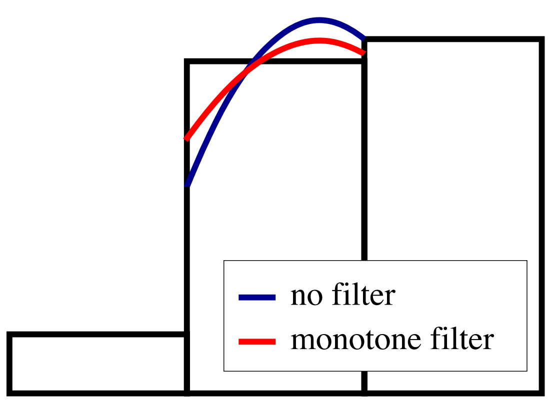
Conservative Semi-LAgrangian Multi-tracer (CSLAM)

Shape-preservation

- Apply limiter to mixing ratio sub-grid cell distribution:

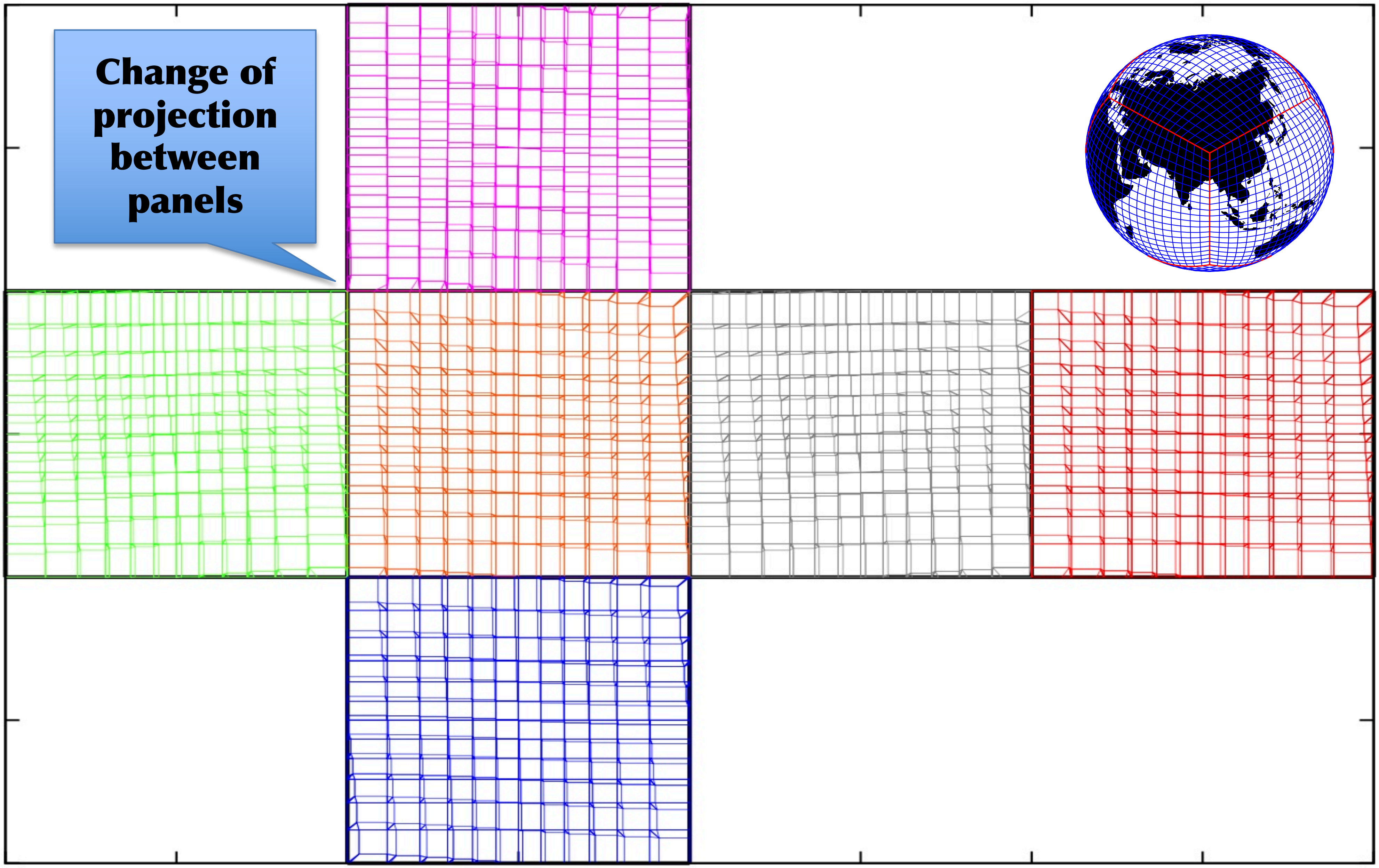
$$q(x,y) = \sum_{\imath+\jmath<3} c^{(\imath,\jmath)} x^{\imath} y^{\jmath},$$

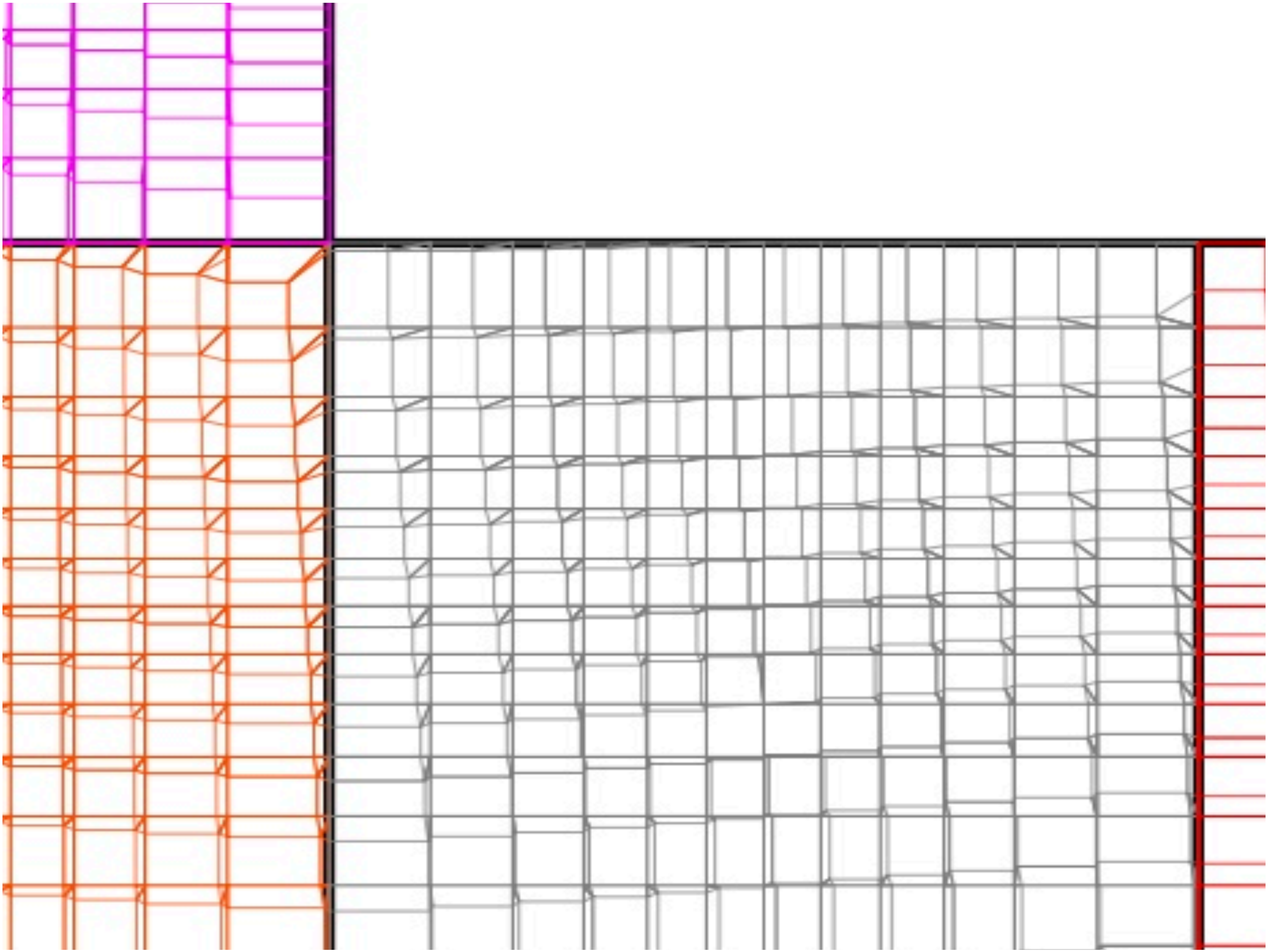
(Barth and Jespersen, 1989) so that extrema of $q(x,y)$ are within range of neighboring $\overline{q}$.



Extension to cubed-sphere:

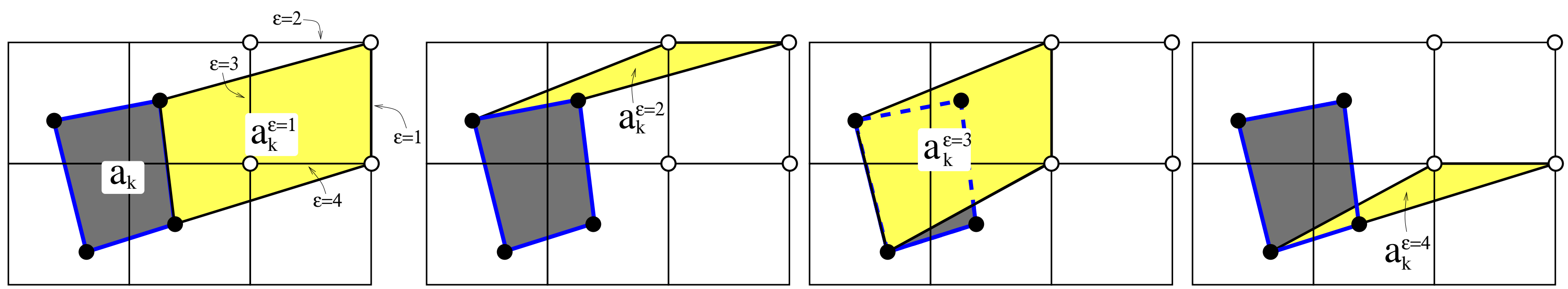
Figure shows upstream Lagrangian grid





A way to accelerate tracer transport:

Flux-form CSLAM ≡ Lagrangian CSLAM



$$\int_{A_k} \psi_k^{n+1}\, dA = \int_{A_k} \psi_k^n\, dA - \sum_{\epsilon=1}^{4} s_{k\ell}^{\epsilon} \int_{a_k^{\epsilon}} \psi\, dA, \quad \psi = \Delta p, \Delta p\, q.$$

where

- a_k^{ϵ} = 'flux-area' (yellow area) = area swept through face ϵ
- $s_{k\ell}^{\epsilon}$ = 1 for outflow and -1 for inflow.

Flux-form and Lagrangian forms of CSLAM are equivalent (Lauritzen et al., 2011).

Coupling finite-volume semi-Lagrangian transport with spectral element dynamics

4. Consistency (tracer and air mass are coupled!)

Continuity equations for air mass and tracer mass:

Spectral elements

$$\frac{\partial(\Delta p)}{\partial t} + \nabla \cdot (\Delta p \vec{v}) = 0,$$

CSLAM

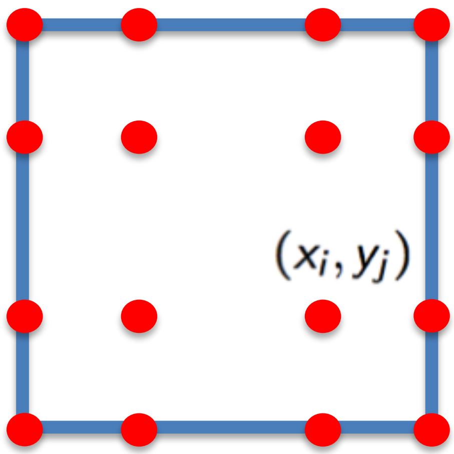
$$\int_{A_k} (\Delta p q)_k^{n+1} \, dA = \int_{a_k} (\Delta p q)^n \, dA.$$

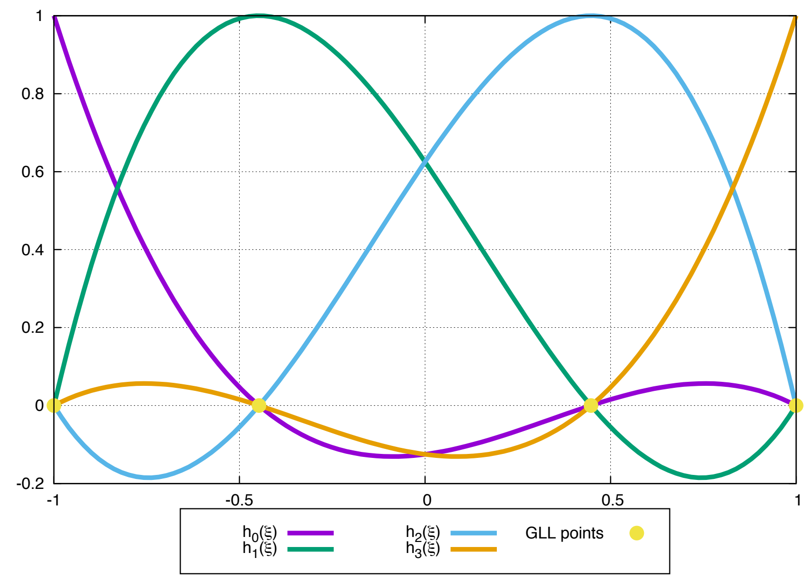
If $q = 1$ then the transport scheme should reduce to the continuity equation for air.

We need to couple without violating mass-conservation, shape-preservation, and consistency

The spectral-element method

Spectral-Element Method (SEM)



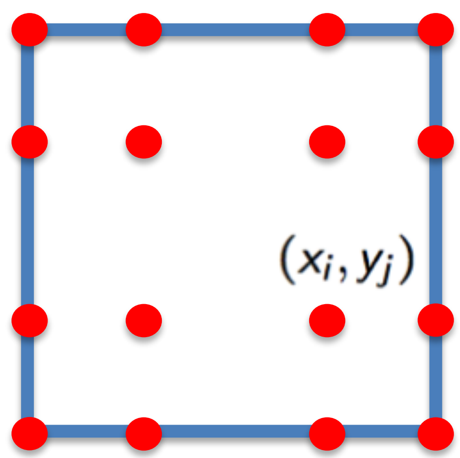


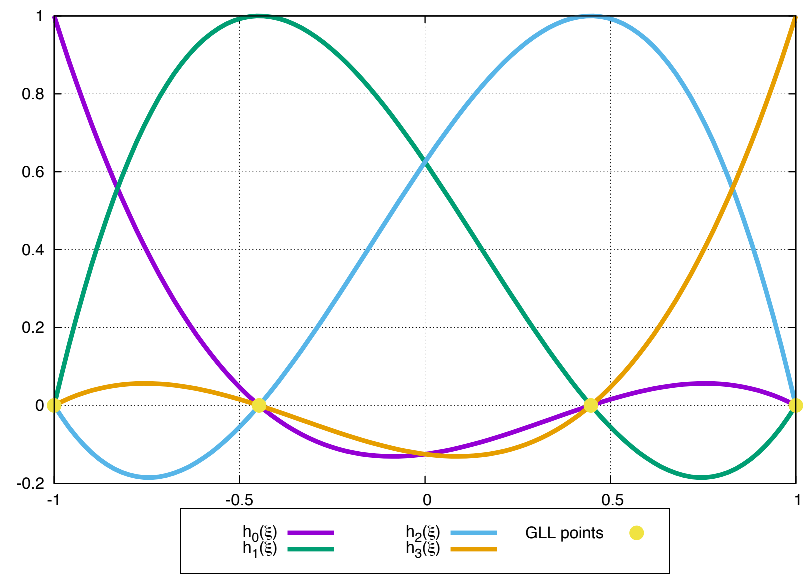
Continuity equation for Δp:

$$\frac{\partial \Delta p}{\partial t} = -\nabla \cdot \Delta p \vec{v} + \tau \nabla^4 \Delta p.$$

The spectral-element method

Spectral-Element Method (SEM)





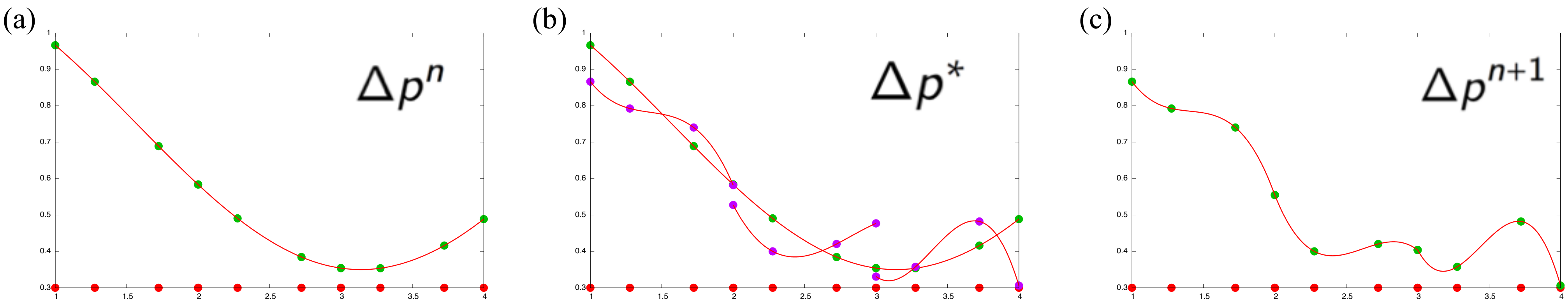
Continuity equation for Δp:

$$\left\langle h_k, \frac{\partial \Delta p}{\partial t} \right\rangle = \langle h_k, -\nabla \cdot \Delta p \vec{v} \rangle + \langle h_k, \tau \nabla^4 \Delta p \rangle ,$$

where $\langle h_k, \cdot \rangle$ is inner product

$$\langle h_k, f \rangle = \sum_{i,j} w_{i,j} h_k(x_i, y_j) f(x_i, y_j) \sim \iint h_k f \, dA.$$

The spectral-element method

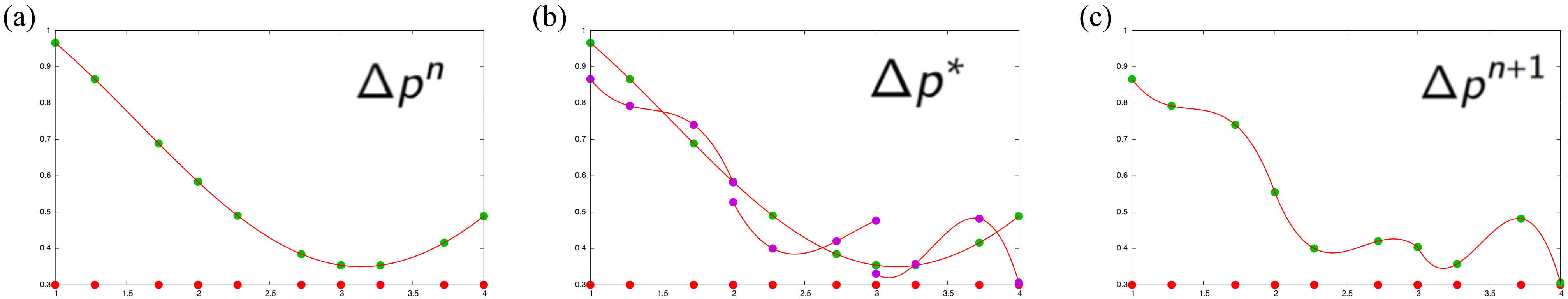


Continuity equation for Δp:

$$\left\langle h_k, \frac{\Delta p^* - \Delta p^n}{\Delta t} \right\rangle = \langle h_k, -\nabla \cdot \Delta p \vec{v} \rangle + \langle h_k, \tau \nabla^4 \Delta p \rangle .$$

Temporal discretization: multi-stage Runge-Kutta time-stepping

The spectral-element method



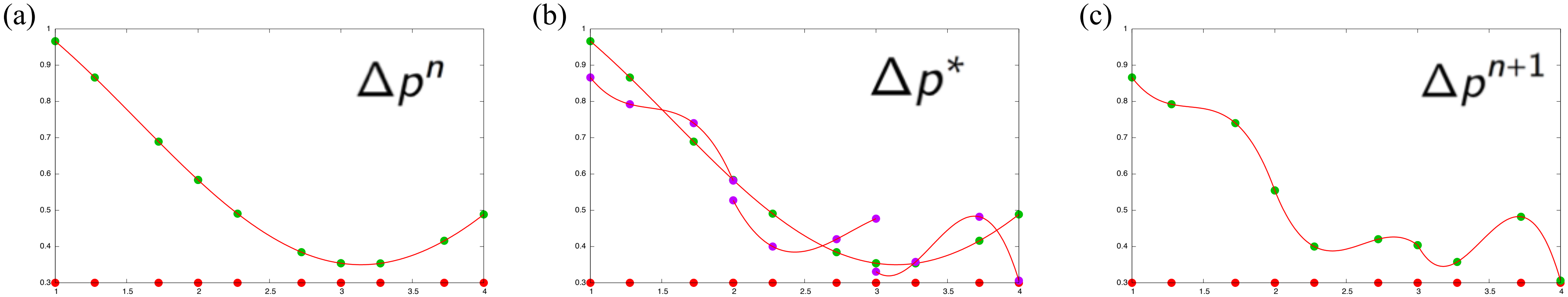
- Projection step

$$\Delta p^{n+1} = DSS\left(\Delta p^*\right)$$

where *DSS* refers to *Direct Stiffness Summation* (also referred to as assembly or inverse mass matrix step).

- Choice of GLL quadrature based inner product and nodal basis functions gives a diagonal mass matrix (Maday and Patera, 1987).

The spectral-element method

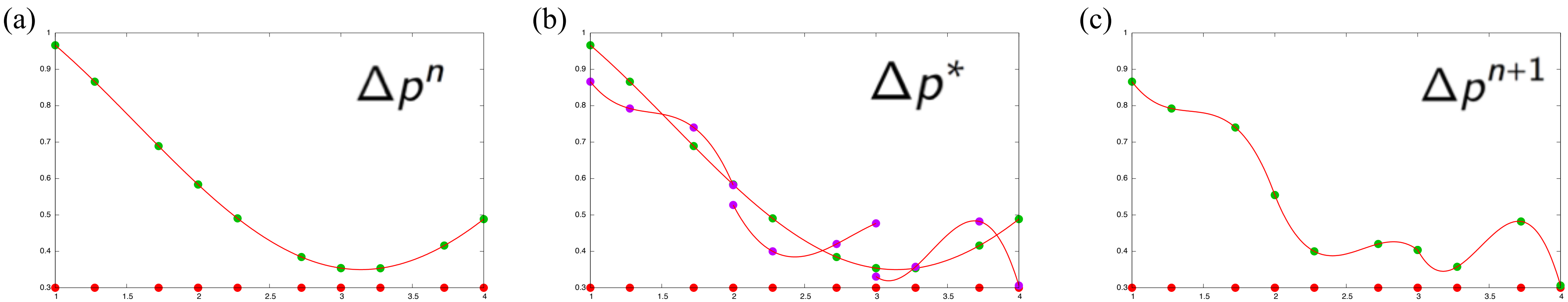


Continuity equation for Δp:

$$\left\langle h_k, \frac{\Delta p^{n+1} - \Delta p^n}{\Delta t} \right\rangle = \langle h_k, -\nabla \cdot \Delta p \vec{v} \rangle + \langle h_k, \tau \nabla^4 \Delta p \rangle + \langle h_k, D \rangle \,.$$

Temporal discretization: multi-stage Runge-Kutta time-stepping

The spectral-element method

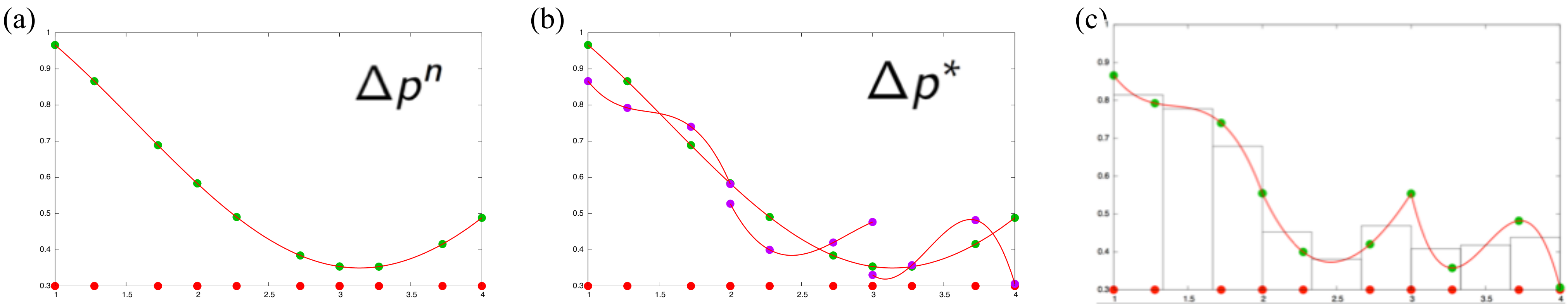


Continuity equation for Δp:

$$\left\langle h_k, \frac{\Delta p^{n+1} - \Delta p^{n}}{\Delta t} \right\rangle = \langle h_k, F \rangle + \langle h_k, G \rangle + \langle h_k, D \rangle \, .$$

Temporal discretization: multi-stage Runge-Kutta time-stepping

The spectral-element method



Setting basis function to 1 yields the mass change in each element

Continuity equation for Δp:

$$\left\langle h_k, \frac{\Delta p^{n+1} - \Delta p^n}{\Delta t} \right\rangle = \langle h_k, F \rangle + \langle h_k, G \rangle + \langle h_k, D \rangle .$$

Temporal discretization: multi-stage Runge-Kutta time-stepping

Diagnosing fluxes from spectral-element method

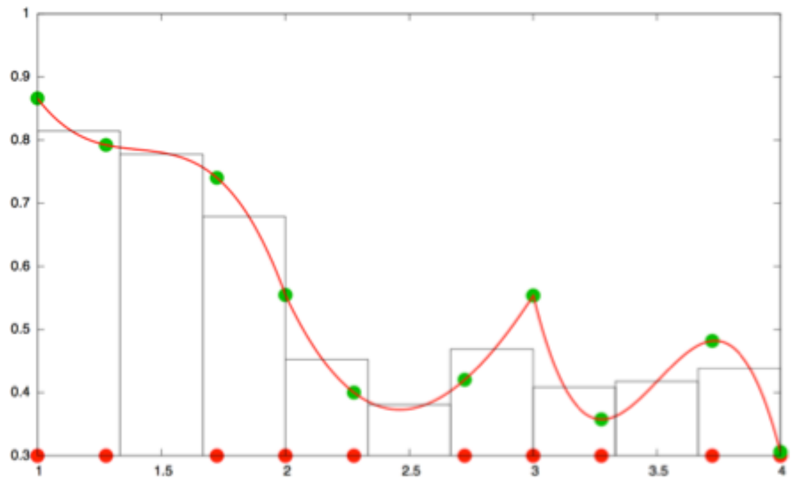
- There exist a basis ϕ_k so that

$$\left\langle \phi_k, \frac{\Delta p^{n+1} - \Delta p^n}{\Delta t} \right\rangle = \langle \phi_k, F \rangle + \langle \phi_k, G \rangle + \langle \phi_k, D \rangle ,$$

gives the change of mass in each CSLAM control volume.

- Moreover, each term on right-hand side can be expressed in terms of edge fluxes:

$$\left(\Delta p^{n+1} - \Delta p^n\right) \Delta A_k = \sum_{\epsilon=1}^{4} \left[\mathcal{F}_F^{(\epsilon)} + \mathcal{F}_G^{(\epsilon)} + \mathcal{F}_D^{(\epsilon)} \right].$$



The story so far

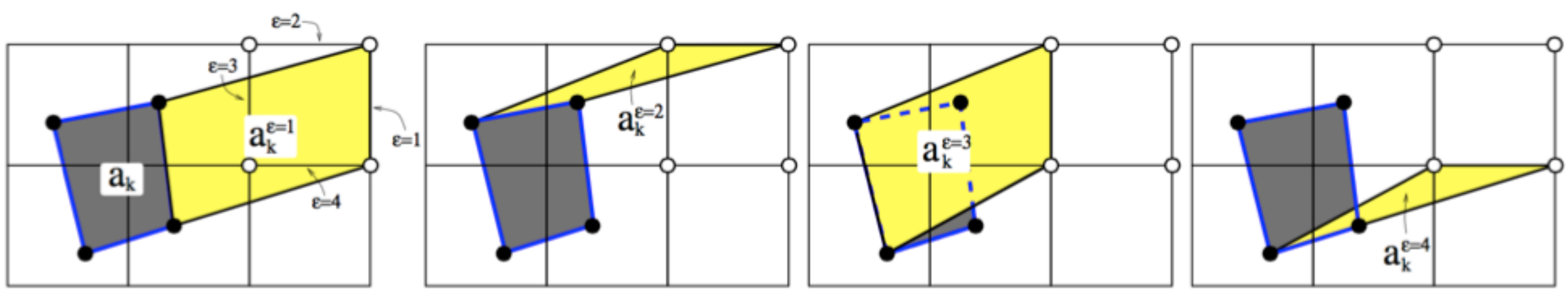
Spectral-Element Method: CAM-SE

Mass change over CSLAM control volume A_k implied by SE

$$\left(\Delta p^{n+1} - \Delta p^{n}\right) \Delta A_k = \sum_{\epsilon=1}^{4} \left[\mathcal{F}_F^{(\epsilon)} + \mathcal{F}_G^{(\epsilon)} + \mathcal{F}_D^{(\epsilon)} \right],$$

(Lauritzen et al., 2016; in prep).

Finite-Volume Method: CSLAM



CSLAM discretization is given by

$$\left(\widetilde{\Delta p}^{n+1} - \widetilde{\Delta p}^{n}\right) \Delta A_k = \sum_{\epsilon=1}^{4} \left[\mathcal{F}_{CSLAM}^{(\epsilon)} \right] = - \sum_{\epsilon=1}^{4} s_{k\ell}^{\epsilon} \int_{a_k^{\epsilon}} \Delta p^{n} \, dA.$$

Lauritzen et al., (2011)

The story so far

Spectral-Element Method: CAM-SE

Mass change over CSLAM control volume A_k implied by SE

$$\left(\Delta p^{n+1} - \Delta p^{n}\right)\Delta A_k = \sum_{\epsilon=1}^{4}\left[\mathcal{F}_F^{(\epsilon)} + \mathcal{F}_G^{(\epsilon)} + \mathcal{F}_D^{(\epsilon)}\right],$$

(Lauritzen et al., 2016; in prep).

Fi

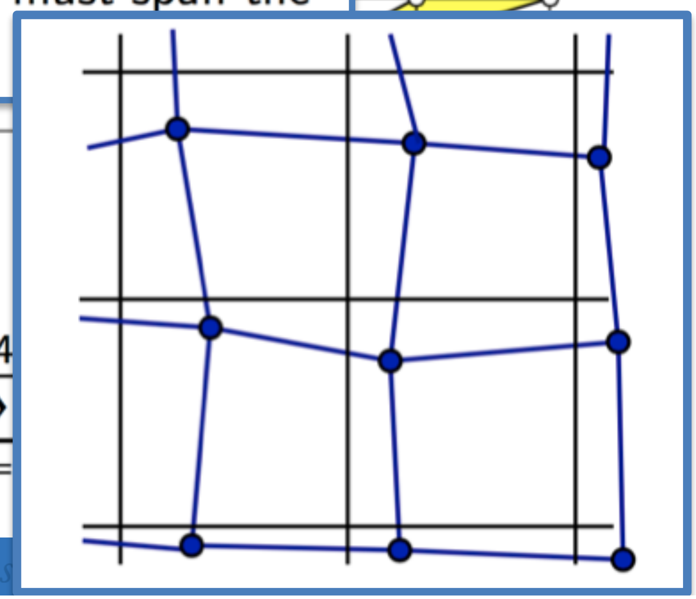
For each face ϵ in cell a_k, find a swept area $a_k^{(\epsilon)}$ so that

$$\mathcal{F}_{CSLAM}^{(\epsilon)} = \mathcal{F}_F^{(\epsilon)} + \mathcal{F}_G^{(\epsilon)} + \mathcal{F}_D^{(\epsilon)}.$$

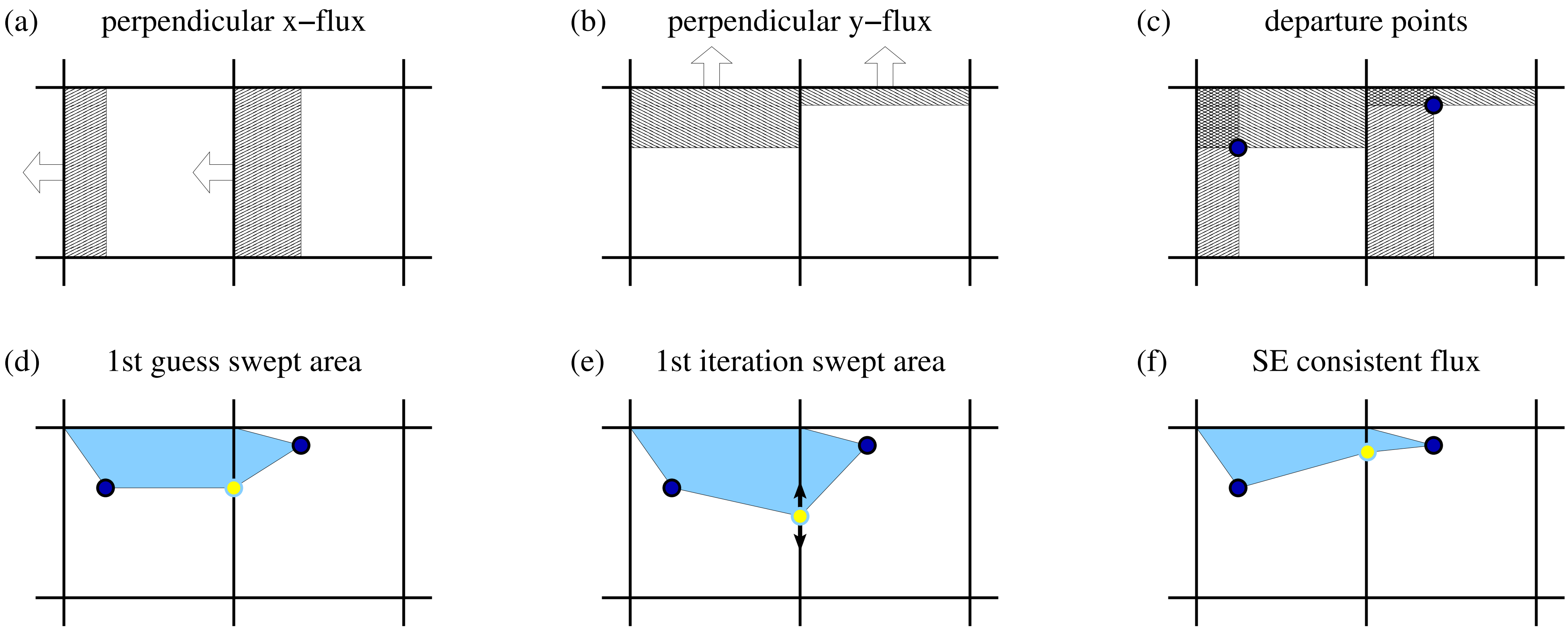
Lagrangian consistency constraint: The upstream areas must span the sphere without cracks or overlaps

CSLAM discretization is given by

$$\left(\widetilde{\Delta p}^{n+1} - \widetilde{\Delta p}^{n}\right)\Delta A_k = \sum_{\epsilon=1}^{4}\left[\mathcal{F}_{CSLAM}^{(\epsilon)}\right] = -\sum_{\epsilon=}^{4}$$



Consistent SE-CSLAM algorithm: step-by-step example



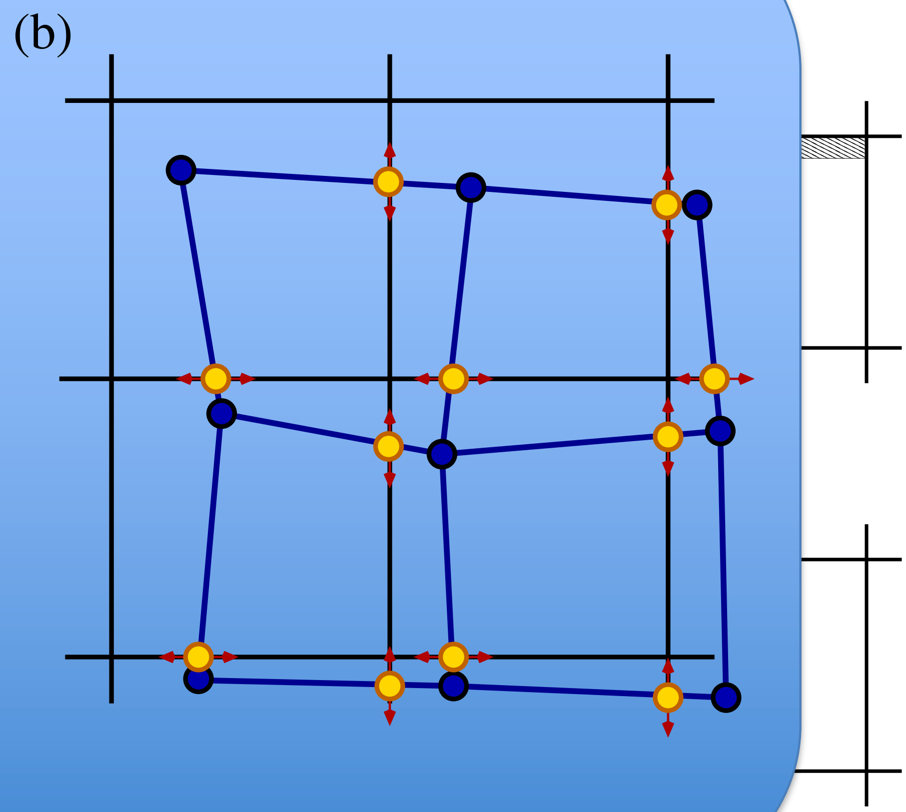
Well-posed? As long as flow deformation $\left|\frac{\partial u}{\partial x}\right| \Delta t \lesssim 1$ (Lipschitz criterion)

Lauritzen et al., 2016

Consistent SE-CSLAM algorithm: step-by-step example

Local iteration problem generating an upstream grid that spans the sphere without cracks and overlaps

=> all CSLAM technology from Lauritzen et al. (2010) can be used



Well-posed? As long as flow deformation $\left|\frac{\partial u}{\partial x}\right| \Delta t \lesssim 1$ (Lipschitz criterion)

Consistent CSLAM algorithm is general

In principle, the consistent CSLAM algorithm can be made consistent with any fluxes that obey the Lipschitz criterion …

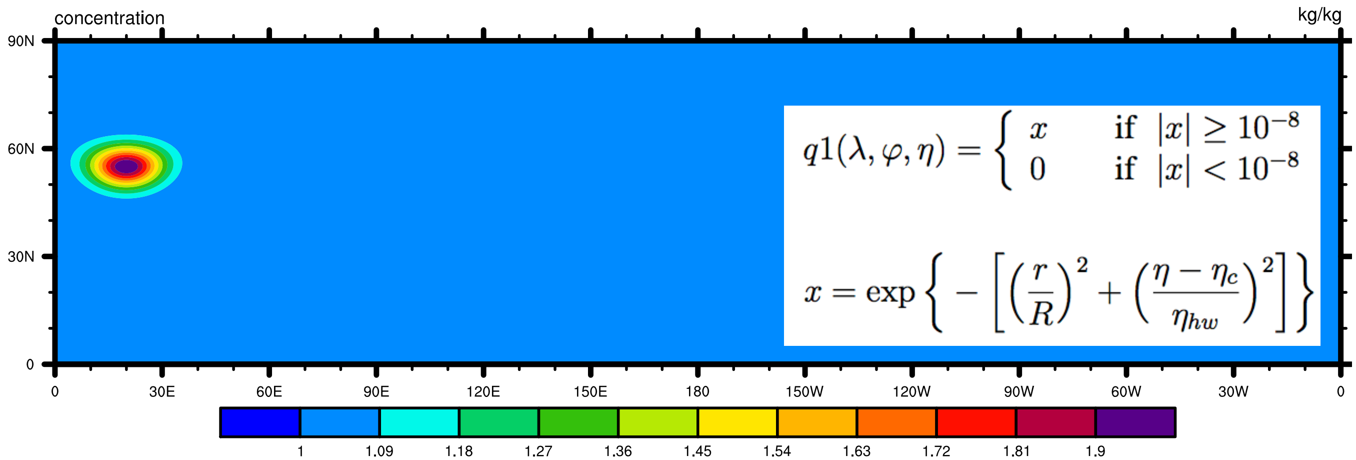
NCAR

Idealized baroclinic wave test

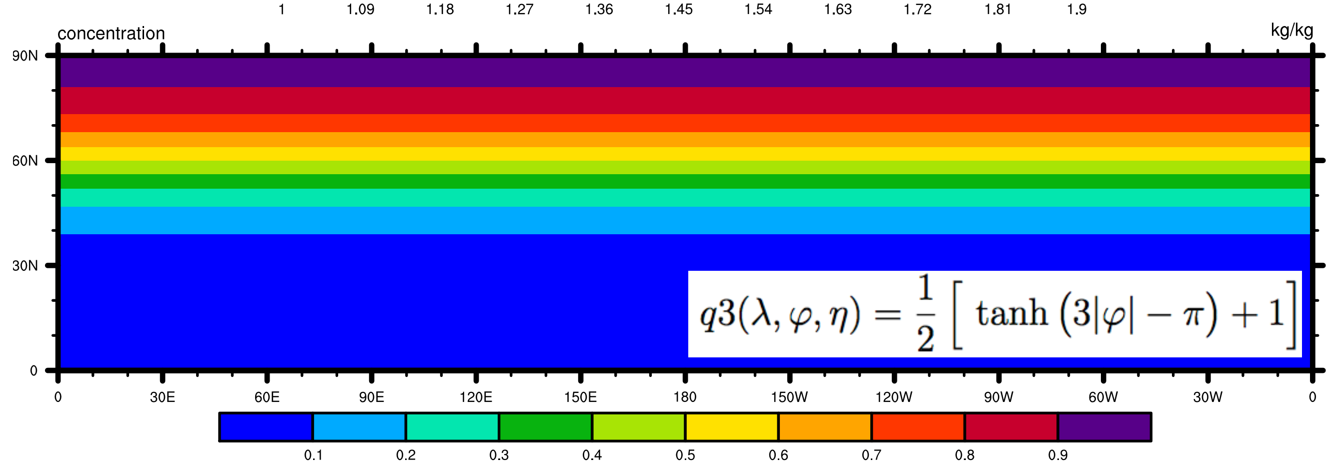
No sub-grid-scale forcing, dry, balanced initial condition with perturbation
Jablonowski and Williamson (2006)

Surface pressure computed with CSLAM is identical to SE (to round-off)

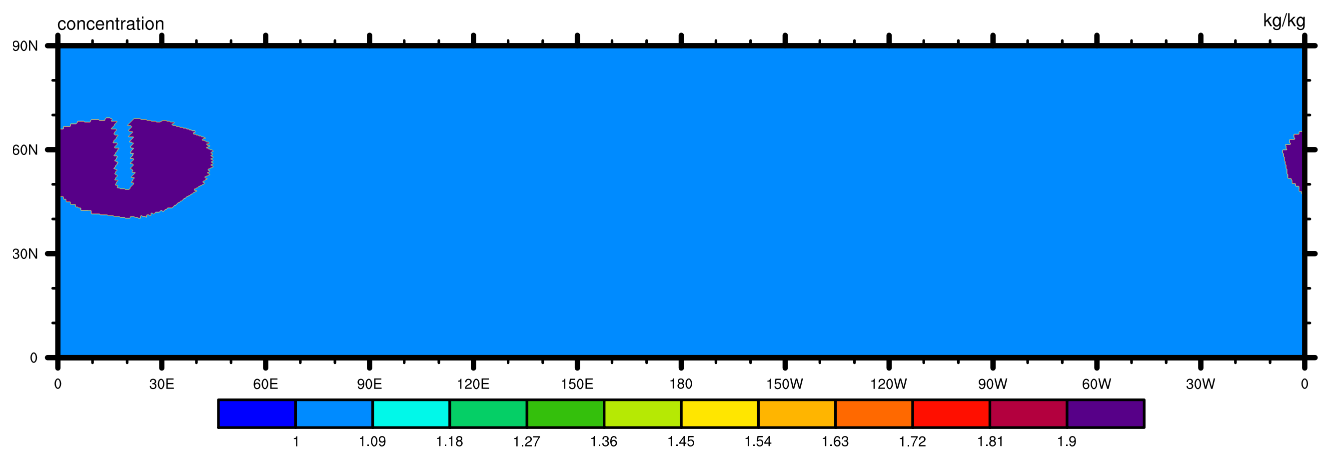
3 tracers: initial conditions



Gaussian "ball"

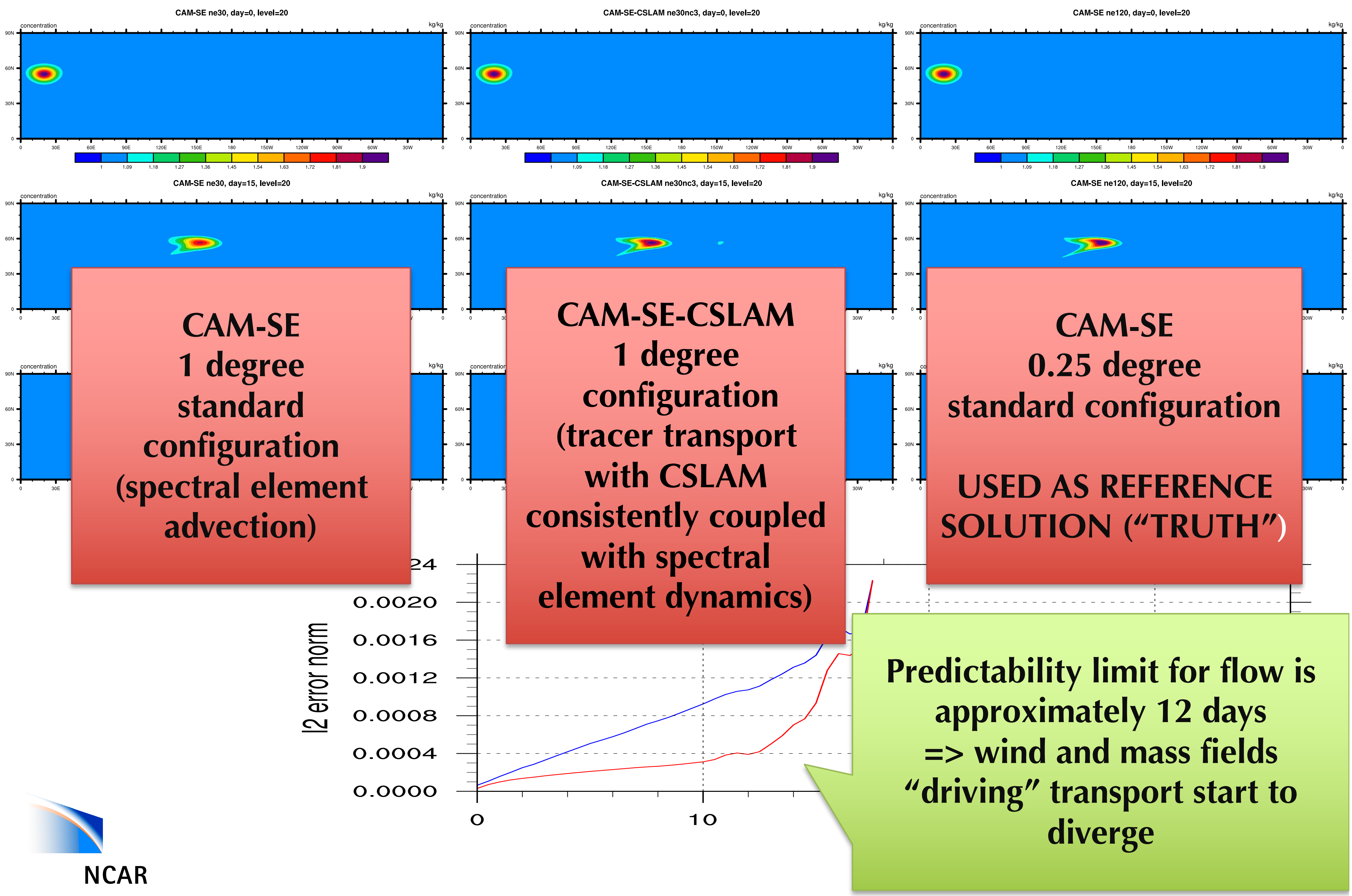


Zonally symmetric (smooth)



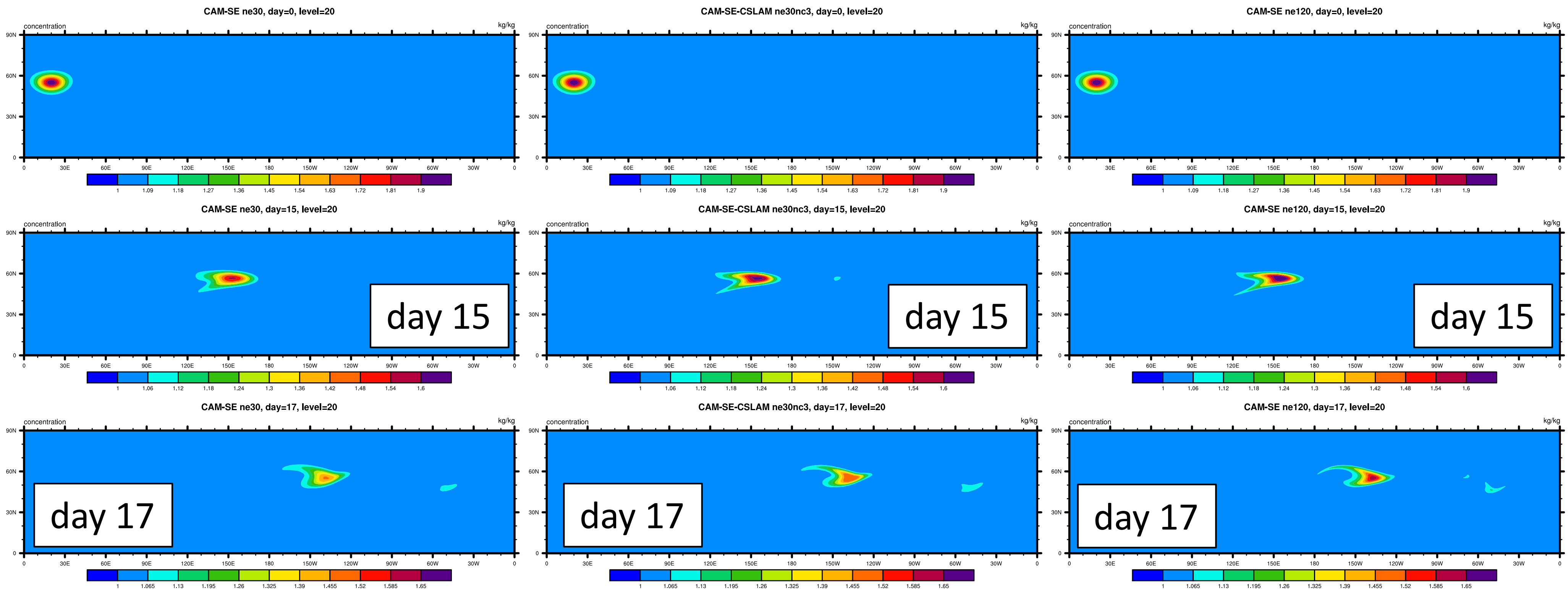
Slotted cylinder (non-smooth)

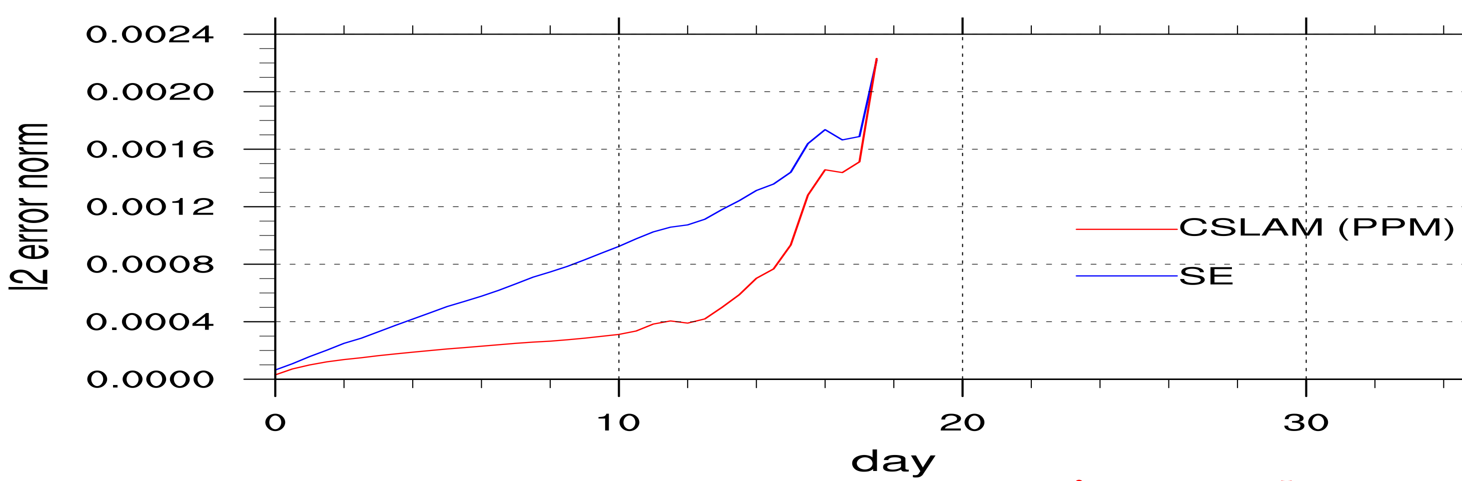
NCAR


CAM-SE ne30, day=0, level=20
CAM-SE-CSLAM ne30nc3, day=0, level=20
CAM-SE ne120, day=0, level=20
CAM-SE ne30, day=15, level=20
CAM-SE-CSLAM ne30nc3, day=15, level=20
CAM-SE ne120, day=15, level=20
concentration
kg/kg
CAM-SE
1 degree
standard
configuration
(spectral element
advection)
CAM-SE-CSLAM
1 degree
configuration
(tracer transport
with CSLAM
consistently coupled
with spectral
element dynamics)
CAM-SE
0.25 degree
standard configuration
USED AS REFERENCE
SOLUTION ("TRUTH")
l2 error norm
0.0020
0.0016
0.0012
0.0008
0.0004
0.0000
0
10
Predictability limit for flow is
approximately 12 days
=> wind and mass fields
"driving" transport start to
diverge

NCAR

CAM-SE CAM-SE-CSLAM CAM-SE reference

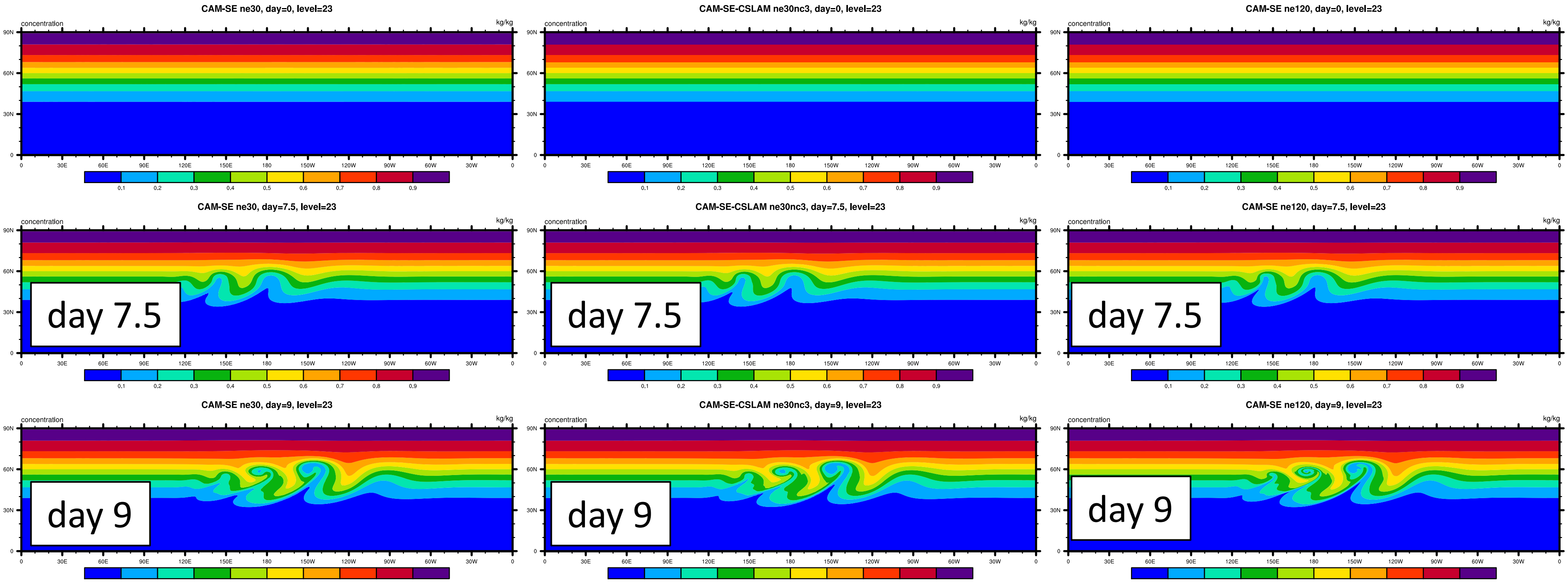


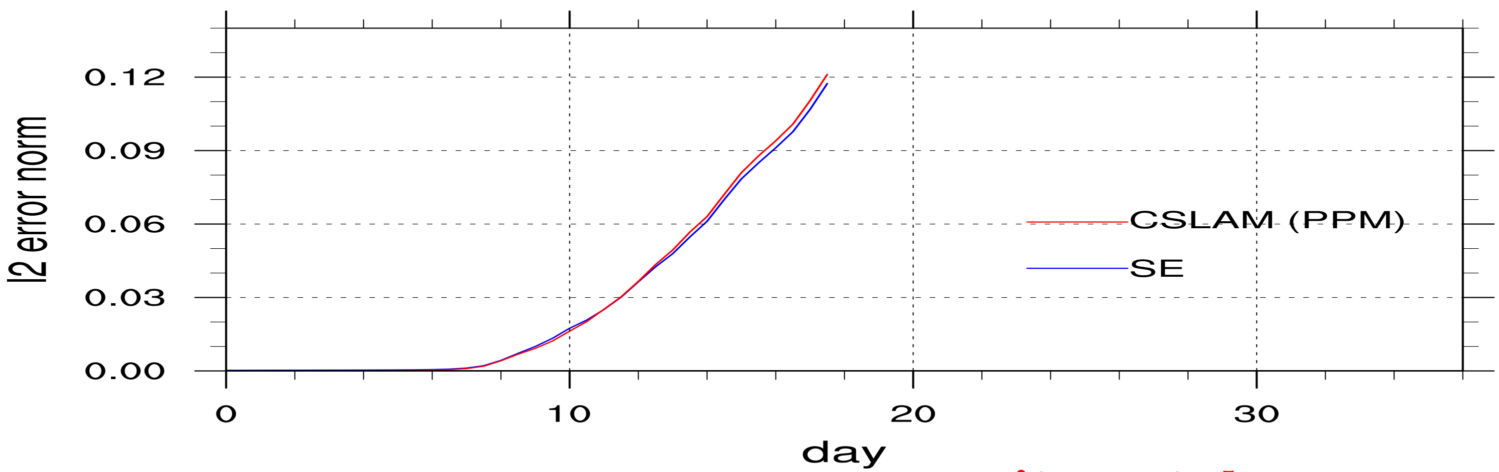


NCAR

Lauritzen et al., 2016

CAM-SE | CAM-SE-CSLAM | CAM-SE reference

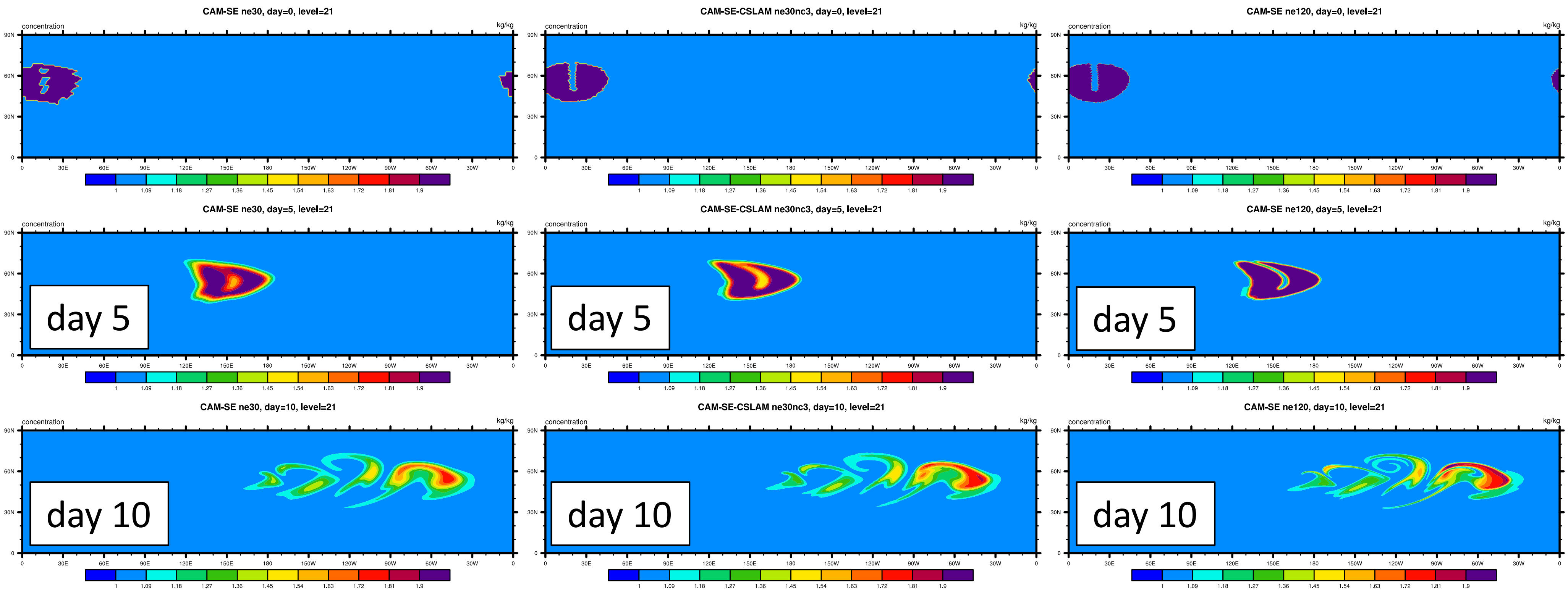


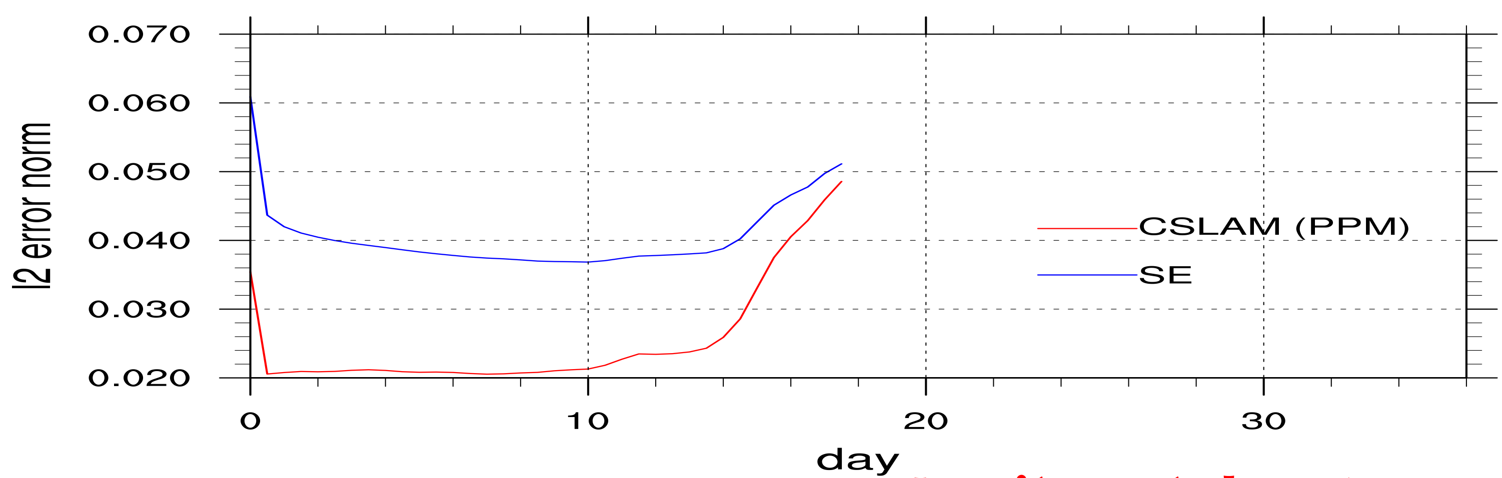


NCAR

Lauritzen et al., 2016

CAM-SE | CAM-SE-CSLAM | CAM-SE reference





NCAR

Lauritzen et al., 2016

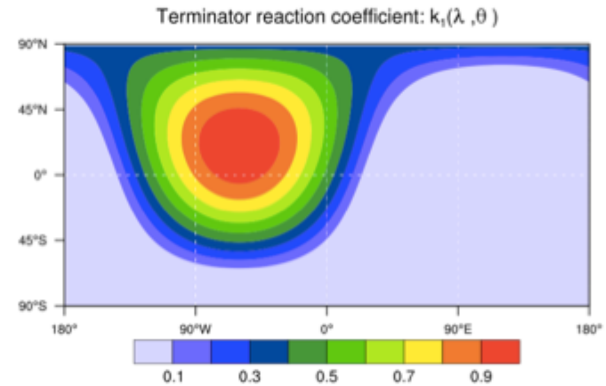
The terminator 'toy'-chemistry test: A simple tool to assess errors in transport schemes

(Lauritzen et al., 2015)

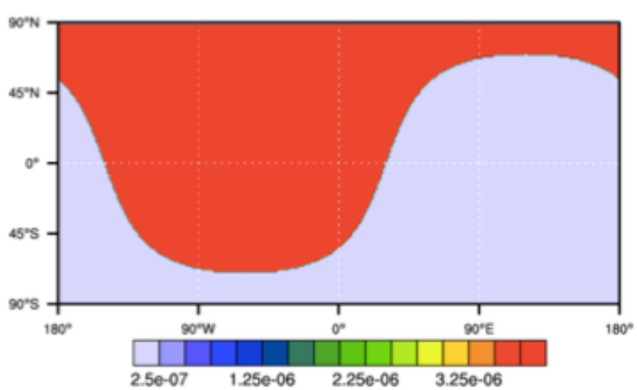
See: http://www.cgd.ucar.edu/cms/pel/terminator.html

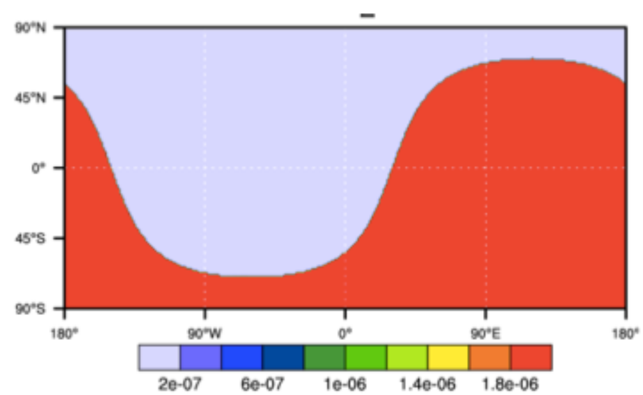
- Consider 2 reactive chemical species, Cl and Cl_2 :

$$Cl_2 \rightarrow Cl + Cl : k_1$$
$$Cl + Cl \rightarrow Cl_2 : k_2$$



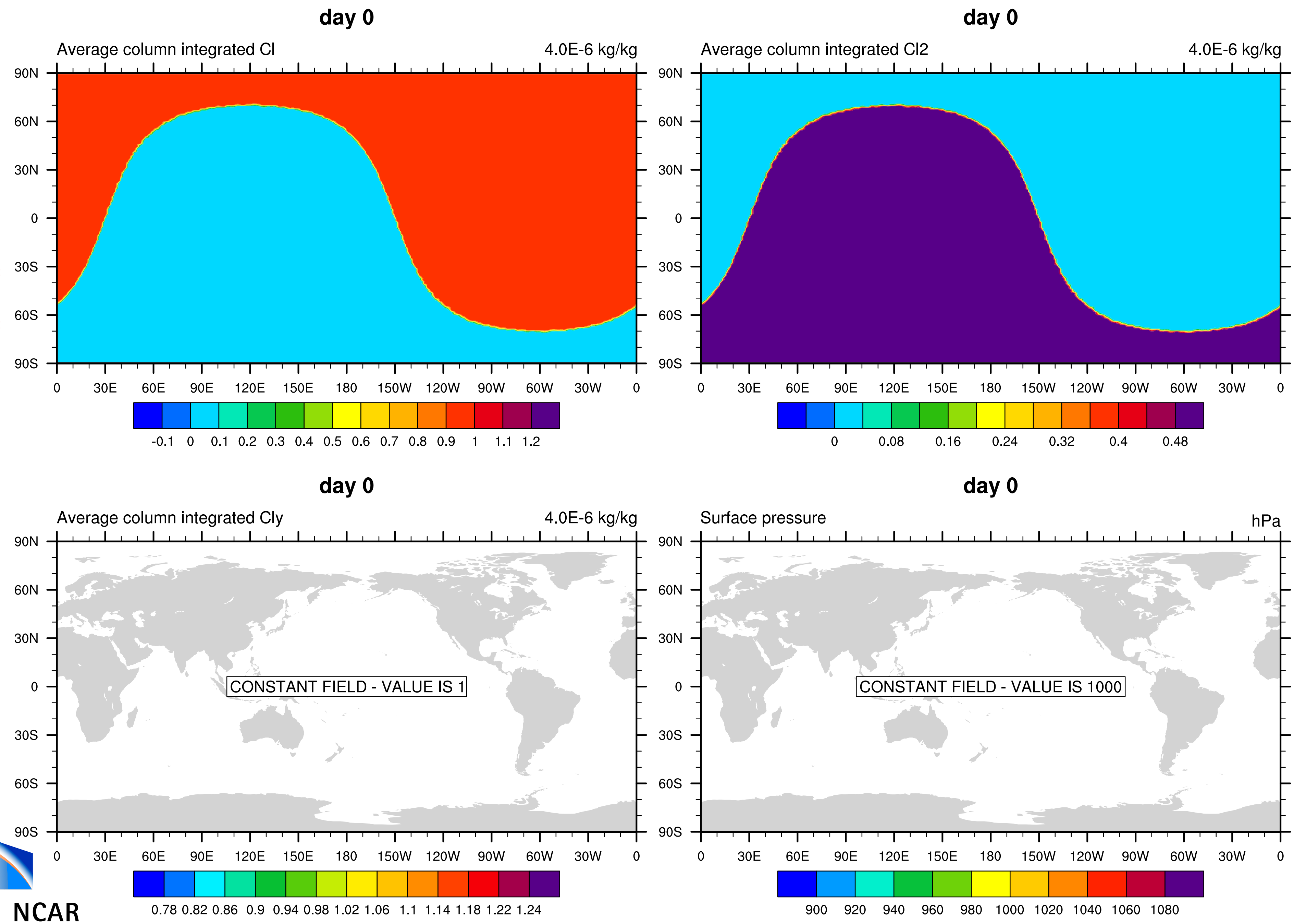
- Steady-state solution (no flow):





- In any flow-field $Cl_y=Cl+2*Cl_2$ should be constant at all times (correlation preservation)

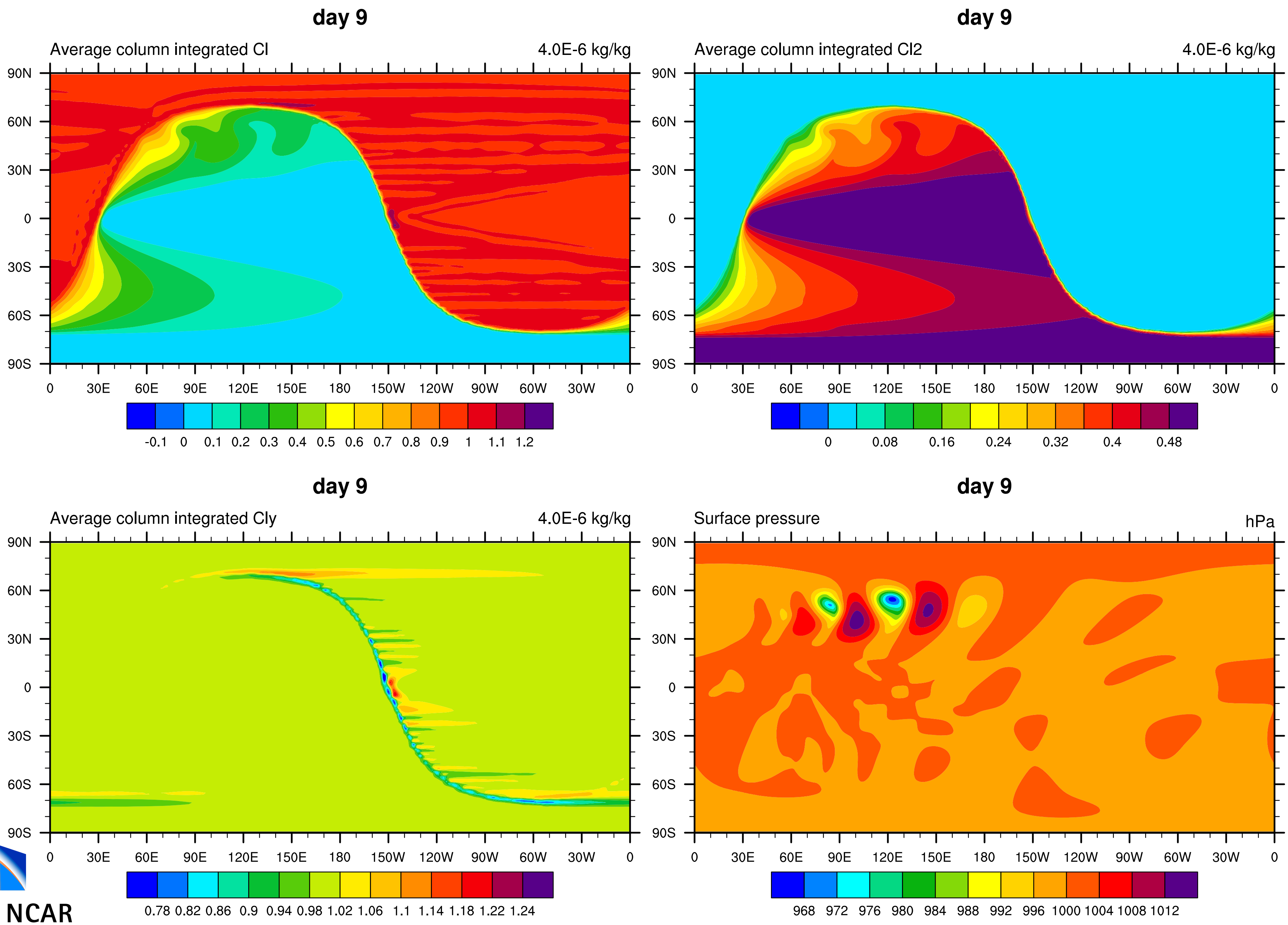
Initial condition



Lauritzen et al., 2016 (in prep.)

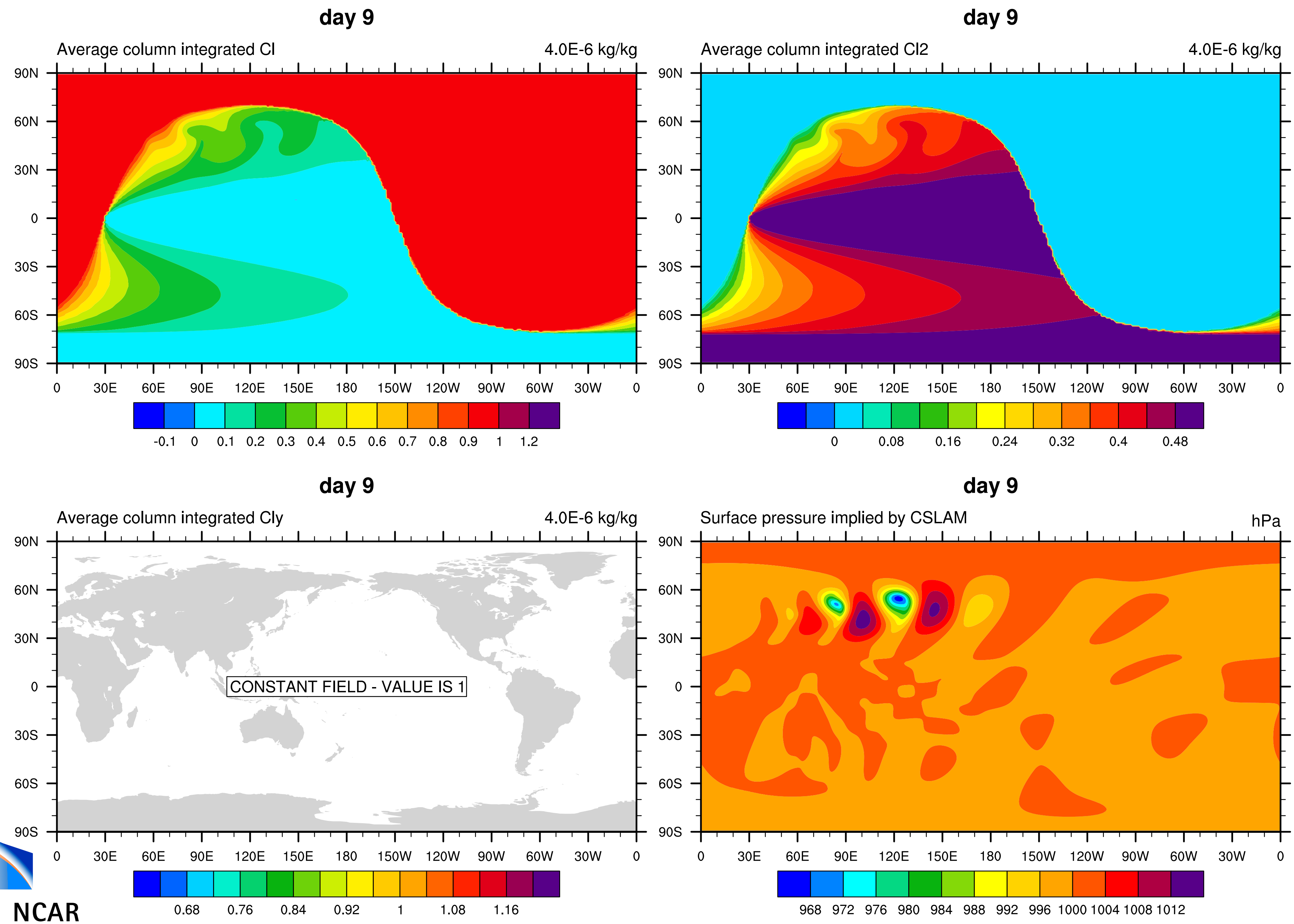
NCAR

CAM-SE



Lauritzen et al., 2016

CAM-SE-CSLAM



Lauritzen et al., 2016

NCAR

Performance

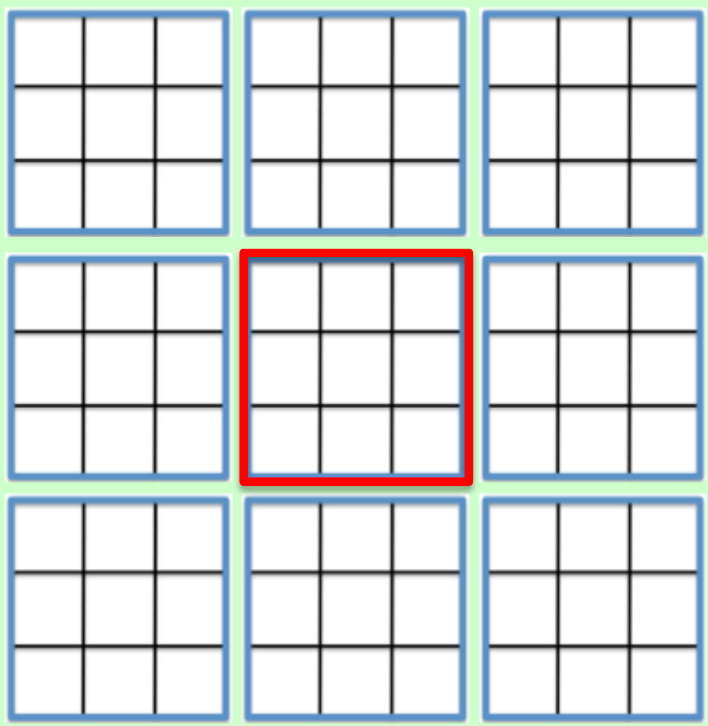
- **All simulations run on NCAR's Yellowstone computer**
- **No exploration of threading**

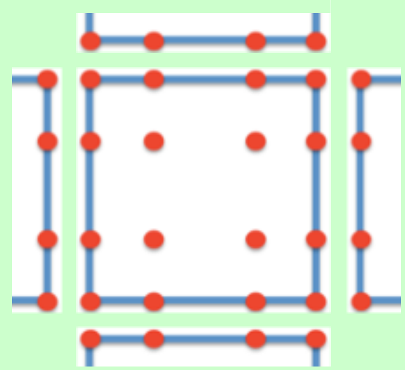
MPI communication

For every 30 minute physics time-step:

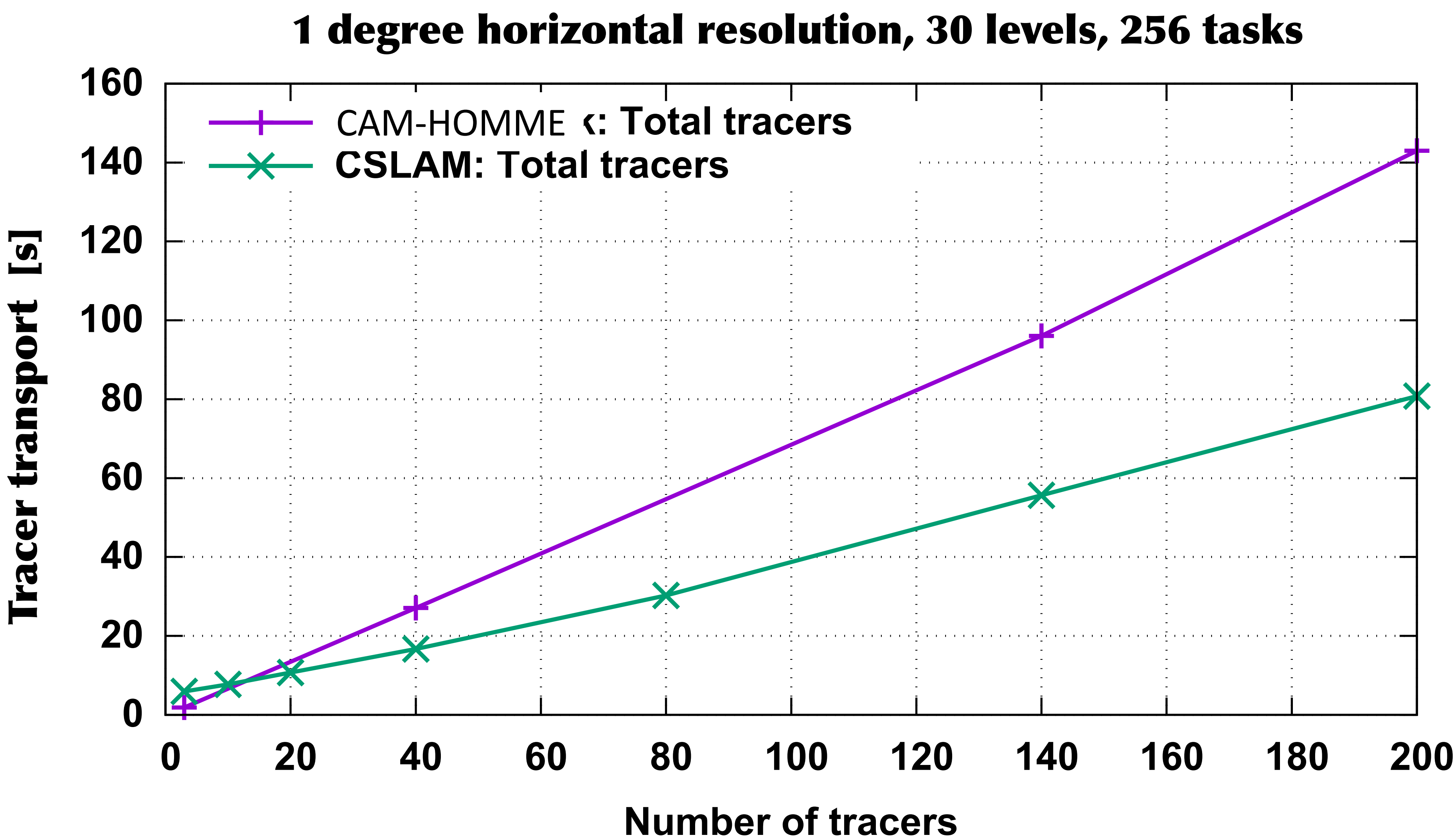
- SE performs 6 tracer time-steps (dt=300s) => 42 MPI calls (7 per tracer dt)
- CSLAM performs 2 tracer time-steps (dt=900s) => 2 MPI calls (1 per tracer dt)

That said, CSLAM needs a much larger halo than SE:

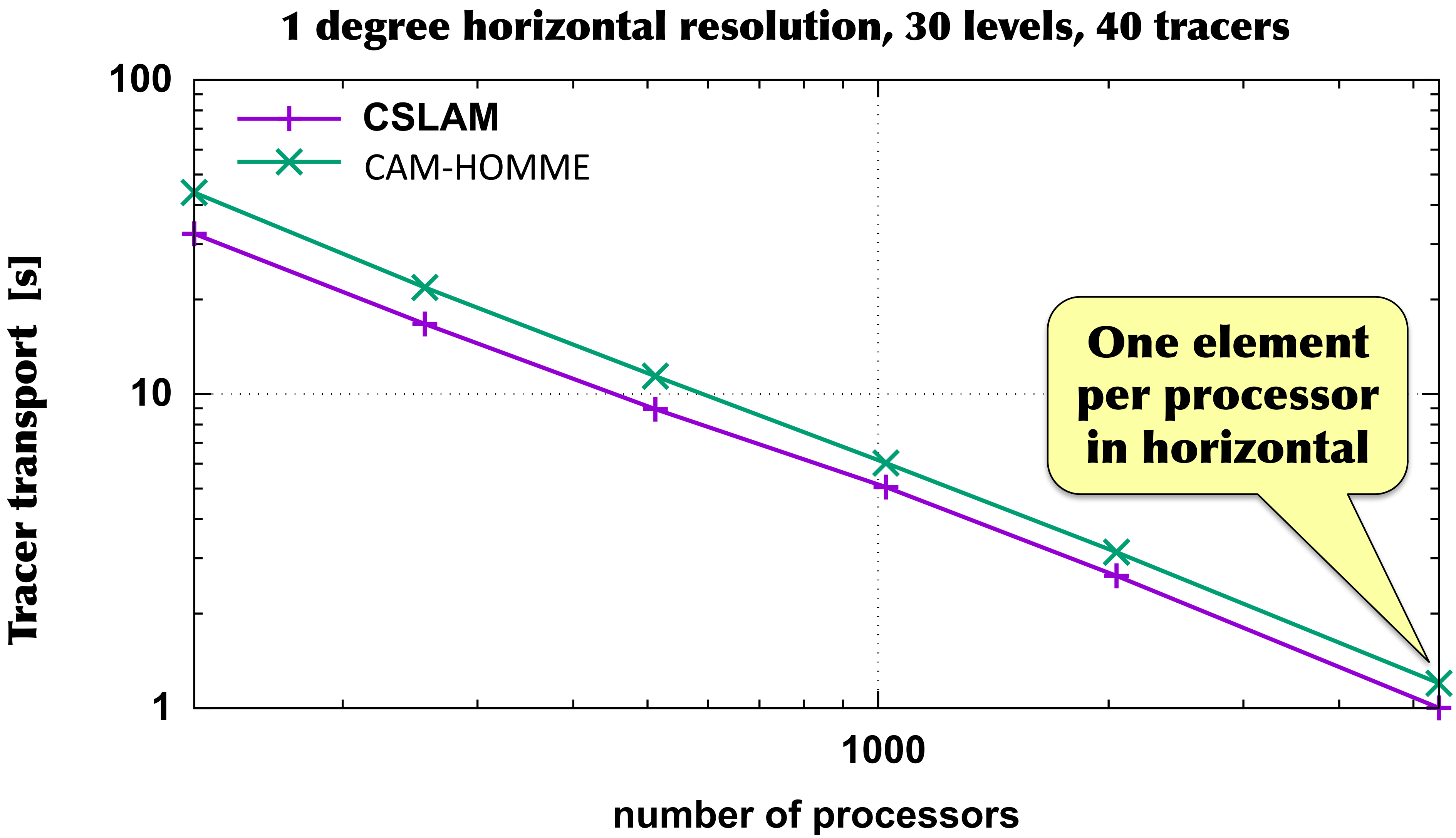




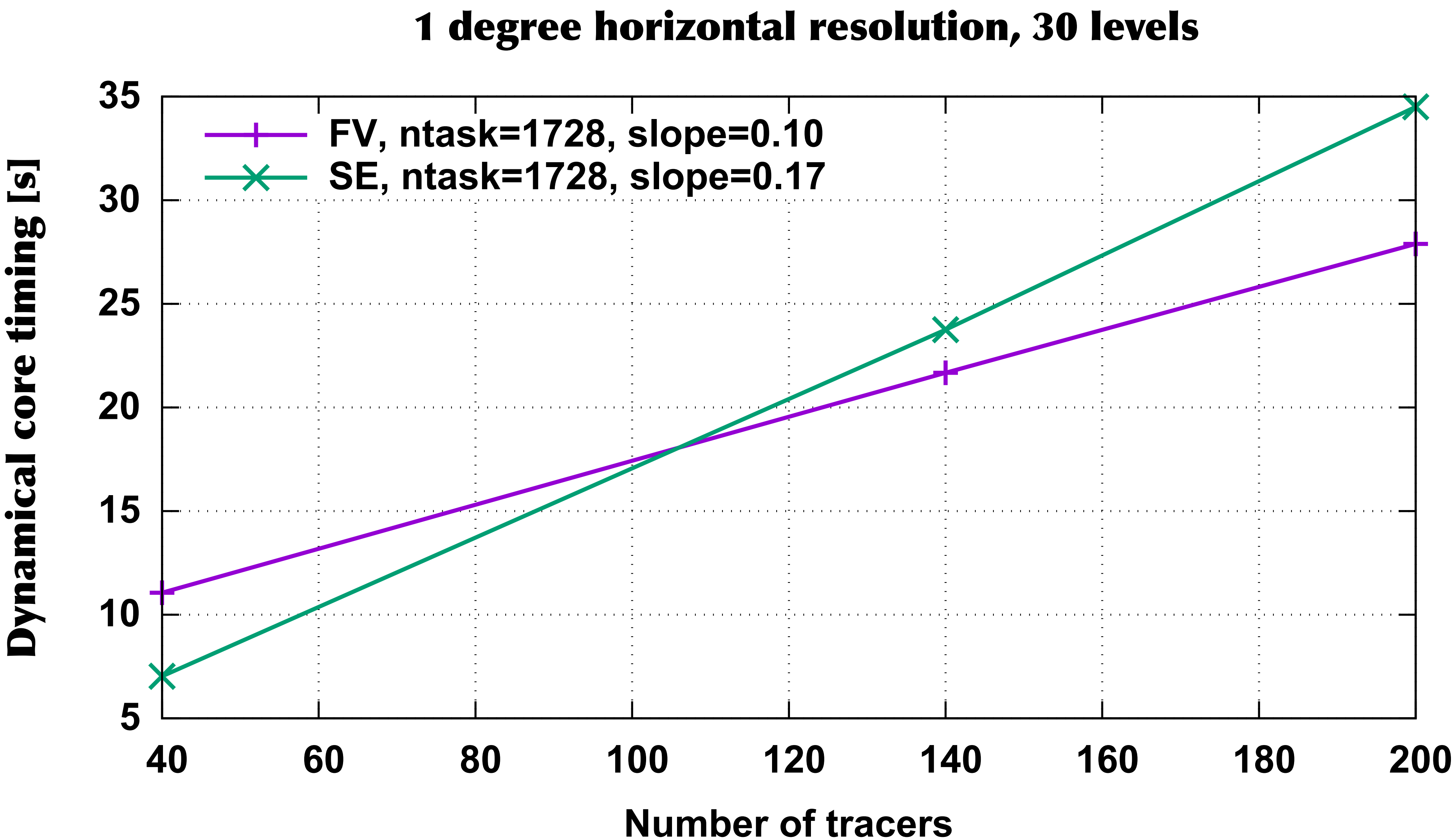
Performance



Performance: strong scaling



How do we compare with CAM-FV (dynamical core timings using 1728 tasks)



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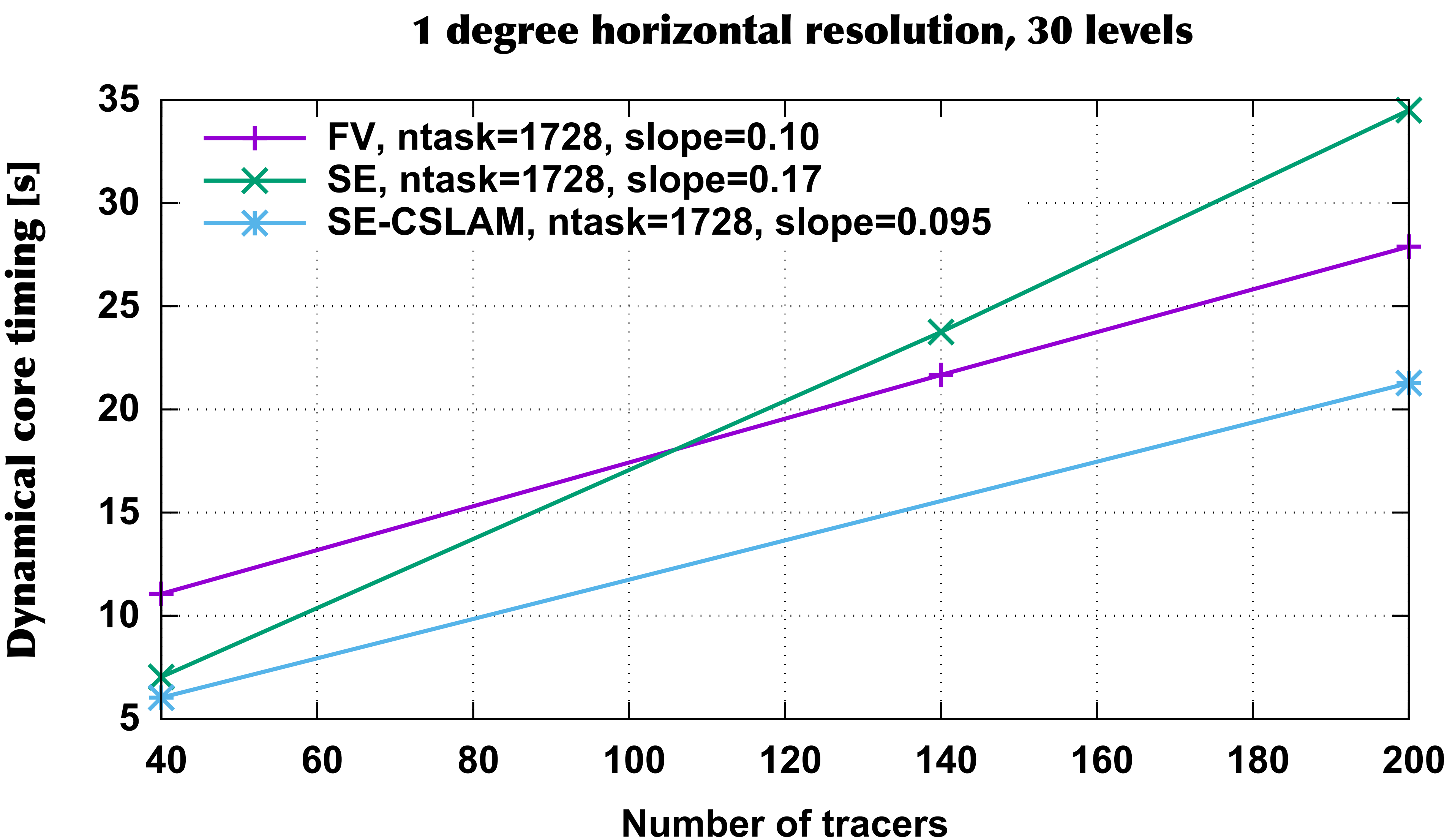
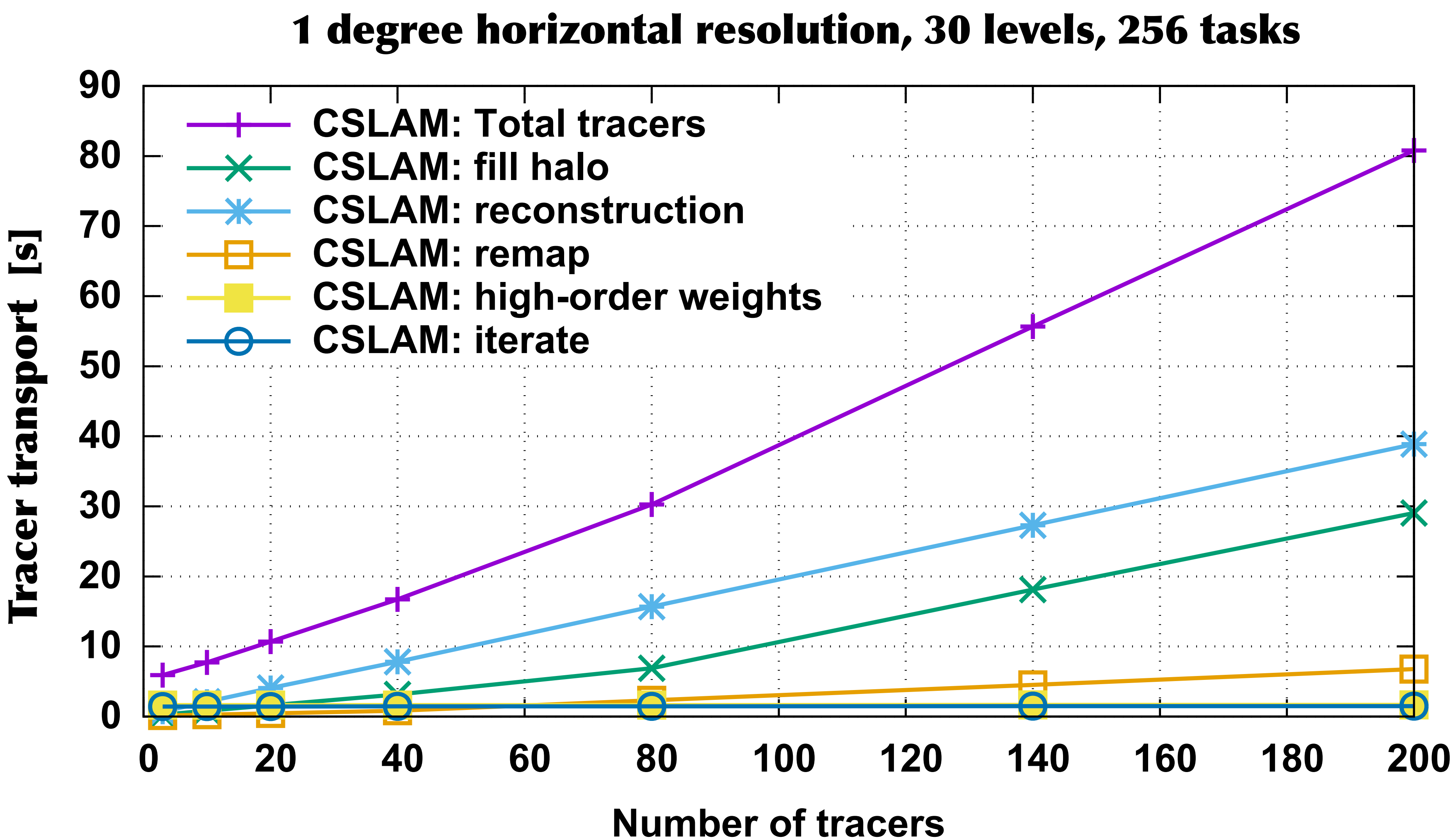
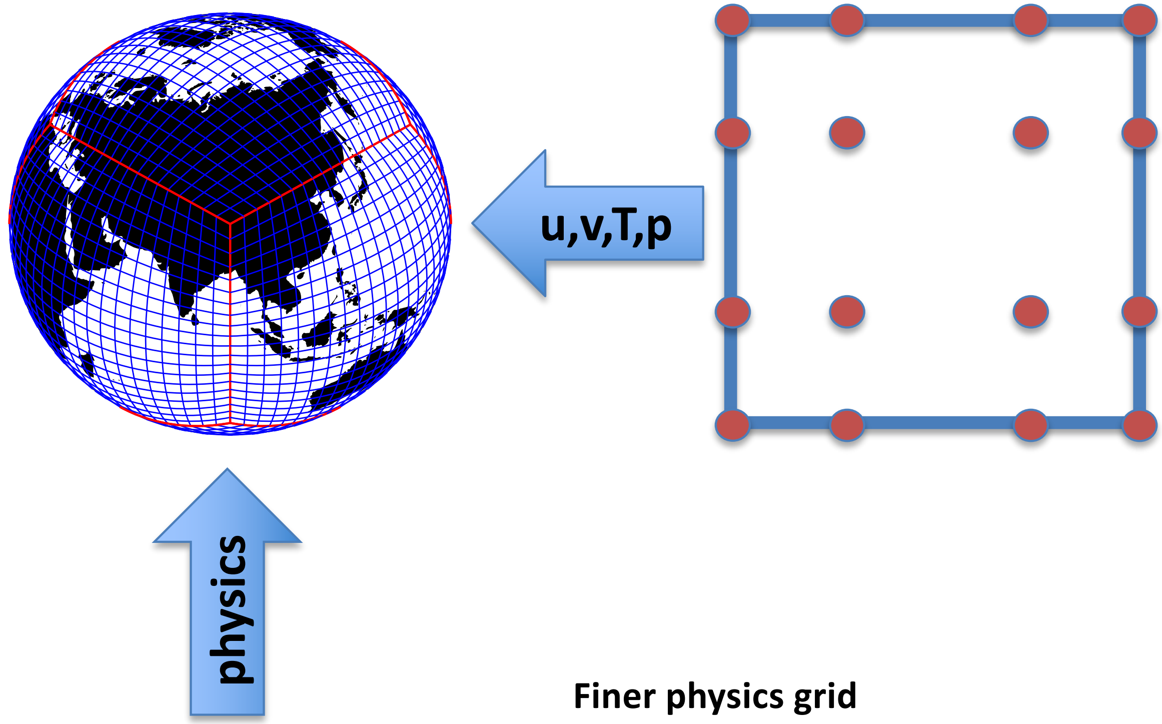


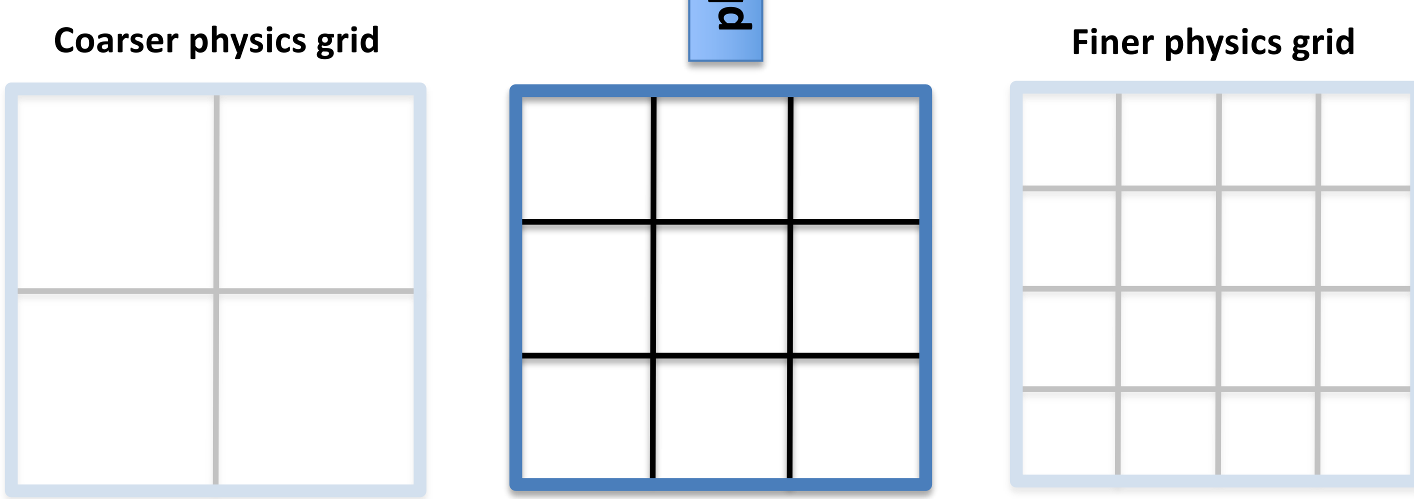
Performance: break-down of CSLAM algorithm



Part II: Coupling to physics

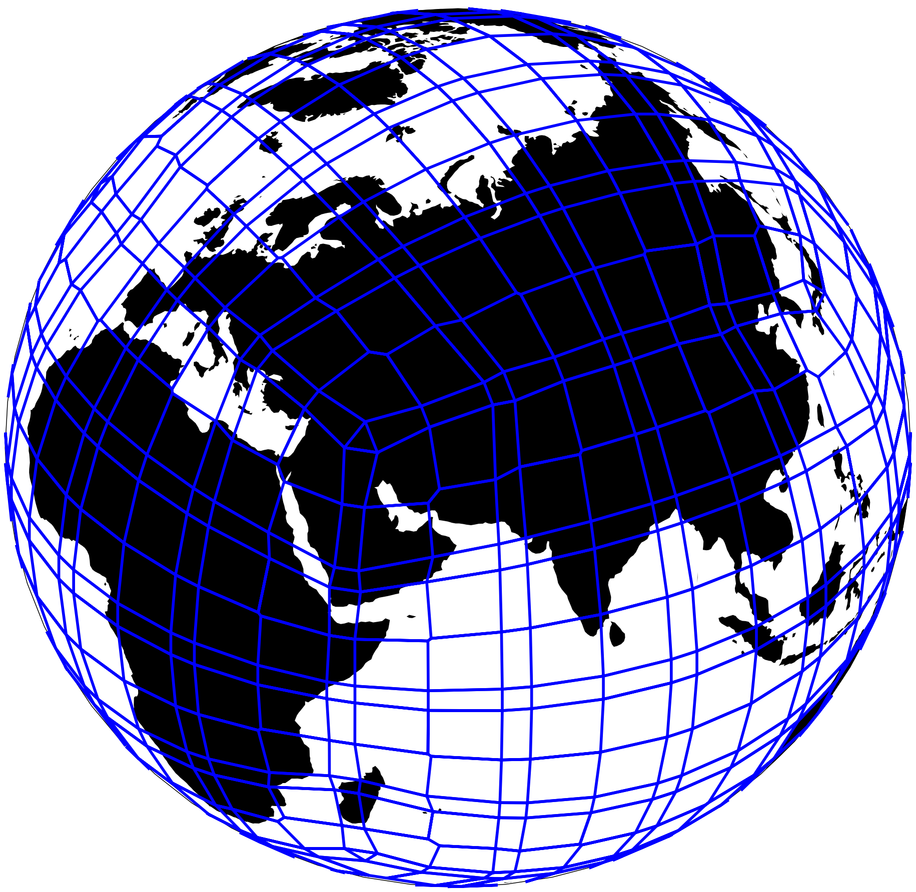
There are several reasons why I do not think one should pass state on GLL points to physics:



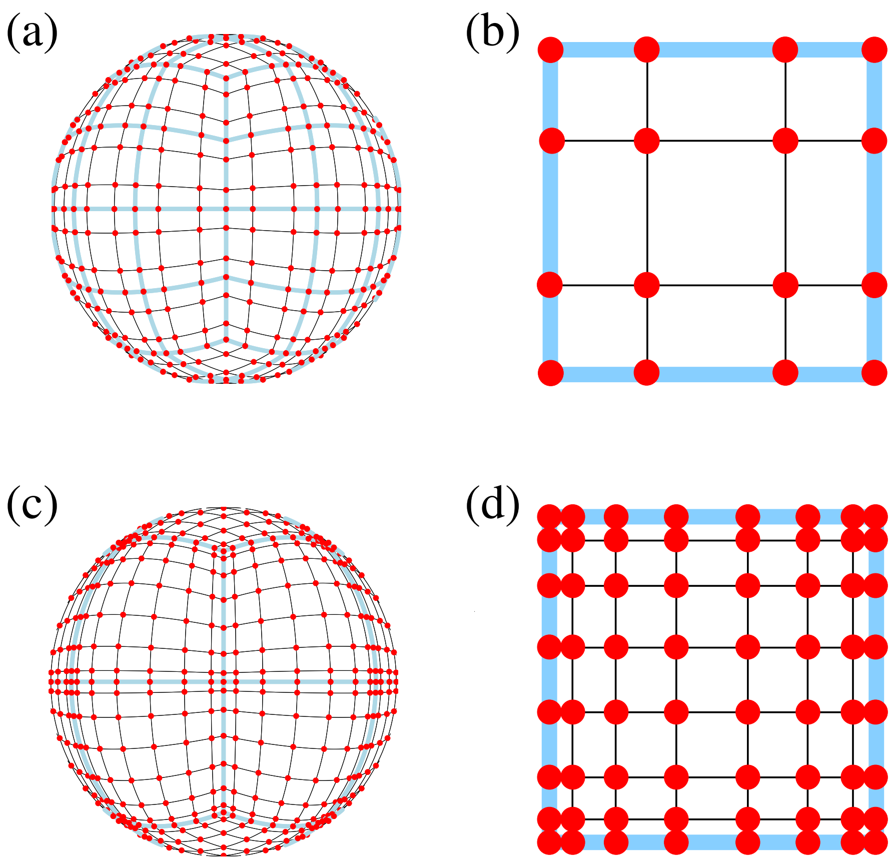


Non-uniform sampling of atmospheric state

Current physics/"coupler" grid

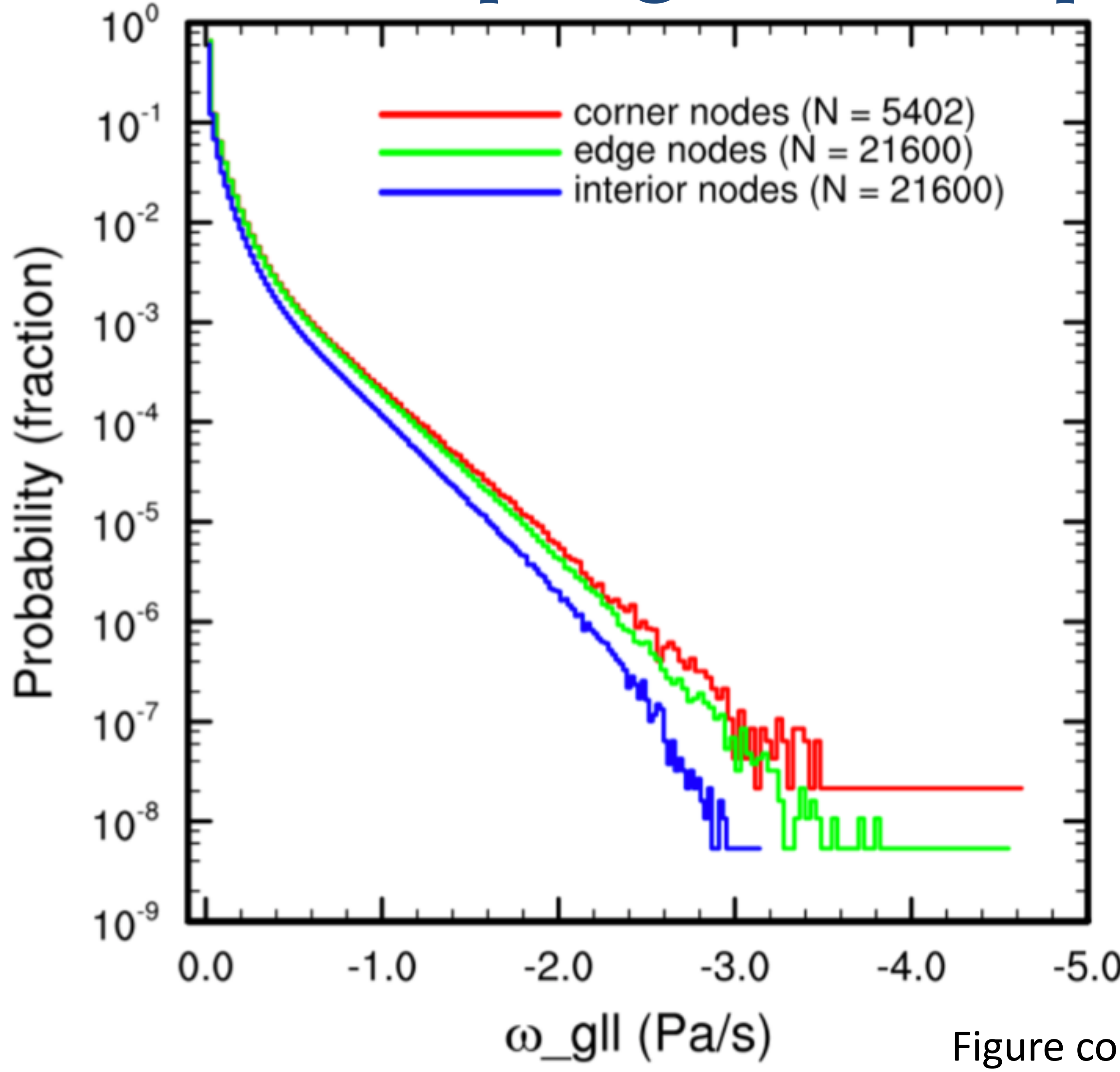


Gets worse with increasing order!



Non-uniform sampling of atmospheric state

Data from aqua-planet simulation



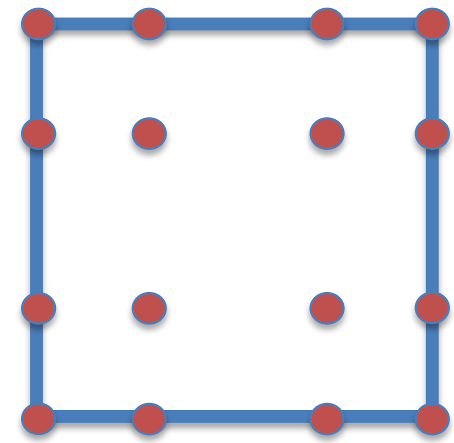
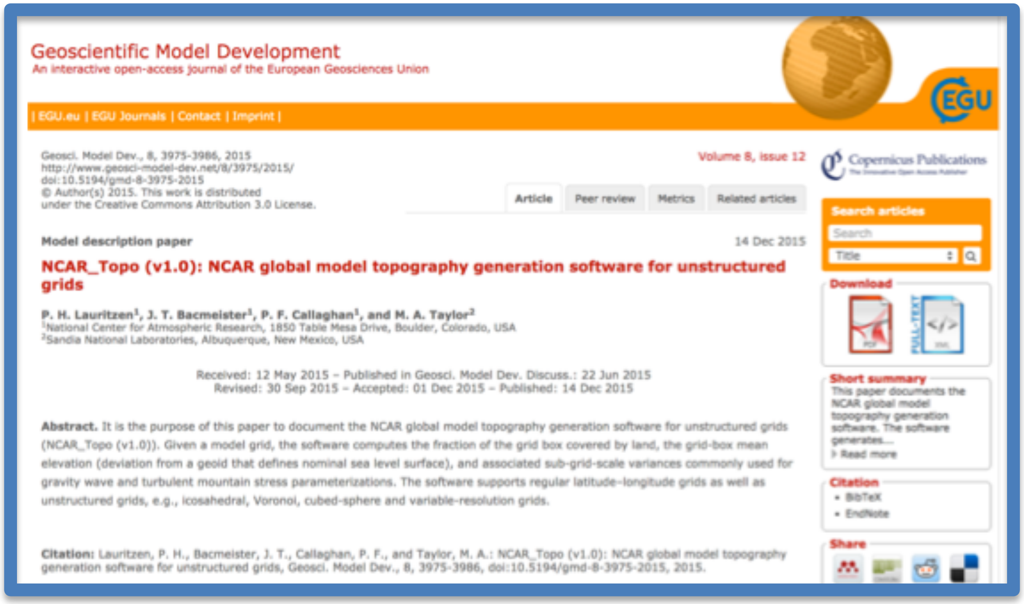


Figure courtesy of A. Herrington

Aside

A couple of comments on topography generation and topography smoothing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Geosci. Model Dev., 8, 3975-3986, 2015
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doi:10.5194/gmd-8-3975-2015

Volume 8, issue 12

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Model description paper

14 Dec 2015

NCAR_Topo (v1.0): NCAR global model topography generation software for unstructured grids

P. H. Lauritzen[1], J. T. Bacmeister[1], P. F. Callaghan[1], and M. A. Taylor[2]
[1]National Center for Atmospheric Research, 1850 Table Mesa Drive, Boulder, Colorado, USA
[2]Sandia National Laboratories, Albuquerque, New Mexico, USA

Received: 12 May 2015 – Published in Geosci. Model Dev. Discuss.: 22 Jun 2015
Revised: 30 Sep 2015 – Accepted: 01 Dec 2015 – Published: 14 Dec 2015

Abstract. It is the purpose of this paper to document the NCAR global model topography generation software for unstructured grids (NCAR_Topo (v1.0)). Given a model grid, the software computes the fraction of the grid box covered by land, the grid-box mean elevation (deviation from a geoid that defines nominal sea level surface), and associated sub-grid-scale variances commonly used for gravity wave and turbulent mountain stress parameterizations. The software supports regular latitude-longitude grids as well as unstructured grids, e.g., icosahedral, Voronoi, cubed-sphere and variable-resolution grids.

Citation: Lauritzen, P. H., Bacmeister, J. T., Callaghan, P. F., and Taylor, M. A.: NCAR_Topo (v1.0): NCAR global model topography generation software for unstructured grids, Geosci. Model Dev., 8, 3975-3986, doi:10.5194/gmd-8-3975-2015, 2015.

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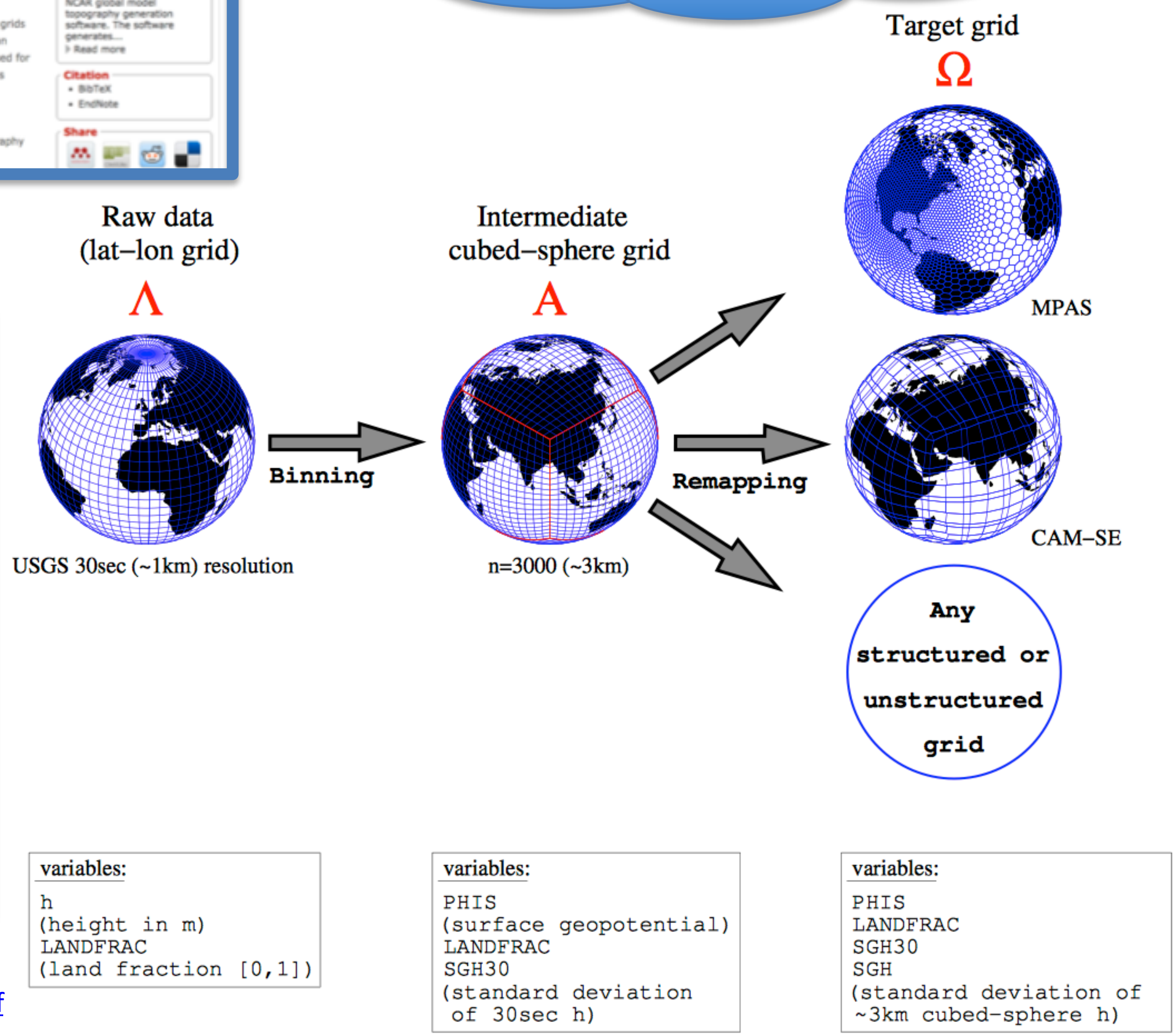
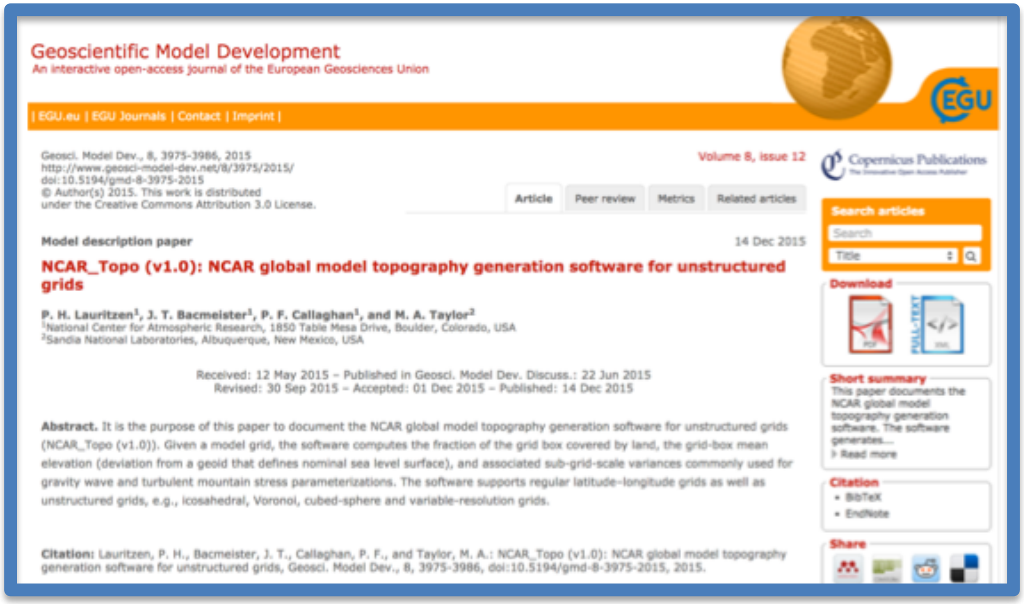
https://github.com/NCAR/Topo



GTOPO30:

USGS ~1km dataset from 1996

http://pubs.usgs.gov/of/2011/1073/pdf/of2011-1073.pdf



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Volume 8, issue 12

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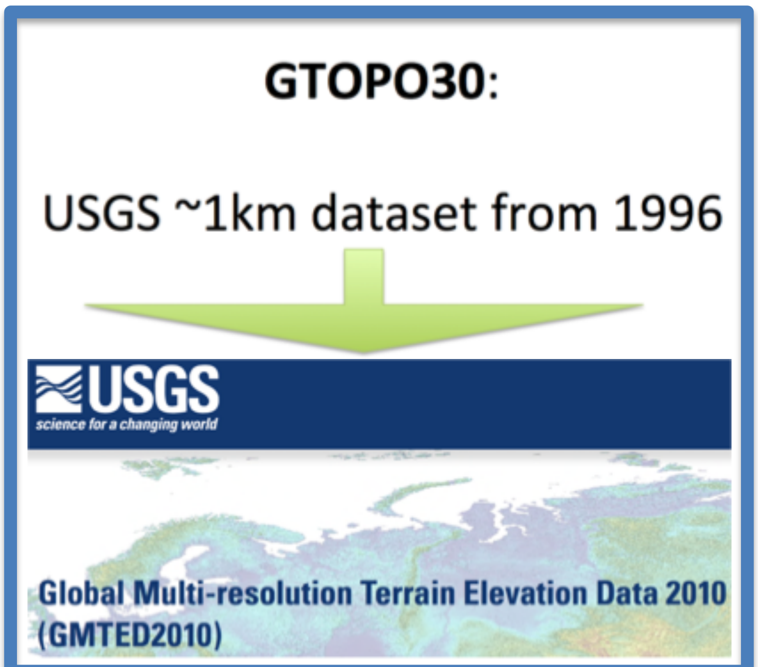
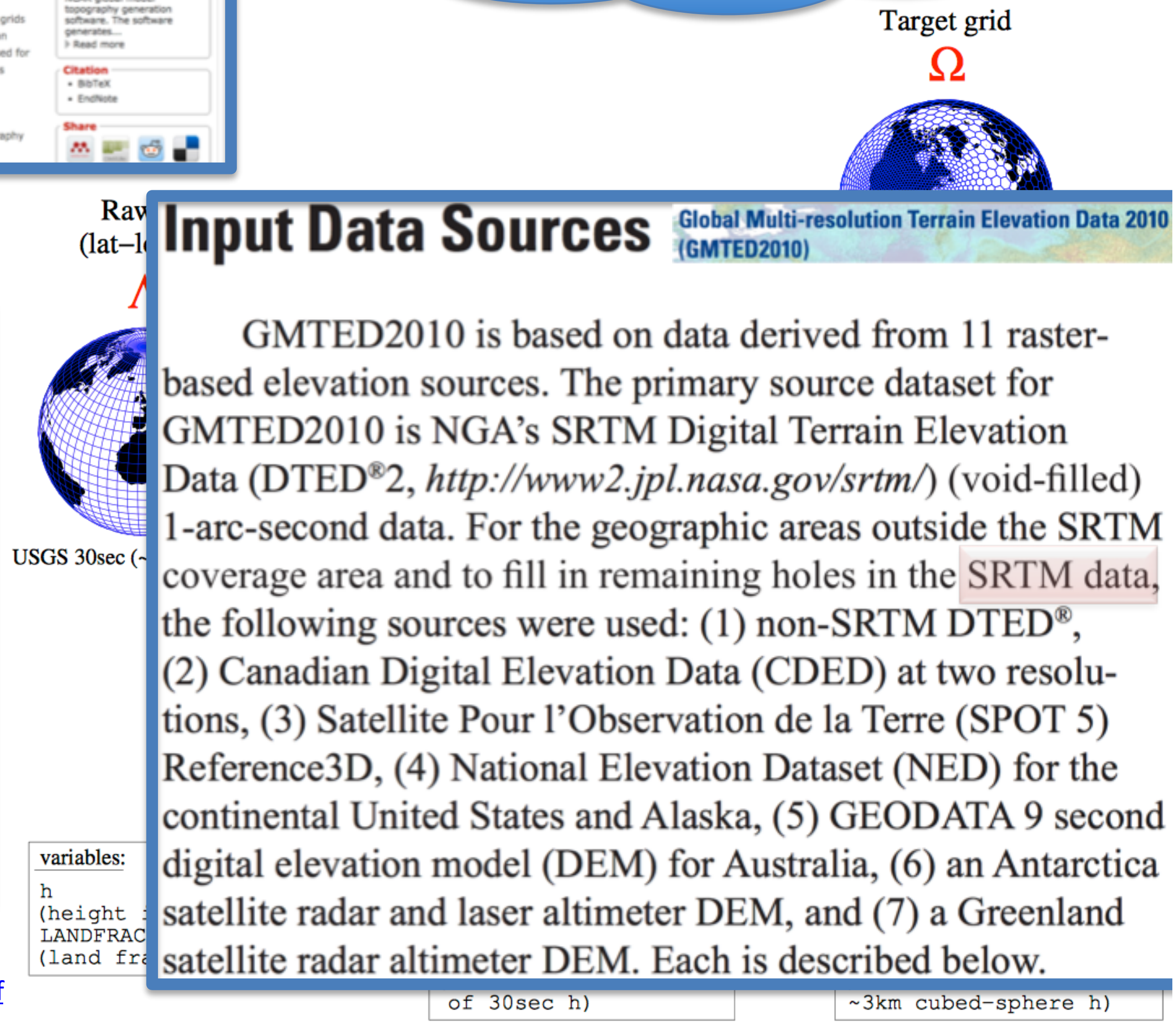
https://github.com/NCAR/Topo



http://pubs.usgs.gov/of/2011/1073/pdf/of2011-1073.pdf



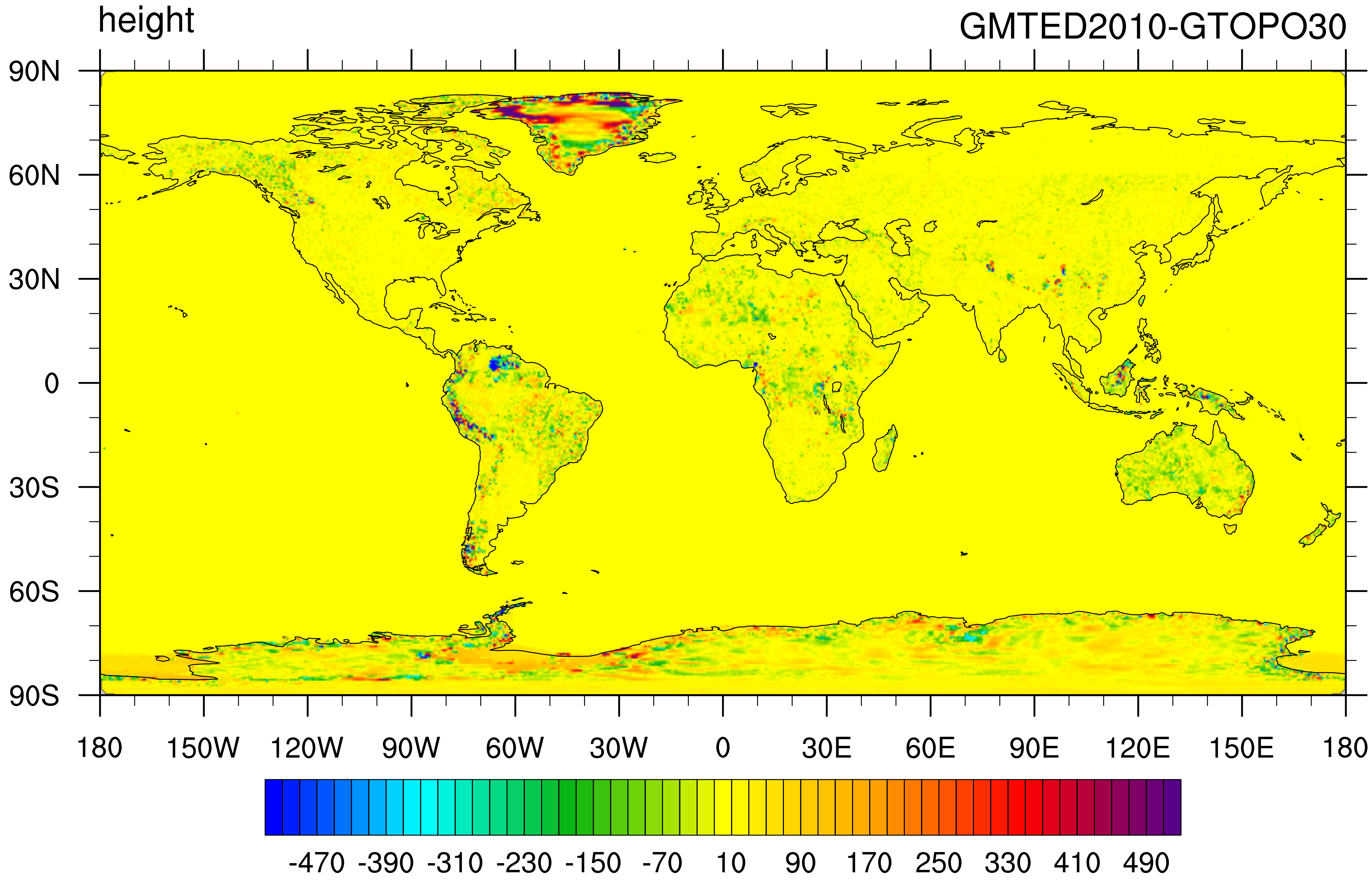
Input Data Sources

Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010)

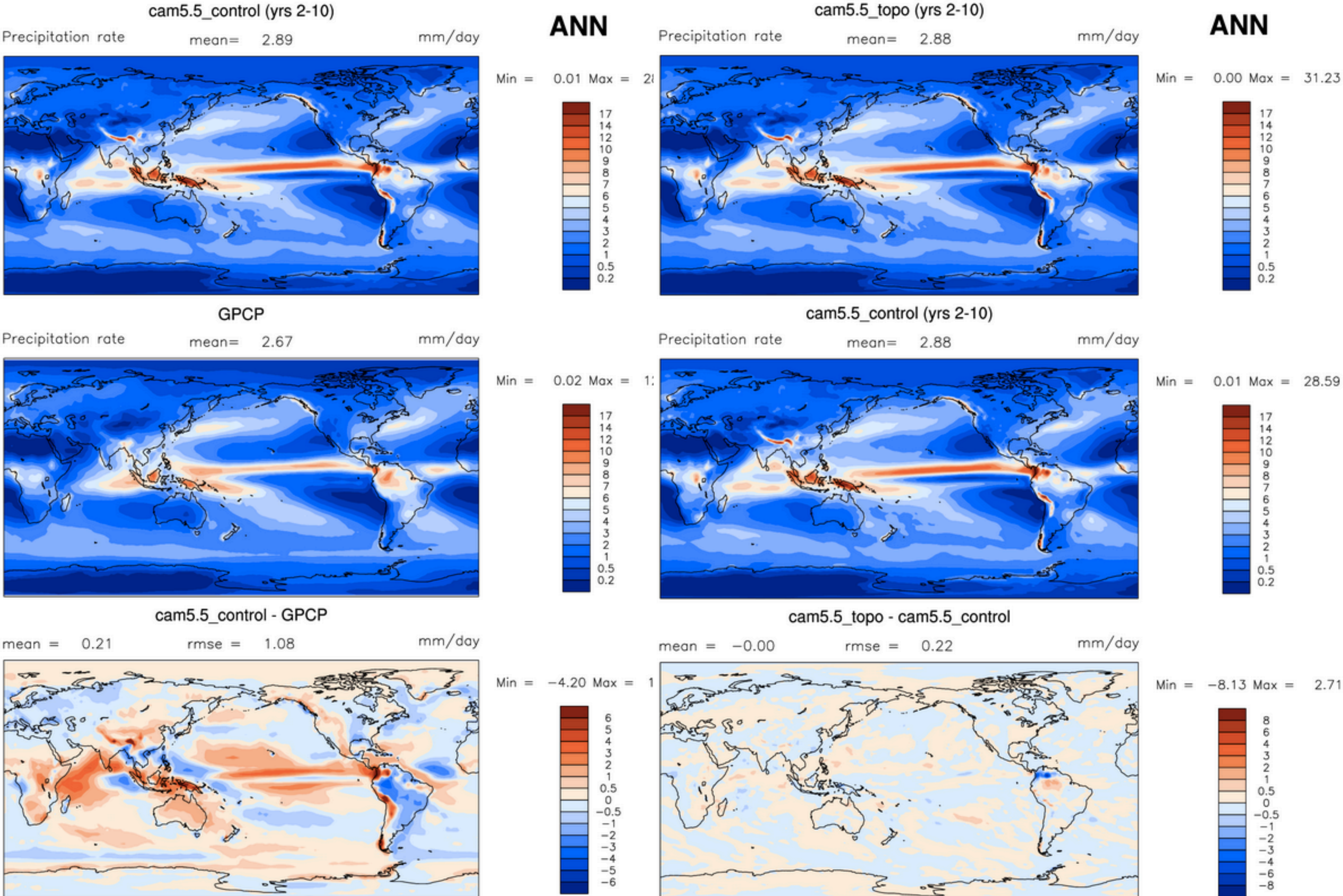
GMTED2010 is based on data derived from 11 raster-based elevation sources. The primary source dataset for GMTED2010 is NGA's SRTM Digital Terrain Elevation Data (DTED®2, *http://www2.jpl.nasa.gov/srtm/*) (void-filled) 1-arc-second data. For the geographic areas outside the SRTM coverage area and to fill in remaining holes in the SRTM data, the following sources were used: (1) non-SRTM DTED®, (2) Canadian Digital Elevation Data (CDED) at two resolutions, (3) Satellite Pour l'Observation de la Terre (SPOT 5) Reference3D, (4) National Elevation Dataset (NED) for the continental United States and Alaska, (5) GEODATA 9 second digital elevation model (DEM) for Australia, (6) an Antarctica satellite radar and laser altimeter DEM, and (7) a Greenland satellite radar altimeter DEM. Each is described below.

Elevation differences [meters]

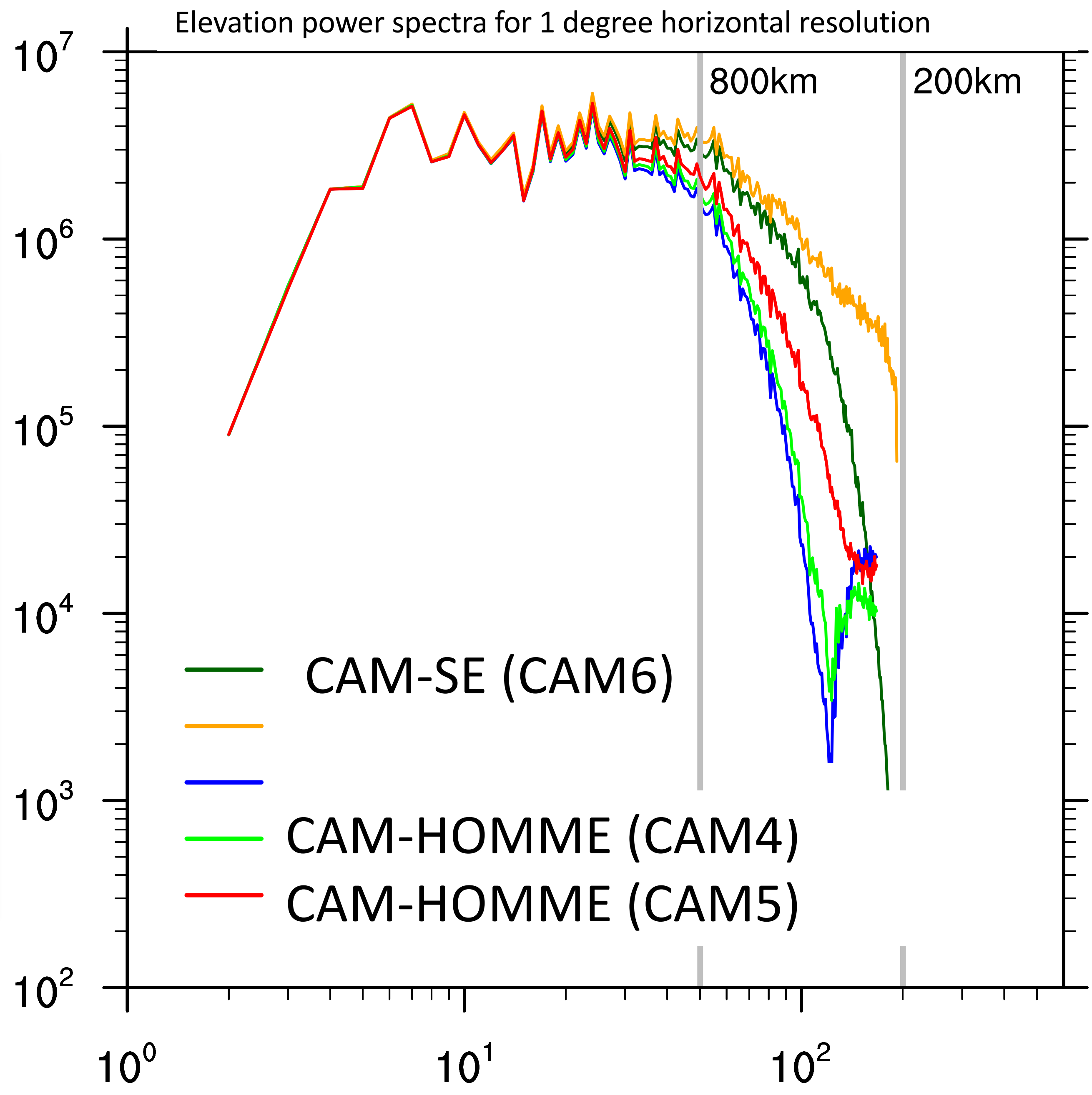
(on 3km cubed-sphere grid)



PRECT


ANN
cam5.5_control (yrs 2-10)
Precipitation rate
mean= 2.89
mm/day
Min = 0.01 Max =
17
14
12
10
9
8
7
6
5
4
3
2
1
0.5
0.2
cam5.5_topo (yrs 2-10)
ANN
Precipitation rate
mean= 2.88
mm/day
Min = 0.00 Max = 31.23
17
14
12
10
9
8
7
6
5
4
3
2
1
0.5
0.2
GPCP
Precipitation rate
mean= 2.67
mm/day
Min = 0.02 Max =
17
14
12
10
9
8
7
6
5
4
3
2
1
0.5
0.2
cam5.5_control (yrs 2-10)
Precipitation rate
mean= 2.88
mm/day
Min = 0.01 Max = 28.59
17
14
12
10
9
8
7
6
5
4
3
2
1
0.5
0.2
cam5.5_control - GPCP
mean = 0.21
rmse = 1.08
mm/day
Min = −4.20 Max =
6
5
4
3
2
1
0.5
0
−0.5
−1
−2
−3
−4
−5
−6
cam5.5_topo - cam5.5_control
mean = −0.00
rmse = 0.22
mm/day
Min = −8.13 Max = 2.71
8
6
4
3
2
1
0.5
0
−0.5
−1
−2
−3
−4
−6
−8

Elevation power spectra

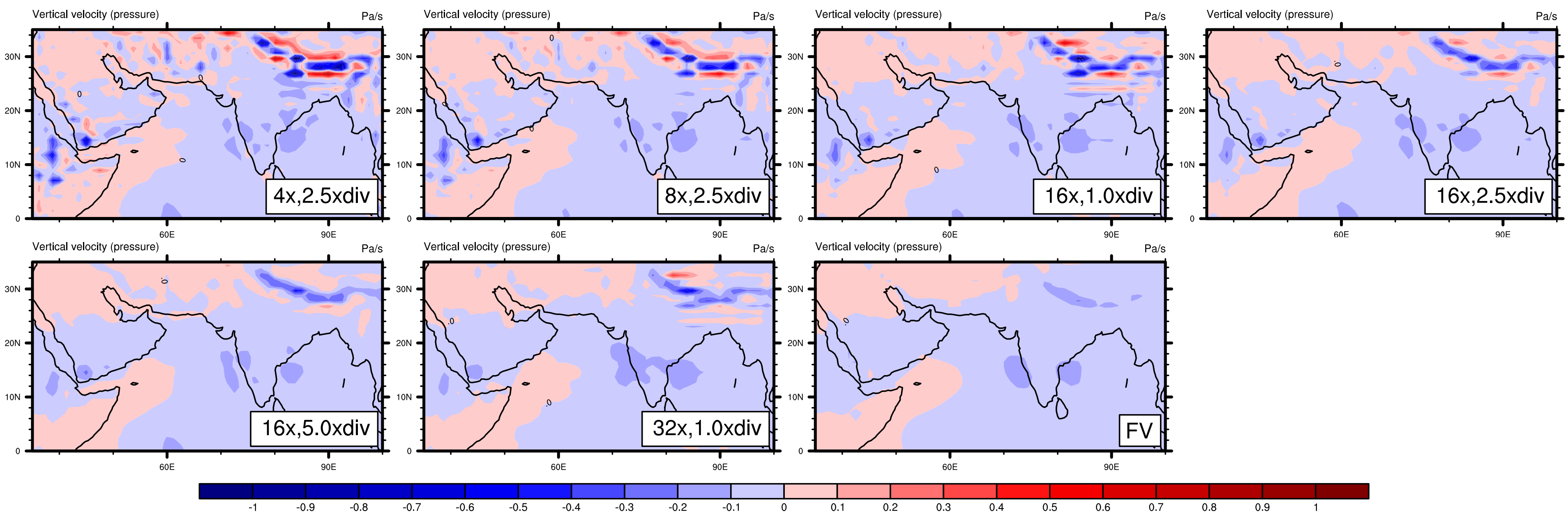


Topography smoothing in CAM

WARNING: CAM-HOMME (with Eulerian vertical advection)
i.e. results NOT CAM-SE (with Lagrangian vertical coordinate)

30 year AMIP simulations

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



Notation: 2.5xdiv = 2.5^2 times more divergence damping than vorticity damping
4x, 8x, …, 32x = smoothing of surface geopotential height

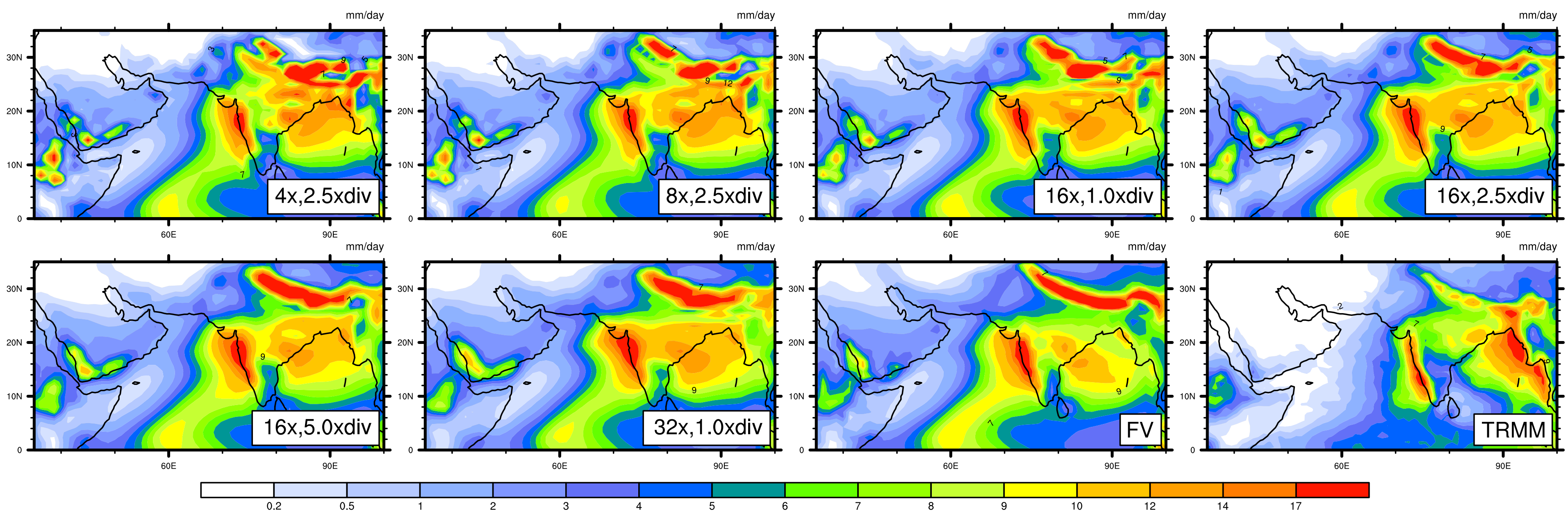
Lauritzen et al., (2015): *NCAR Global Model Topography Generation Software for Unstructured Grids*

Topography smoothing in CAM

WARNING: CAM-HOMME (with Eulerian vertical advection)
i.e. results NOT CAM-SE (with Lagrangian vertical coordinate)

30 year AMIP simulations

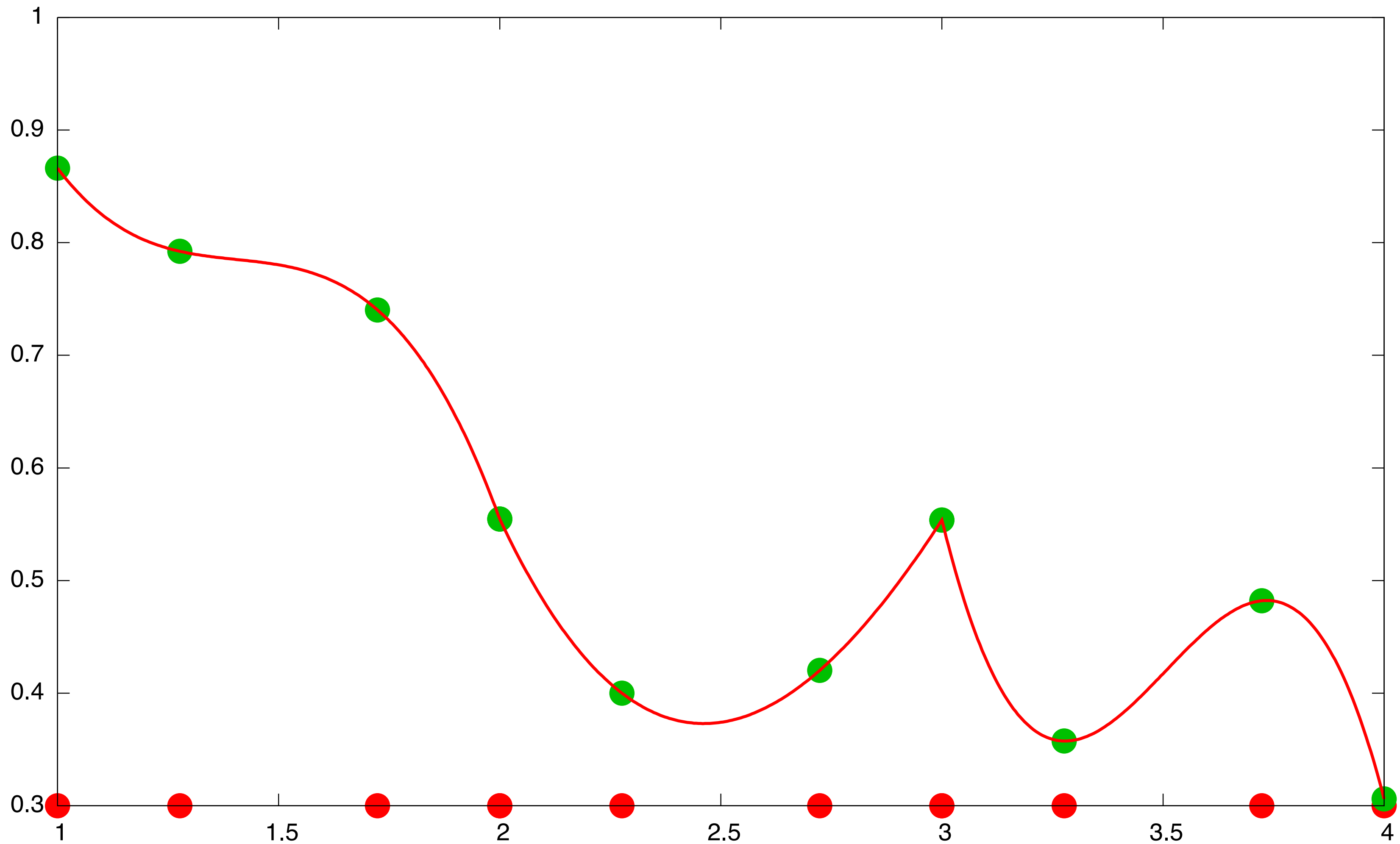
Total precipitation rate



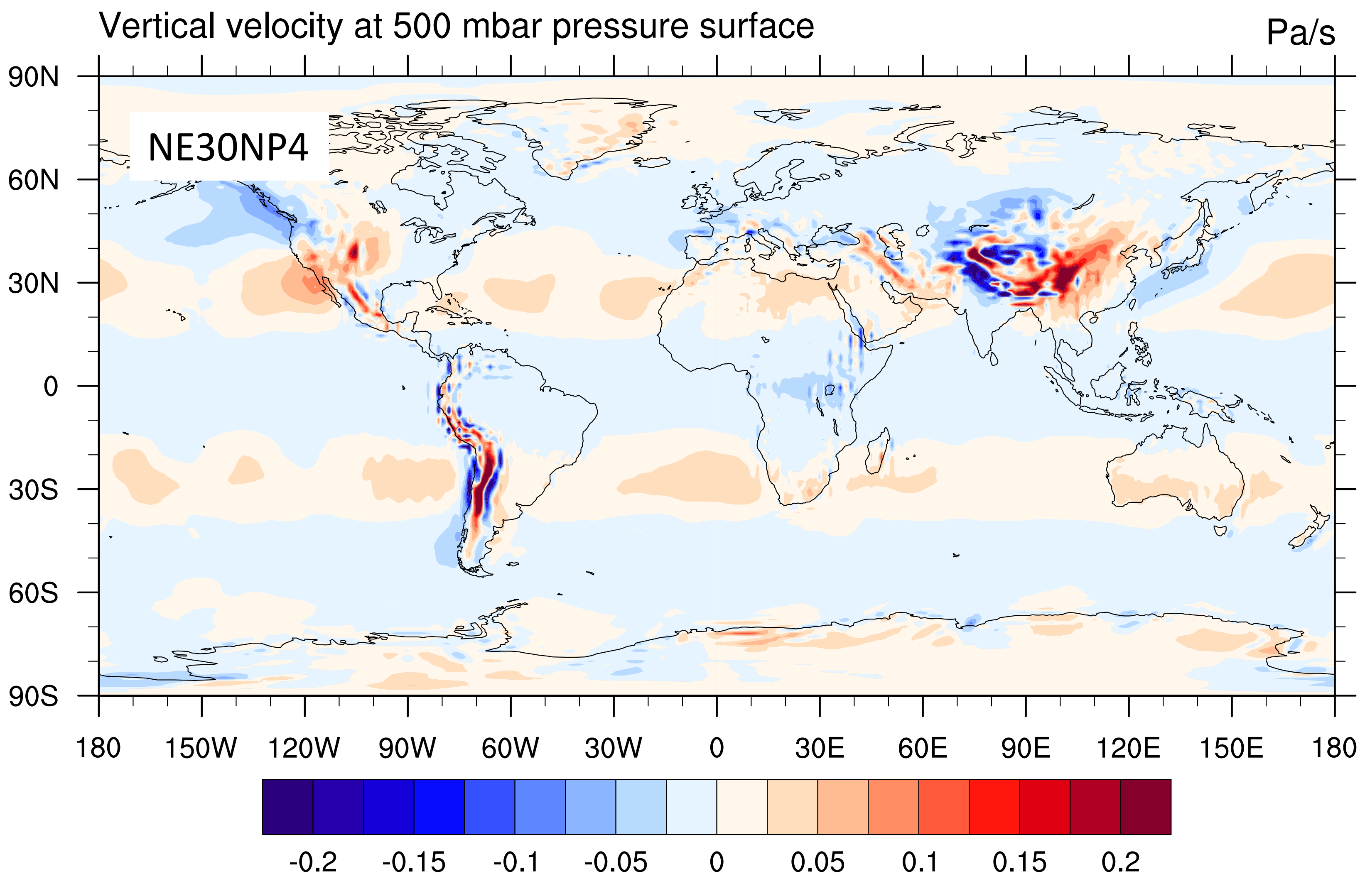
Mean sea level pressure differences, DJF, diff

Lauritzen et al., (2015): *NCAR Global Model Topography Generation Software for Unstructured Grids*

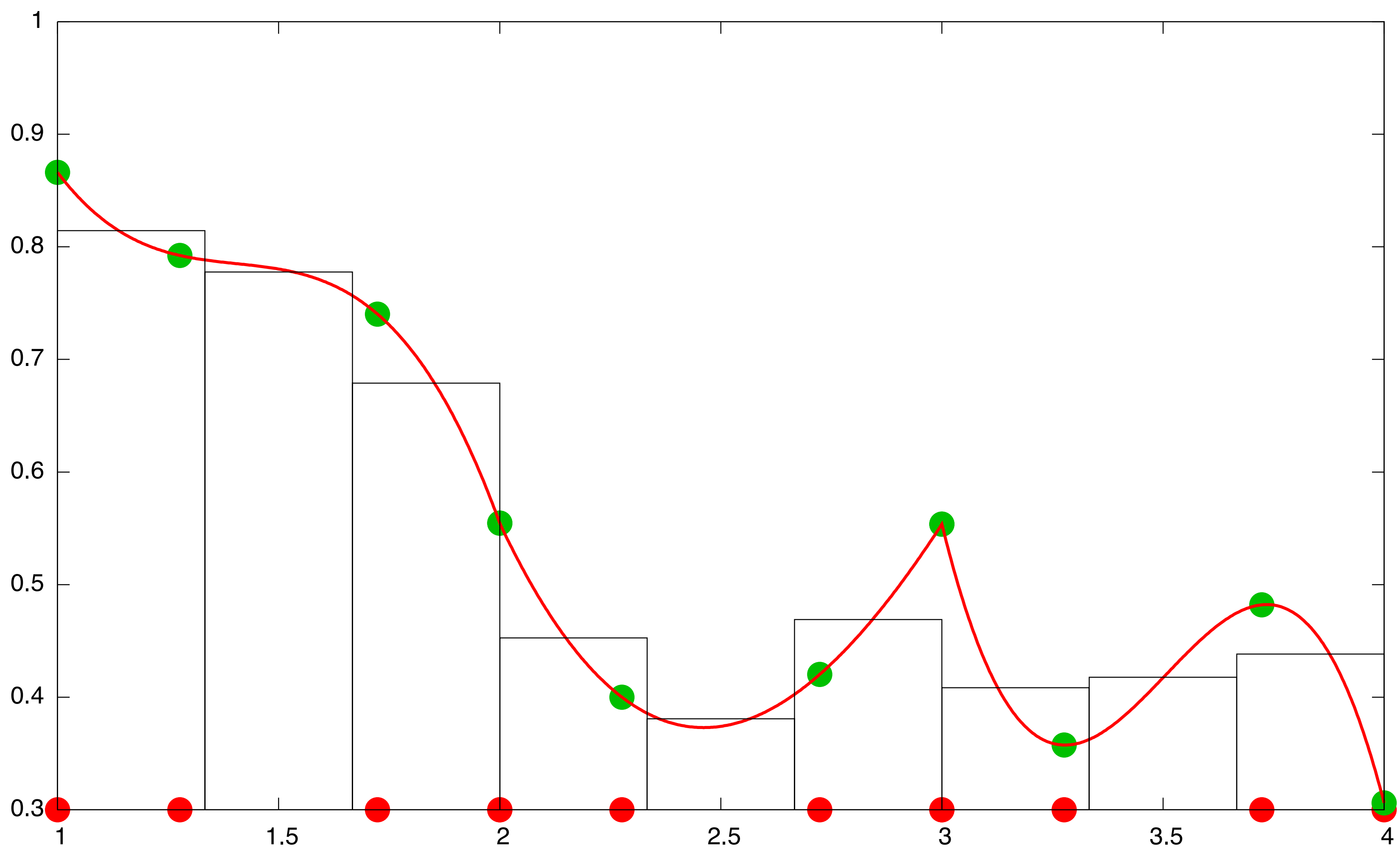
Grid-scale forcing

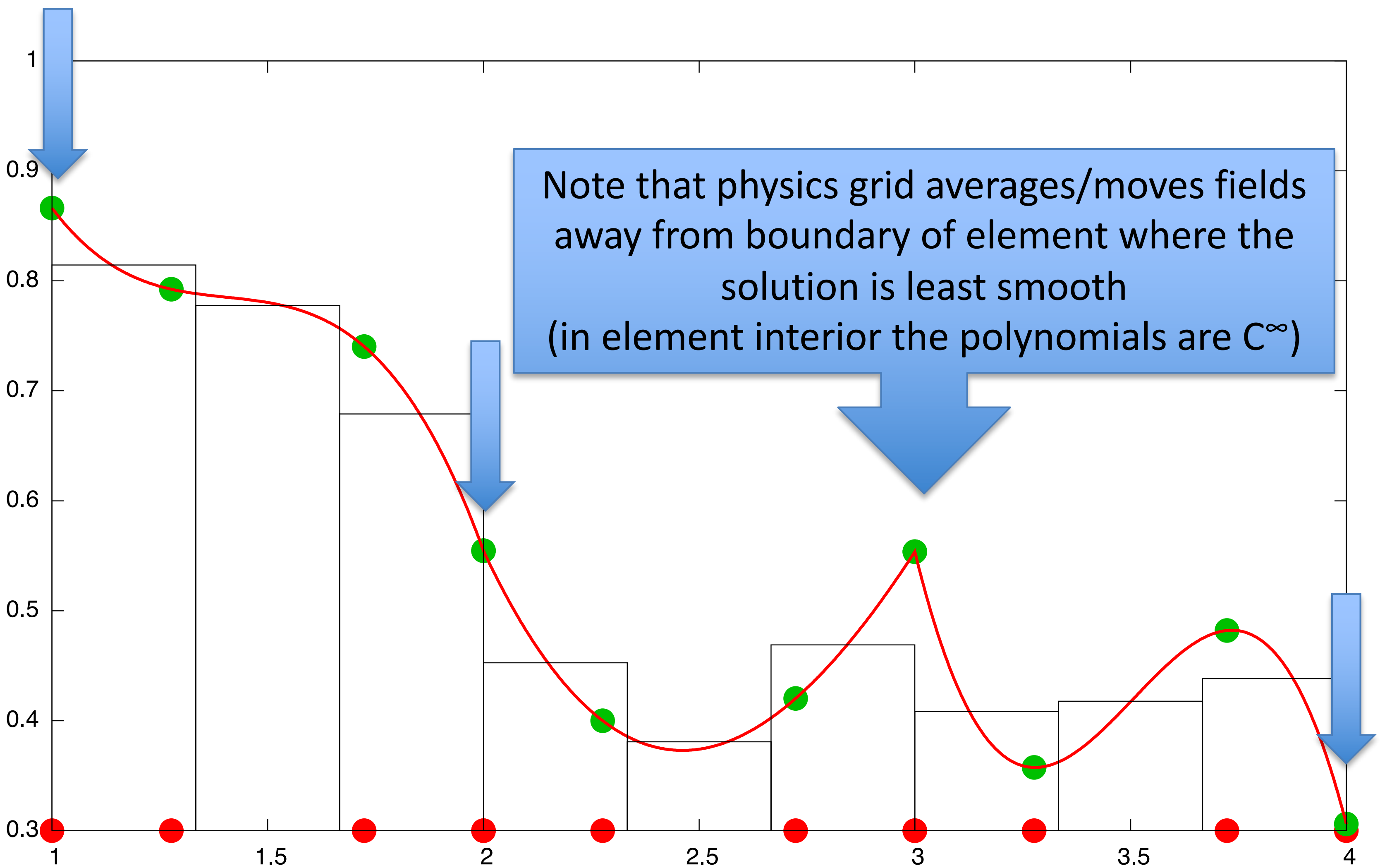


Held-Suarez with topography



NCAR UCAR National Center for Atmospheric Research Climate & Global Dynamics climate • models • society

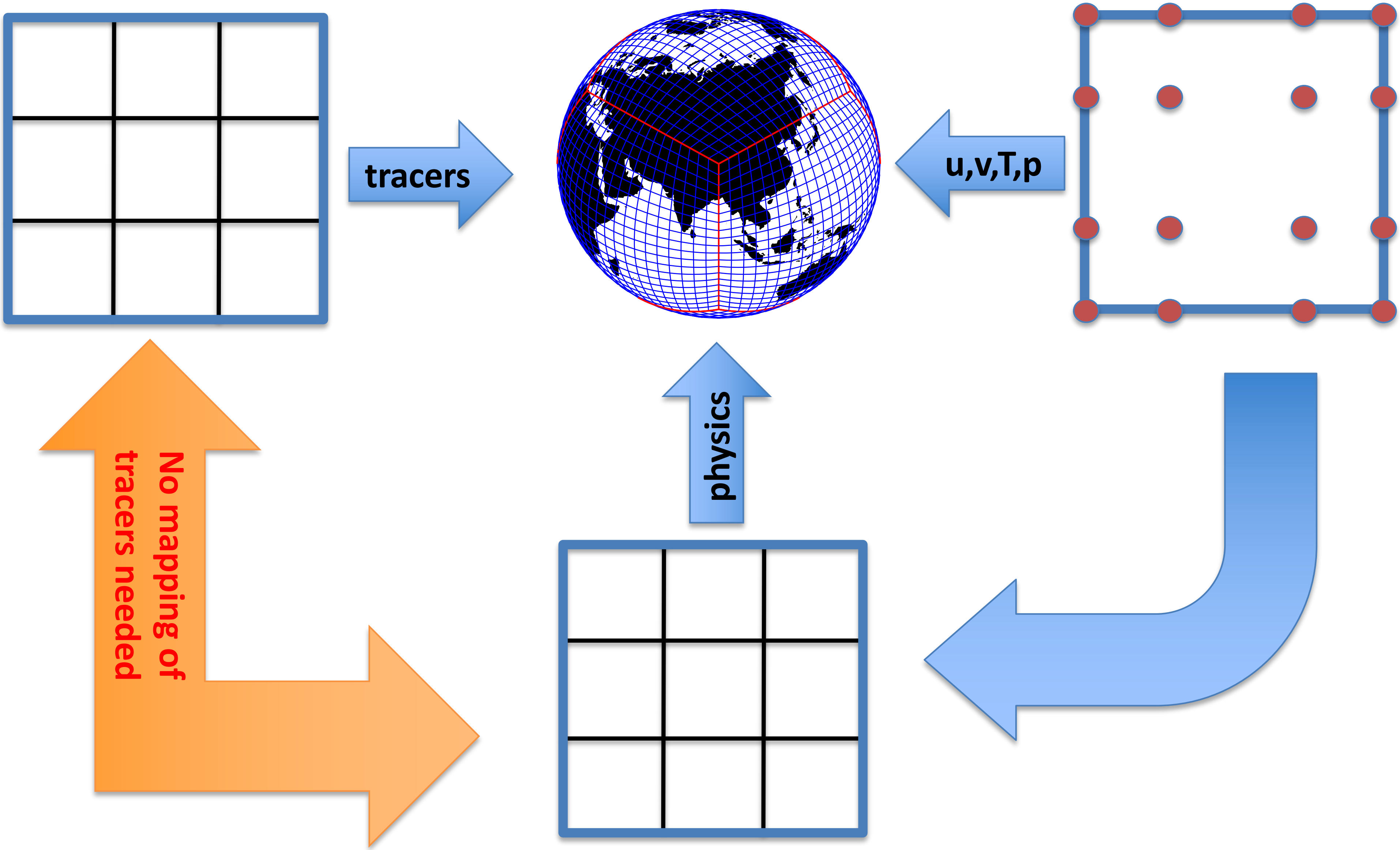

1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
1
1.5
2
2.5
3
3.5
4



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∞)

CAM-SE-CSLAM with moisture

"This is where the fun begins!" – Staniforth et al. (2006)

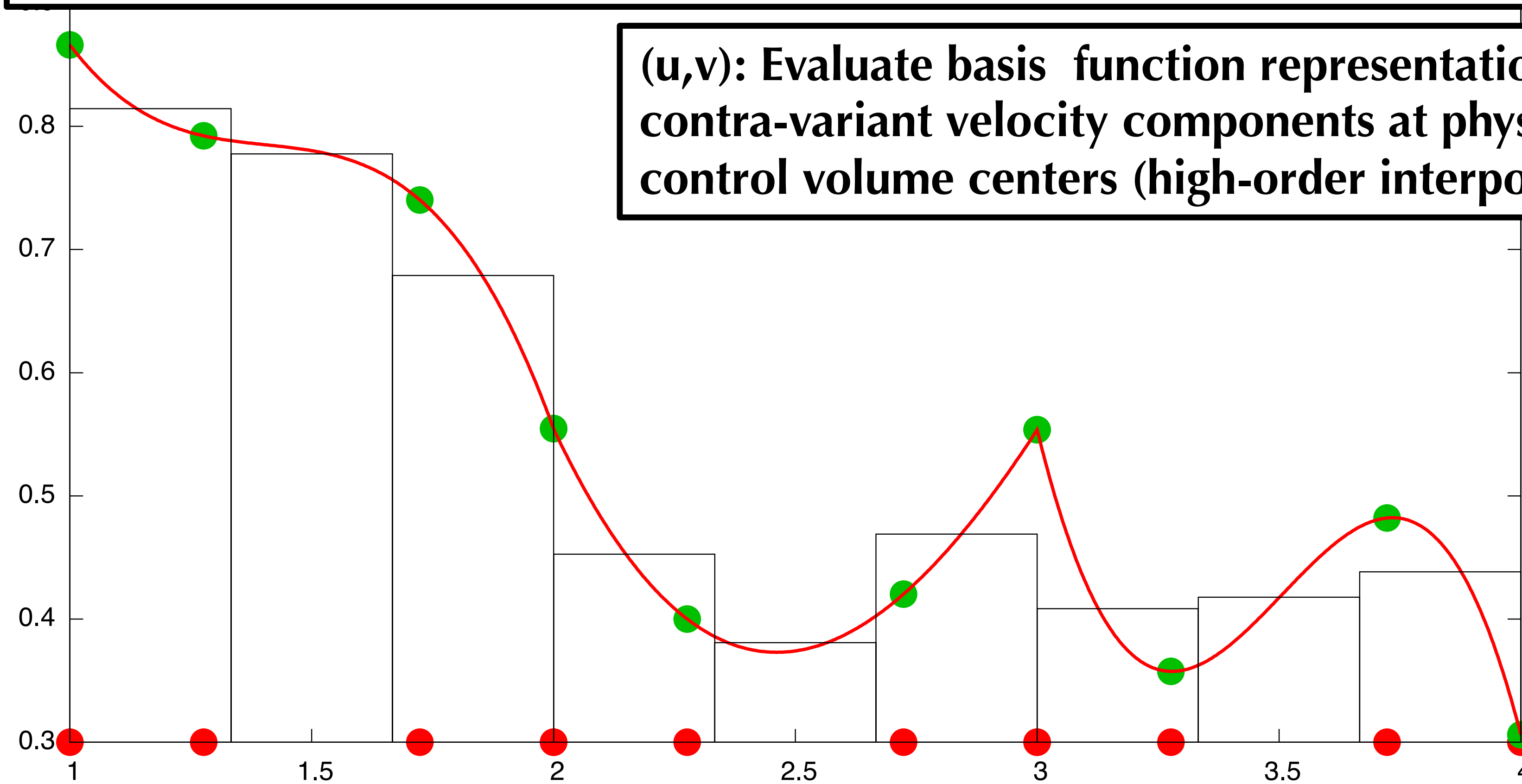


Scientific Discovery through Advanced Computing

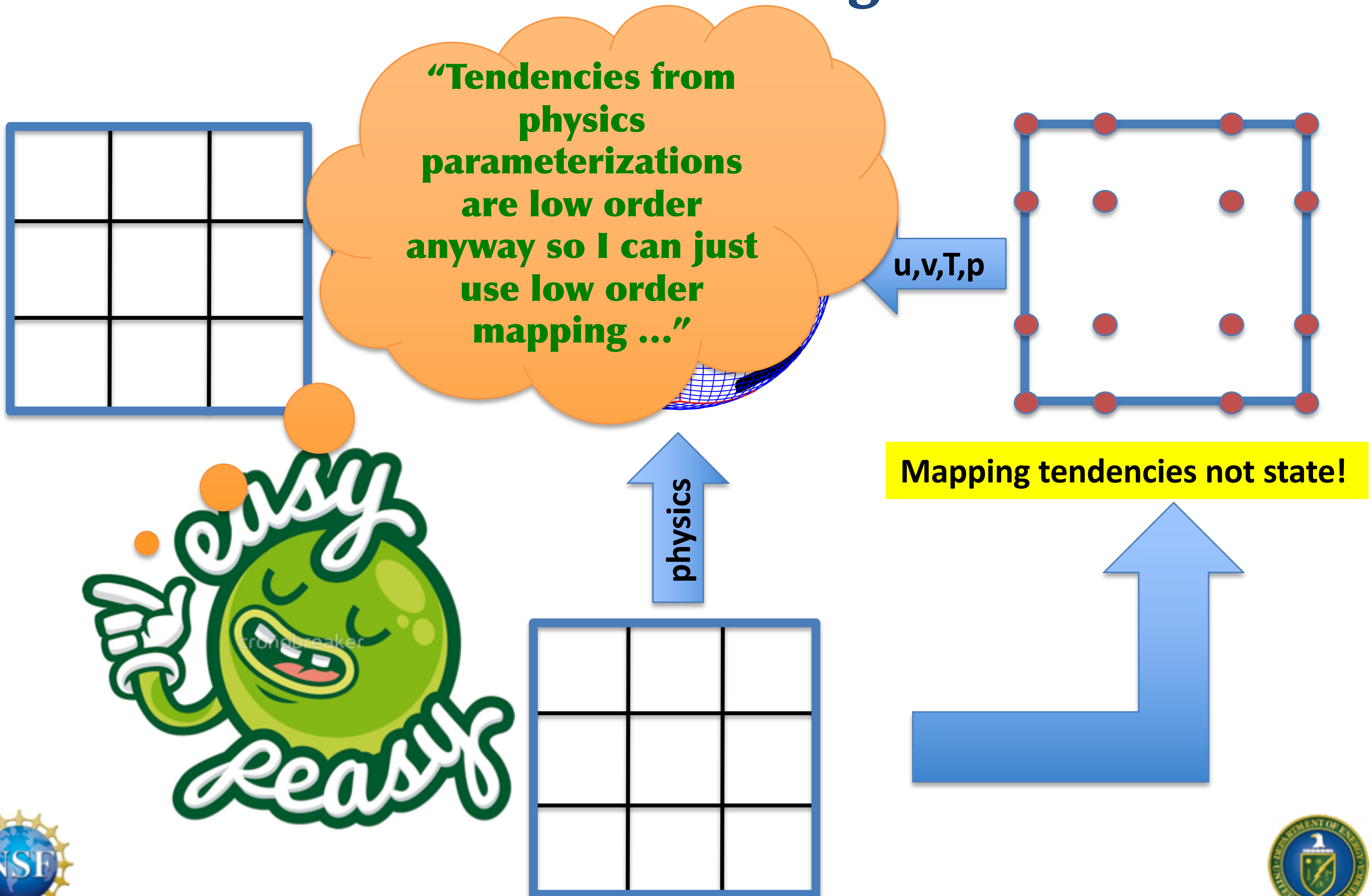
Mapping u,v, T, omega from dynamics grid (GLL) to finite-volume (CSLAM) grid

Temperature: Integrate basis function representation of dp*T over physics grid control volumes (high-order remapping; conserves dry internal energy)

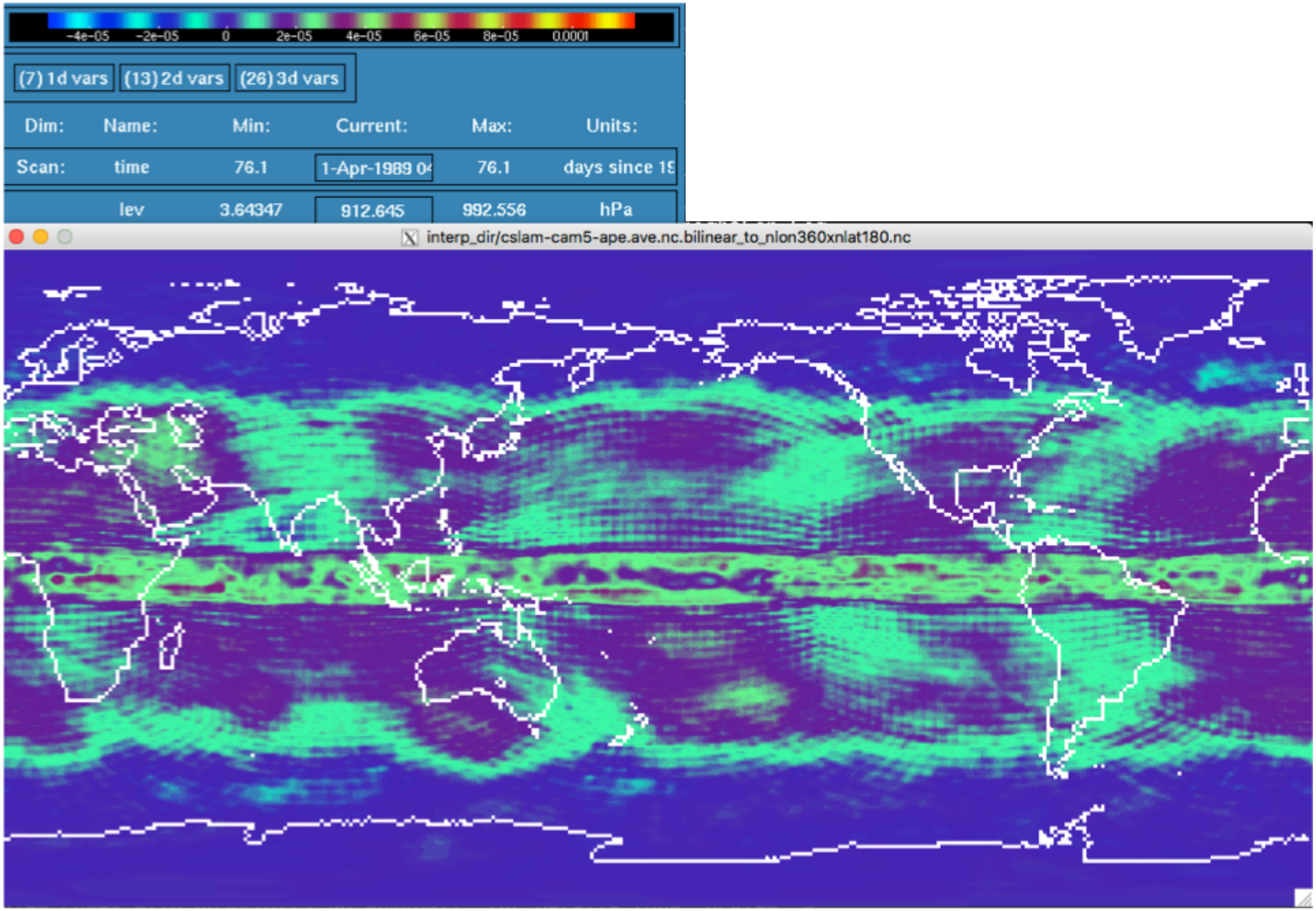
(u,v): Evaluate basis function representation of contra-variant velocity components at physics control volume centers (high-order interpolation)



CAM-SE-CSLAM configuration

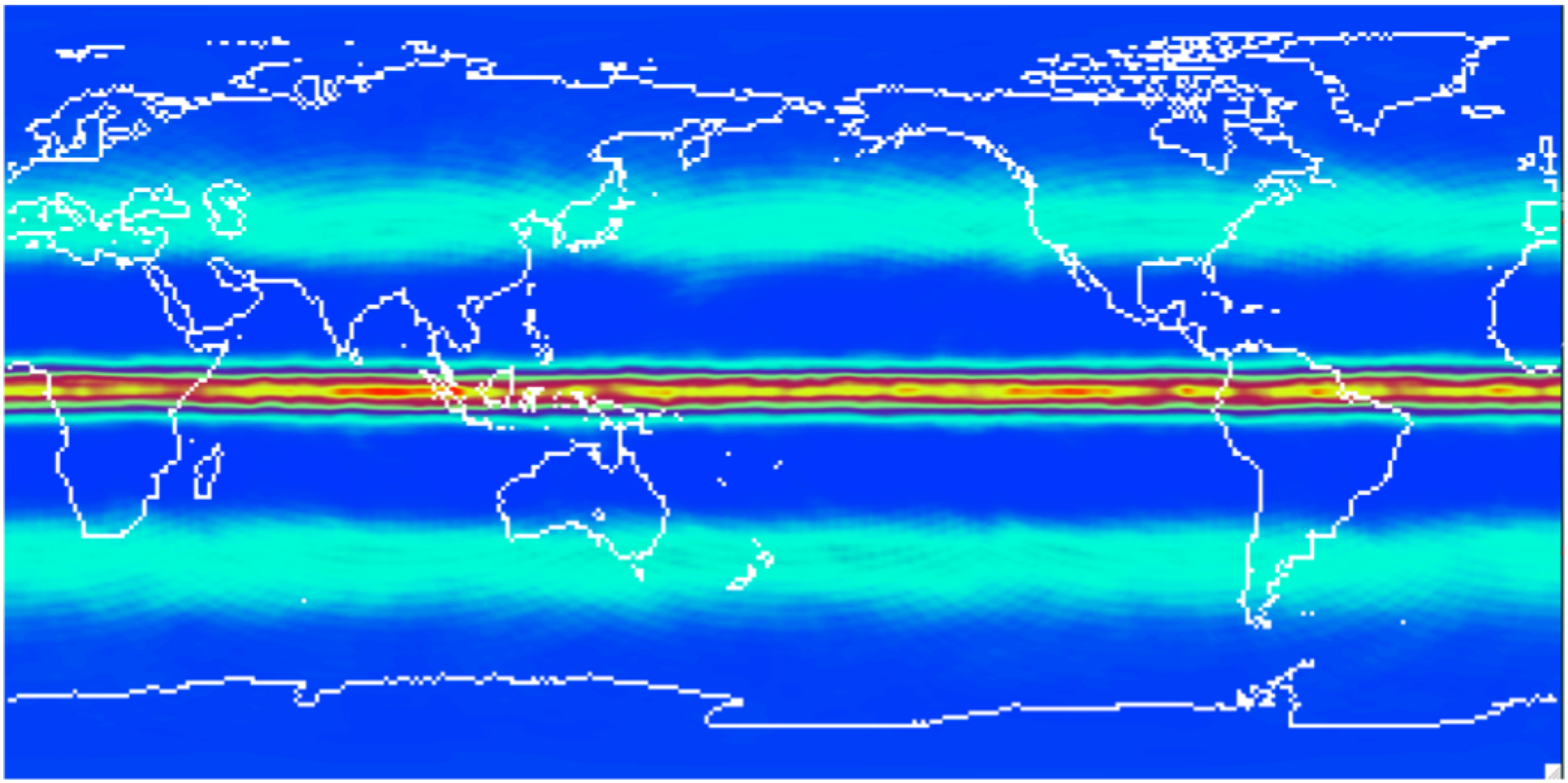


Temperature tendency: FT



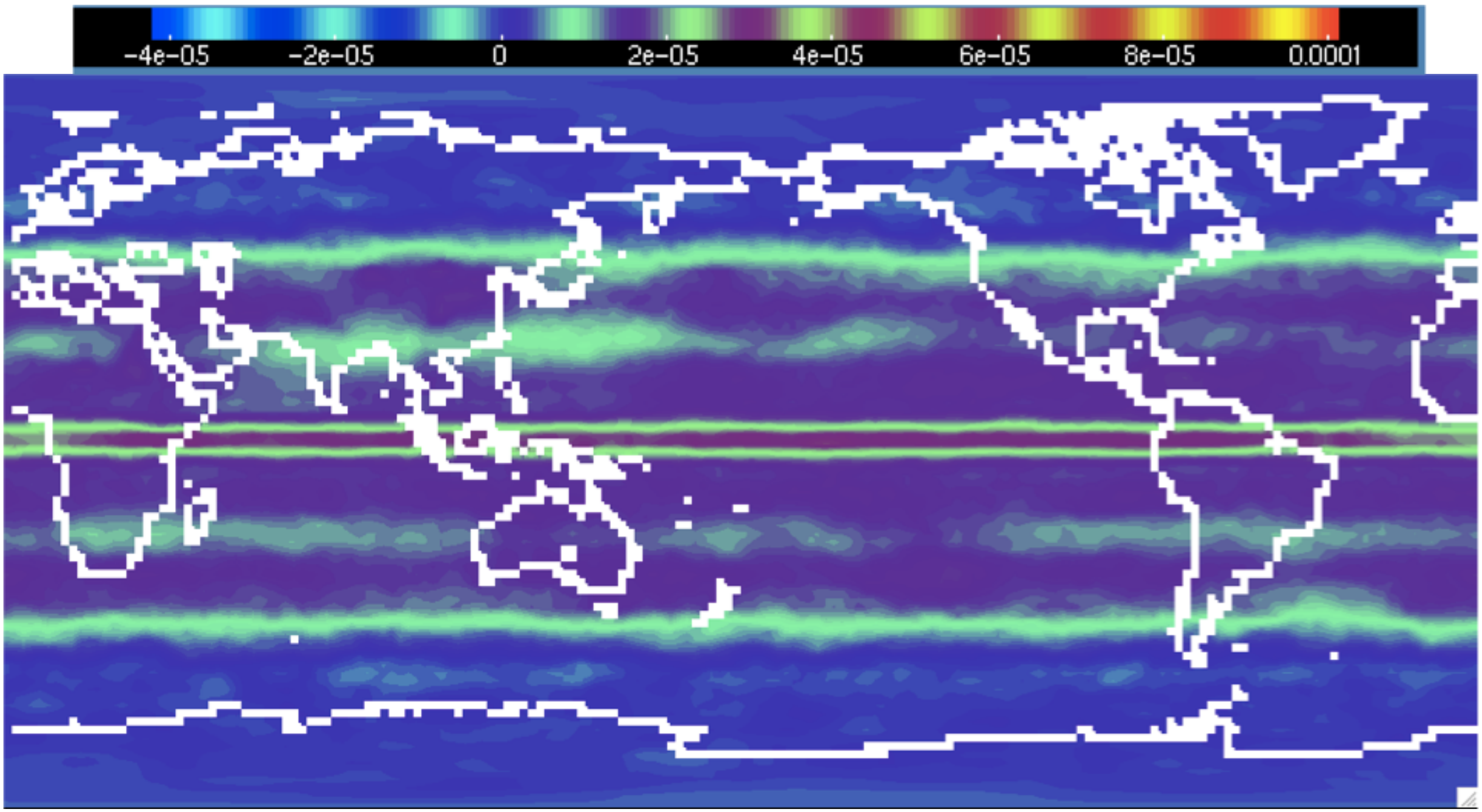
CAM-SE-CSLAM with linear interpolation from phys to dyn: 5 month average

PRECT
(TOTAL PRECIPITATION RATE)



CAM4 SE-CSLAM-physgrid: linear interpolation phys to dyn: 5 month average

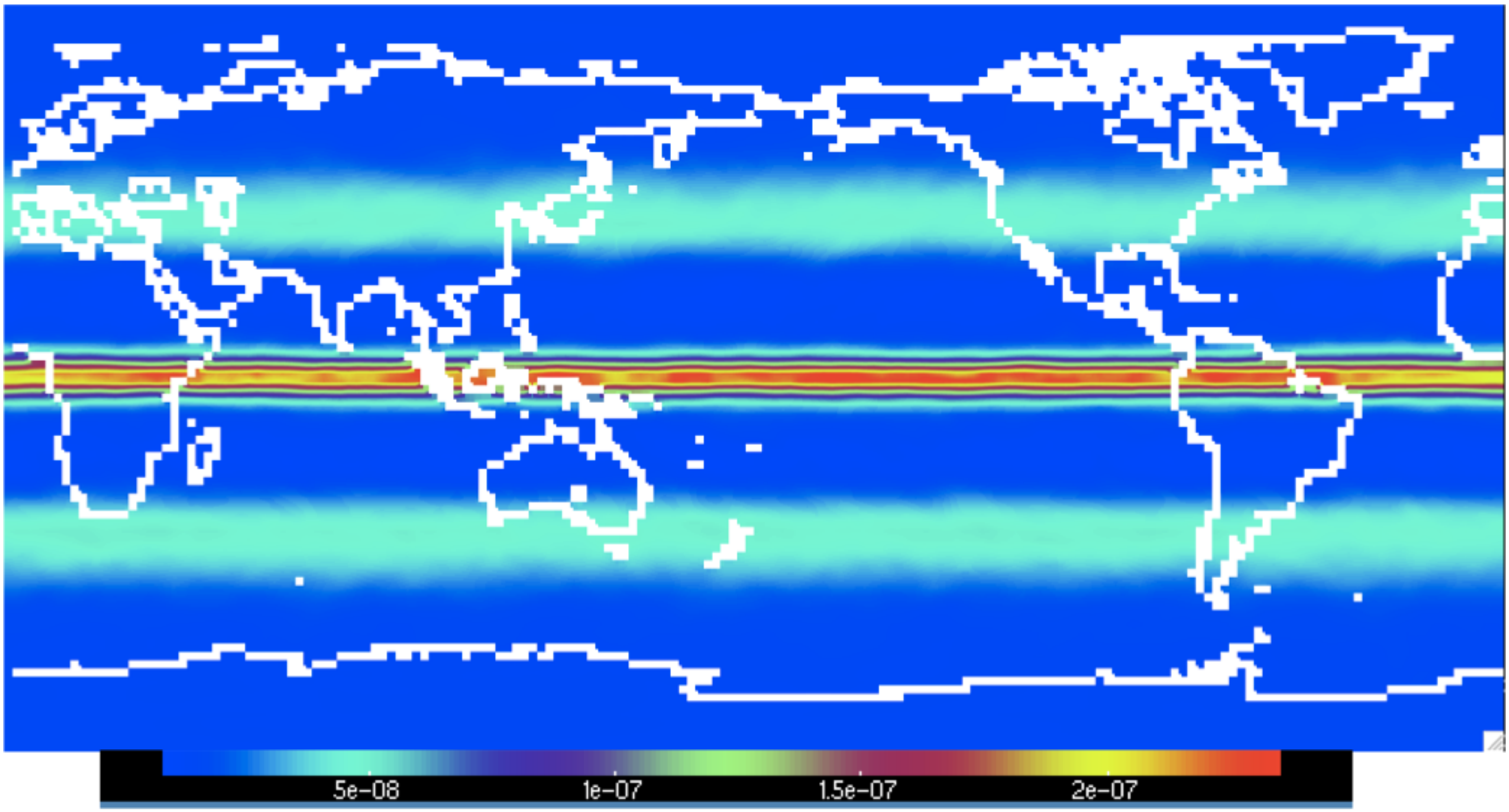
Temperature tendency: FT



CAM-SE-CSLAM with cubic tensor product interpolation from phys to dyn: 18 month average

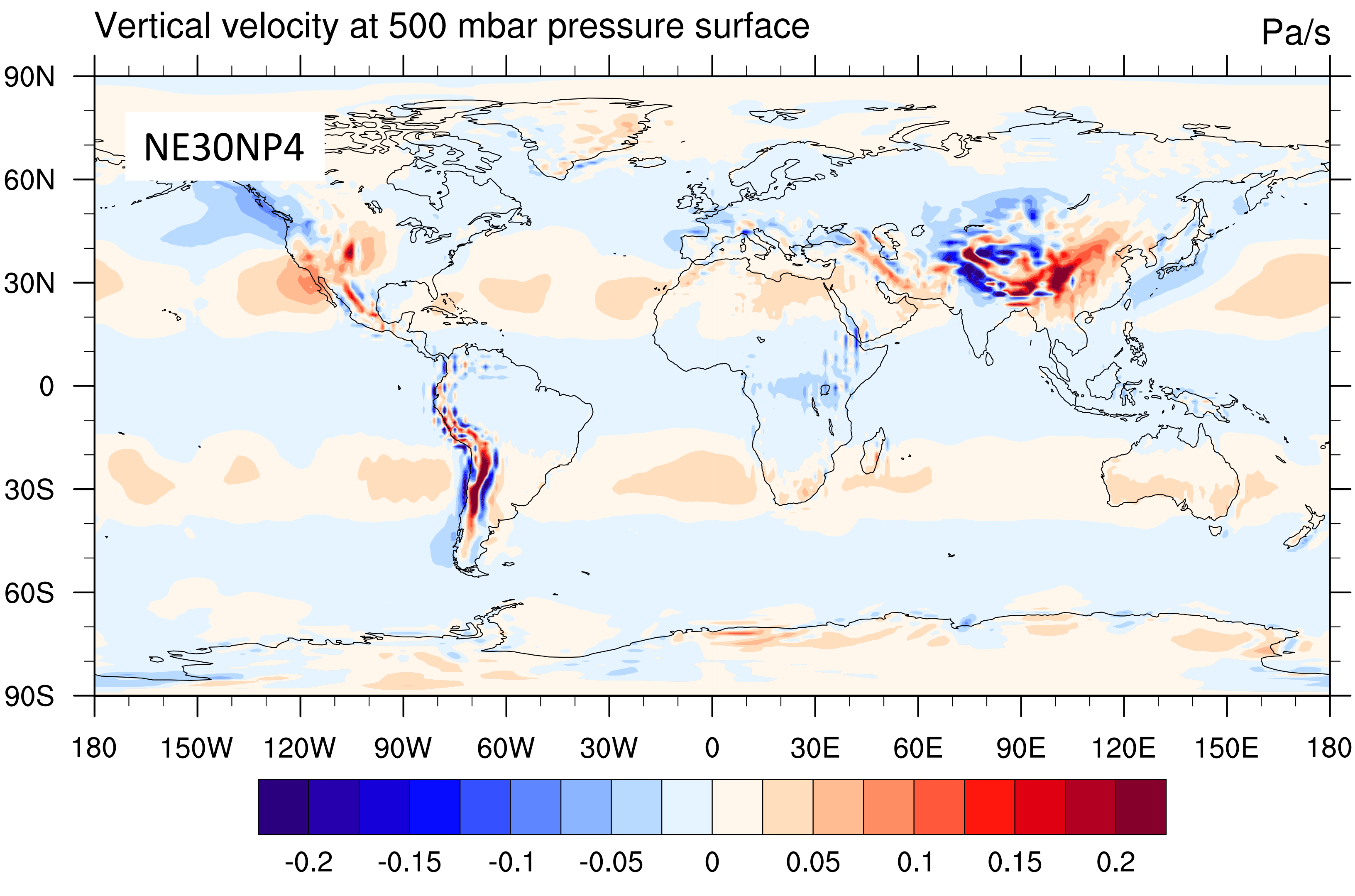
PRECT

(TOTAL PRECIPITATION RATE)

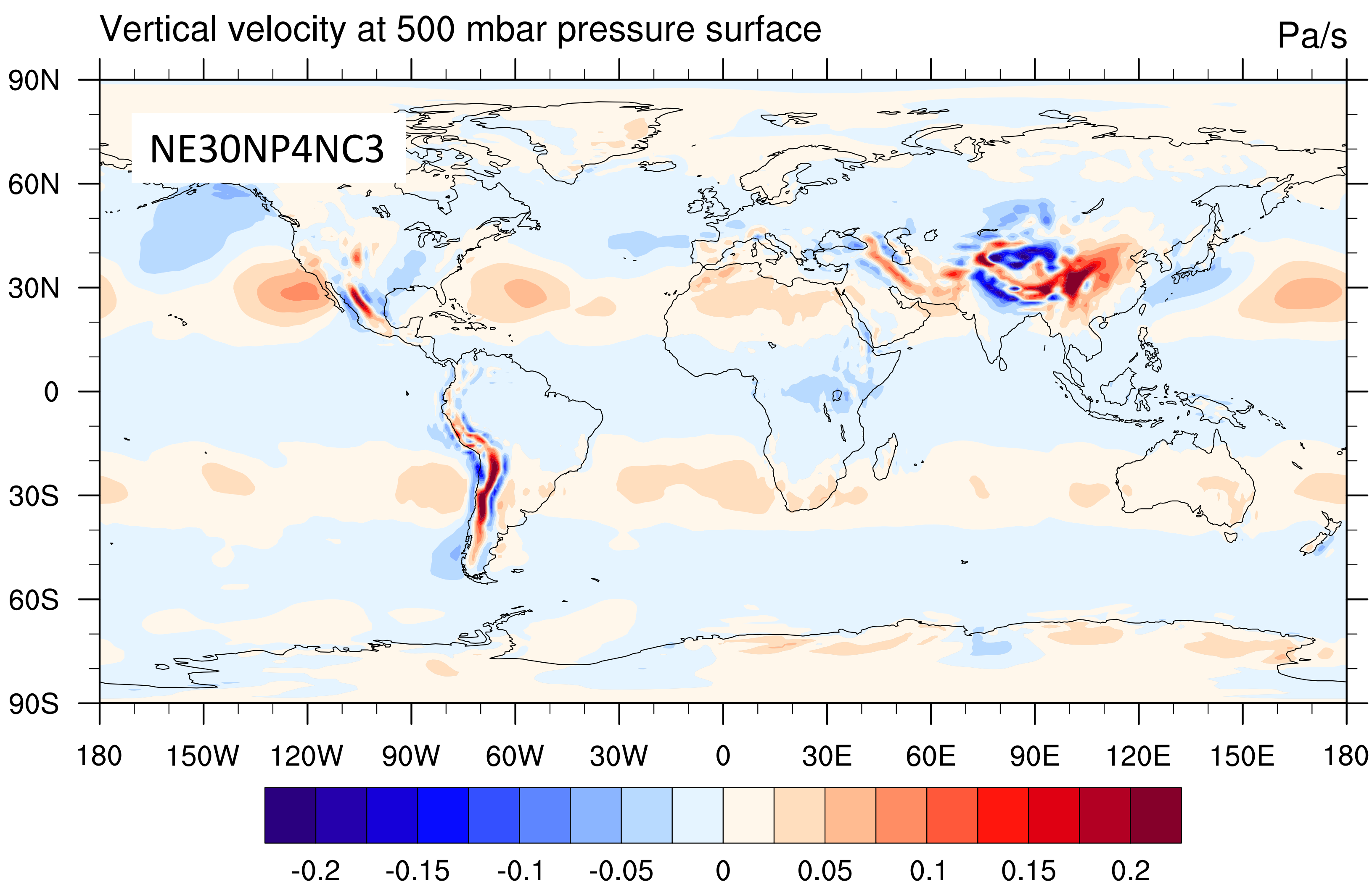


CAM-SE-CSLAM with cubic tensor product interpolation from phys to dyn: 18 month average

Held-Suarez with topography

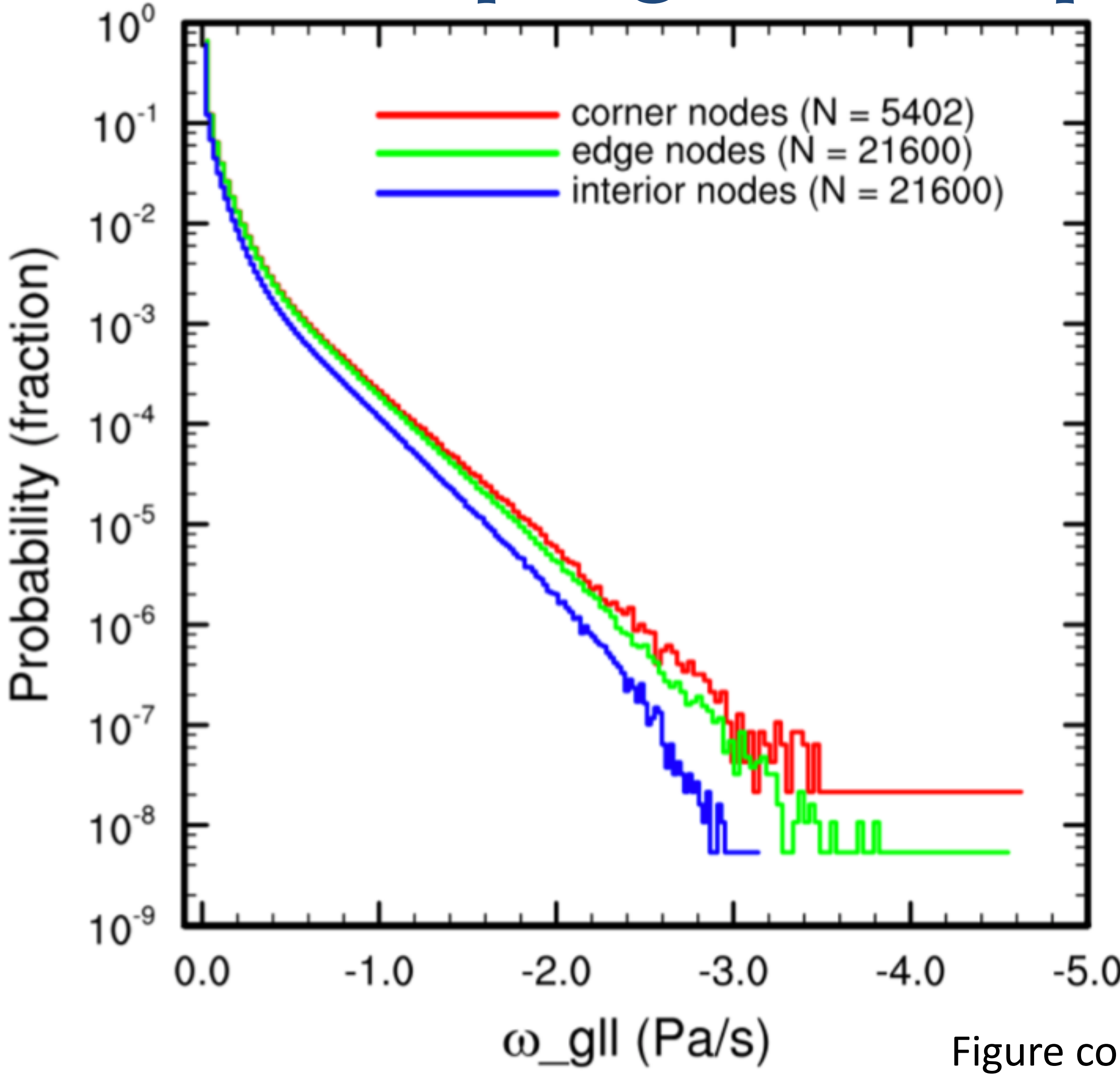


Held-Suarez with topography



Non-uniform sampling of atmospheric state

Data from aqua-planet simulation



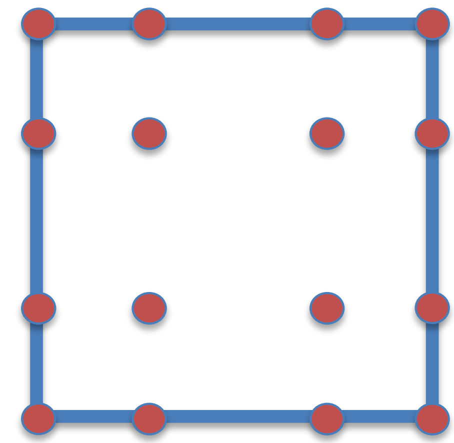
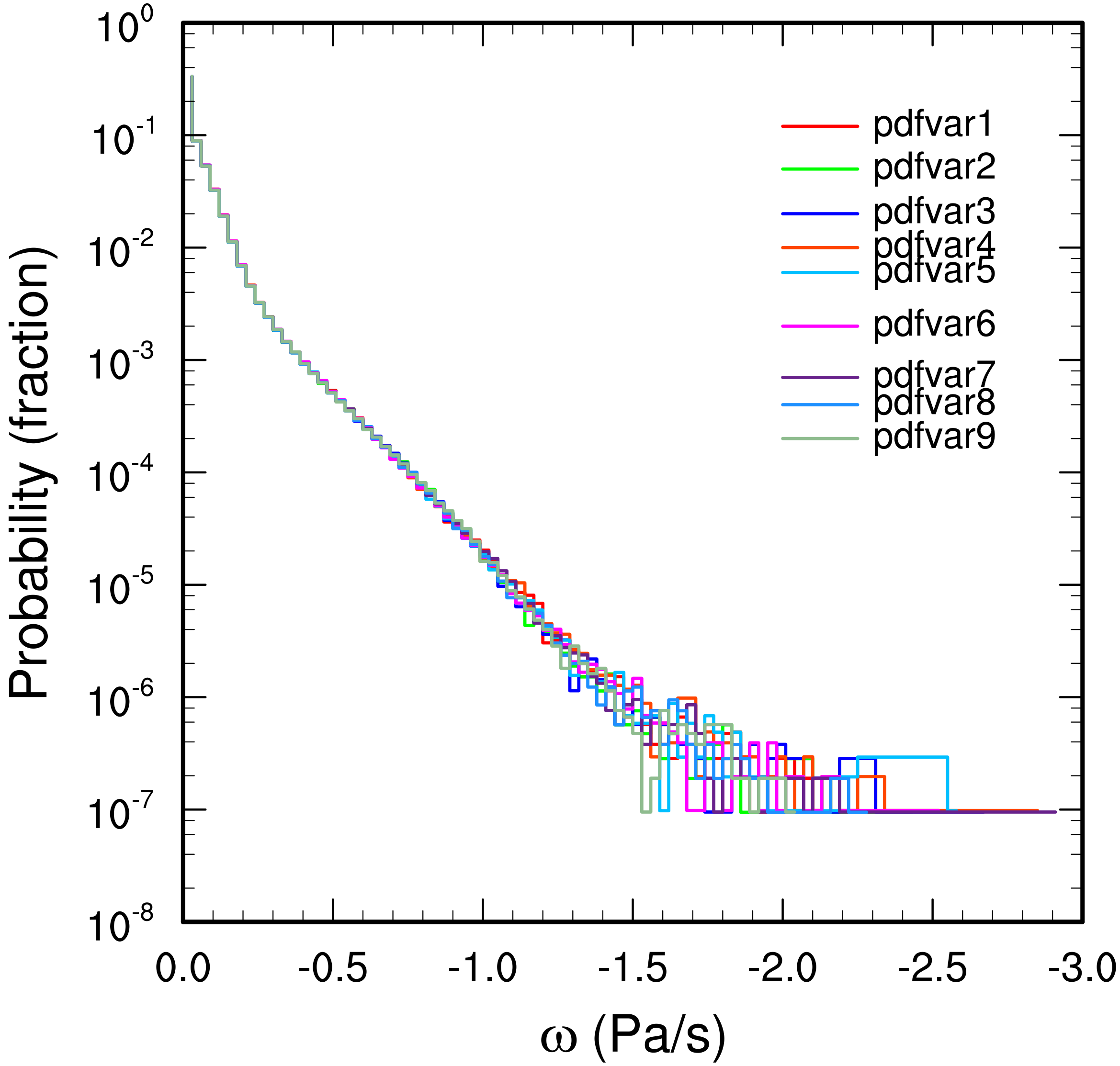


Figure courtesy of A. Herrington

Uniform sampling of atmospheric state

Data from aqua-planet simulation



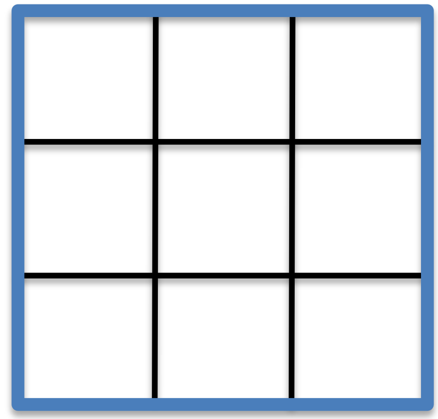
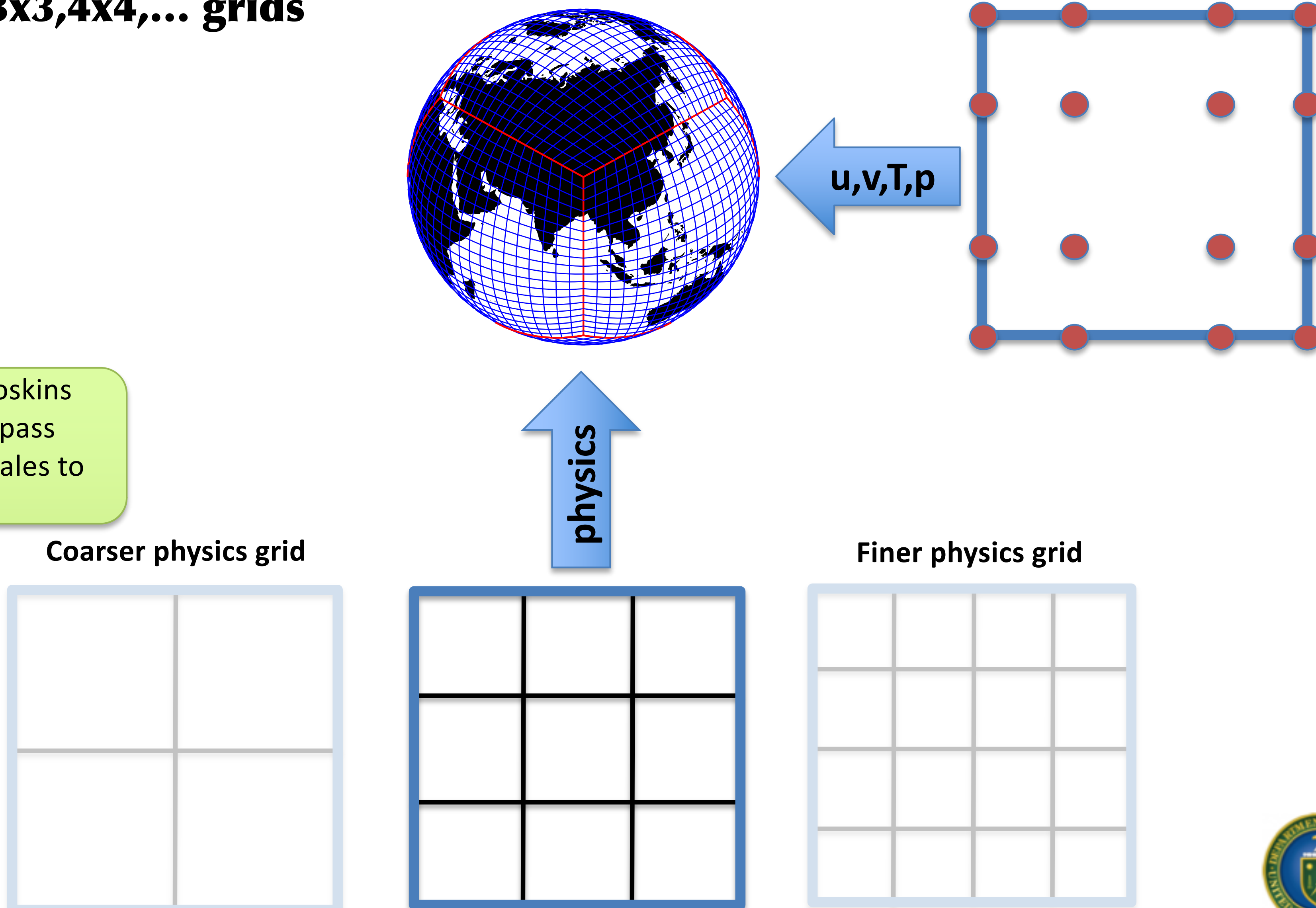


Figure courtesy of A. Herrington

CAM-SE-physgrid

- **Capability to run physics on 2x2,3x3,4x4,… grids**

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



Summary

- Presented algorithm to consistently couple spectral-element dynamics with remap finite-volume transport
- Accuracy is improved for "non-smooth" tracer distributions when using CAM-SE-CSLAM compared to CAM-SE.
- Note that our modeling framework is quite unique in the sense that we support finite-volume and high-order Galerkin methods in the same framework
- Capability to run physics on different grid than dynamics
- CAM-SE physgrid and CAM-SE-CSLAM (uses physgrid) are scheduled to be released with CESM2 later this year

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