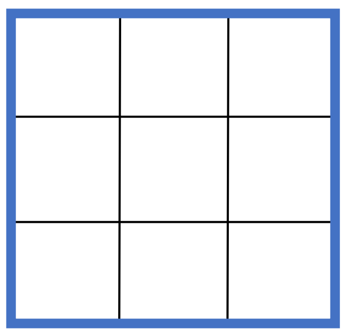
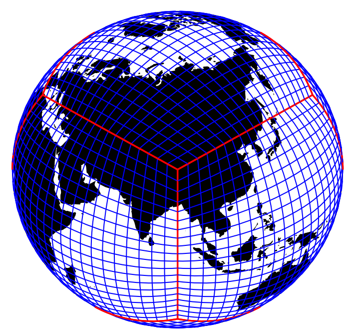
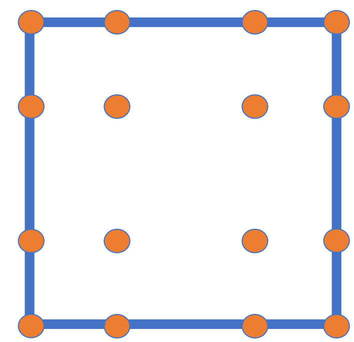
Physics-dynamics coupling with element-based high-order Galerkin methods: quasi equal-area physics grid







P.H. Lauritzen[1], A.R. Herrington[2], M.A. Taylor[3], K.A.Reed[2]

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3rd workshop on Physics Dynamics Coupling (PDC18), ECMWF, Reading, U.K.

Outline

- **Background information: NCAR release of CAM-SE in CESM2.0**

  CESM= NCAR's Community Earth System Model
  CAM = NCAR's Community Atmosphere Model
  SE = Spectral Elements

- **Motivation: SE method in some detail**

- **Quasi equal-area physics grid: CAM-SE-CSLAM (upcoming CESM2.1 release)**

  CSLAM = Conservative Semi-LAgrangian Multi-tracer transport scheme)

- **Lower resolution physics grid**

For a long time the SE (spectral-element) **dynamical core in HOMME** (High-Order Methods Modeling Environment) **was developed jointly with DOE** (US Department of Energy) **(referred to as CAM-HOMME in this talk)**

DOE E3SM

(Energy Exascale Earth System Model)

repository

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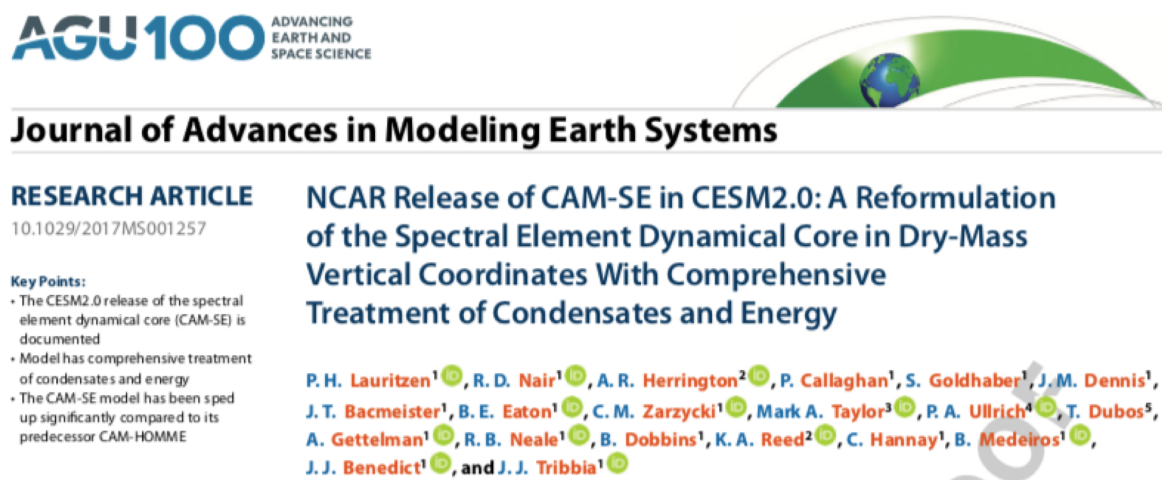
HOMME no longer imported as an external into CAM but part of CAM (referred to as CAM-SE in this talk) &



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Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE

10.1029/2017MS001257

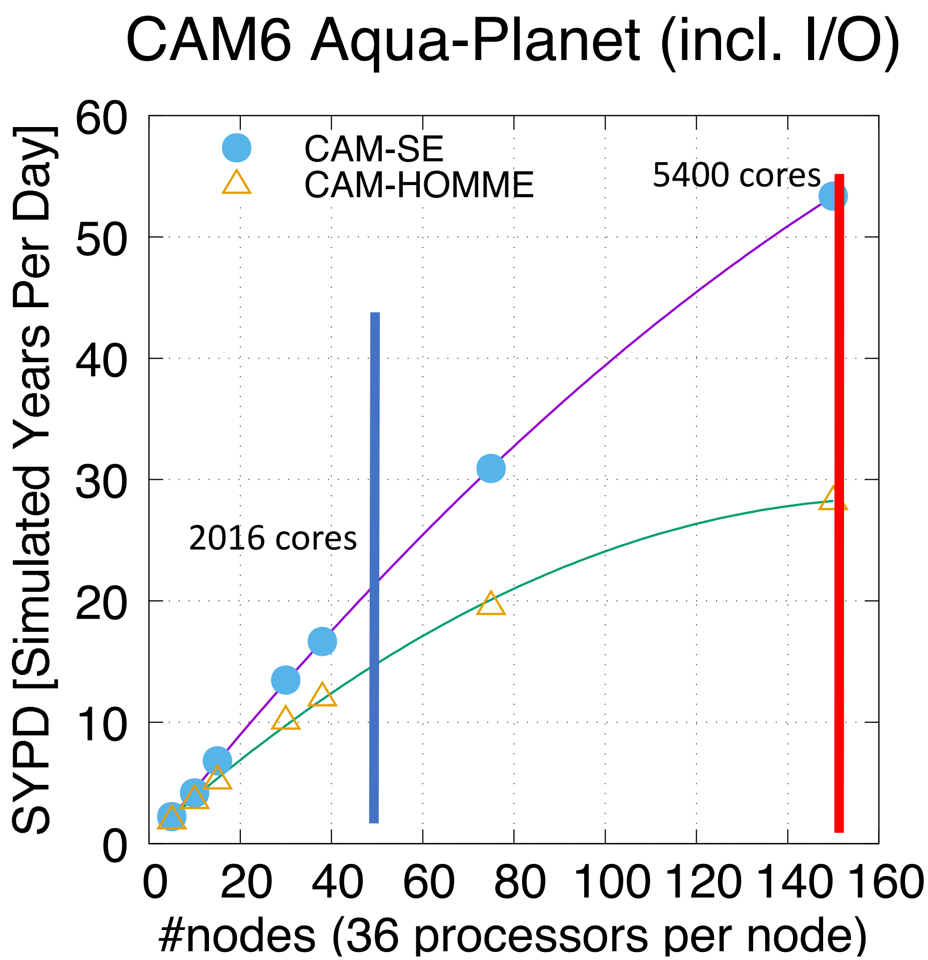
Key Points:

- The CESM2.0 release of the spectral element dynamical core (CAM-SE) is documented
- Model has comprehensive treatment of condensates and energy
- The CAM-SE model has been sped up significantly compared to its predecessor CAM-HOMME

NCAR Release of CAM-SE in CESM2.0: A Reformulation of the Spectral Element Dynamical Core in Dry-Mass Vertical Coordinates With Comprehensive Treatment of Condensates and Energy

P. H. Lauritzen[1], R. D. Nair[1], A. R. Herrington[2], P. Callaghan[1], S. Goldhaber[1], J. M. Dennis[1], J. T. Bacmeister[1], B. E. Eaton[1], C. M. Zarzycki[1], Mark A. Taylor[3], P. A. Ullrich[4], T. Dubos[5], A. Gettelman[1], R. B. Neale[1], B. Dobbins[1], K. A. Reed[2], C. Hannay[1], B. Medeiros[1], J. J. Benedict[1], and J. J. Tribbia[1]

What changed (CAM-HOMME -> CAM-SE)? 0. Throughput



Lauritzen et al. (2018)

What changed? 1. Vertical coordinate & condensate loading

(CAM-HOMME -> CAM-SE)

- Dry-mass vertical coordinate ($M^{(d)}$ is dry air mass per unit area):

$$M^{(d)}_{k+1/2} = A_{k+1/2} M^{(d)}_t + B_{k+1/2} M^{(d)}_s$$

Pressure is a diagnostics:

$$p_{k+1/2} = p_t + g \sum_{j=1}^{k} \Delta M^{(d)}_j \left(\sum_{\ell \in \mathcal{L}_{all}} m^{(\ell)}_j \right)$$

where

$$\mathcal{L}_{all} = \{`d`, `wv`, `cl`, `ci`, `rn`, `sw`\}$$

Lauritzen et al. (2018)

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What changed? 2. More comprehensive energy equation

(CAM-HOMME -> CAM-SE)

The total energy equation integrated over the global domain is also derived in Appendix B: . The final equation is

$$\frac{\partial}{\partial t}\int_{\eta=0}^{\eta=1}\iint_S \left(\frac{\partial M^{(d)}}{\partial \eta^{(d)}}\right)\sum_{\ell\in\mathcal{L}_{all}}\left[m^{(\ell)}\left(K+c_p^{(\ell)}T+\Phi_s\right)\right] dA d\eta^{(d)} = 0. \quad (61)$$

Note that the energy terms (inside square brackets) in (61) separate into contributions from each component of moist air

$$\left(\frac{\partial M^{(d)}}{\partial \eta^{(d)}}\right)\sum_{\ell\in\mathcal{L}_{all}}\left[m^{(\ell)}\left(K+c_p^{(\ell)}T+\Phi_s\right)\right]. \quad (62)$$

$$\left(\frac{\partial M^{(d)}}{\partial \eta^{(d)}}\right)\left(1+m^{(wv)}\right)\left[\left(K+c_p^{(d)}T+\Phi_s\right)\right]$$

CAM physics version of (62)
Discrepancy ~ 0.5W/m²

Lauritzen et al. (2018)

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What changed? 3. Reduced viscosity coefficients and viscosity applied to dM-dM(ref) instead of dM

(CAM-HOMME -> CAM-SE)

Reduces large spurious vertical velocities over steep orography => allows for reduced damping coefficients compared to CAM-HOMME (divergence damping reduced by over 6x)

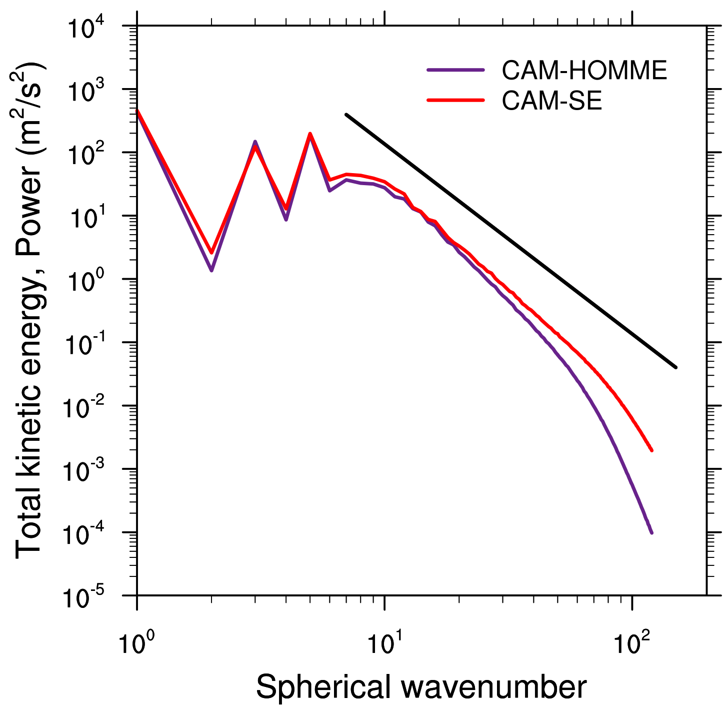

Figure 6. Total kinetic energy spectrum of the horizontal winds at the 200 hPa level in CAM-HOMME and CAM-SE at 1° horizontal resolution (N_e = 30 and N_p = 4), computed as the mean spectra from 30 days of 6-hourly instantaneous spectra. Black line is the κ^{-3} reference scaling, where κ is wave-number.

Lauritzen et al. (2018)

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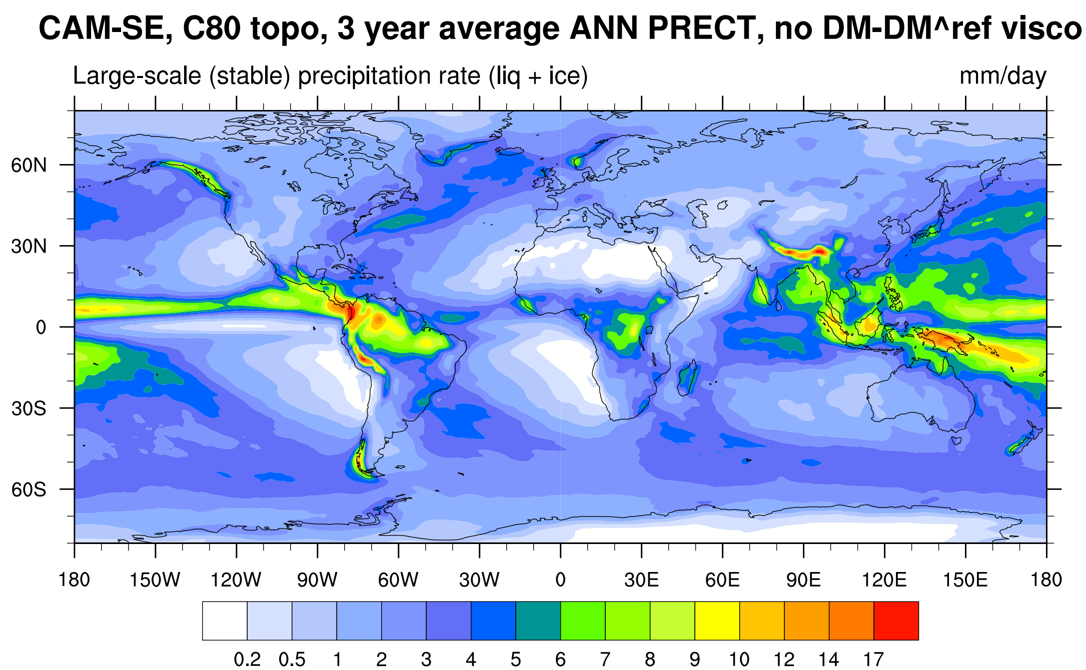
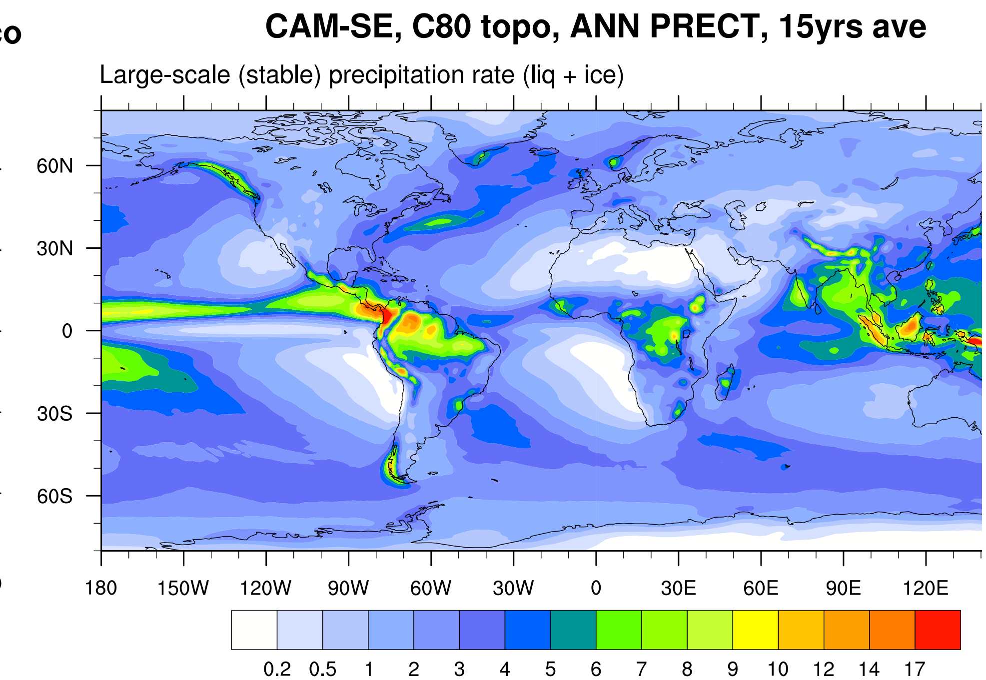
What changed? 3. Reduced viscosity coefficients and viscosity applied to dM-dM$^{(ref)}$ instead of dM

(CAM-HOMME -> CAM-SE)



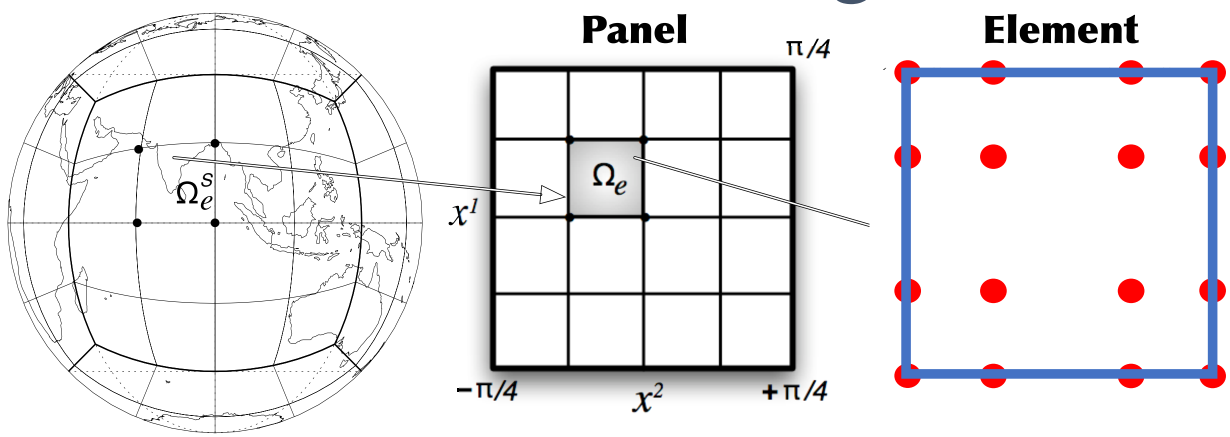


Lauritzen et al. (2018)

6-hourly instantaneous spectra. Black line is the κ^{-3} reference scaling, where κ is wave-number.

Part I (motivation):
The spectral-element (SE) method
in some detail

The spectral-element method: discretization grid



Physical Domain

Computational Domain

GLL Quadrature Grid

Nodal 1D polynomial basis functions

GLL=Gauss-Lobatto-Legendre

The spectral-element method: discretization grid

Panel $\pi/4$ **Element**

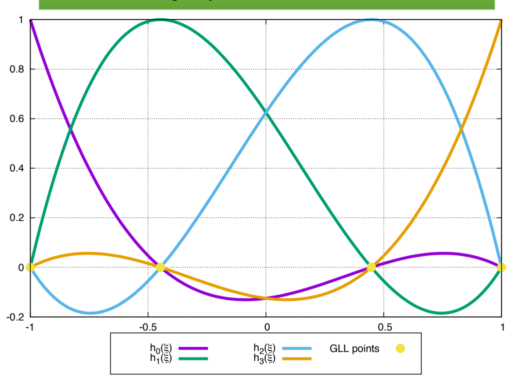
For any arbitrary variable f (e.g., T, u, v, ...) one can approximate f as a function of a tensor product of 1D basis functions on the 2D GLL grid:

$$f(x,y) = \sum_{i,j} f_{i,j} h_i(x_i) h_j(y_j),$$

where $f_{i,j}$ is grid point values of f.

Physical Domain Computational Domain GLL Quadrature Grid

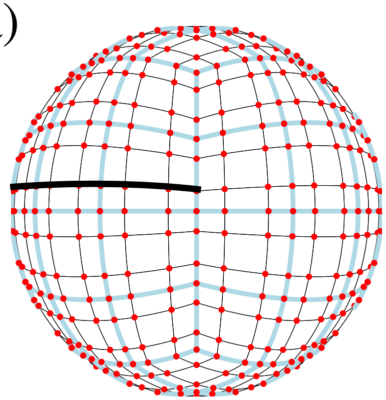
Nodal 1D polynomial basis functions

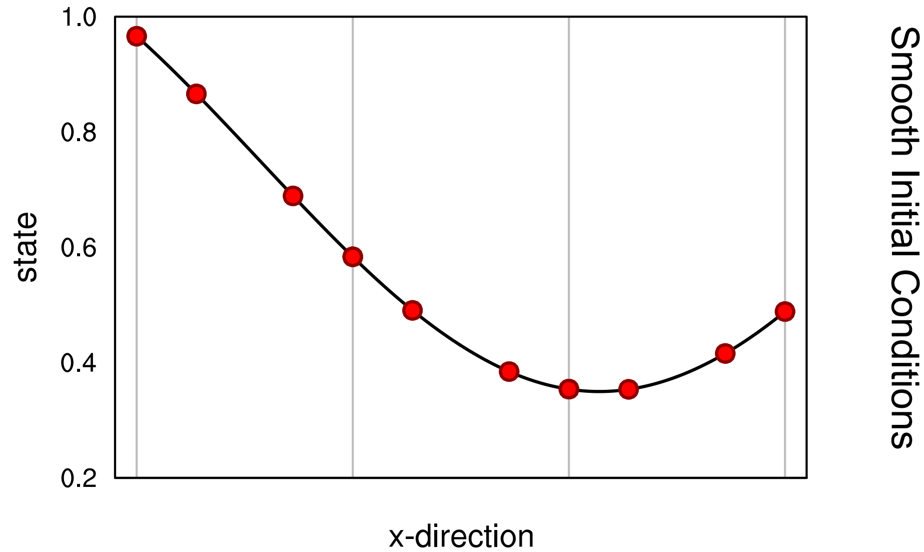


GLL=Gauss-Lobatto-Legendre

Consider transect through 3 elements

(a)



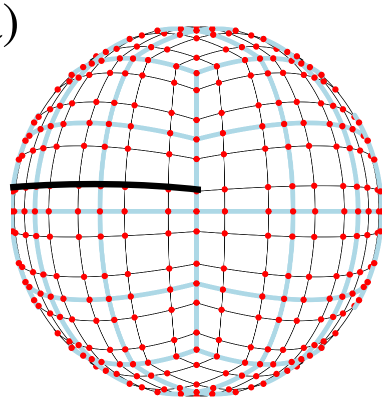


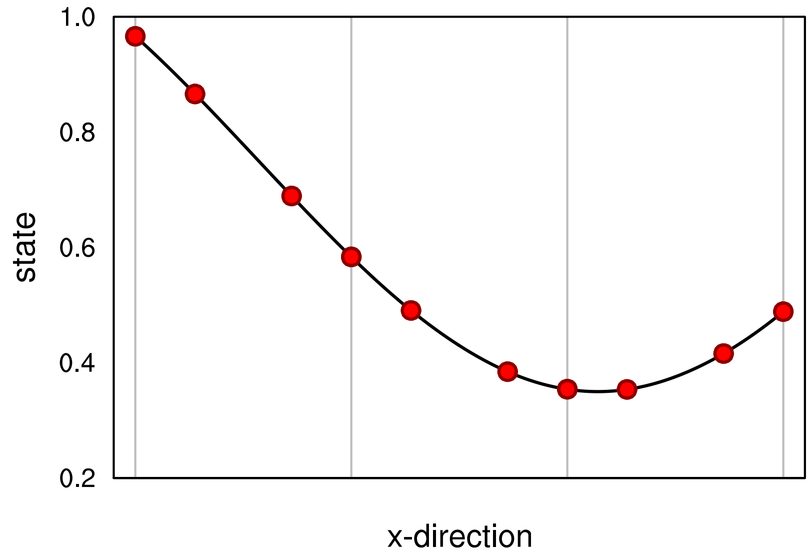
Continuity equation for Δp:

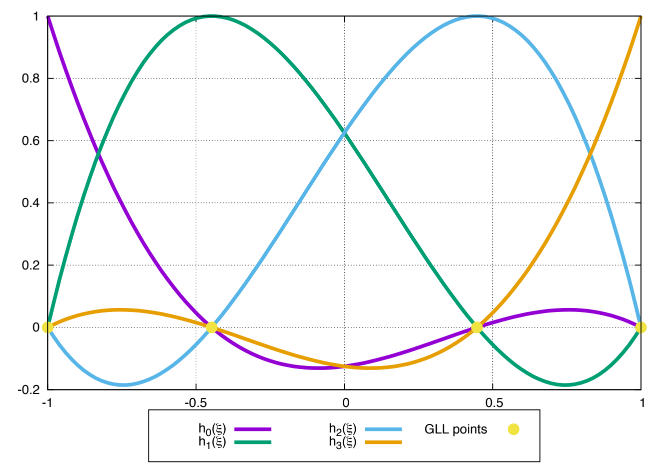
$$\frac{\partial \Delta p}{\partial t} = -\nabla \cdot \Delta p \vec{v} + \tau \nabla^4 \Delta p.$$

Consider transect through 3 elements

(a)







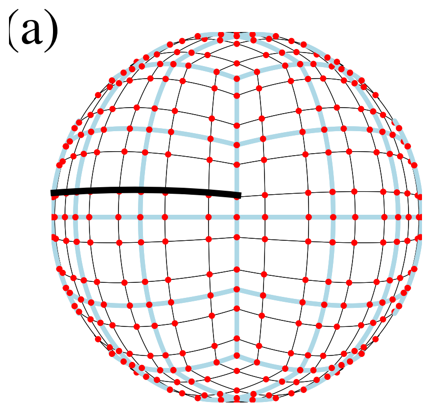
Continuity equation for Δp:

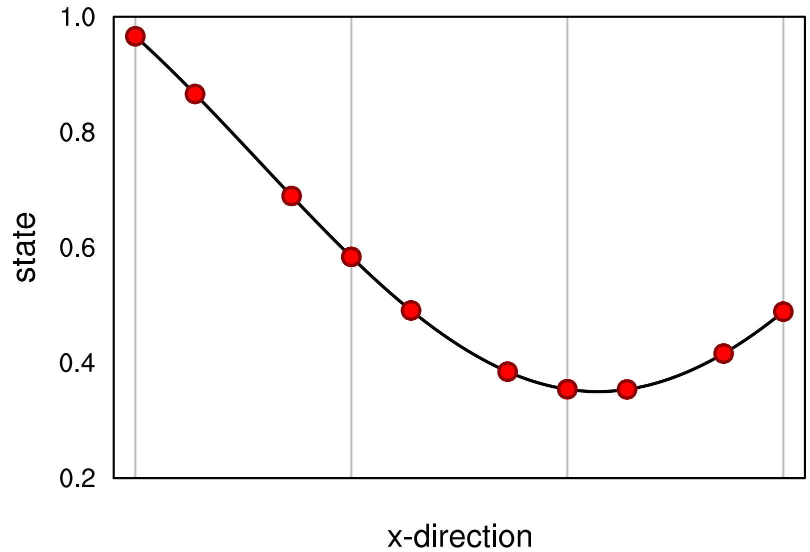
$$\left\langle h_k, \frac{\partial \Delta p}{\partial t} \right\rangle = \langle h_k, -\nabla \cdot \Delta p \vec{v} \rangle + \langle h_k, \tau \nabla^4 \Delta p \rangle,$$

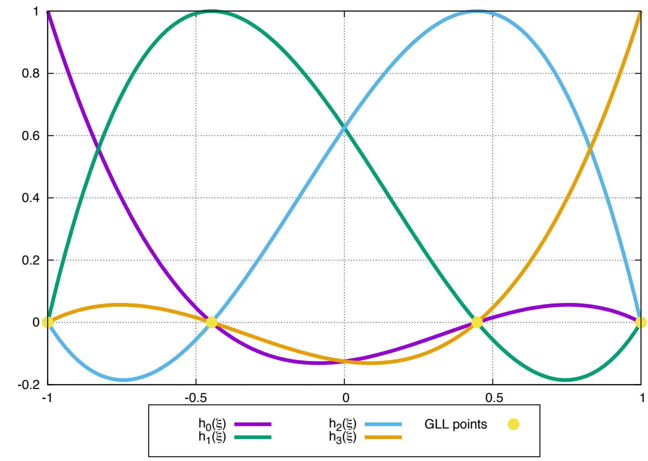
where $\langle h_k, \cdot \rangle$ is inner product

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

Consider transect through 3 elements







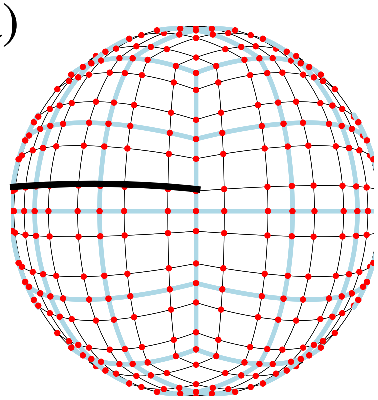
Continuity equation for Δp:

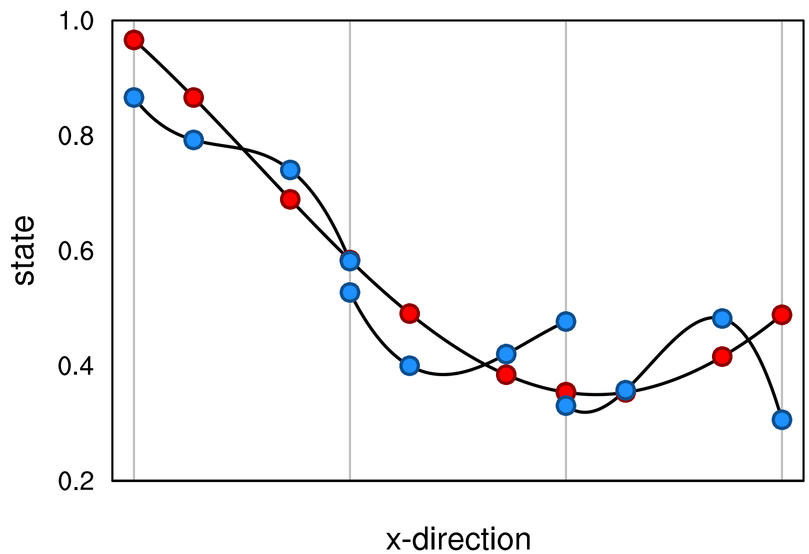
$$\left\langle h_k, \frac{\Delta p^* - \Delta p^n}{\Delta t} \right\rangle = \langle h_k, -\nabla \cdot \Delta p \vec{v} \rangle + \left\langle h_k, \tau \nabla^4 \Delta p \right\rangle .$$

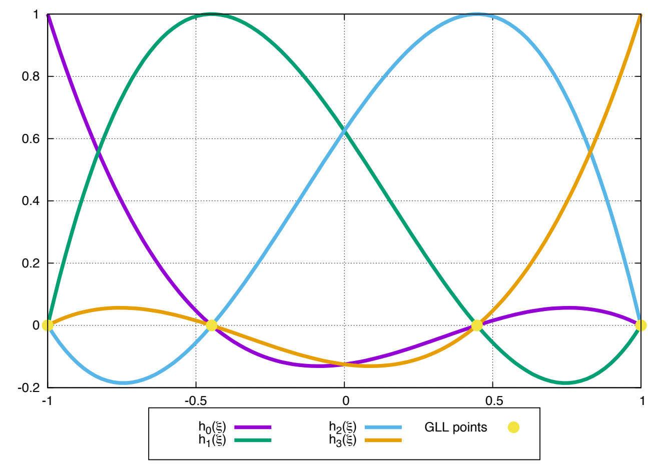
Temporal discretization: multi-stage Runge-Kutta time-stepping

Consider transect through 3 elements

(a)







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

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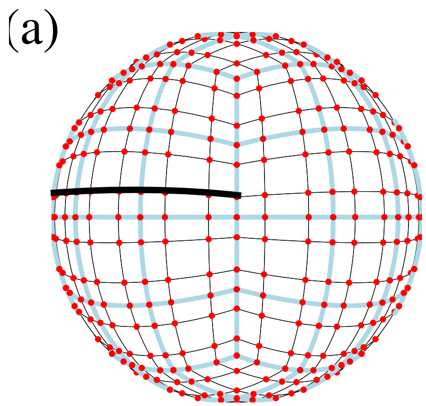
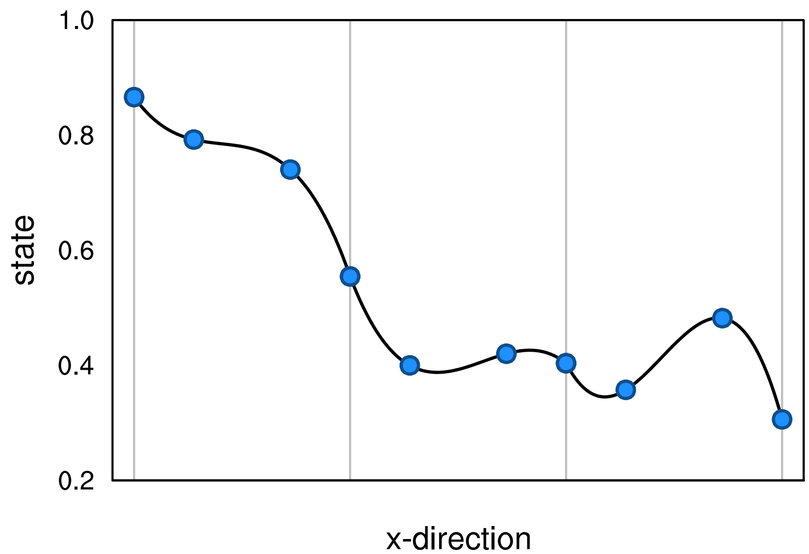
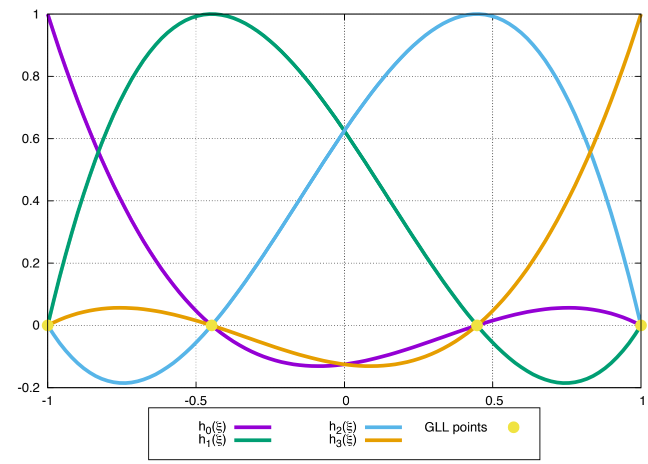




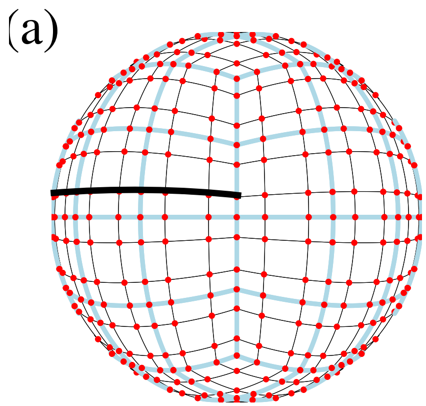


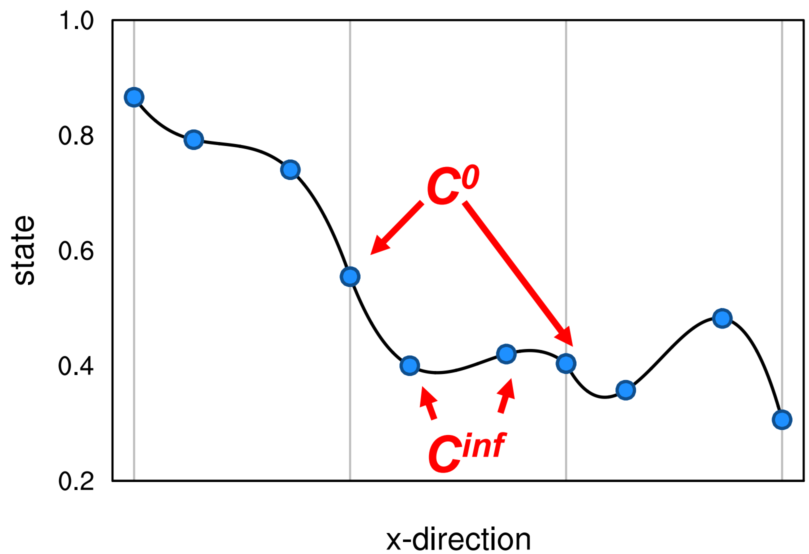
- Projection step

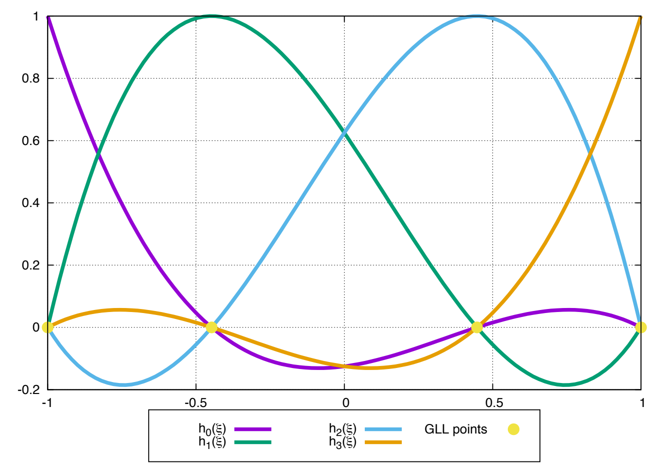
$$\Delta p^{n+1} = DSS\left(\Delta p^{*}\right)$$

  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).

Consider transect through 3 elements







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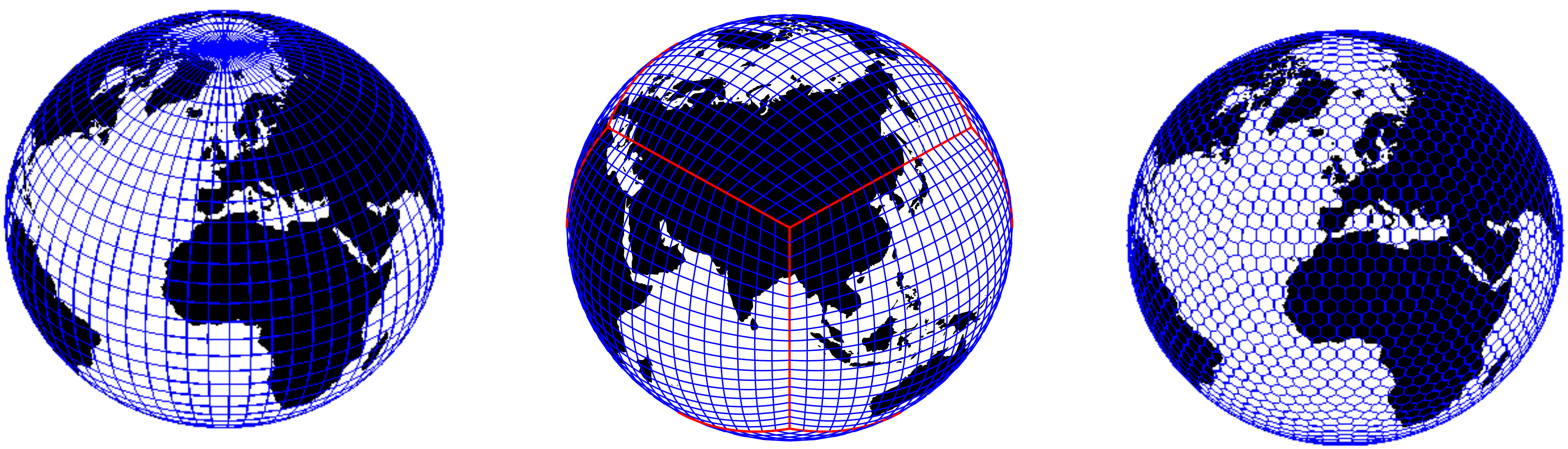
The physics dynamics coupling paradigm

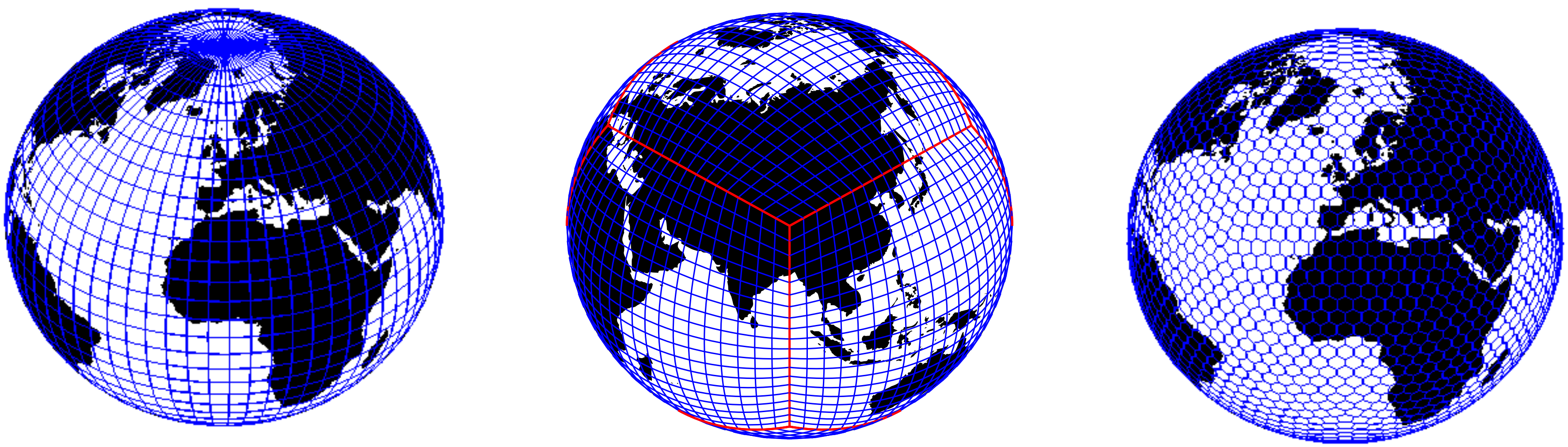
Assumptions inherent to the physical parameterizations require the state passed by the dynamical core represent a 'large-scale state', for example, in quasi-equilibrium-type convection schemes (Arakawa and Schubert 1974)



The physics dynamics coupling paradigm

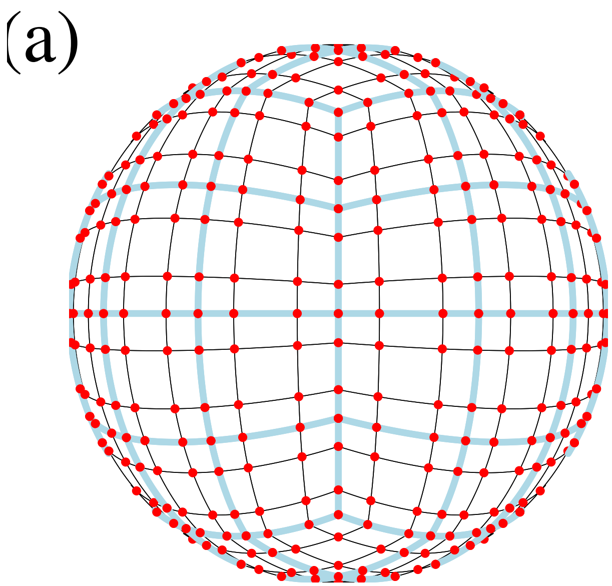
Finite-volume methods : dynamical core state = average state over a control volume
Finite-difference methods : point value representative for dynamical core state - in the vicinity of point value one can usually associate a volume with the grid-point that is representative of state.

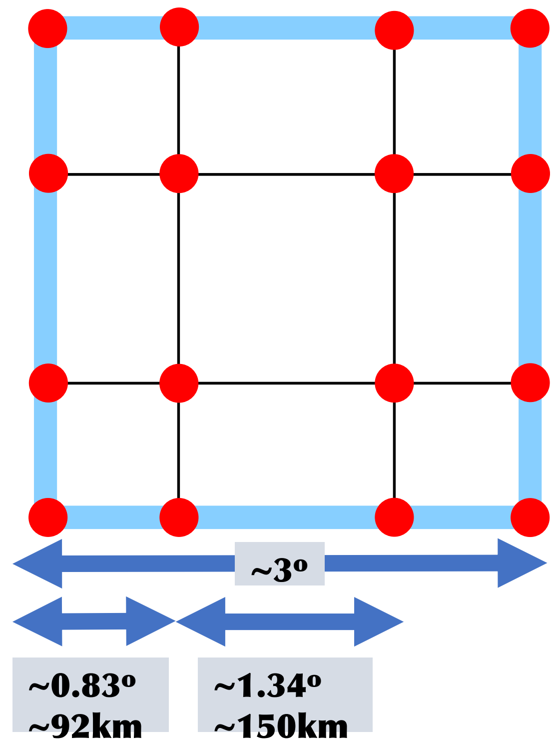
For the regular latitude-longitude, cubed-sphere and icosahedral grids the distance between the grid-points is gradually varying for finite-volume/finite-difference discretizations!



The physics dynamics coupling paradigm

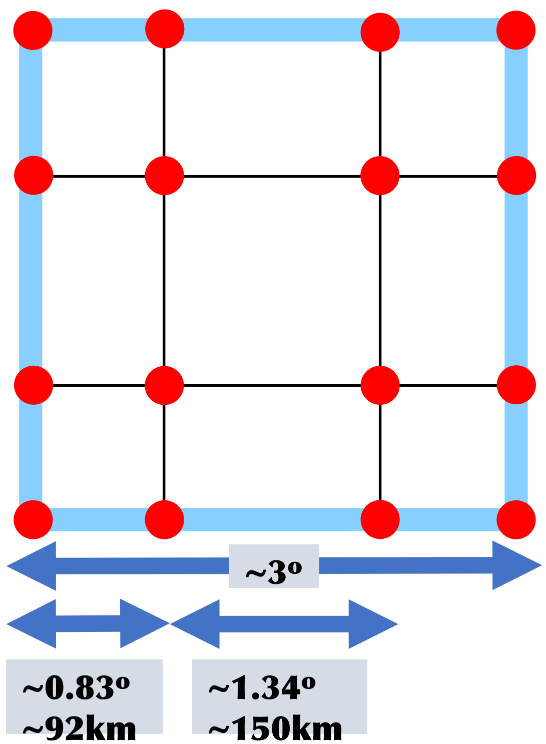
A unique aspect of the high-order quadrature rules is that the nodes within an element are located at the roots of the basis set, which may be irregularly spaced

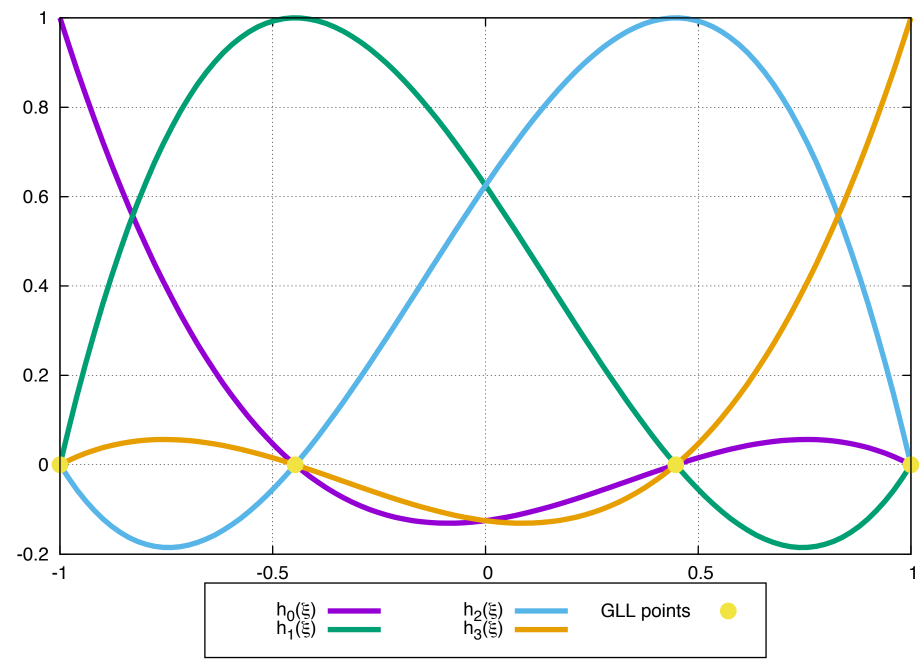




The physics dynamics coupling paradigm

The resolved scales of motion are not determined by the distance between quadrature nodes, but rather the degree of the polynomial basis in each element. The nodes may be viewed as irregularly spaced samples of an underlying spectrally truncated state.

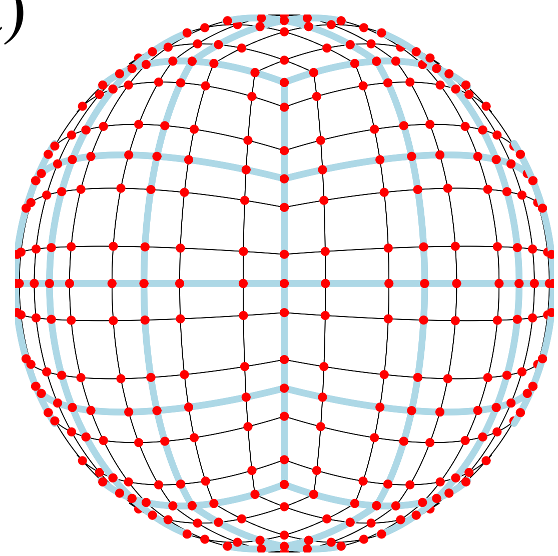


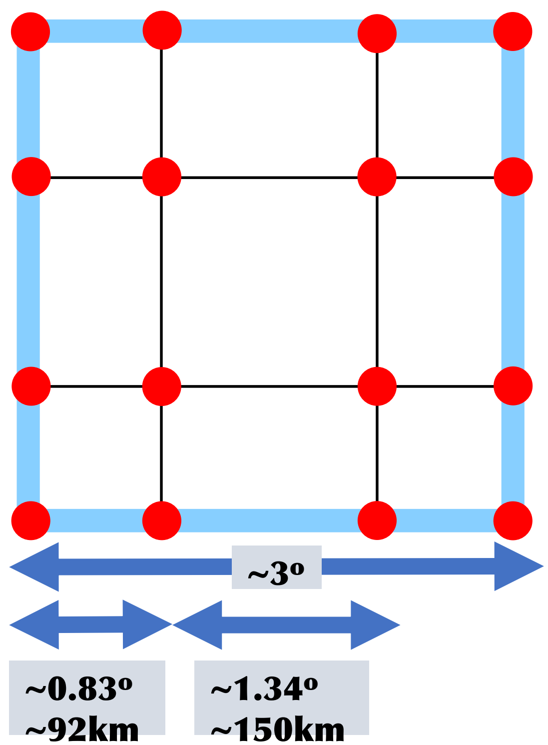


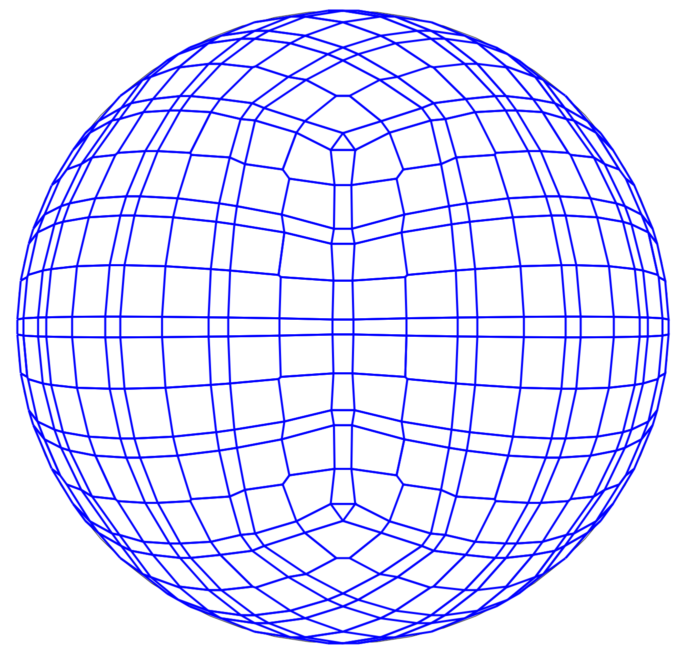
If we apply convention physics dynamics coupling paradigm to higher-order Galerkin method …

then state passed to physics is the state at the quadrature node values

(a)







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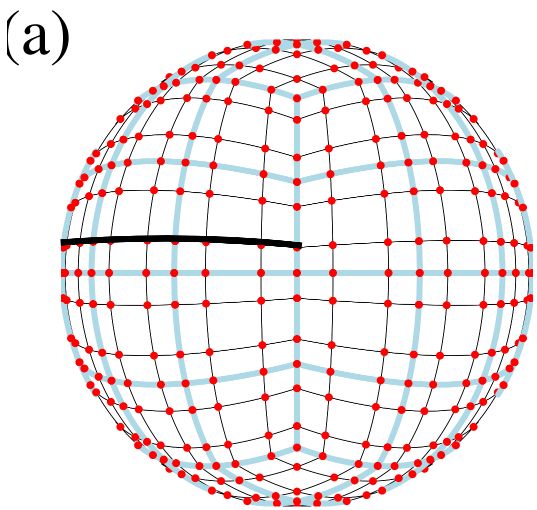
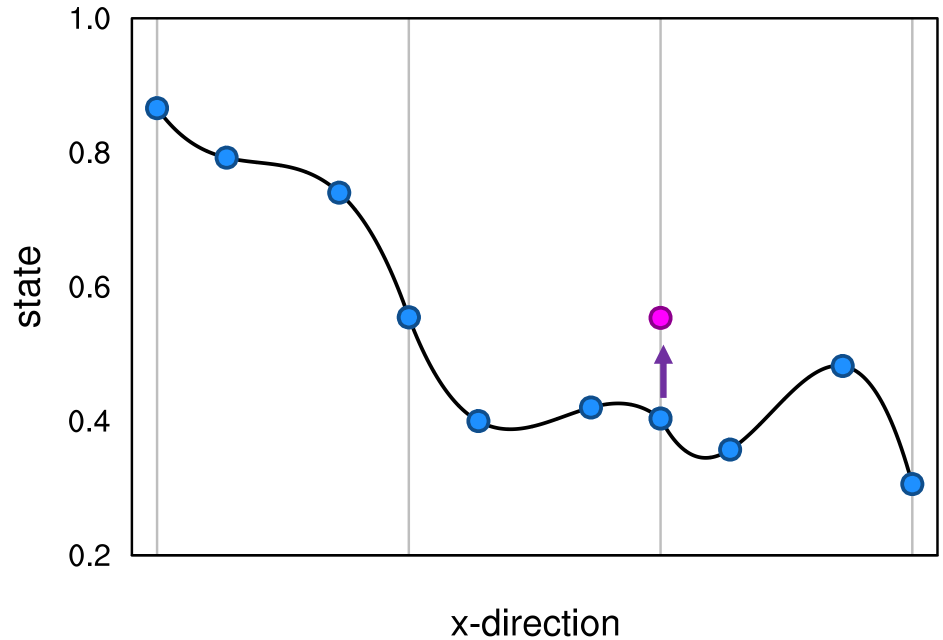
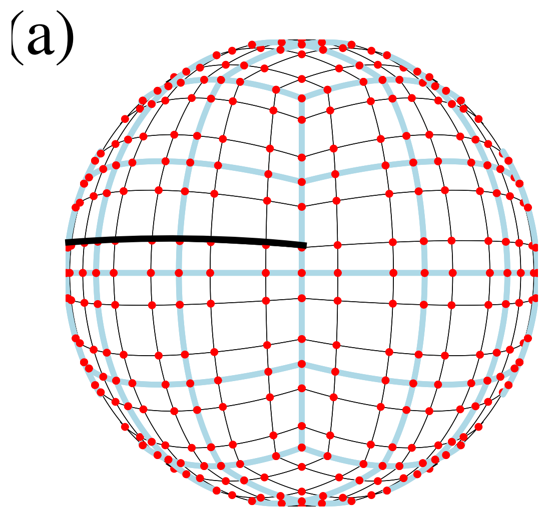
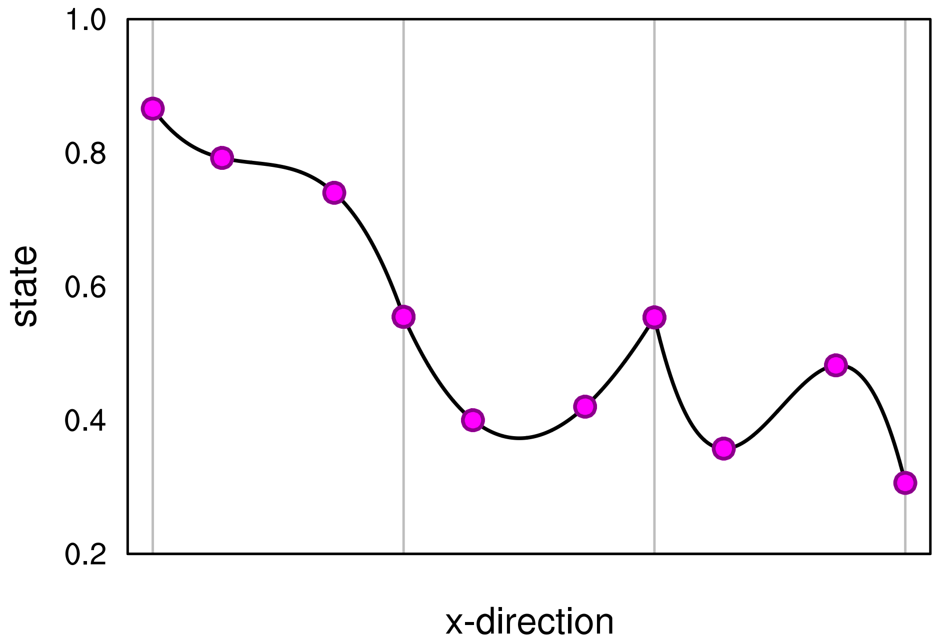




The physics forms a cloud on a boundary node

If we apply convention physics dynamics coupling paradigm to higher-order Galerkin method …



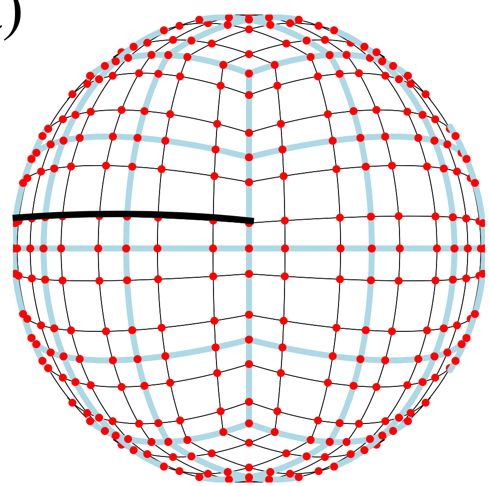


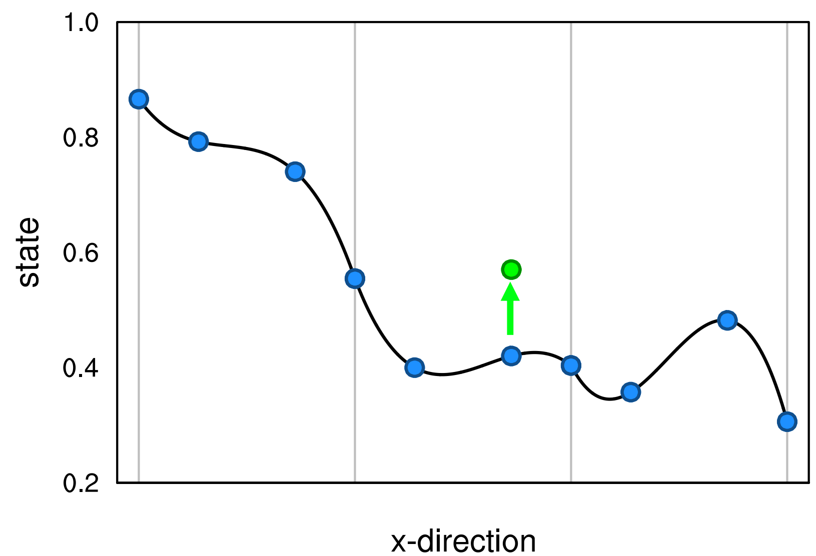
Note … non-local effect by changing one node value

The physics forms a cloud on a boundary node

If we apply convention physics dynamics coupling paradigm to higher-order Galerkin method …

(a)

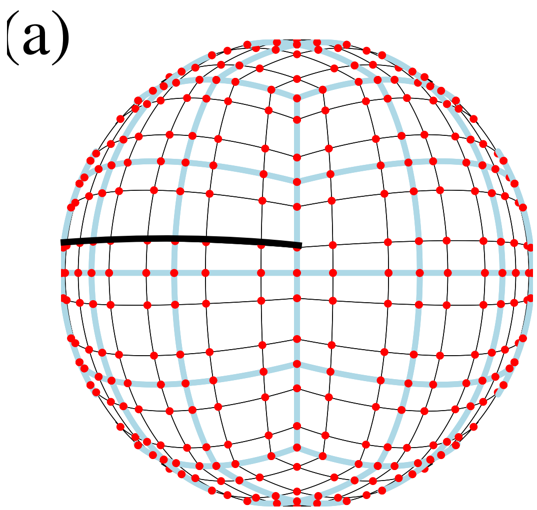


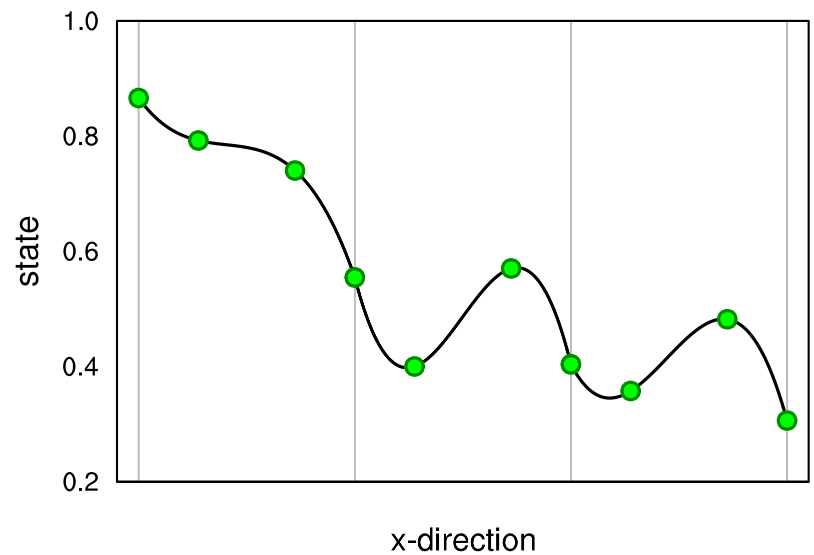


Note … non-local effect by changing one node value

Lets say the cloud instead forms at an interior node…

If we apply convention physics dynamics coupling paradigm to higher-order Galerkin method …





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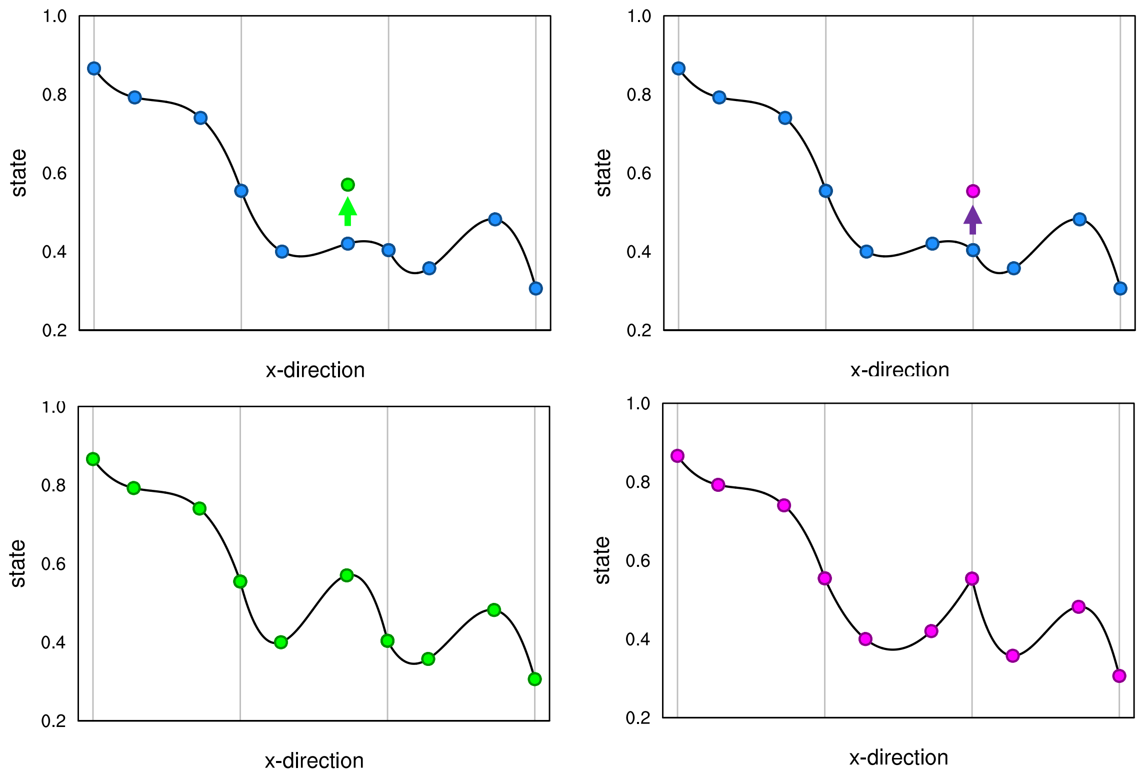
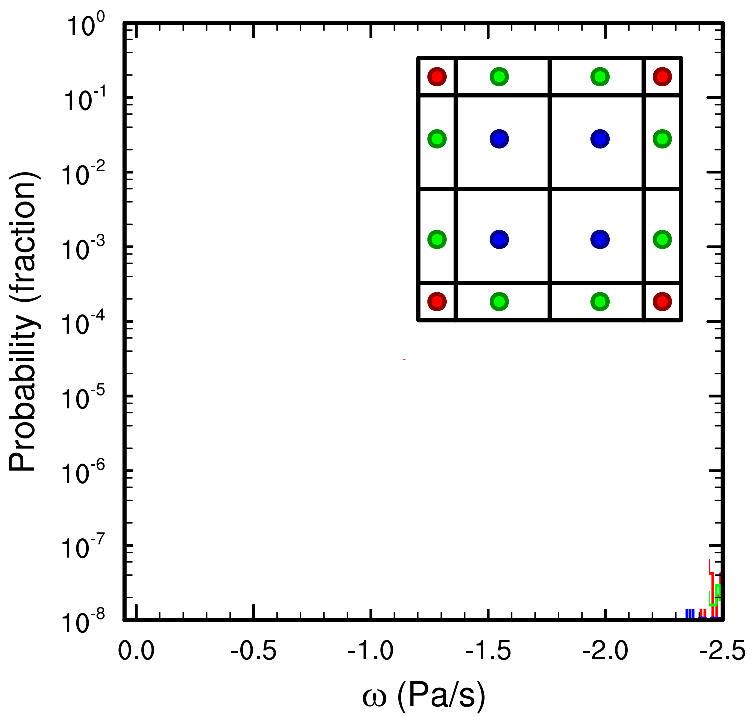
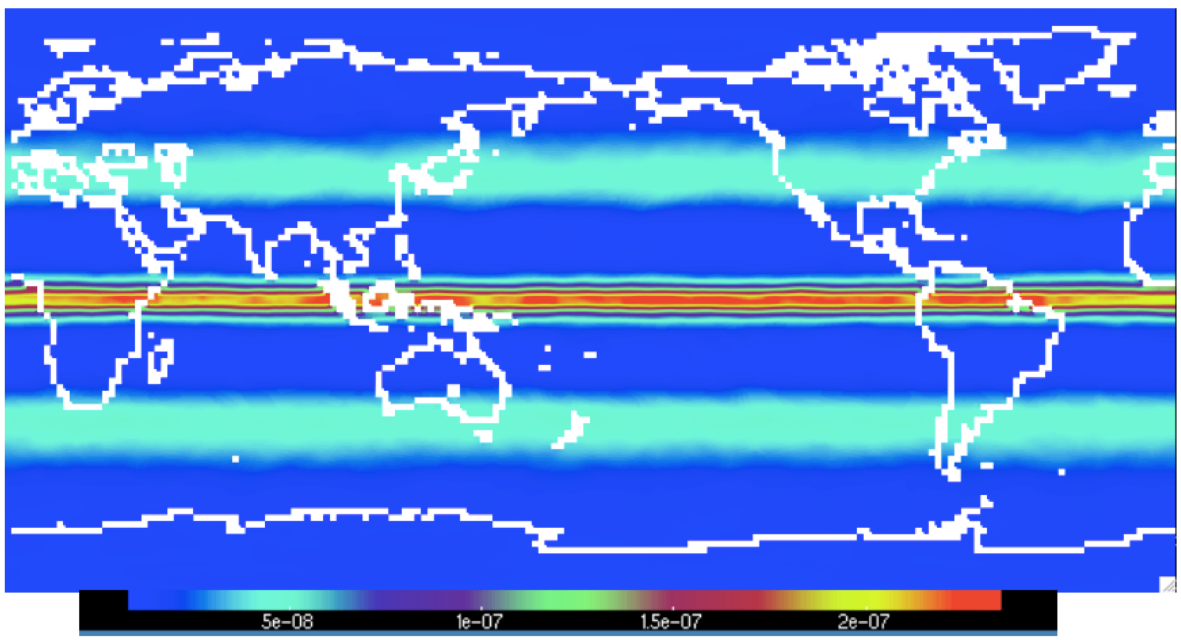


The irregular physical distance between nodes seems to have less bearing on the solution, compared with whether one is, or is not on an element boundary

For an Aqua-planet simulation the climatology (of any variable) is zonal:

... so the climatology at any quadrature should be the same!





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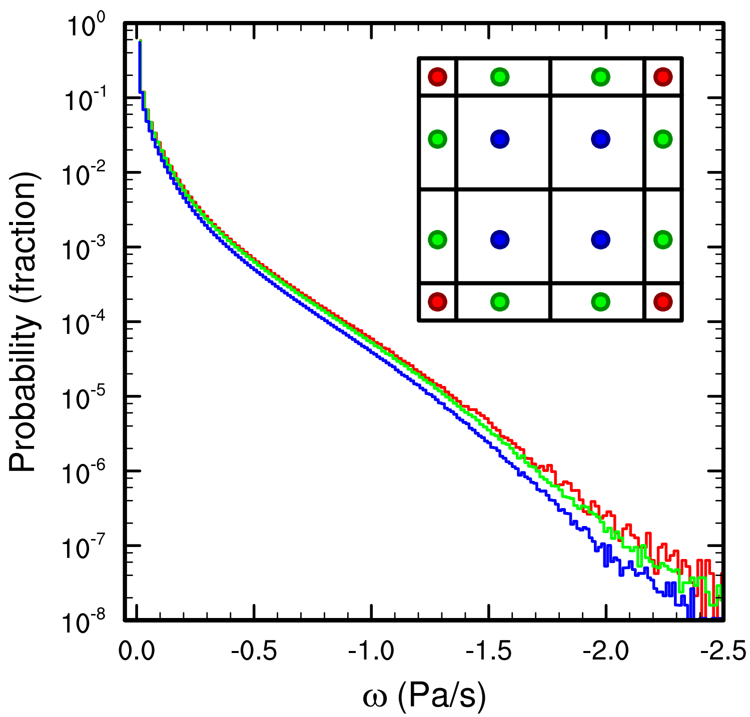

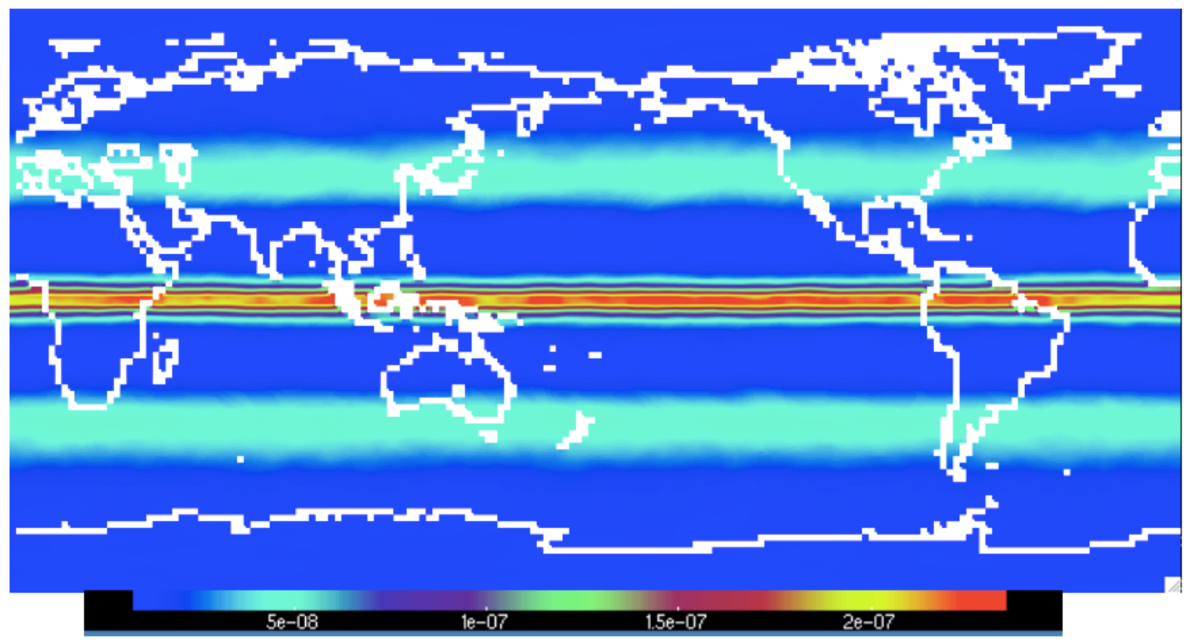

For an Aqua-planet simulation the climatology (of any variable) is zonal:

... so the climatology at any quadrature should be the same!

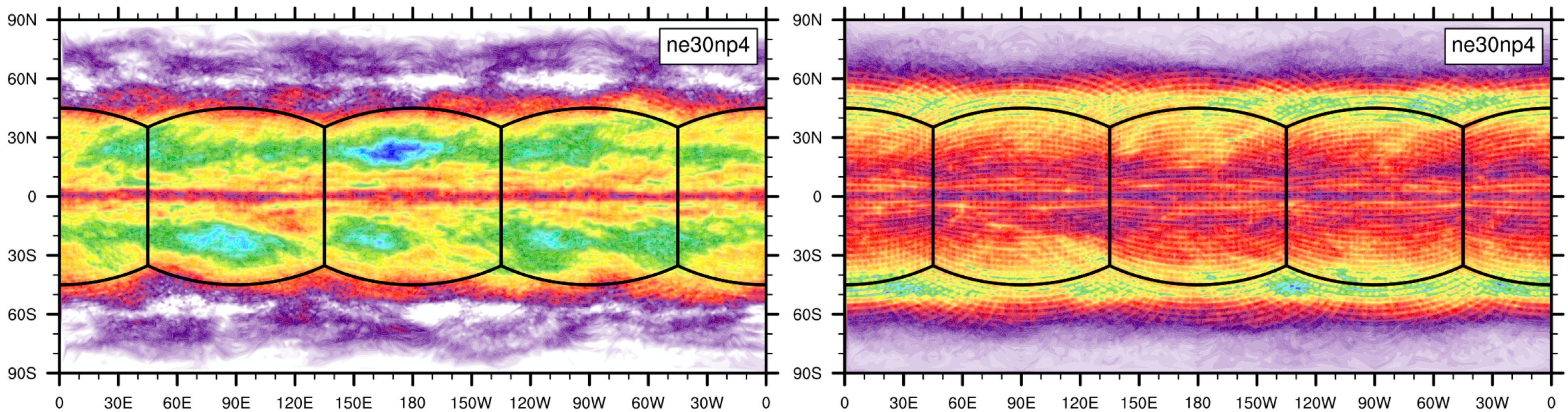

Figure: (left) Mean and (right) variance of low level temperature tendency (using CAM4 physics)

Held-Suarez simulation with real-world topography

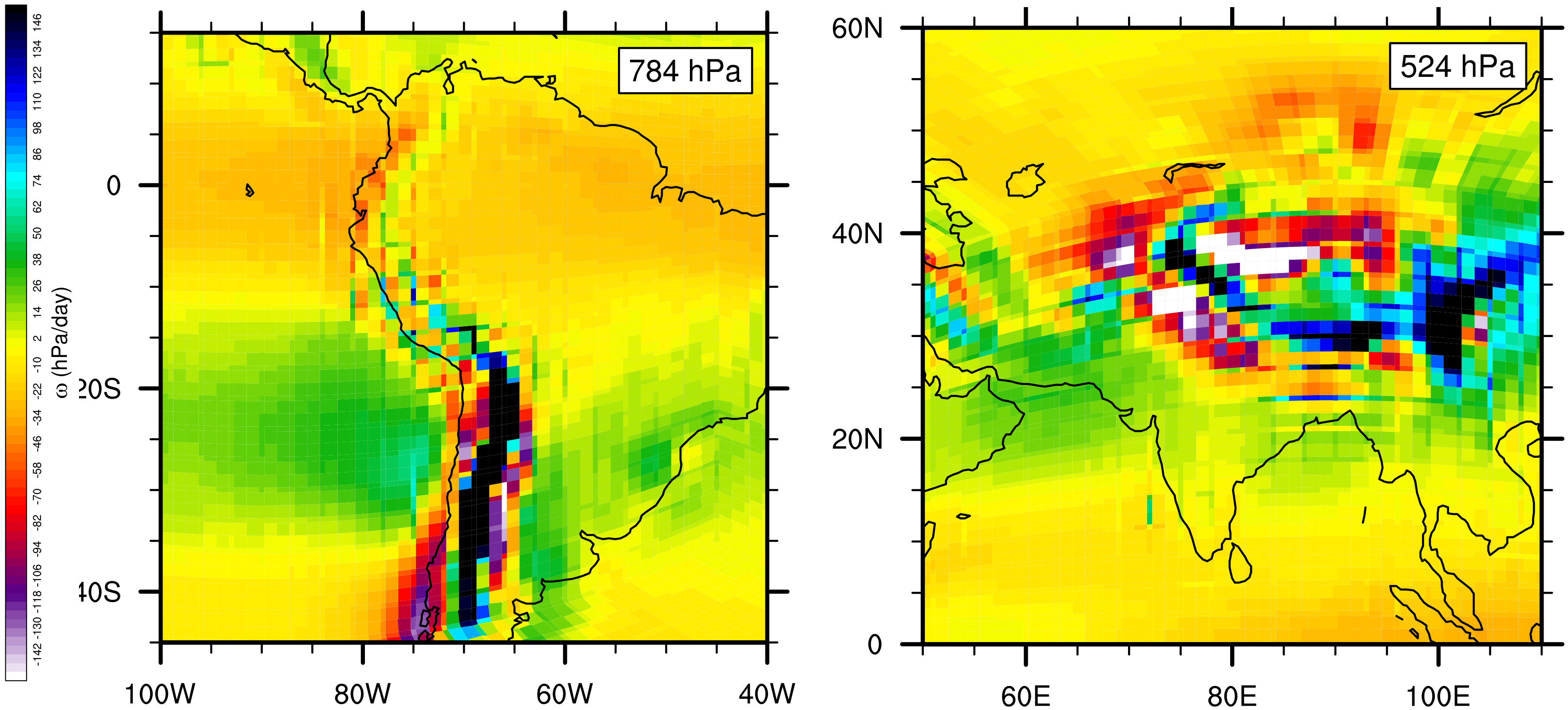

Figure: Mean OMEGA for CAM-SE at two model levels in the middle troposphere, in a Held-Suarez configuration outfitted with real world topography. The data are contoured according to a 'cell fill' approach.

-> using the conventional physics-dynamics coupling paradigm leads to spurious dependencies on location within element

Part II: Quasi-equal area physics grid

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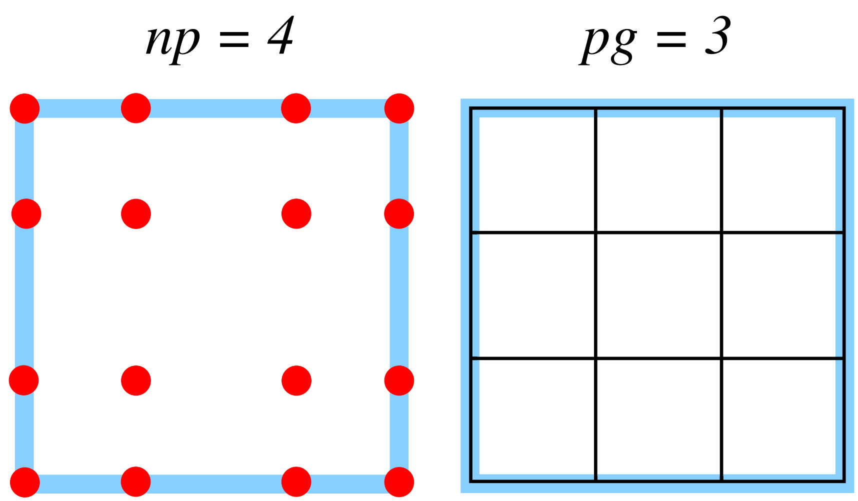
Introducing an ~equal area physics grid



Herrington et al. (MWR, revising)

Mapping u,v, T, and omega from dynamics grid (GLL) to finite-volume grid:
Important properties for mapping operators

1. conservation of scalar quantities such as mass (and dry thermal energy),

2. for tracers; shape-preservation (monotonicity), i.e. the mapping method must not introduce new extrema in the interpolated field, in particular, negatives,

3. consistency, i.e. the mapping preserves a constant,

4. linear correlation preservation.

Other properties that may be important, but not pursued here, includes total energy conservation and axial angular momentum.

Herrington et al. (MWR, revising)

Mapping u,v, T and tracer tendencies from finite-volume grid to dynamics grid (GLL)

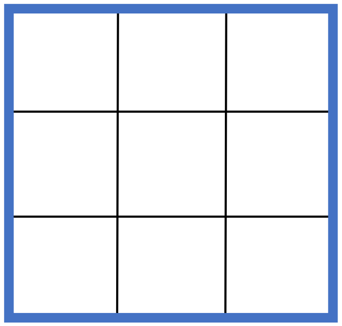
Important properties for mapping operators

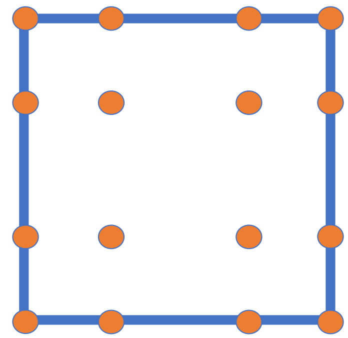
1. for tracers; mass tendency is conserved,
2. for tracers; in each tracer grid cell the mass tendency from physics must not exceed tracer mass available in tracer grid cell (i.e. physics tendency will not drive tracer mixing ratio negative on the GLL grid),
3. linear correlation preservation (at least for tracers),
4. consistency, i.e. the mapping preserves a constant tendency.

Other properties that may be important, but not pursued here, includes total energy conservation (incl. components of total energy) and axial angular momentum conservation.

Herrington et al. (MWR, revising)

To my knowledge there is no reversible map using the SE Lagrange basis
(let alone shape-preserving and mass conservative)





Herrington et al. (MWR, revising)

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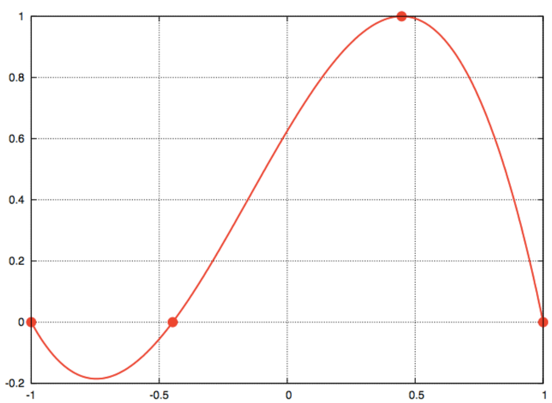
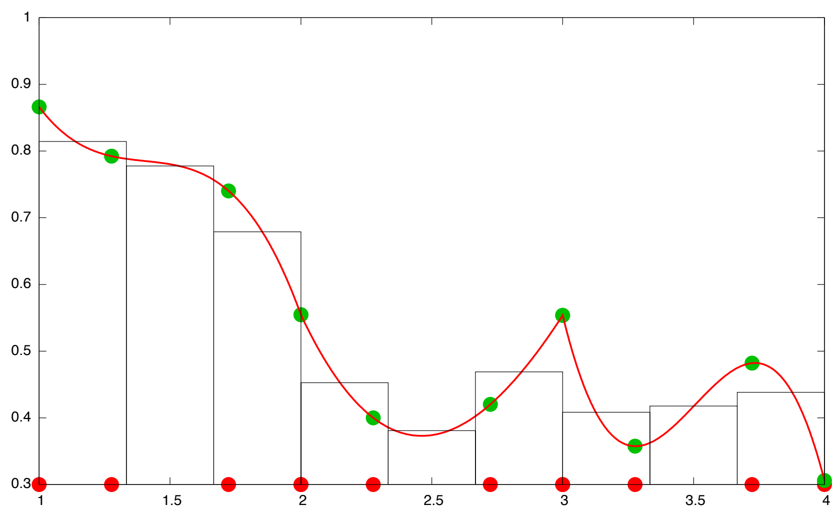


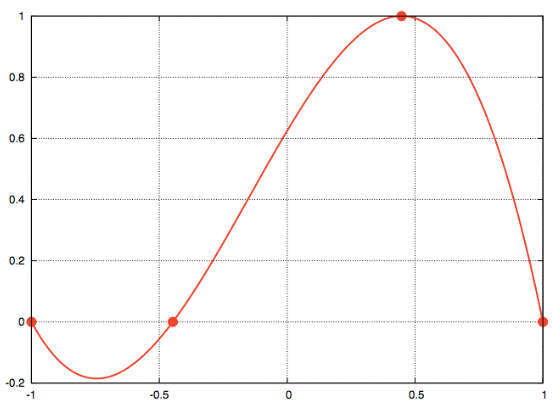


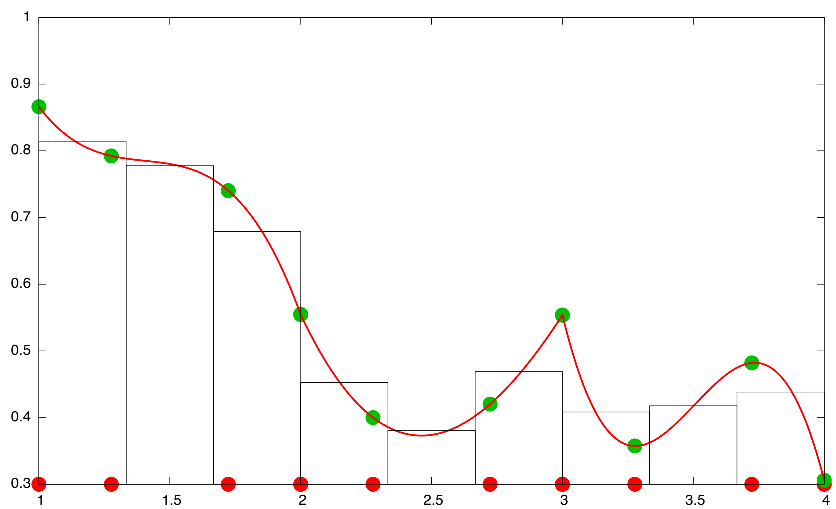
Integrate SE basis functions over finite-volume control volumes (right plot):

- conserves scalar mass
- not shape-preserving (see left plot)

Herrington et al. (MWR, revising)

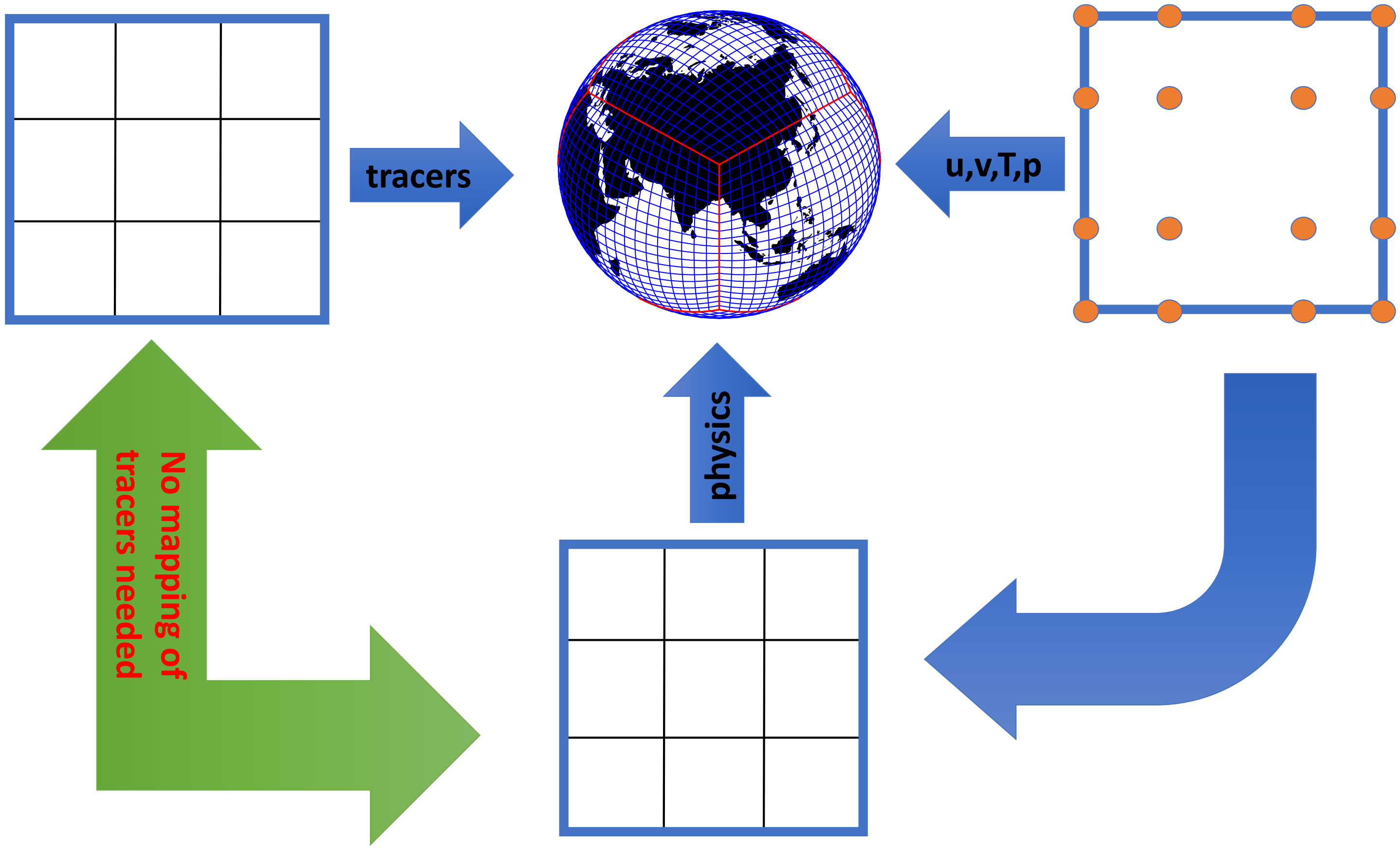
To my knowledge there is no reversible map using the SE Lagrange basis
(let alone shape-preserving and mass conservative)



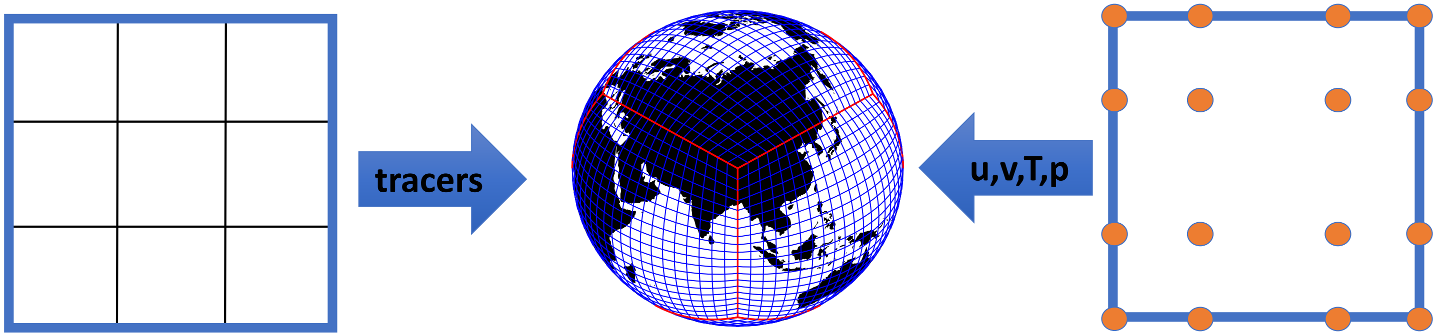


Herrington et al. (MWR, revising)

Use CSLAM for transport: conservation, consistency & shape-preservation in tracer physics-dynamics coupling



Use CSLAM for transport: conservation, consistency & shape-preservation in tracer physics-dynamics coupling



MARCH 2017 LAURITZEN ET AL. 833

CAM-SE–CSLAM: Consistent Coupling of a Conservative Semi-Lagrangian Finite-Volume Method with Spectral Element Dynamics

PETER HJORT LAURITZEN

National Center for Atmospheric Research,[a] Boulder, Colorado

MARK A. TAYLOR AND JAMES OVERFELT

Sandia National Laboratories, Albuquerque, New Mexico

Mon. Wea. Rev.

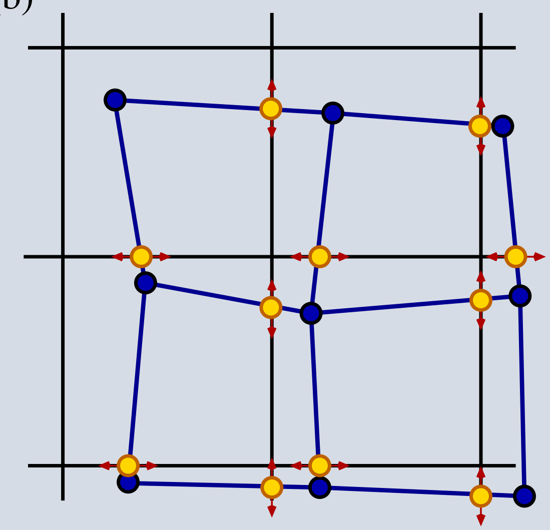
Use CSLAM for transport: conservation, consistency & shape-preservation in tracer physics-dynamics coupling

Dry air mass fluxes computed from SE method (derived by M. Taylor).

Local iteration problem generating an upstream grid that spans the sphere without cracks and overlaps and 'matches' SE fluxes to round-off

=> all CSLAM technology from Lauritzen et al. (2010) can be used and method is consistent, shape-preserving, mass-conservative, linear correlation preserving, multi-tracer efficient, ...

(b)



PETER HJORT LAURITZEN

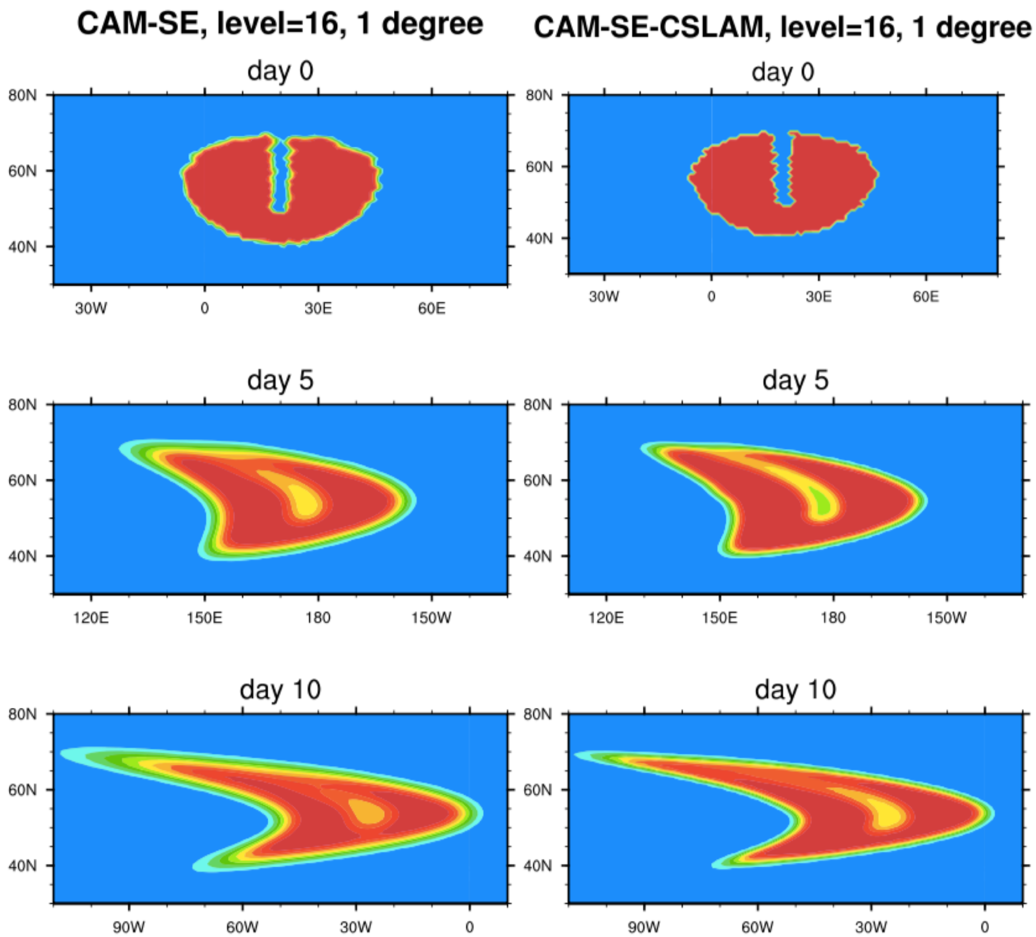
National Center for Atmospheric Research,[a] Boulder, Colorado

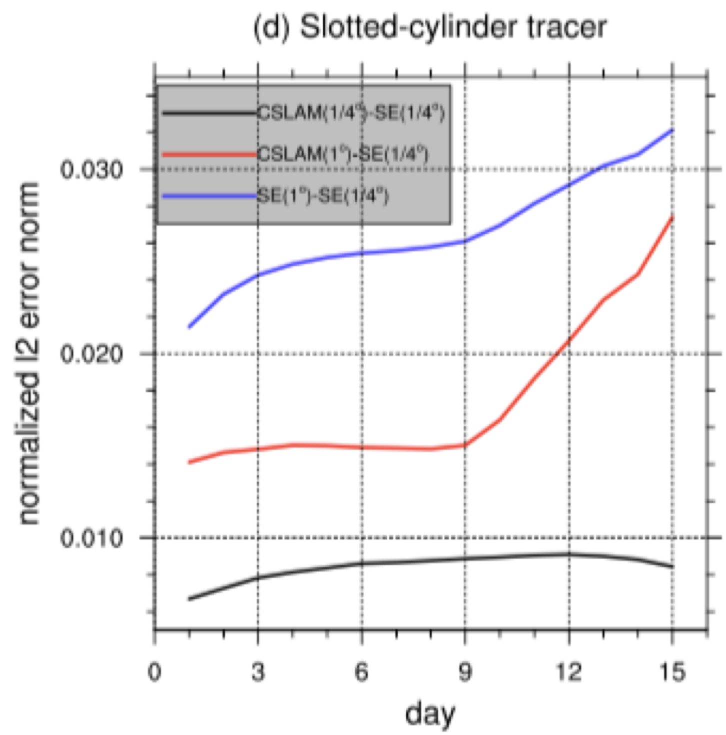
Mon. Wea. Rev.

MARK A. TAYLOR AND JAMES OVERFELT

Sandia National Laboratories, Albuquerque, New Mexico

Aside: "Benefit" of using CSLAM for transport is more accurate and faster (if enough tracers) transport



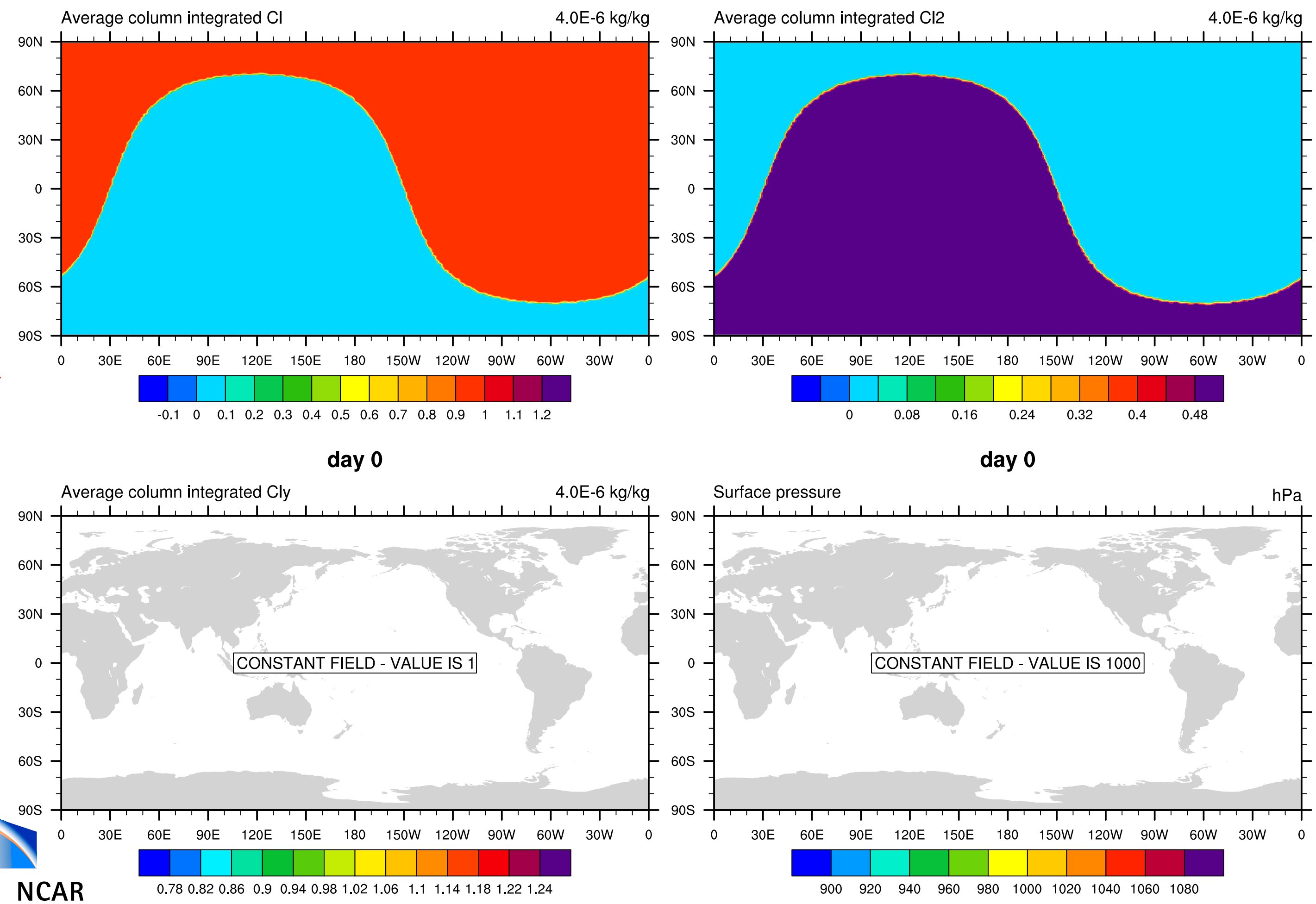


Lauritzen et al. (MWR, 2017)

Aside: "Benefit" of using CSLAM for transport is more accurate and faster (if enough tracers) transport

Initial condition "Terminator test" **(Lauritezn et al., 2015)**

Lauritzen et al., 2017

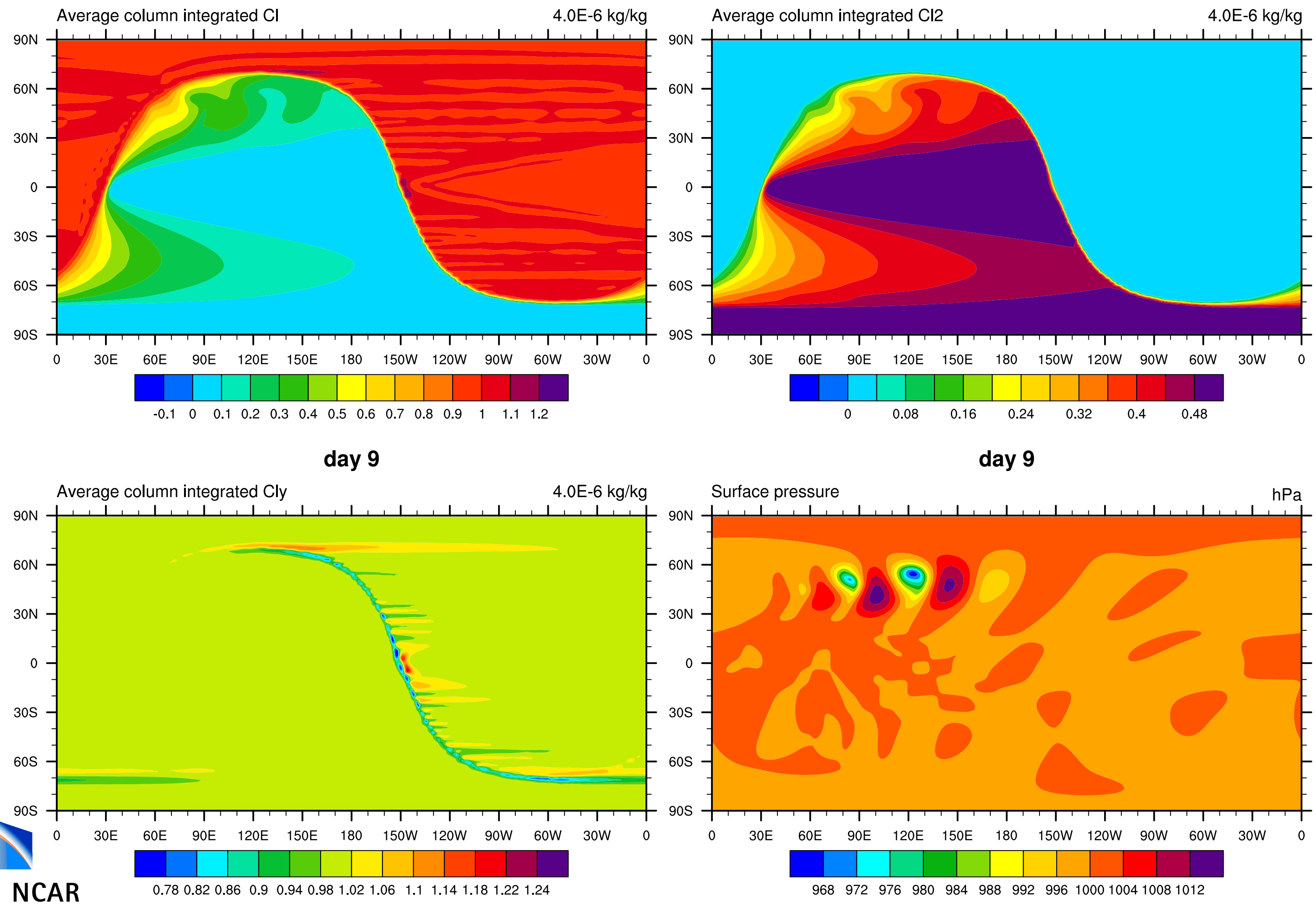


NCAR

Aside: “Benefit” of using CSLAM for transport is more accurate and faster (if enough tracers) transport

“Terminator test” (Lauritezn et al., 2015)

Lauritzen et al., 2017

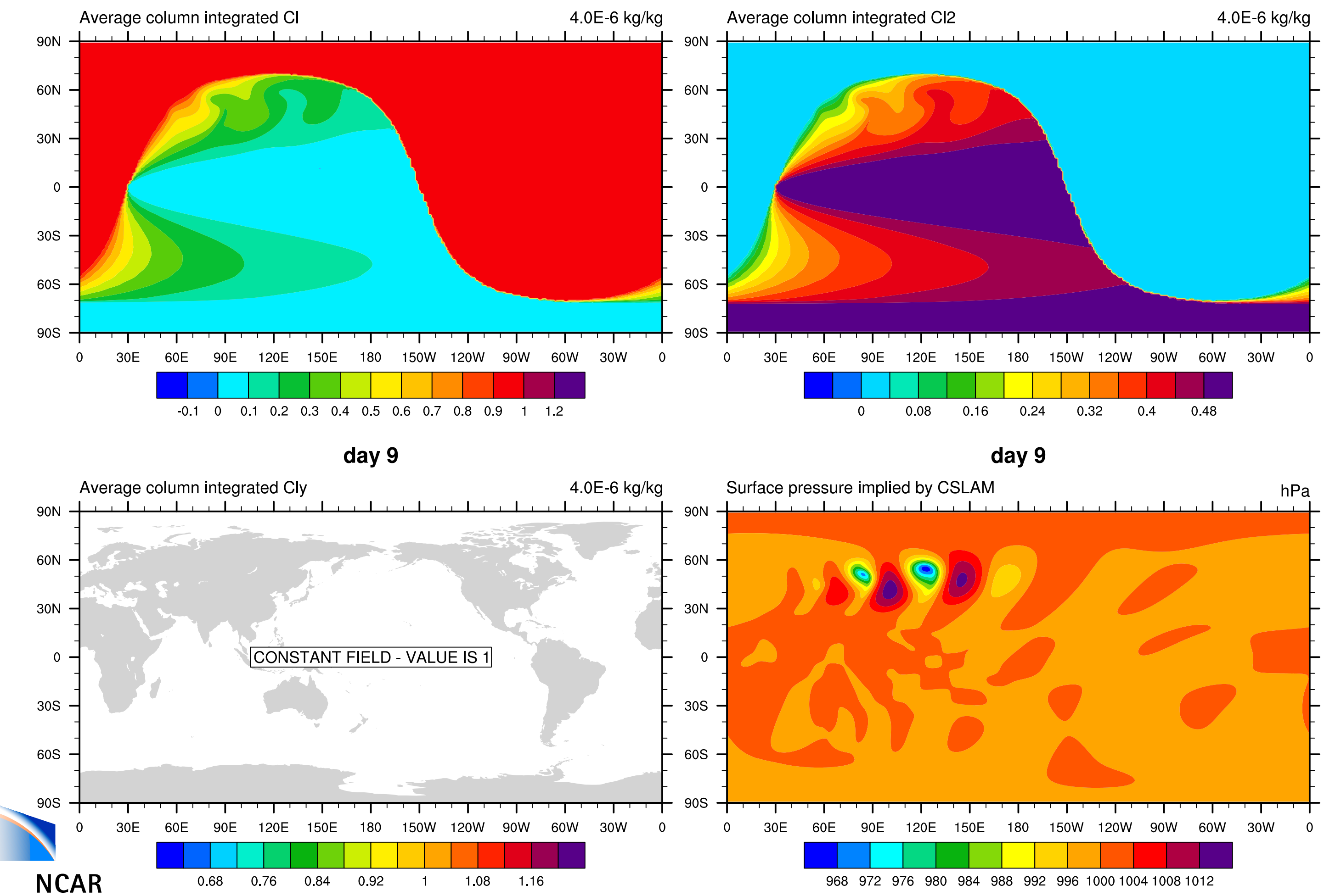


CAM-SE, day 9

NCAR

Aside: “Benefit” of using CSLAM for transport is more accurate and faster (if enough tracers) transport

“Terminator test” (Lauritezn et al., 2015)

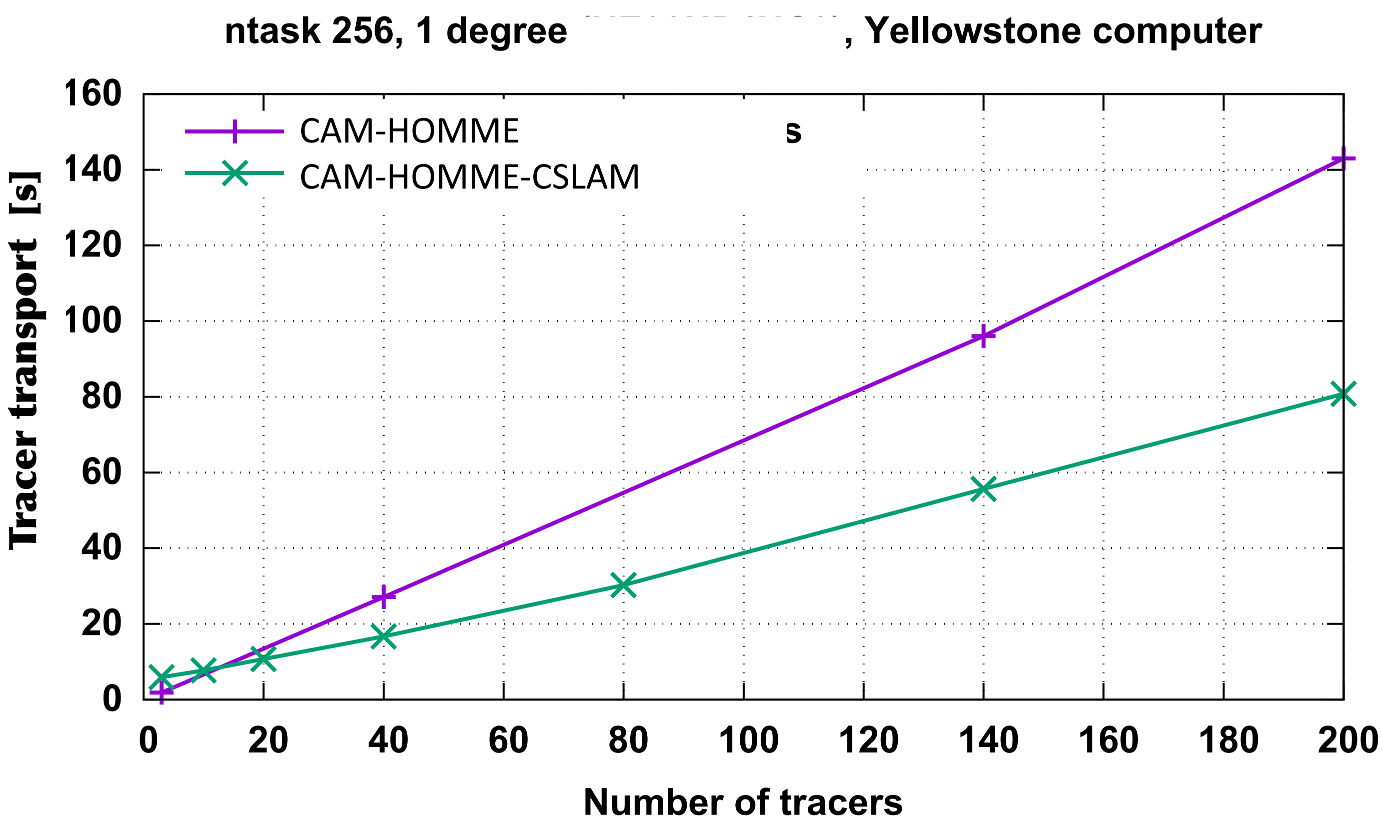


CAM-SE-CSLAM, day 9

NCAR

Aside: "Benefit" of using CSLAM for transport is more accurate and faster (if enough tracers) transport

WARNING: OLD CODE ON OLD COMPUTER



NCAR

Aside: “Benefit” of using CSLAM for transport is more accurate and faster (if enough tracers) transport

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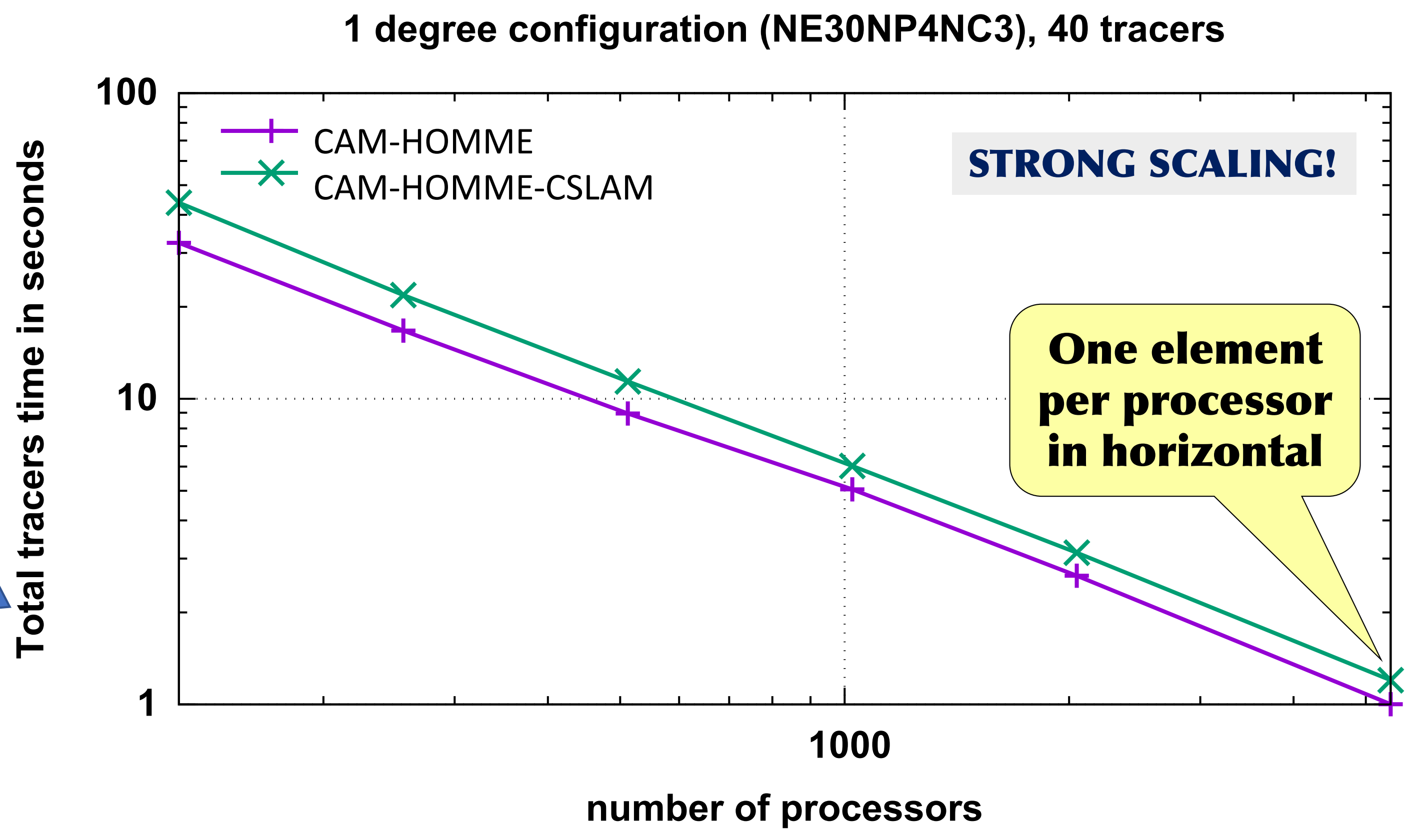


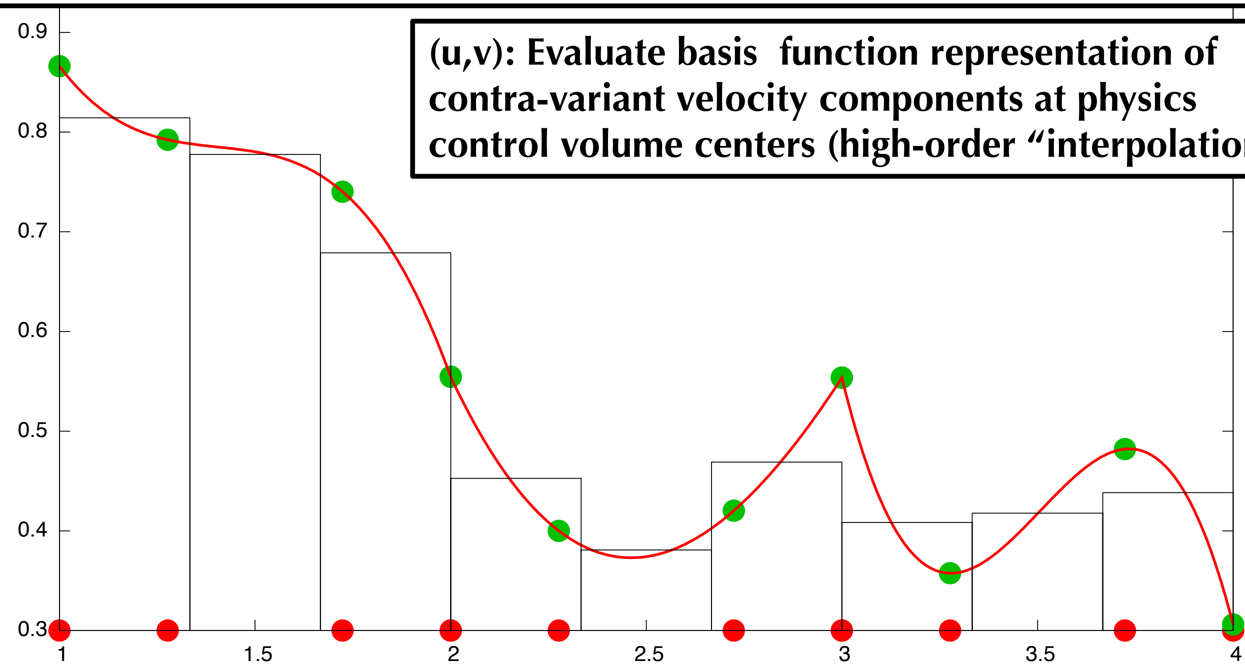
NCAR

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

Temperature: Integrate basis function representation of dM*T over physics grid control volumes

- Conserves dry thermal energy (dp*T)
- Not total energy conserving
- Not axial angular momentum conserving

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

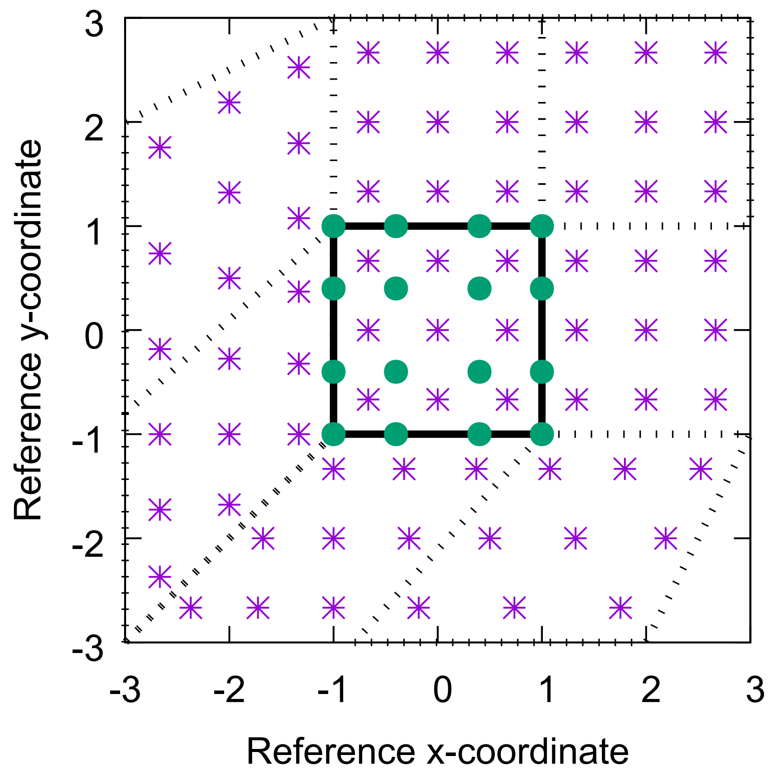


Herrington et al. (MWR, revising)

Mapping tendencies for u,v, and T from finite-volume (physics) grid to dynamics grid (GLL):

Cubic tensor-product interpolation in central angle coordinates (high-order interpolation was found to be important!)

- Preserves constant
- Not total energy conserving
- Not thermal energy conserving (dM*T)
- Not axial angular momentum conserving



Mapping errors lead to ~0.0025 W/m^2 spurious total energy sink

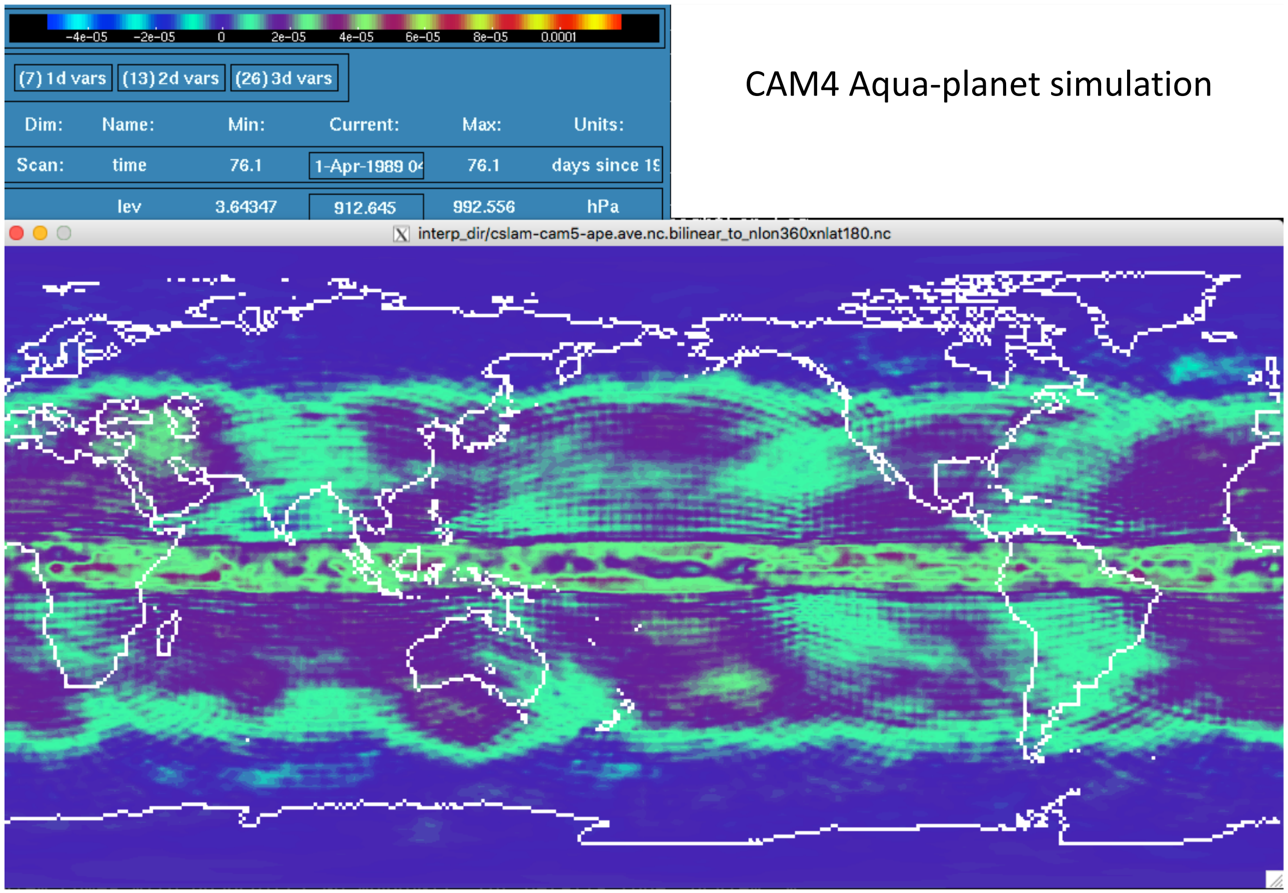
For comparison: CAM-SE conserves total energy to ~0.1W/m^2

(for ~1 degree horizontal resolution)

Herrington et al. (MWR, revising)

High-order interpolation was found to be important

Temperature tendency: FT



CAM4 Aqua-planet simulation

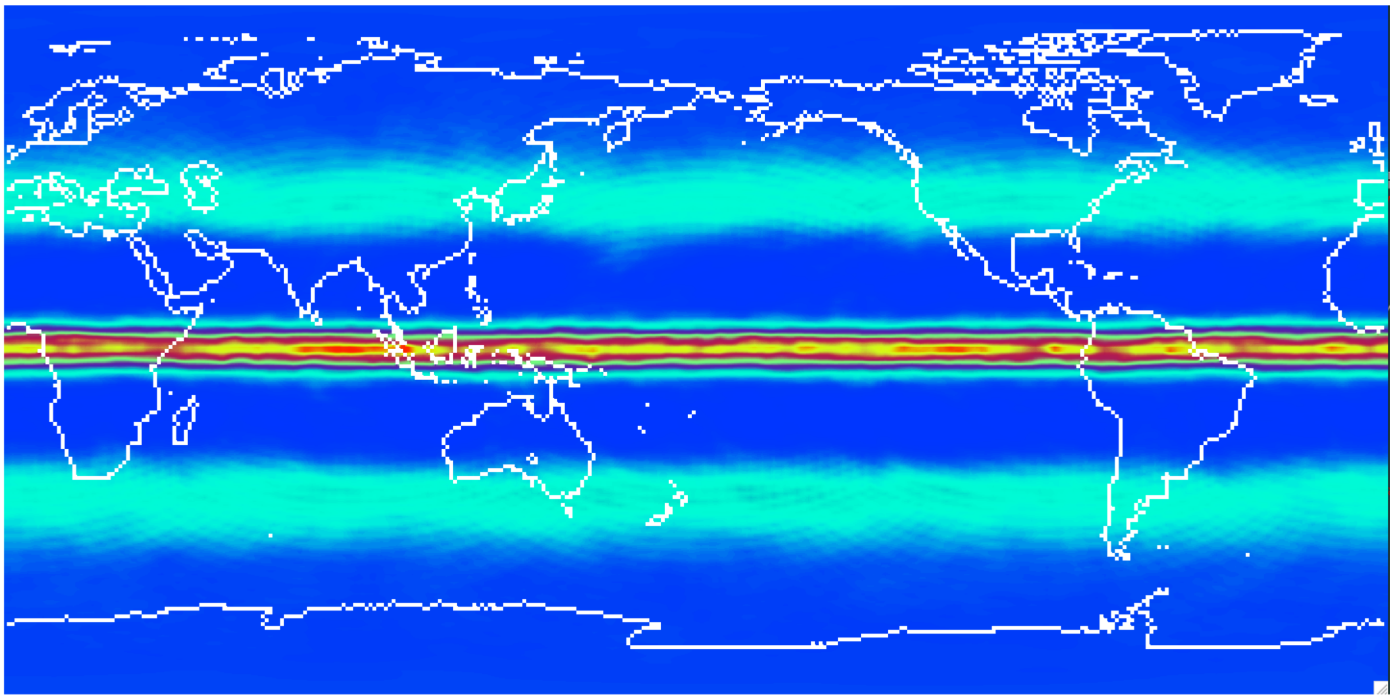
CAM-SE-CSLAM with linear interpolation from phys to dyn: 5 month average

High-order interpolation was found to be important

CAM4 Aqua-planet simulation

PRECT

(TOTAL PRECIPITATION RATE)

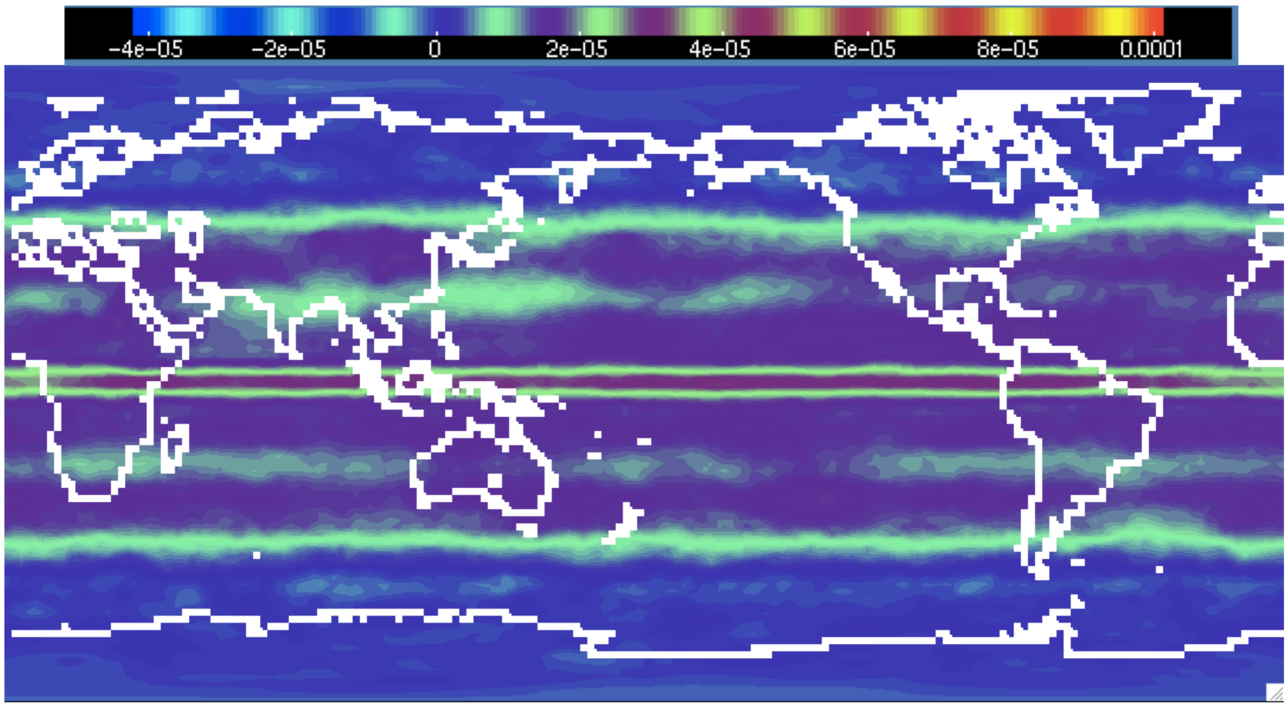


CAM4 SE-CSLAM-physgrid: linear interpolation phys to dyn: 5 month average

High-order interpolation was found to be important

Temperature tendency: FT

CAM4 Aqua-planet simulation

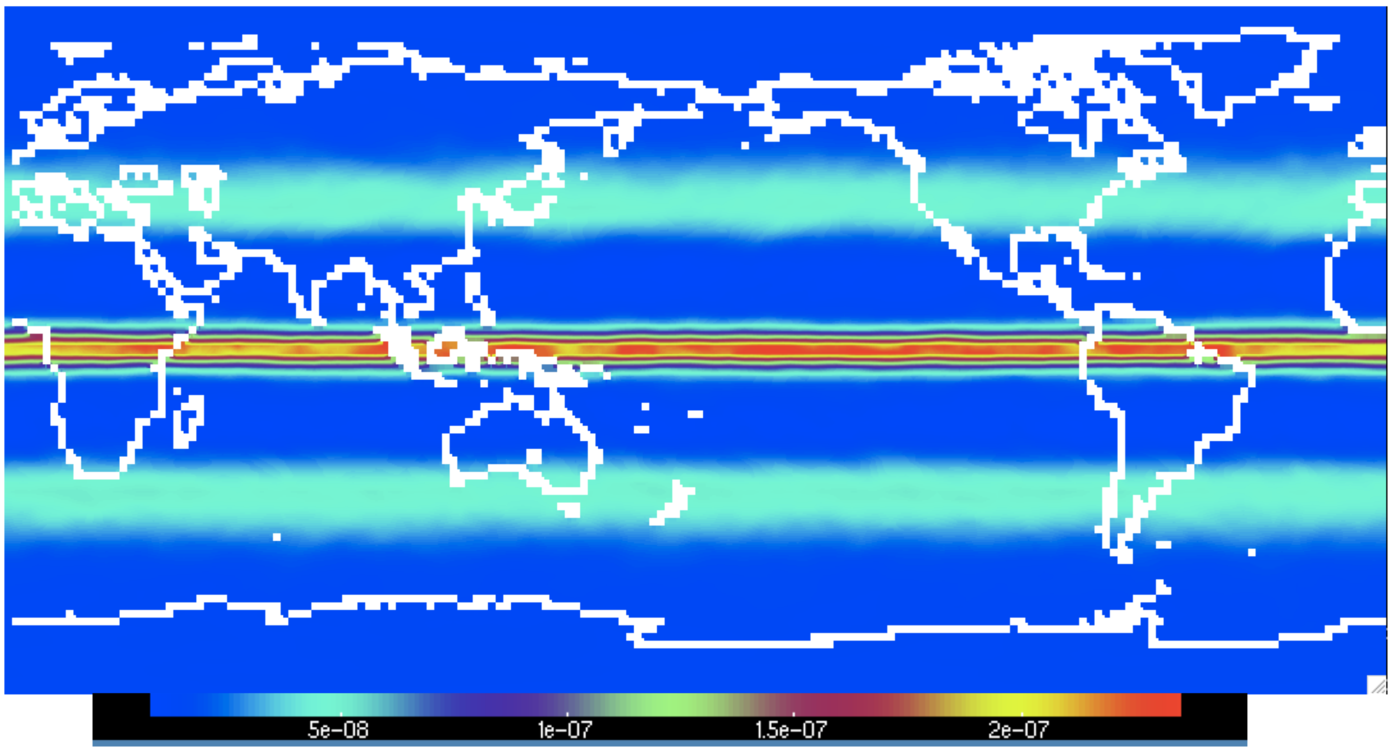


CAM-SE-CSLAM with **cubic tensor product interpolation** **from phys to dyn:**
18 month average

High-order interpolation was found to be important

CAM4 Aqua-planet simulation

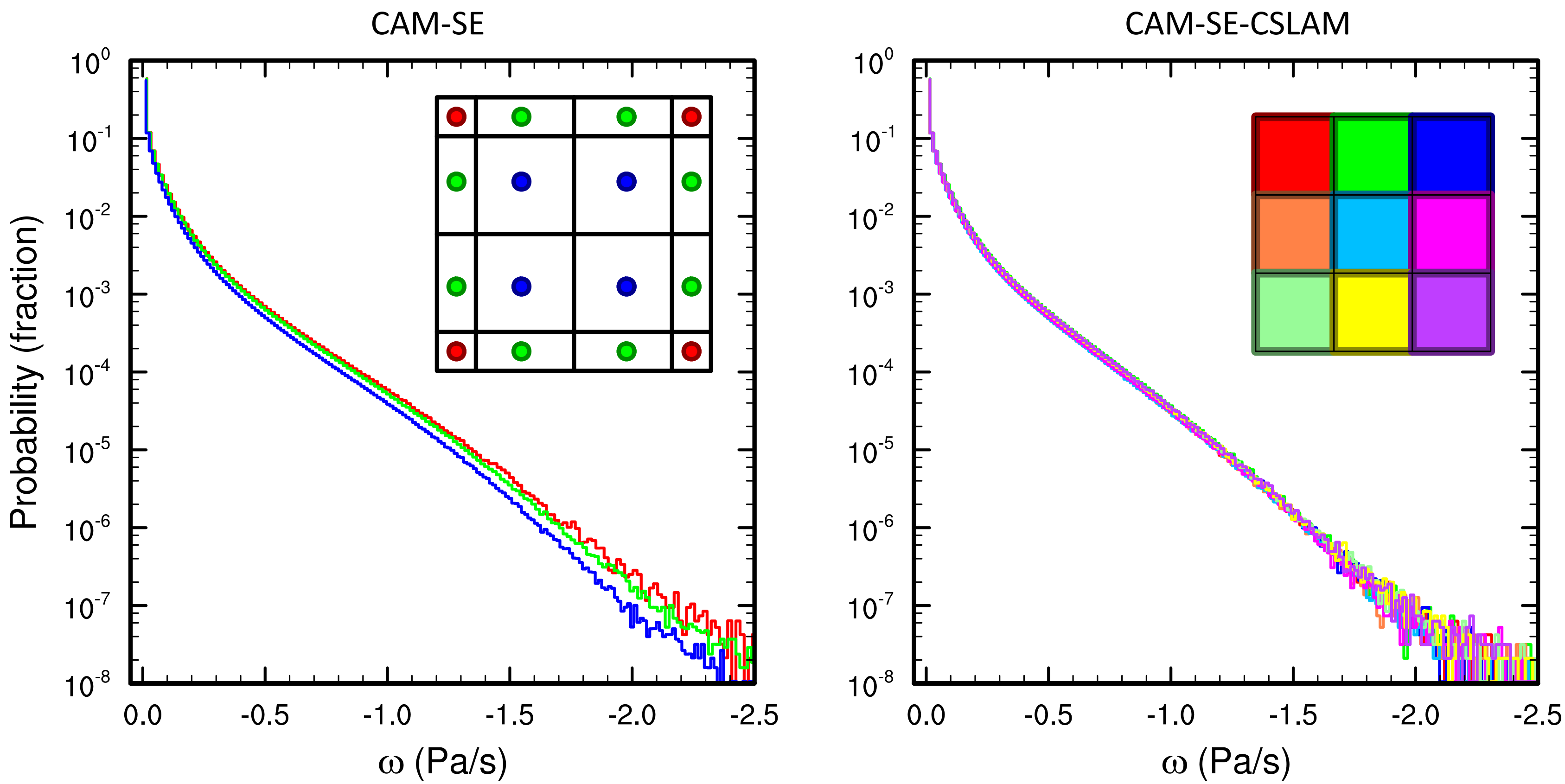
PRECT (TOTAL PRECIPITATION RATE)



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

Results – CAM4 Aqua-planets

CAM4 Aqua-planet simulation



State the physics 'see' is now independent of location within element!

Herrington et al. (MWR, revising)

Results – CAM4 Aqua-planets

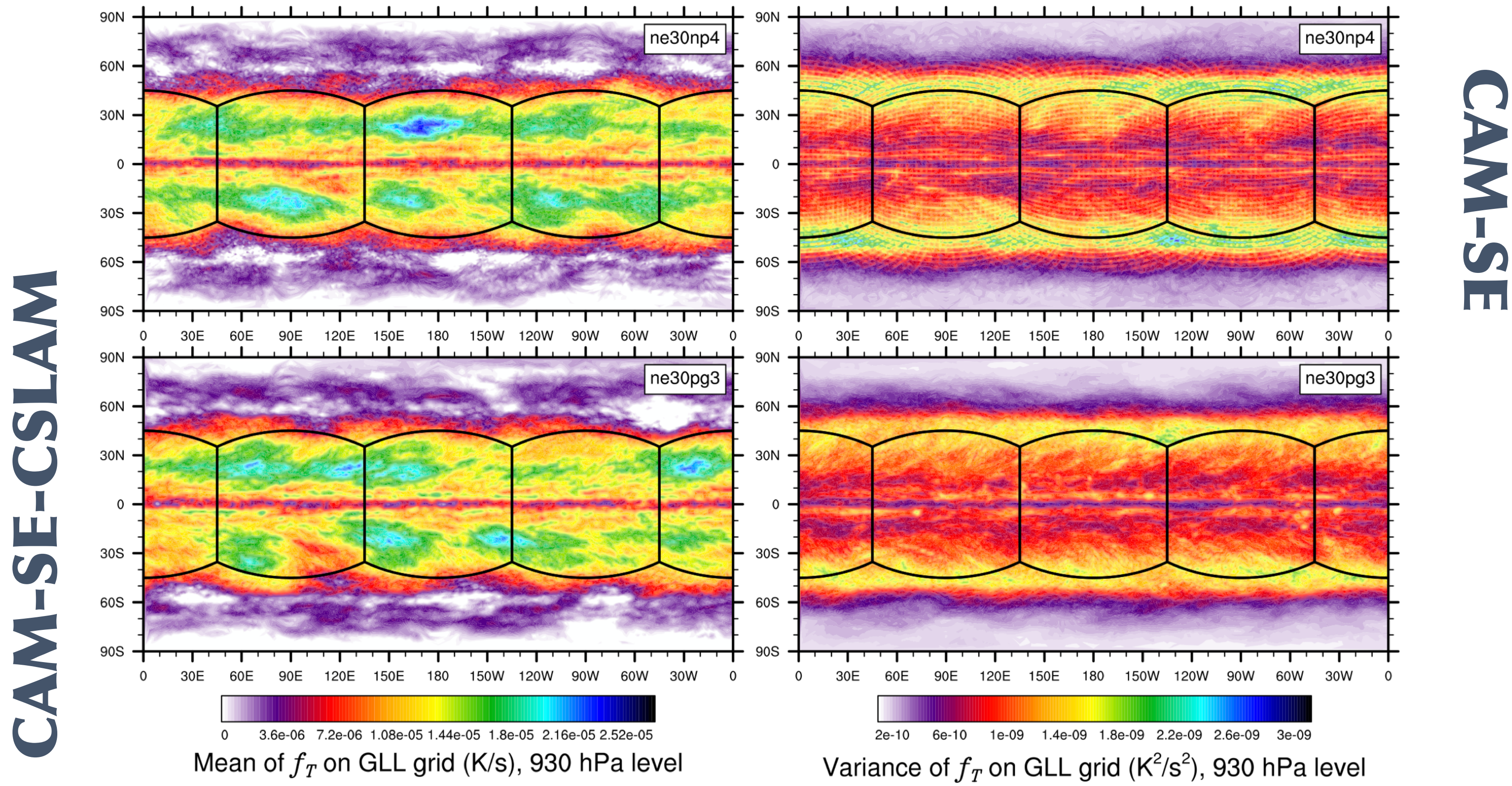
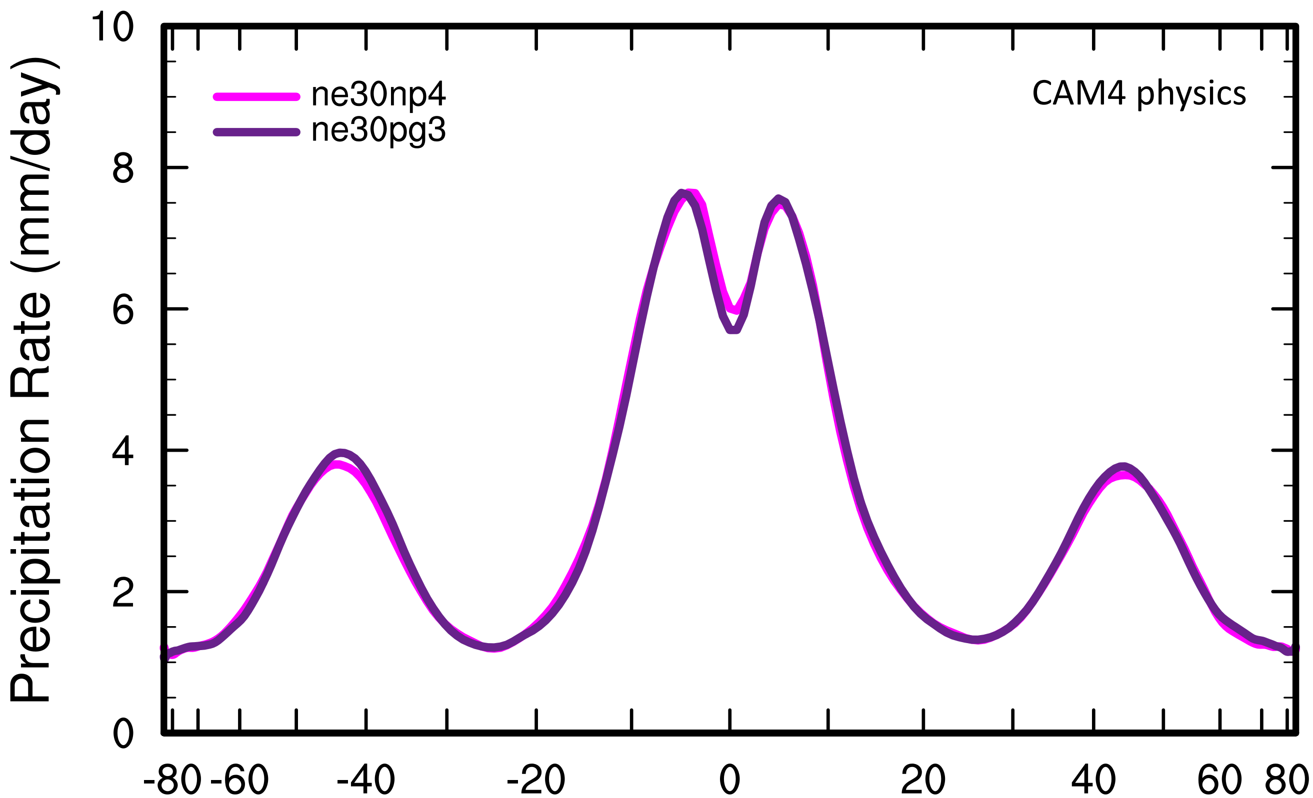


Figure: (left column) Mean and (right column) variance of low level temperature tendency

Herrington et al. (MWR, revising)

That said, the zonal means look very similar …



Held-Suarez simulation with real-world topography

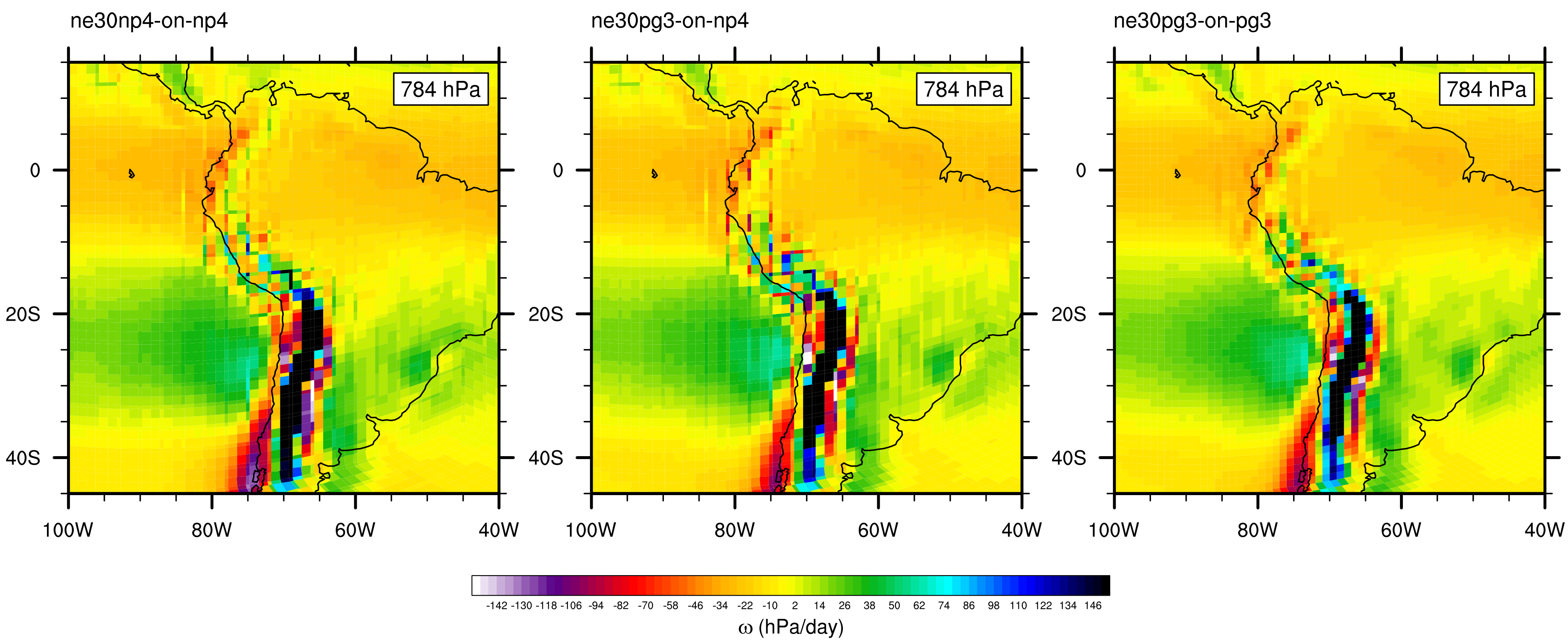


Figure: Mean OMEGA for CAM-SE (left), CAM-SE-CSLAM but on GLL grid and CAM-SE-CSLAM grid. The data are contoured according to a 'cell fill' approach.

Herrington et al. (MWR, revising)

Held-Suarez simulation with real-world topography

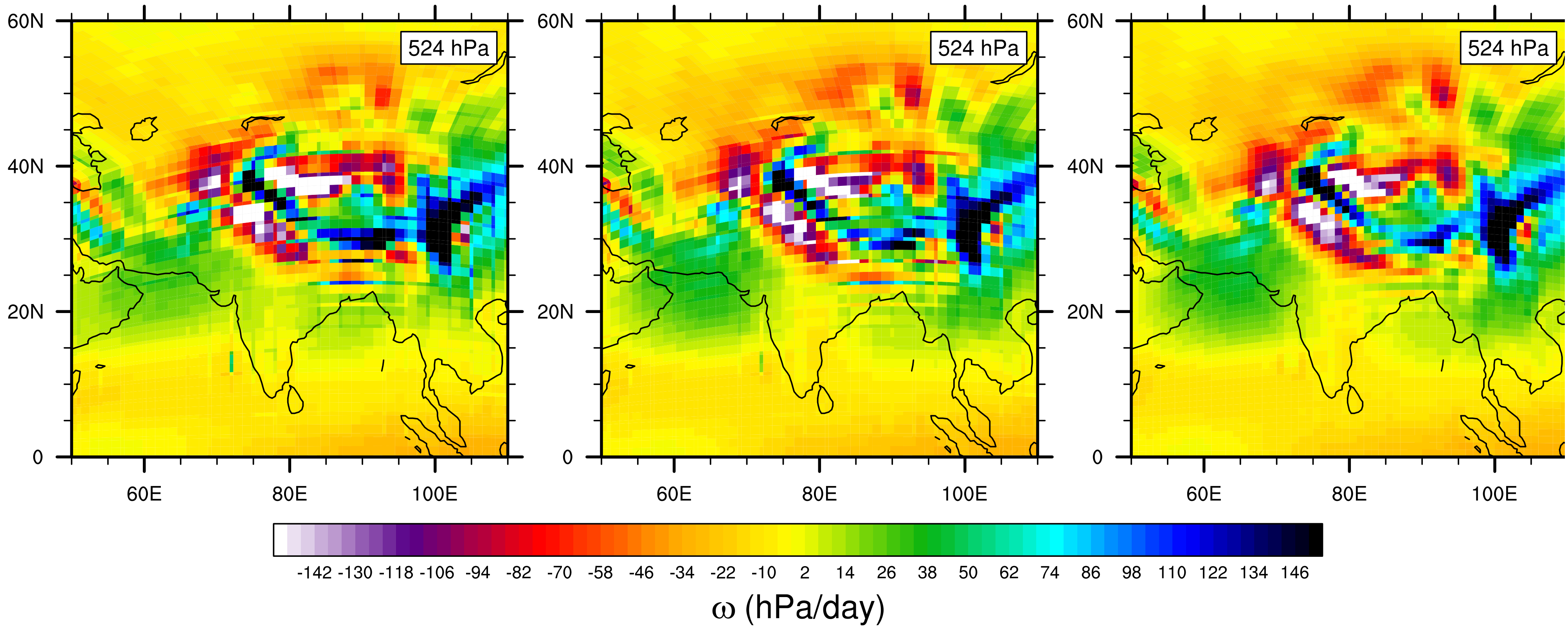
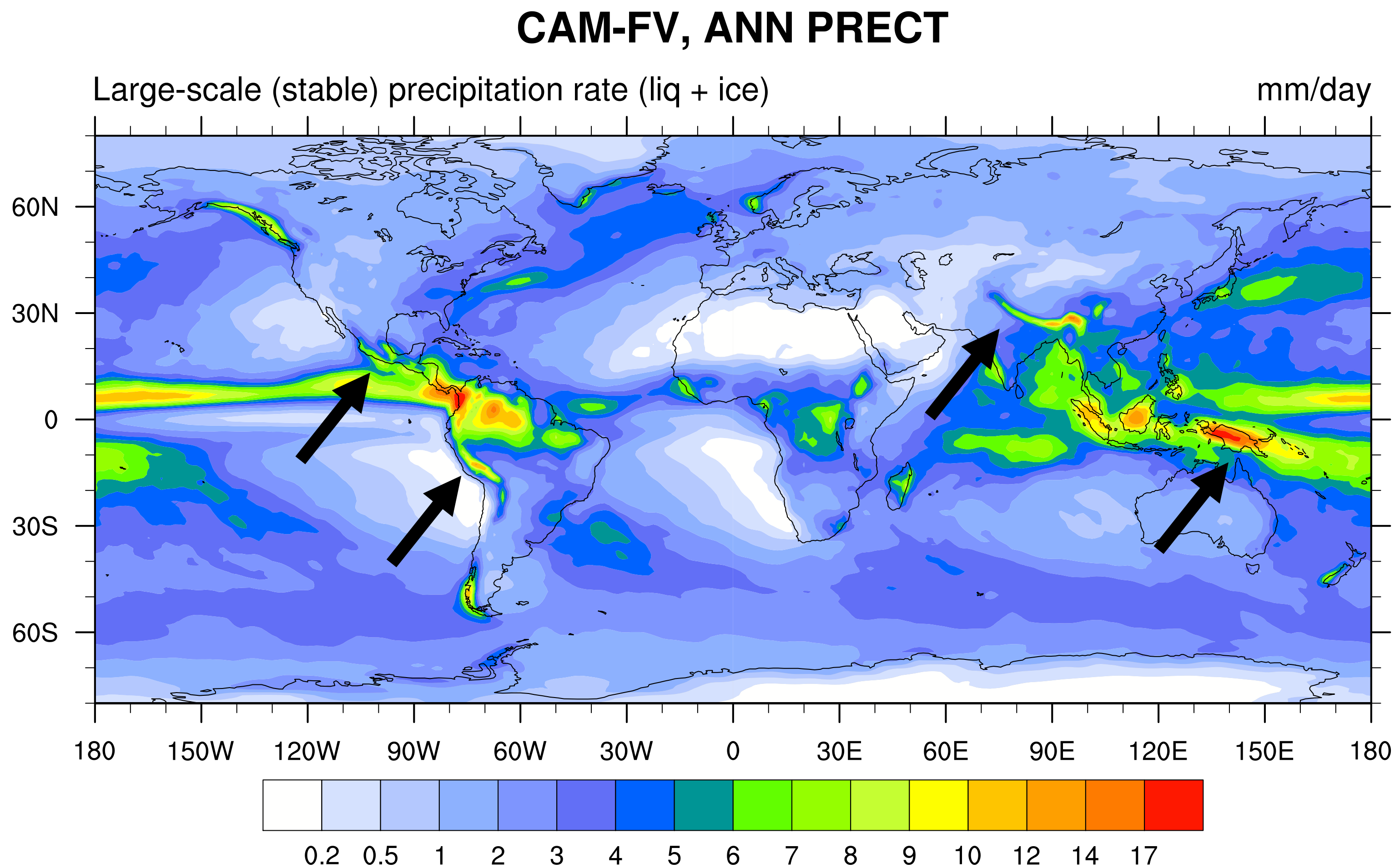


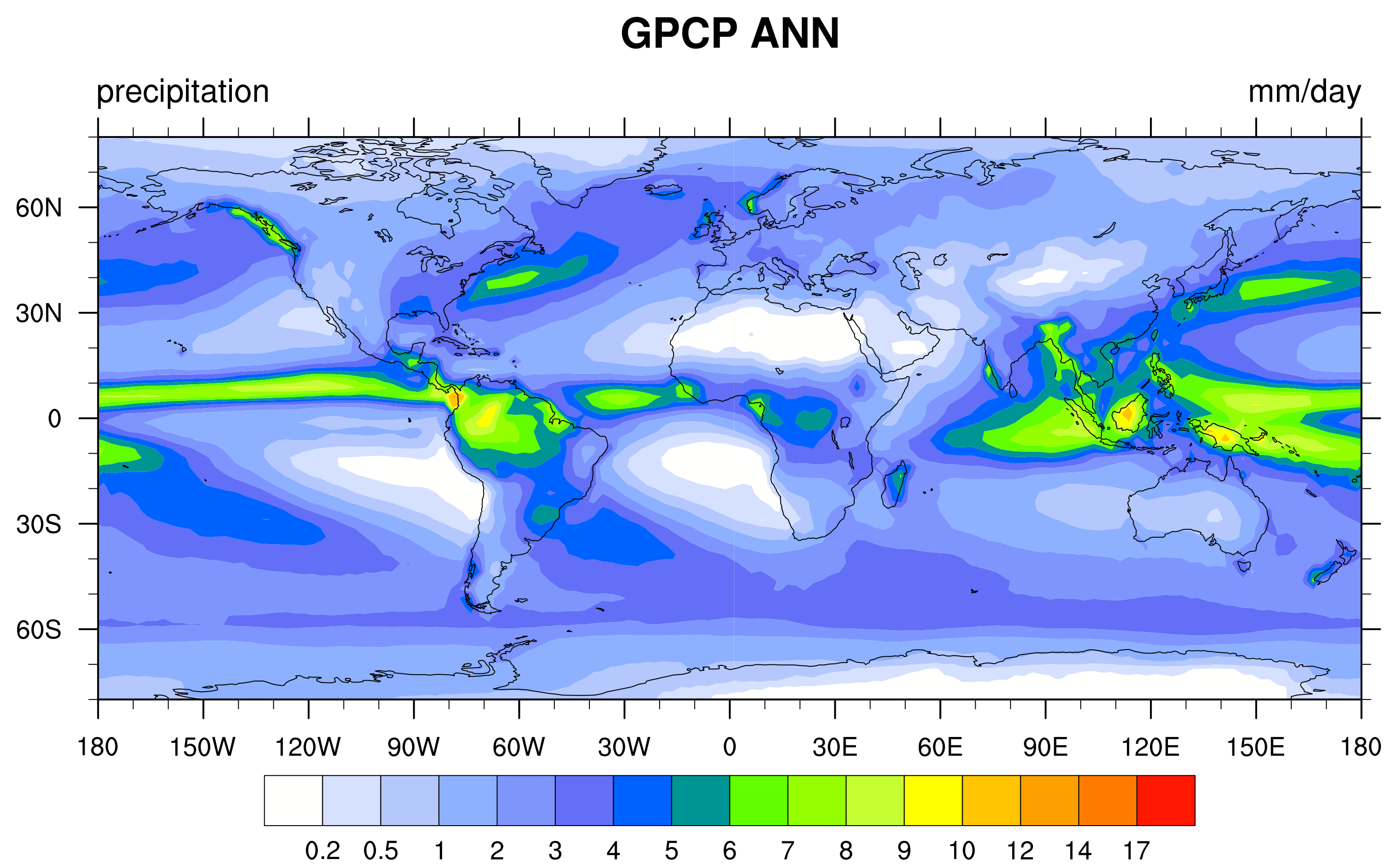
Figure: Mean OMEGA for CAM-SE (left), CAM-SE-CSLAM but on GLL grid and CAM-SE-CSLAM grid.
The data are contoured according to a 'cell fill' approach.

Herrington et al. (MWR, revising)

AMIP simulation

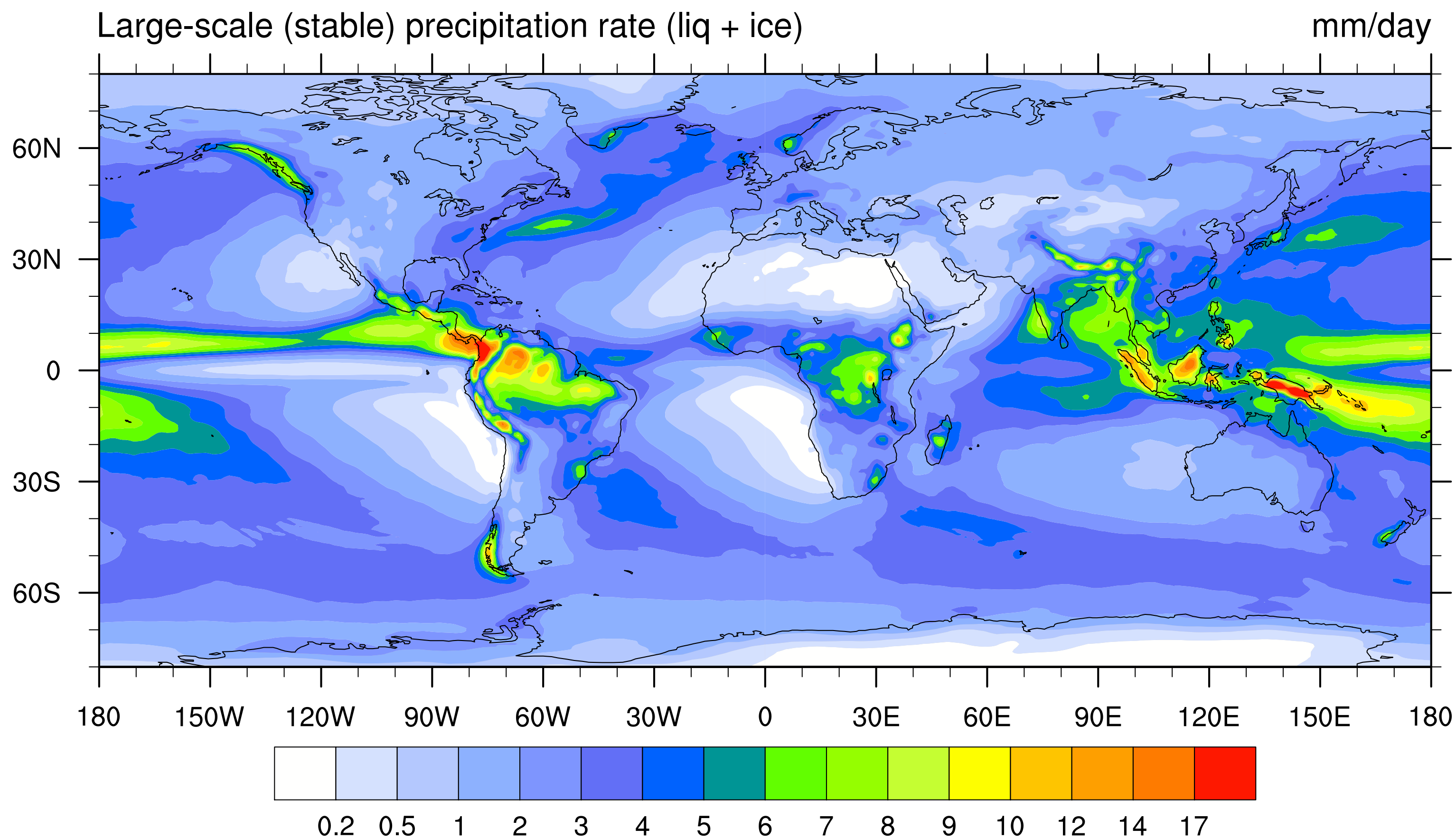


CAM6 release physics, only 3 year average

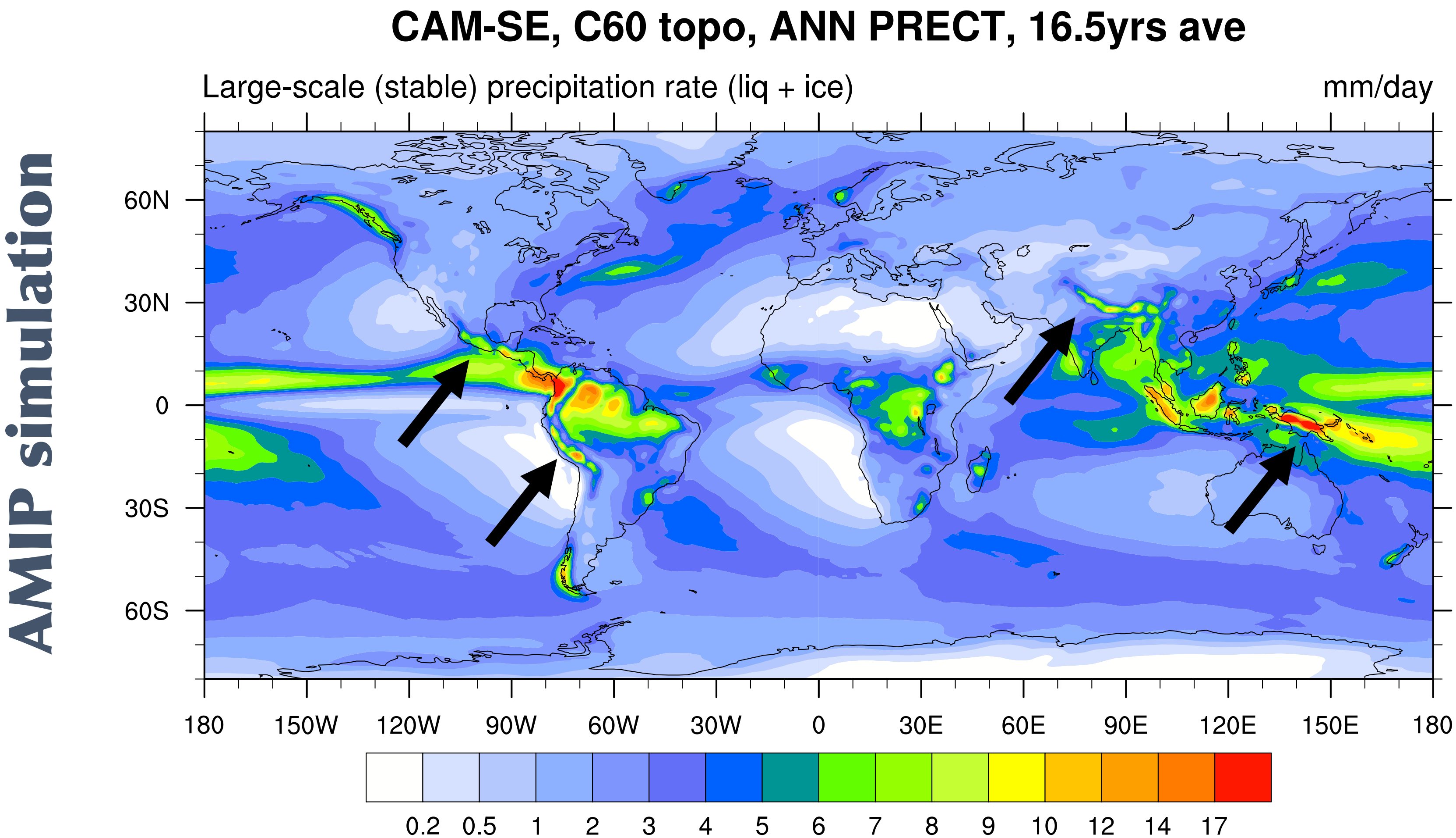

GPCP ANN
precipitation
mm/day
60N
30N
0
30S
60S
180
150W
120W
90W
60W
30W
0
30E
60E
90E
120E
150E
180
0.2
0.5
1
2
3
4
5
6
7
8
9
10
12
14
17

AMIP simulation

CAM-SE, C60 topo, ANN PRECT, 16.5yrs ave

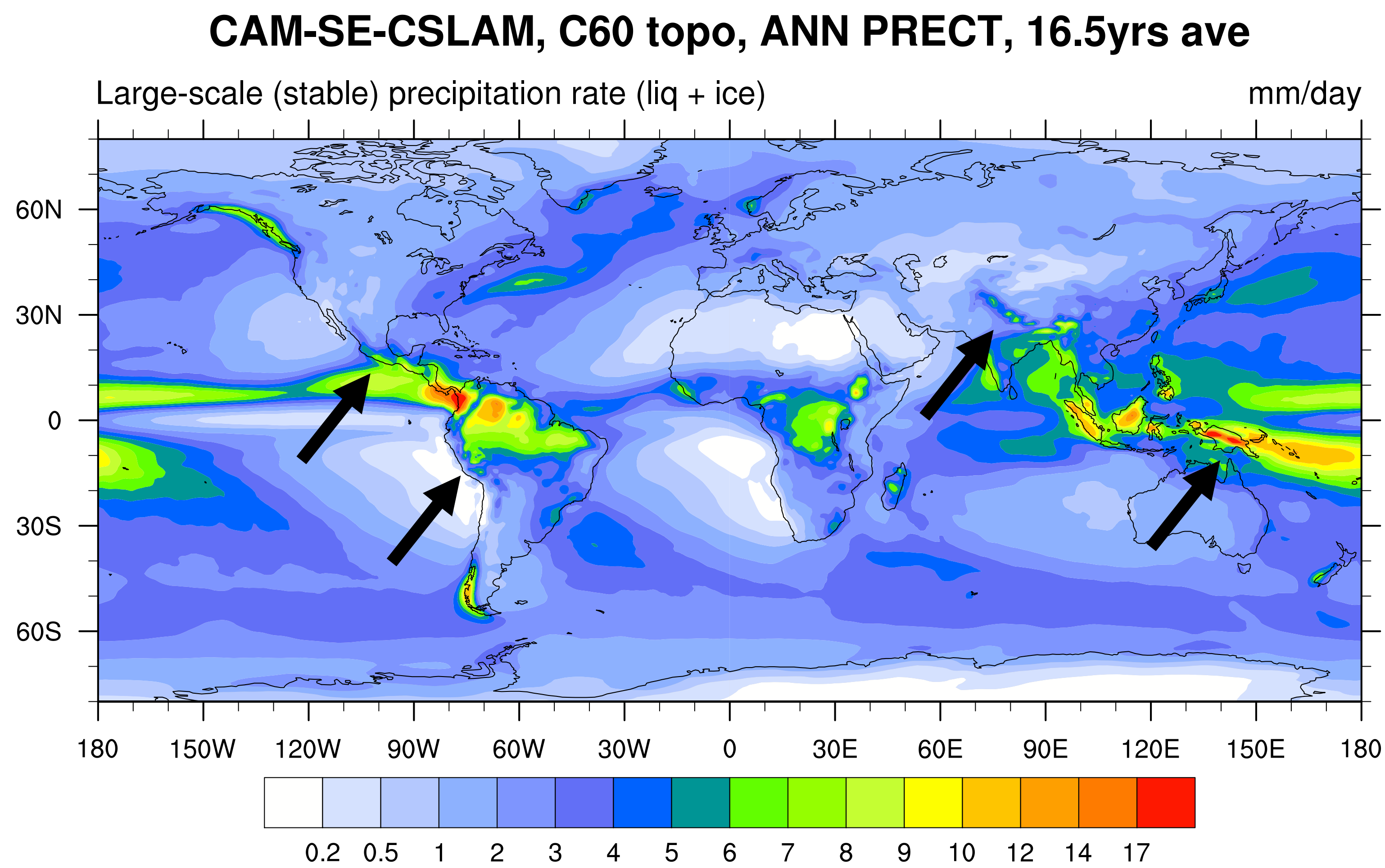


CAM6 release physics



CAM6 release physics

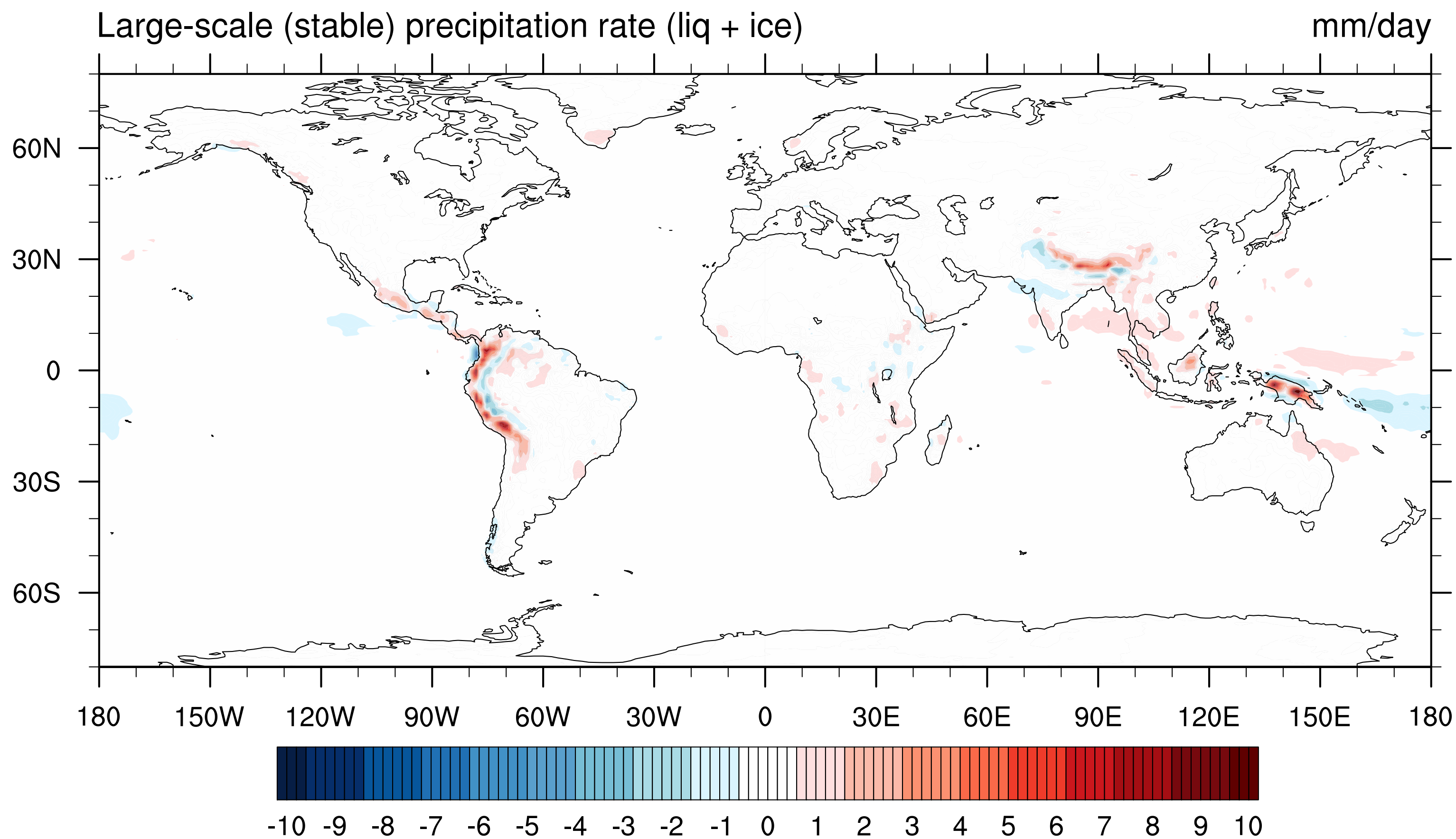
AMIP simulation



CAM6 release physics

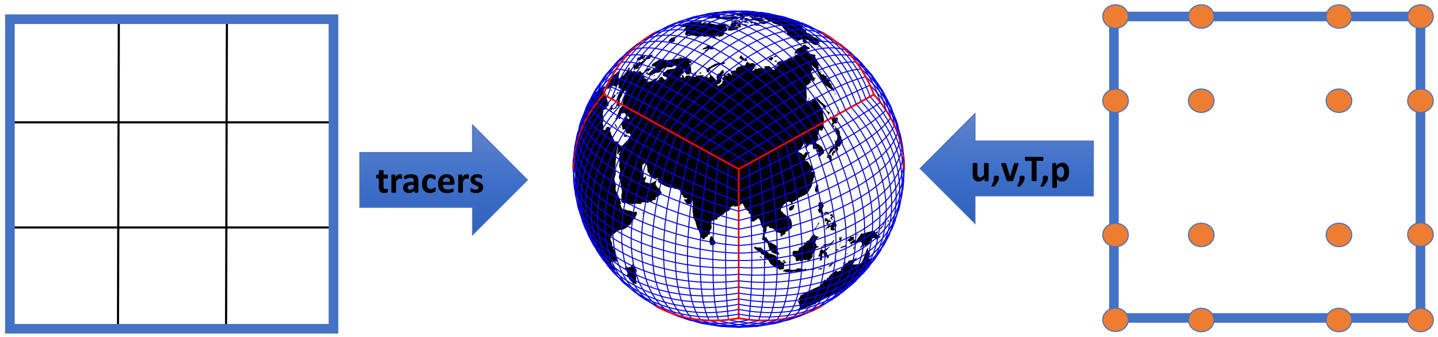
AMIP simulation

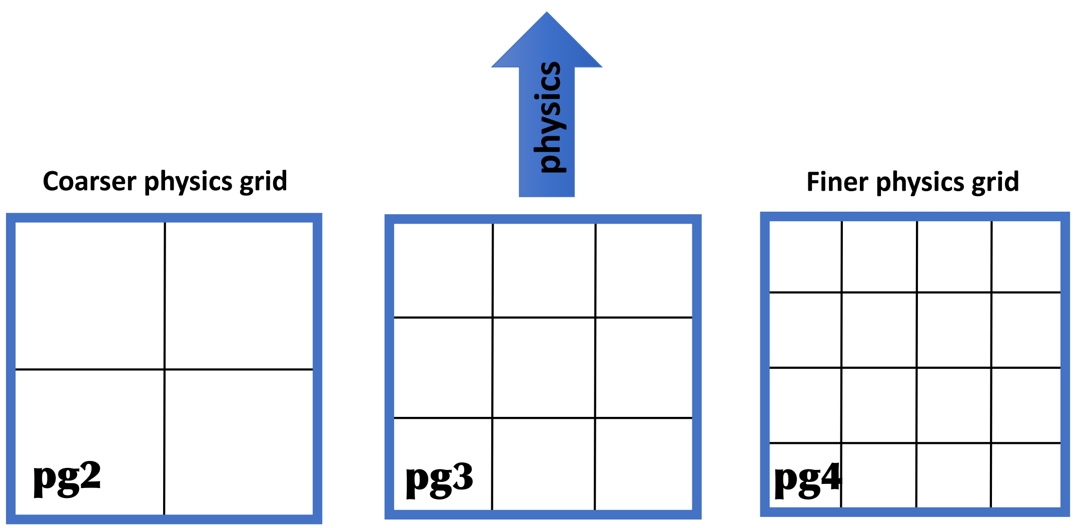
CAM-SE minus CSLAM, C60 topo, ANN PRECT, 16.5yrs ave



Part III: Lower resolution physics grid

CAM-SE-CSLAM: varying physics grid resolution





- Lander and Hoskins (1997): only pass “believable” scales to physics!
- 4 physics cells instead of 9 => speed-up of physics

CAM-SE-CSLAM: varying physics grid resolution

Lauritzen et al. (2018)

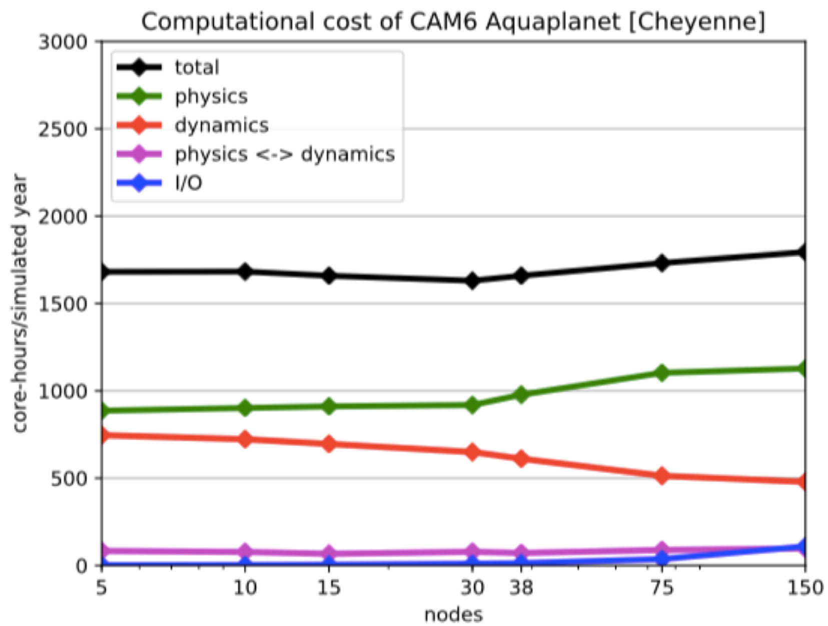


Figure 12. The cost in core-hours per simulated-year is provided for several different sub-components of CAM for the 1° horizontal resolution Aquaplanet simulation on Cheyenne (see text for more details).

- Lander and Hoskins (1997): only pass "believable" scales to physics!
- 4 physics cells instead of 9 => 2x speed-up of physics

pg2

pg3

pg4

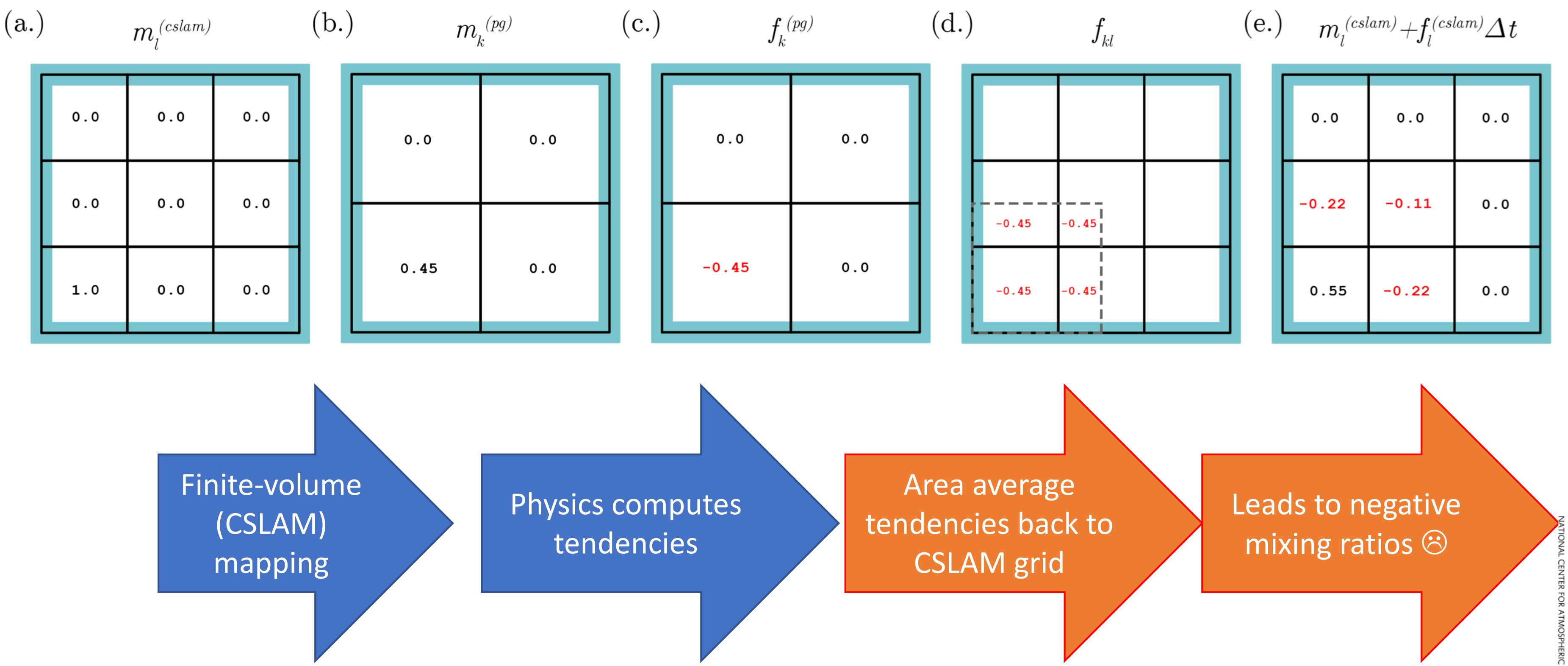
Mapping tracer tendencies from pg2 physics grid to pg3 CSLAM grid

Important properties for mapping operators

1. for tracers; mass tendency is conserved,
2. for tracers; in each tracer grid cell the mass tendency from physics must not exceed tracer mass available in tracer grid cell (i.e. physics tendency will not drive tracer mixing ratio negative),
3. linear correlation preservation,
4. consistency, i.e. the mapping preserves a constant tendency.

Other properties that may be important, but not pursued here, includes total energy conservation (incl. components of total energy) and axial angular momentum conservation.

Requirement for conservation: In each tracer grid cell the mass tendency from physics must not exceed tracer mass available in tracer grid cell



Herrington et al. (in prep.)

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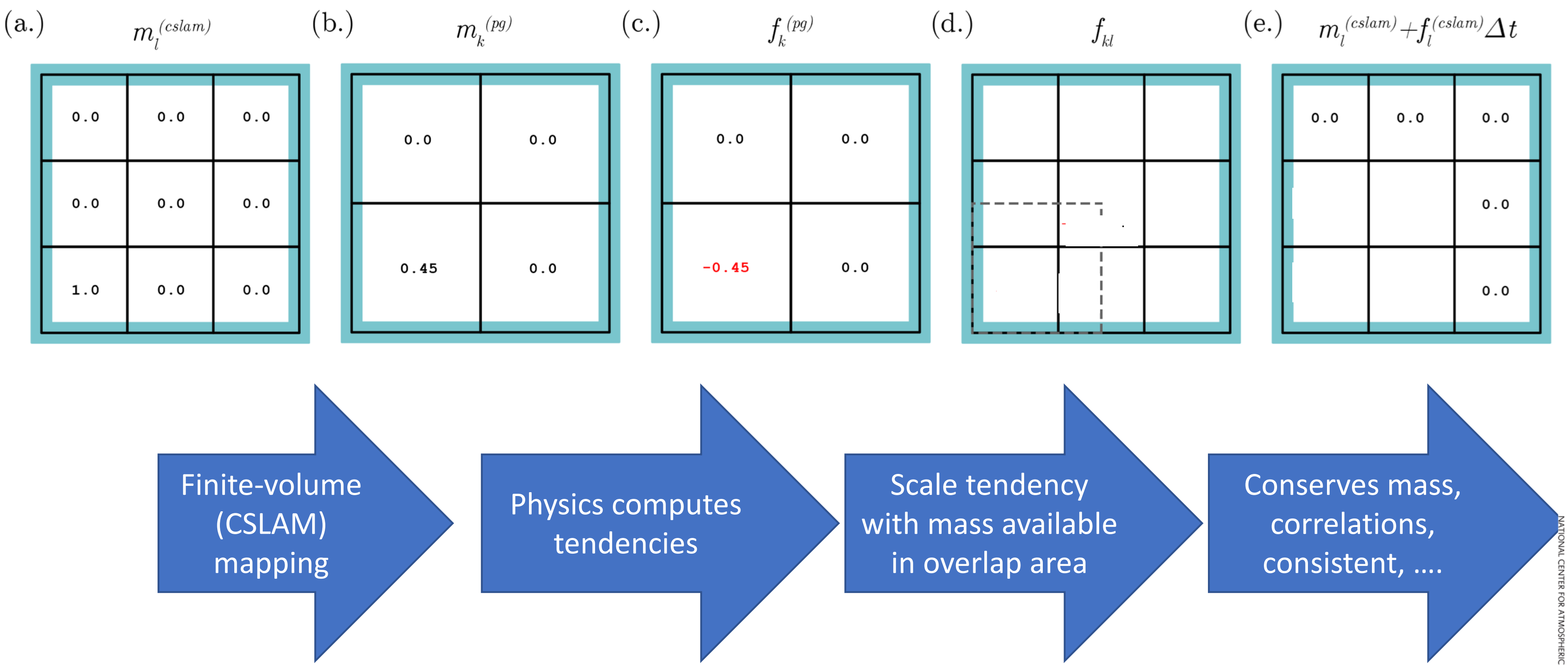
Requirement for conservation: In each tracer grid cell the mass tendency from physics must not exceed tracer mass available in tracer grid cell

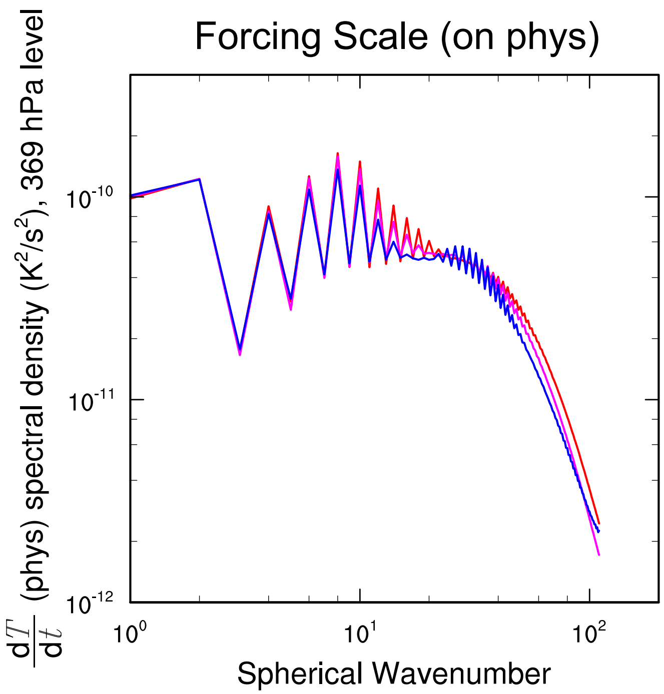


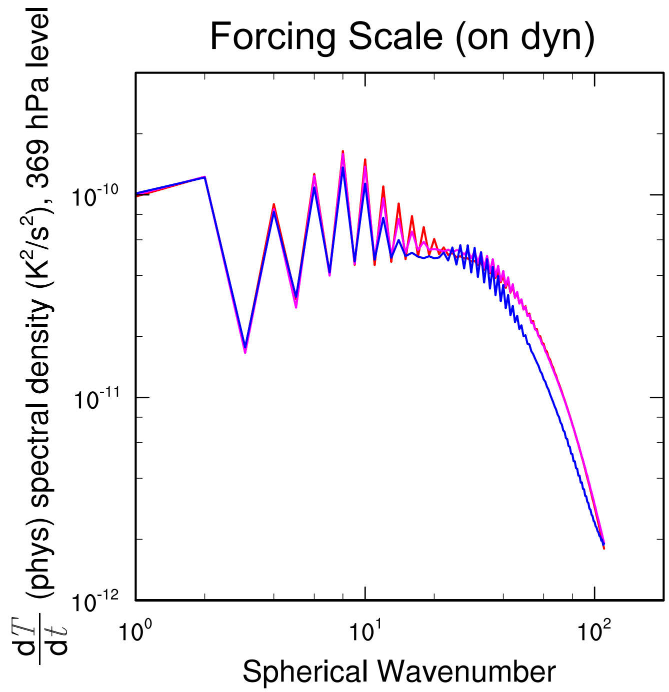
Herrington et al. (in prep.)

Low versus high order mapping

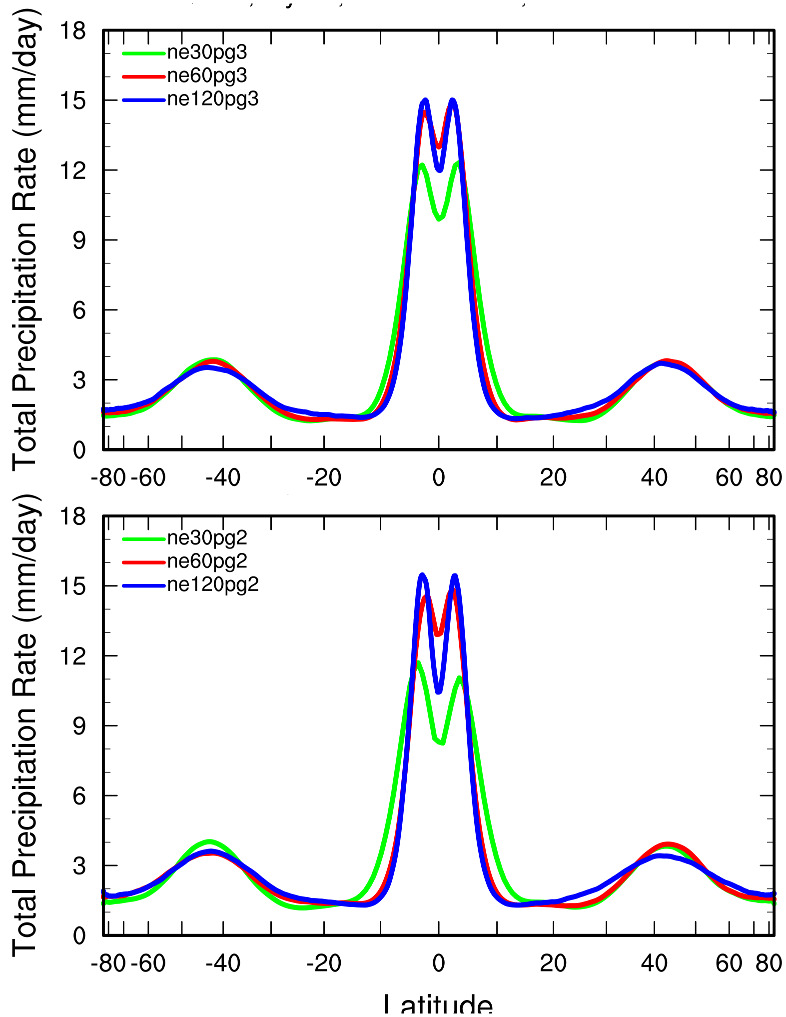
	Grid name	Δx_{dyn}	Δt_{dyn}	Δx_{phys}	Δt_{phys}
*	ne30pg2	111.2km	300s	166.8km	1800s
	ne30pg2	111.2km	300s	166.8km	1800s
	ne30pg3	111.2km	300s	111.2km	1800s

*low order mapping (bilinear in pg2->dyn, PCoM in CSLAM<->pg2)





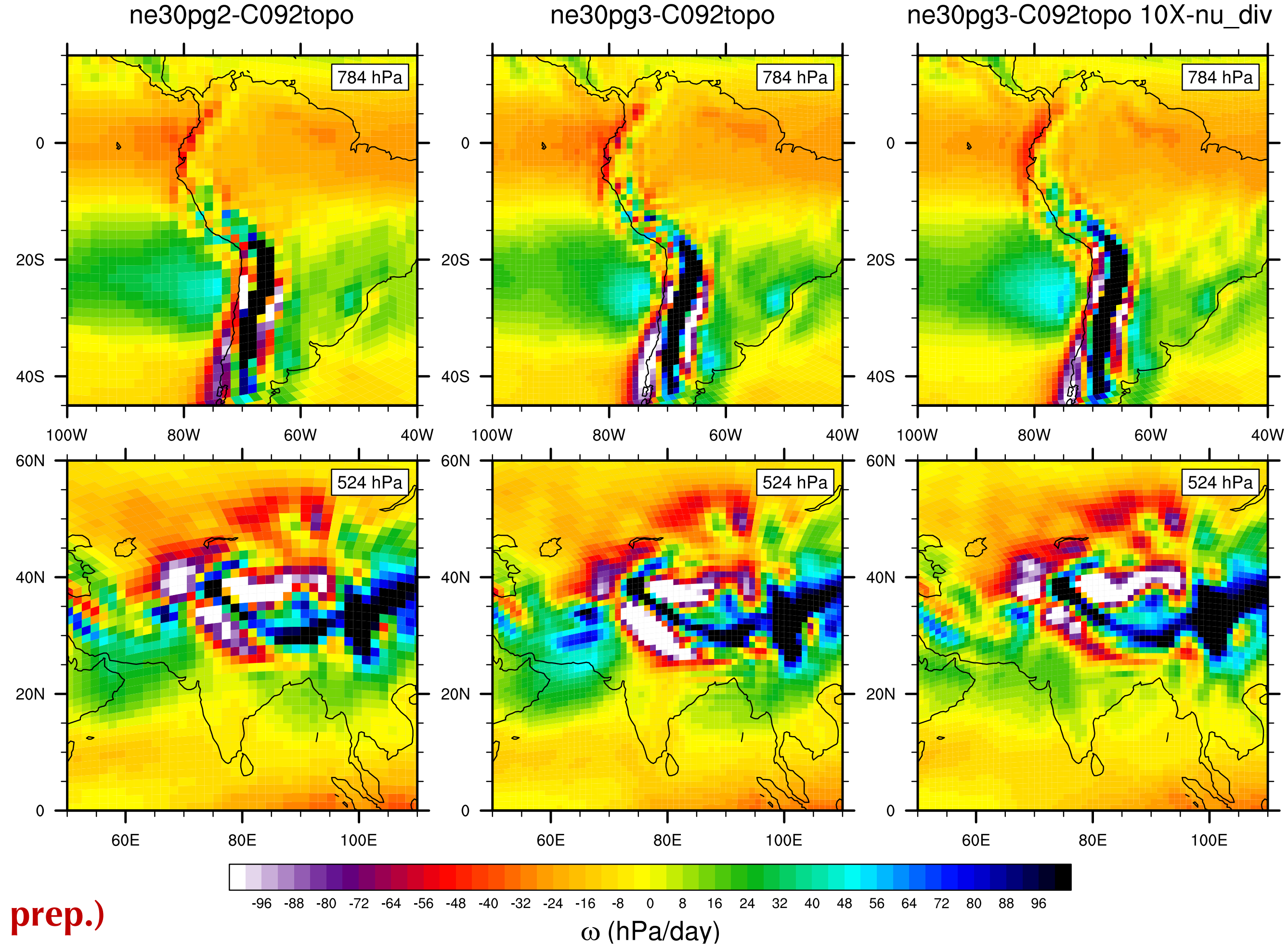
Mean climate of Aqua-planet simulations



Herrington et al. (in prep.)

Fix Dynamics, change physics grid resolution

(but, same topography smoothing)



Herrington et al. (in prep.)

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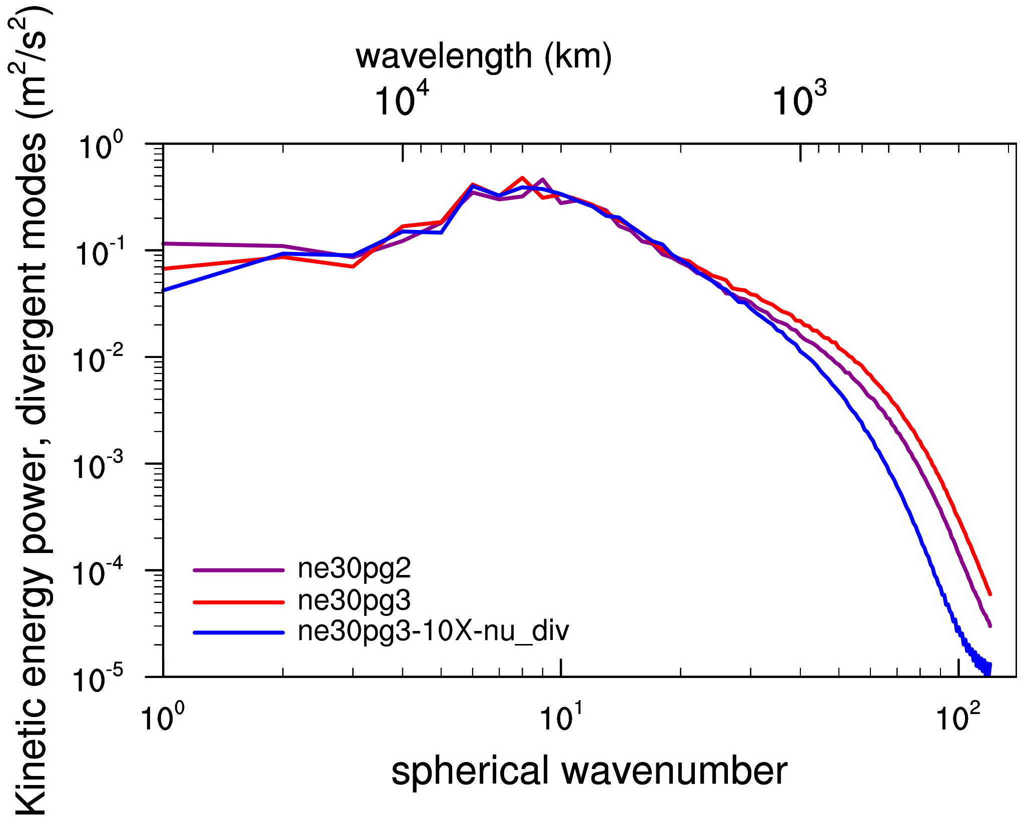
Fix Dynamics, change physics grid resolution

(but, same topography smoothing)

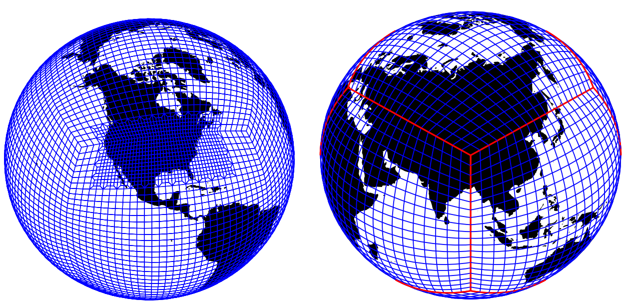


Herrington et al. (in prep.)

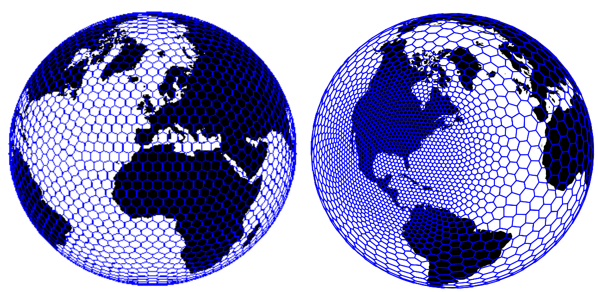
Final Remarks

- **CAM-SE-CSLAM (pg3) will be released with CESM2.1**
  (scheduled for early Fall)
- **FV3 and MPAS are being integrated into the CESM**
  -> early next year we should be able to evaluate FV3, MPAS and SE(-CSLAM) in the same framework

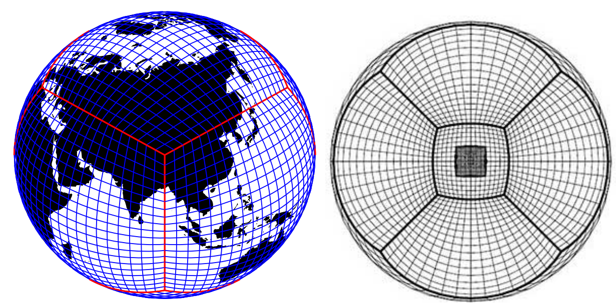
CAM-SE(CSLAM)



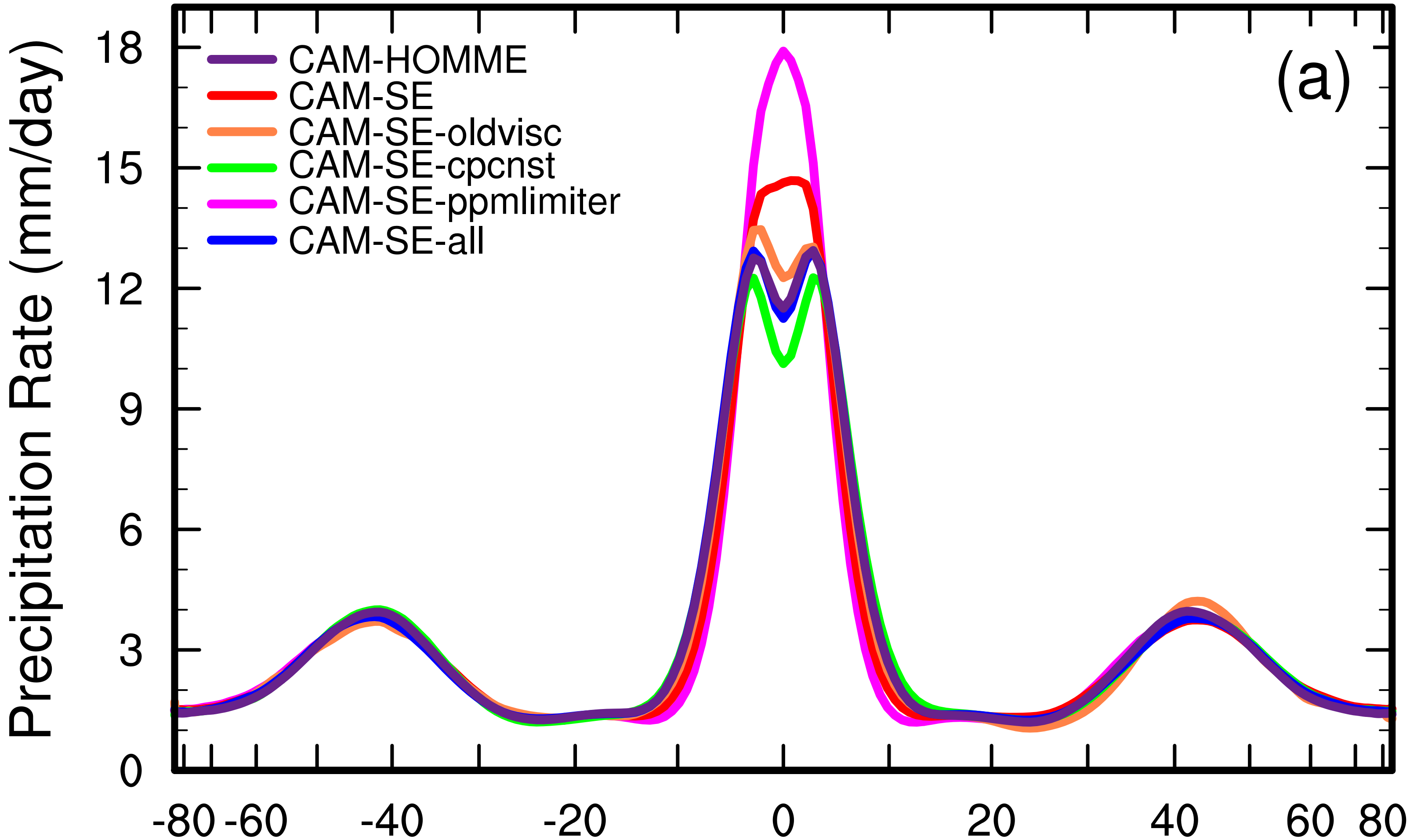
CAM-MPAS



CAM-FV3



4.5 year average using CAM6 physics (QPC6 compset)



Lauritzen et al. (2018)

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