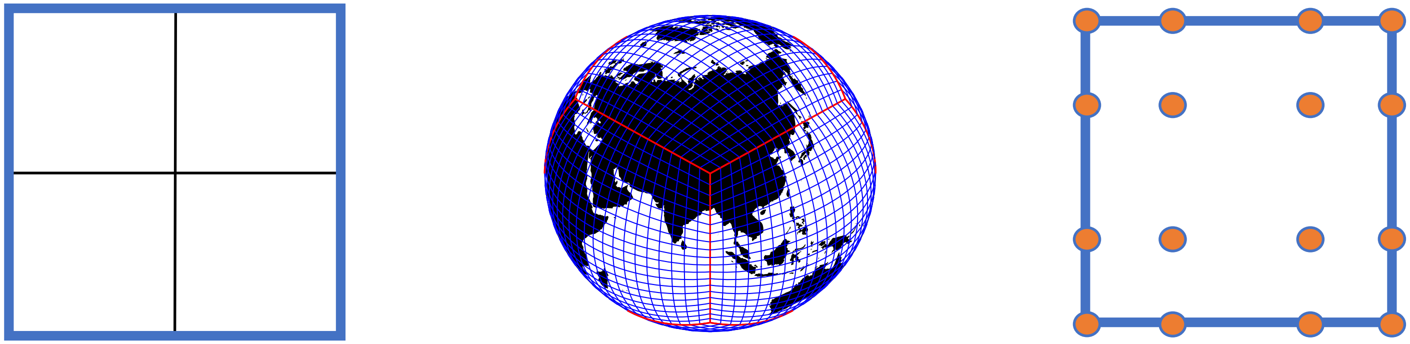
Evaluating the Physics at a Lower Resolution in CAM-SE-CSLAM



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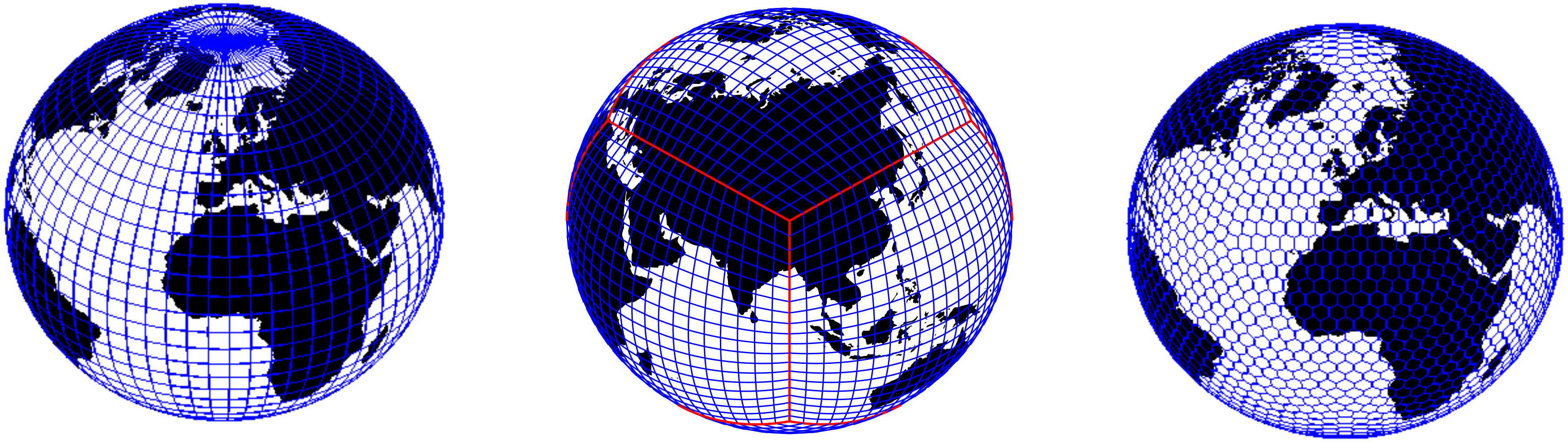
Workshop on the solution to partial differential equations on the sphere, April 29 – May 3, 2019, Montréal, Québec, Canada

Why are we separating physics and dynamics grids with spectral-elements?

The physics dynamics coupling paradigm

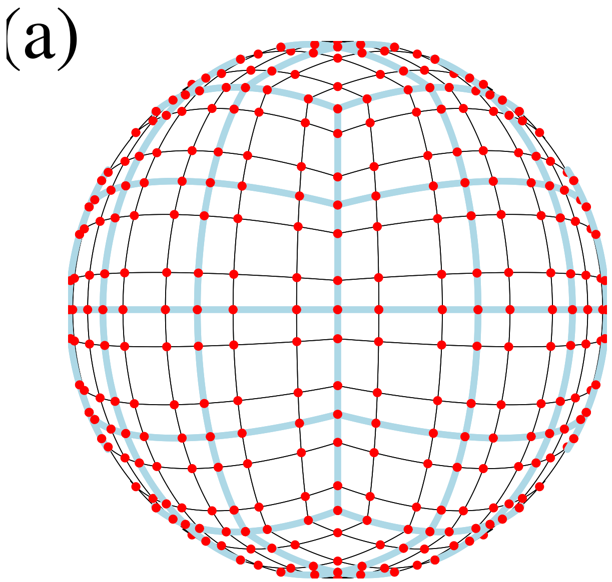
Assumptions inherent to the physical parameterizations require the state passed by the dynamical core represent a ‘large-scale state’, for example, in quasi-equilibrium-type convection schemes (Arakawa and Schubert 1974)

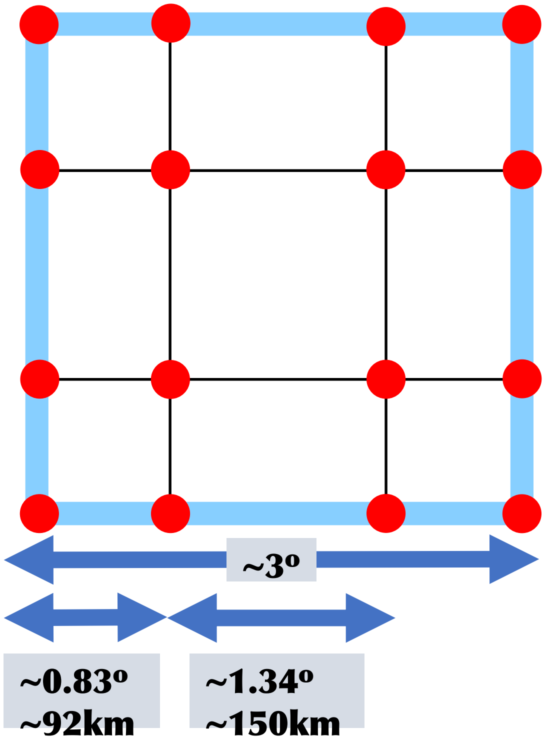
Consistent with finite-volume/finite-difference methods on gradually varying meshes



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

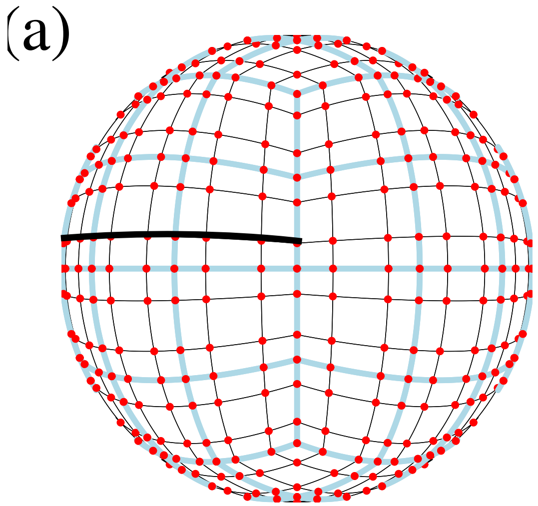
A unique aspect of the high-order quadrature rules is that the nodes within an element are located at the roots of the basis set, which may be irregularly spaced

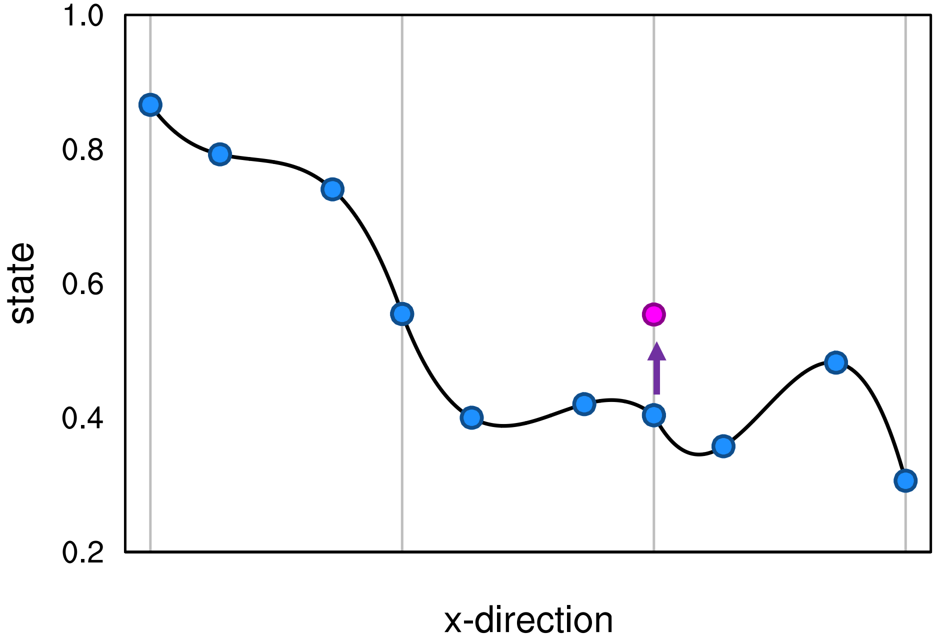




Non-uniform resolution argument

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

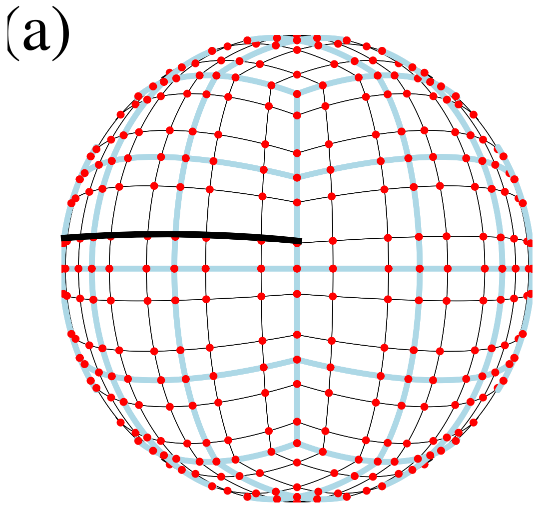


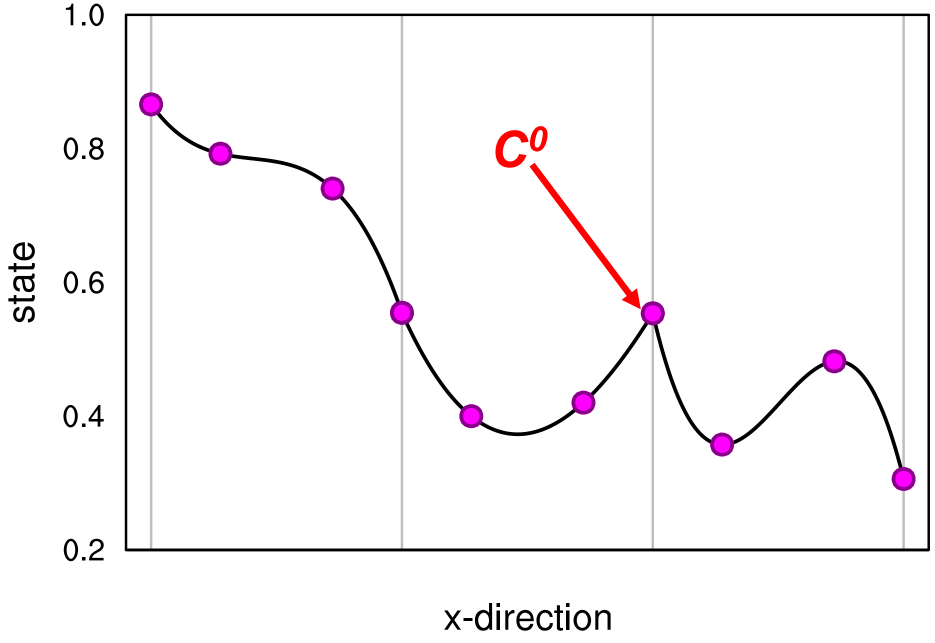


The physics forms a cloud on a boundary node

“Non-uniform smoothness” argument

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



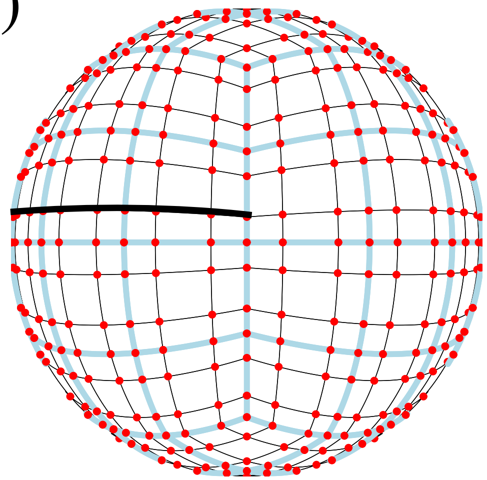


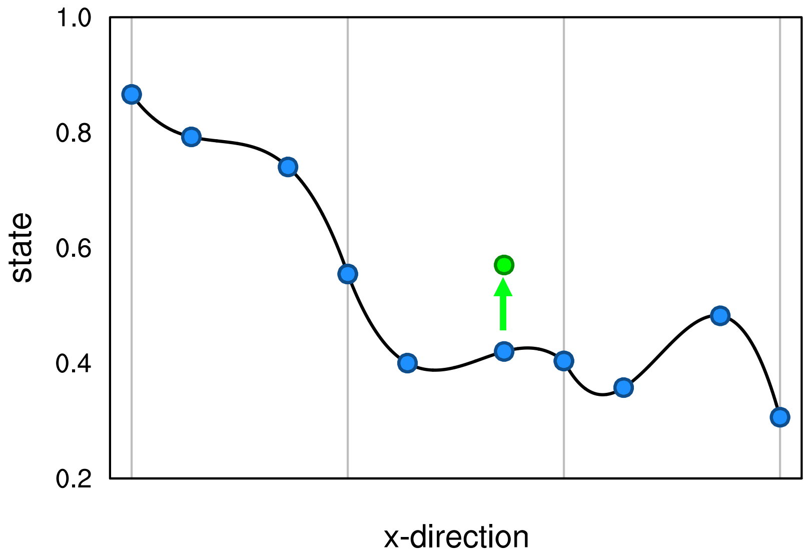
Note … non-local effect by changing one node value

“Non-uniform smoothness” argument

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

(a)

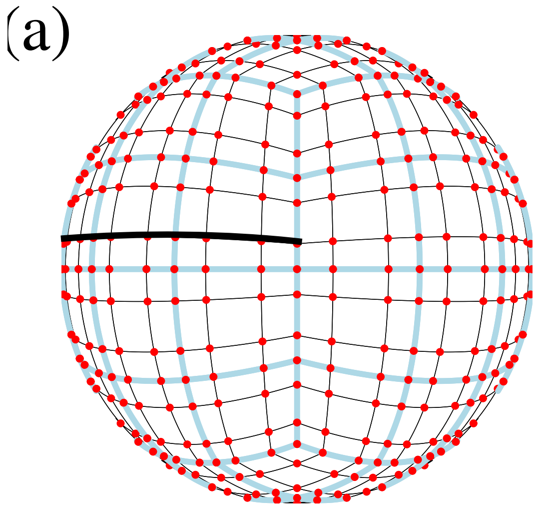


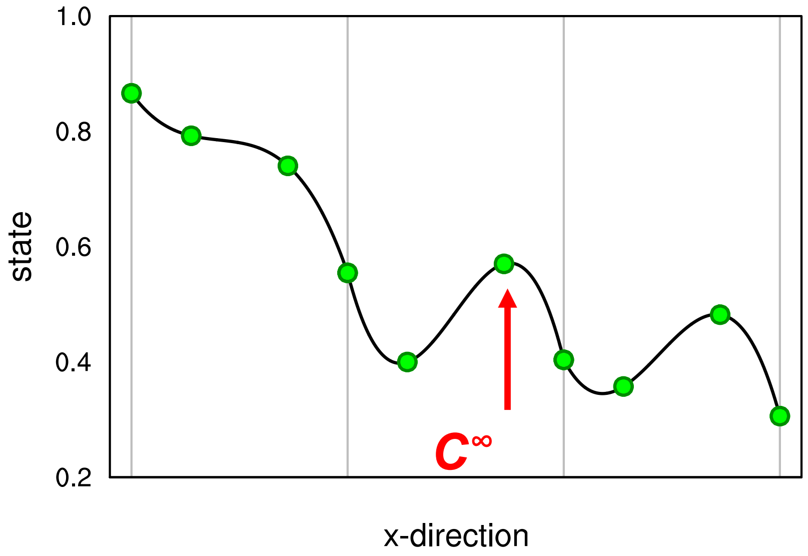


Lets say the cloud instead forms at an interior node…

“Non-uniform smoothness” argument

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



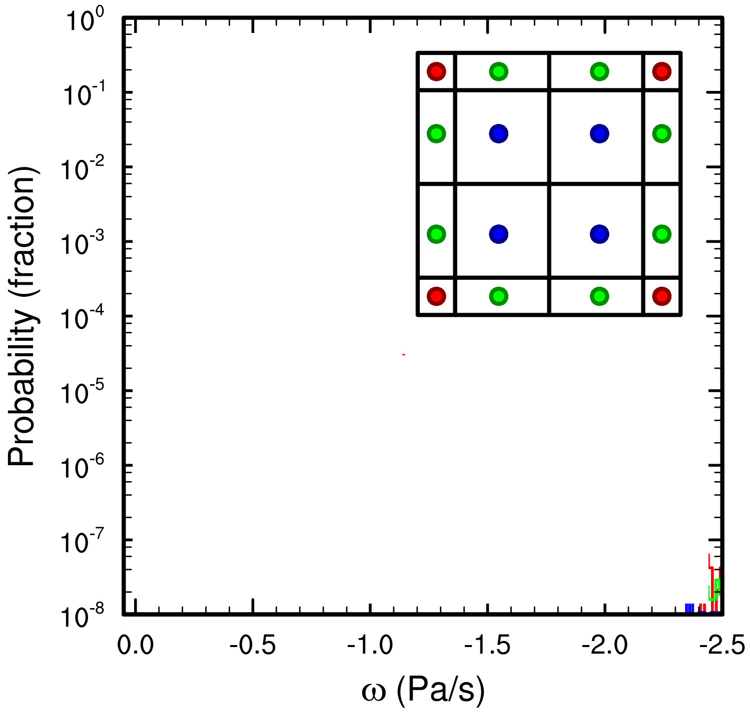


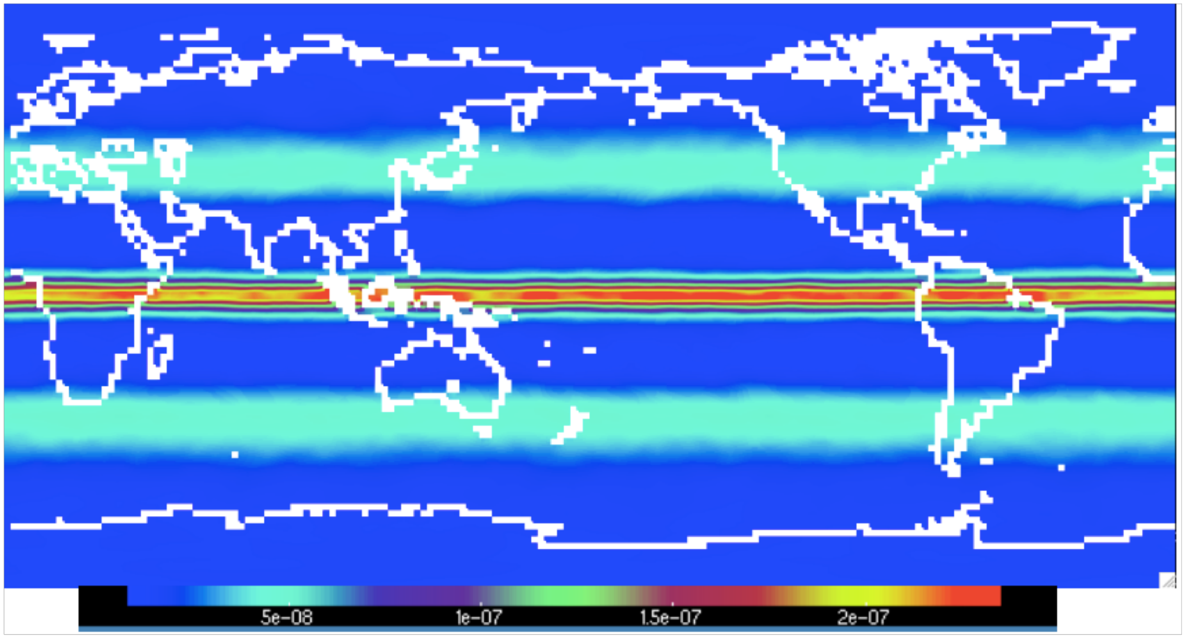
Lets say the cloud instead forms at an interior node…

“Non-uniform smoothness” argument

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

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





Herrington et al. (MWR, 2018)

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

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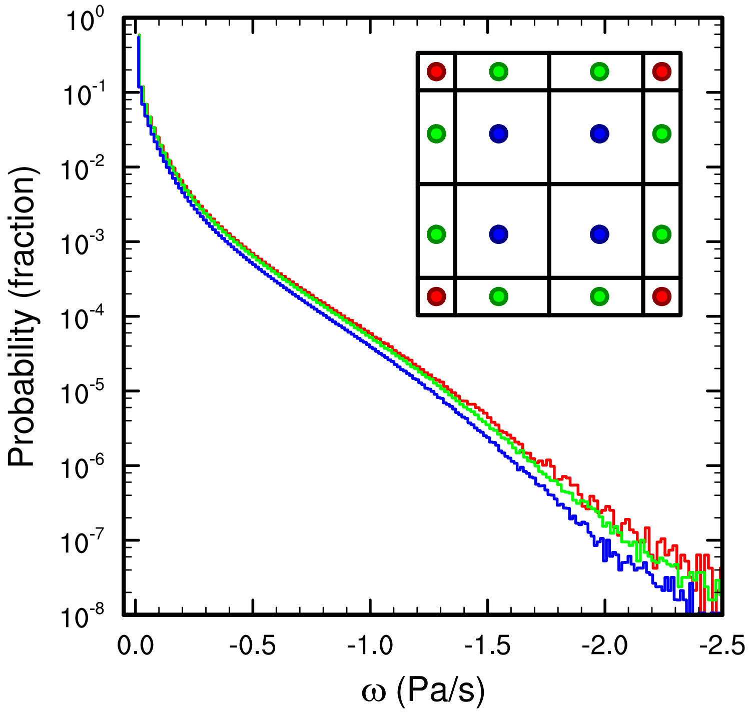
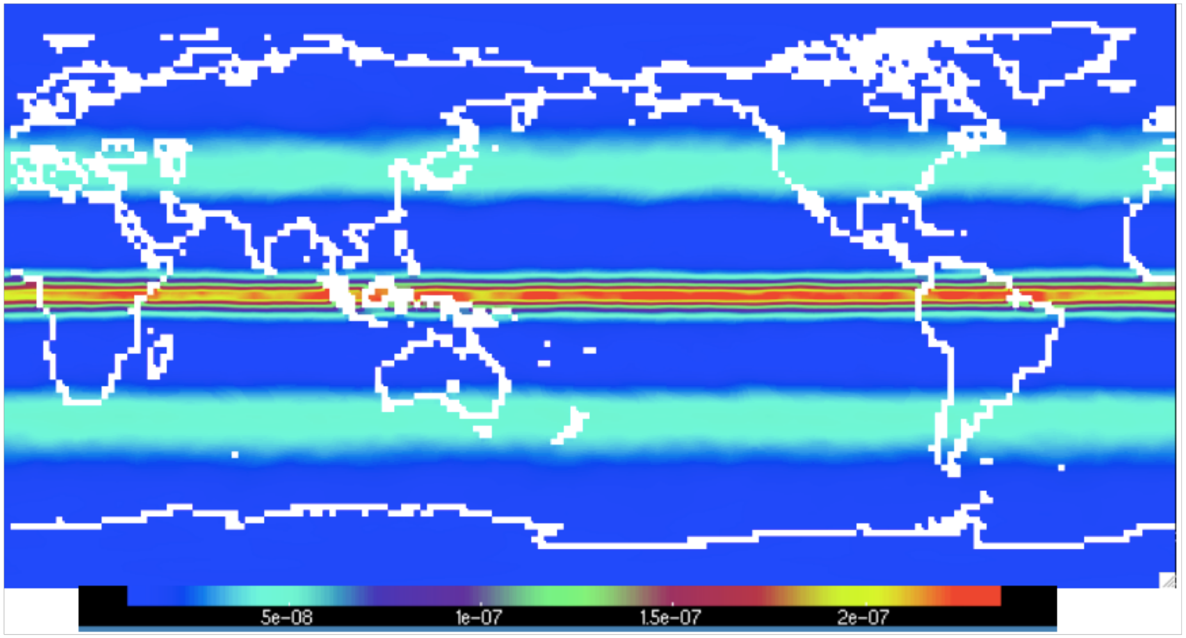
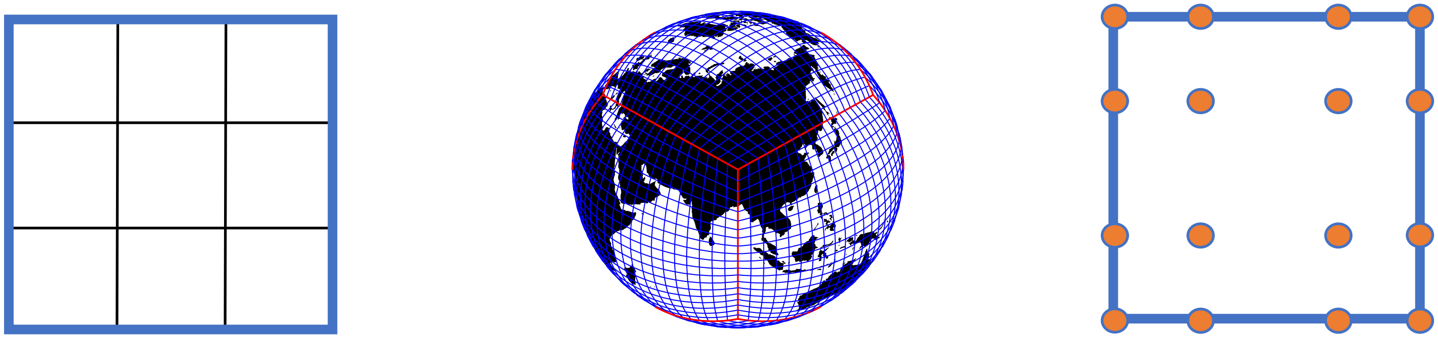




Herrington et al. (MWR, 2018)

A solution:

Quasi-equal area physics grid



Mapping state from dynamics to physics 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 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, 2018)

Mapping tendencies (NOT STATE) from physics to dynamics grid:

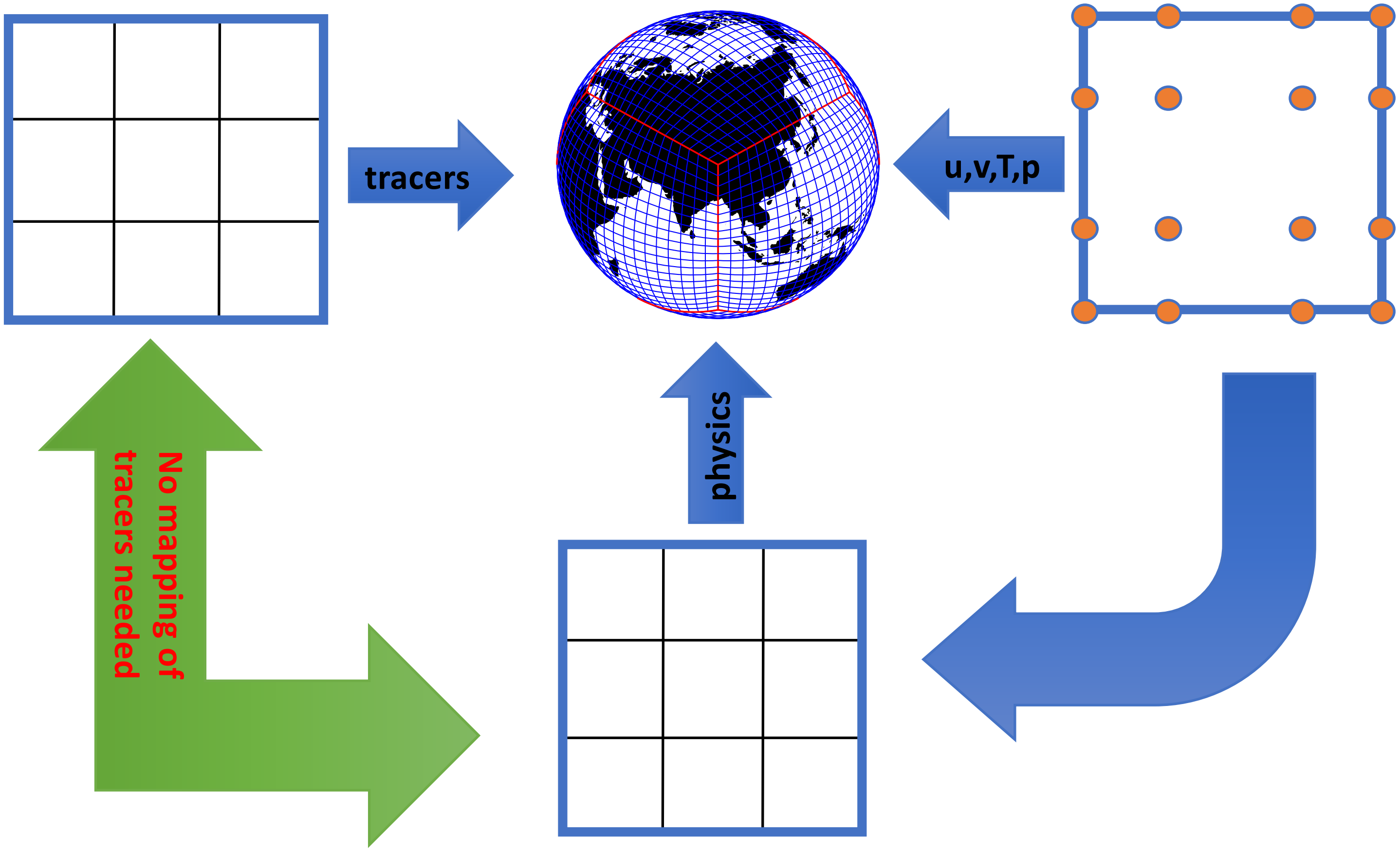
Important properties for mapping operators

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 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, 2018)

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



tracers

u,v,T,p

physics

No mapping of tracers needed

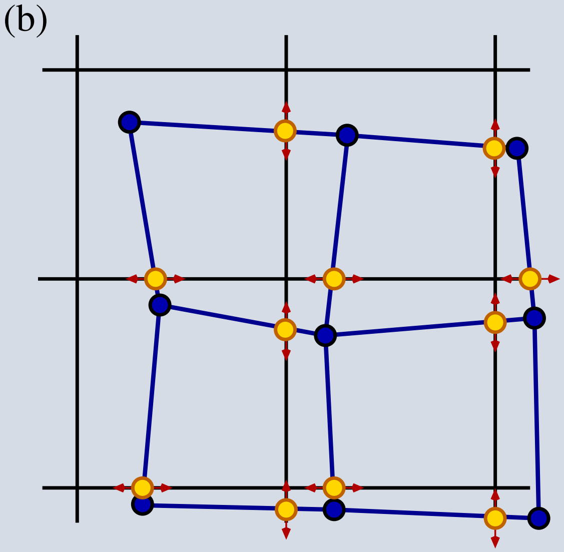
CSLAM = Conservative Semi-LAgrangian Multi-tracer scheme

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, ….



Lauritzen et al. (2016)

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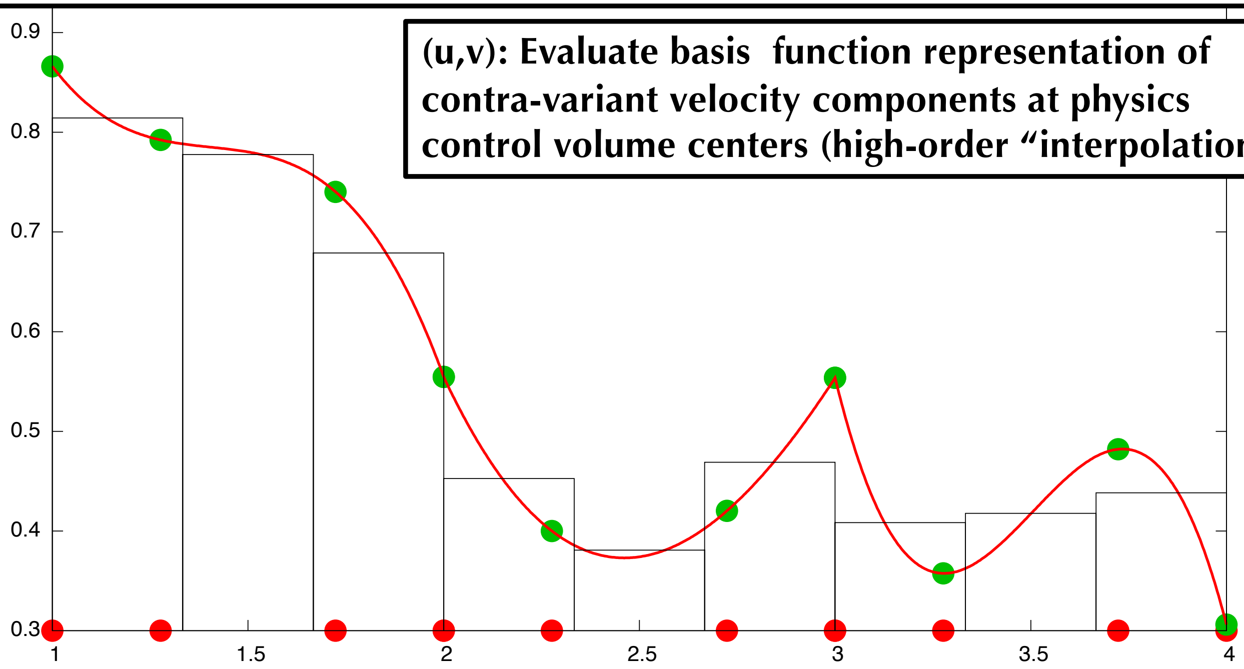
Sandia National Laboratories, Albuquerque, New Mexico

Mon. Wea. Rev.

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 (dM is dry pressure level thickness)

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



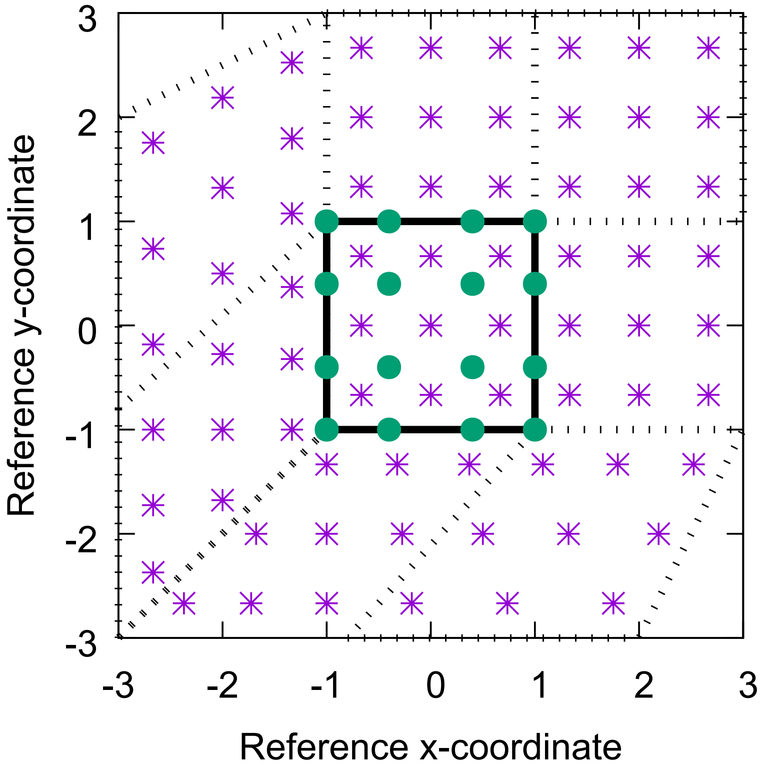
(u,v): Evaluate basis function representation of contra-variant velocity components at physics control volume centers (high-order "interpolation")

Herrington et al. (MWR, 2018)

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 ~0.6W/m^2

(for ~1 degree horizontal resolution)

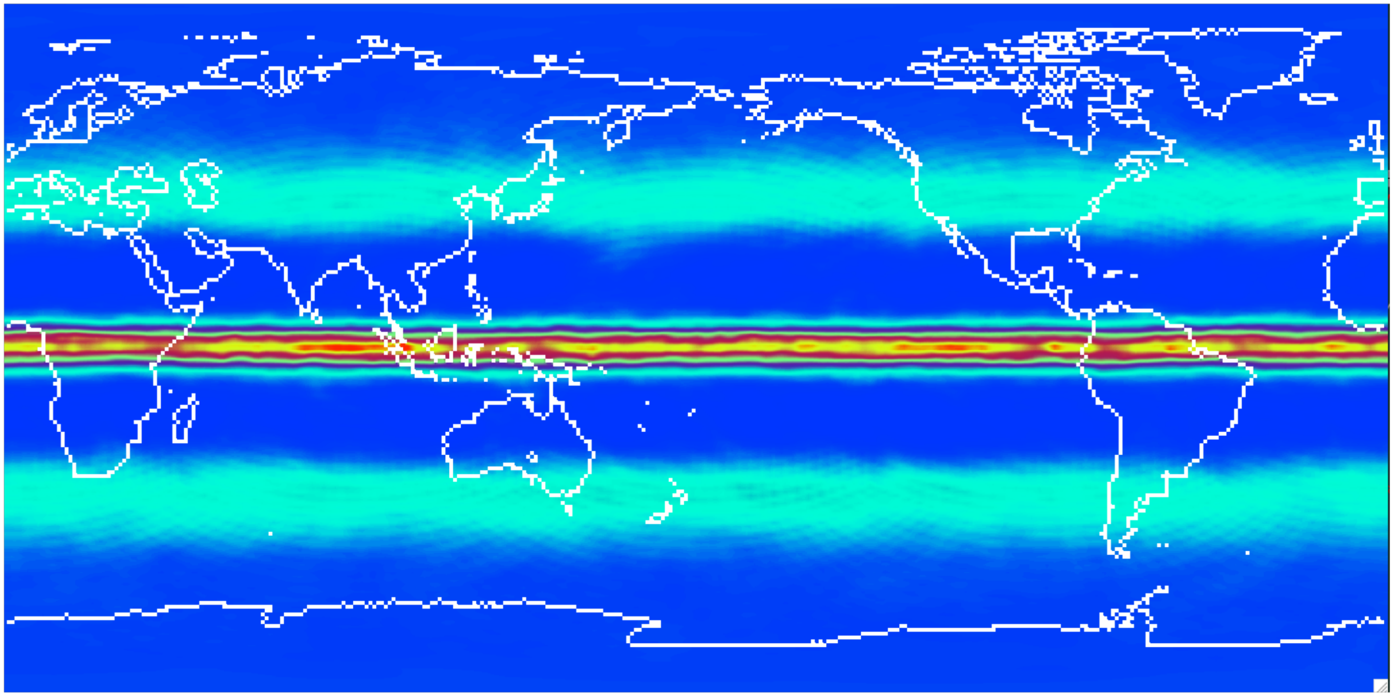
Herrington et al. (MWR, 2018)

High-order interpolation was found to be important

CAM4 Aqua-planet simulation

PRECT

(TOTAL PRECIPITATION RATE)



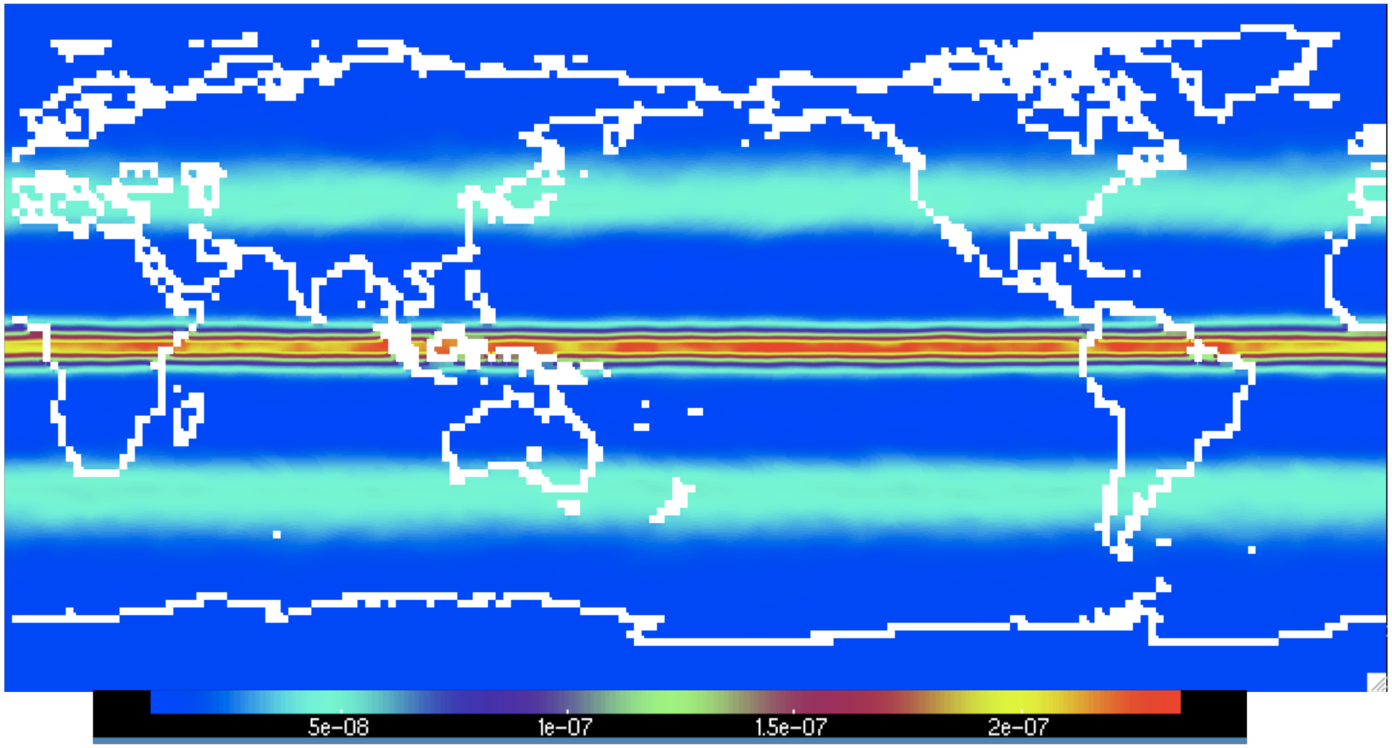
CAM4 SE-CSLAM-physgrid: linear interpolation phys to dyn: 5 month average

High-order interpolation was found to be important

PRECT

(TOTAL PRECIPITATION RATE)

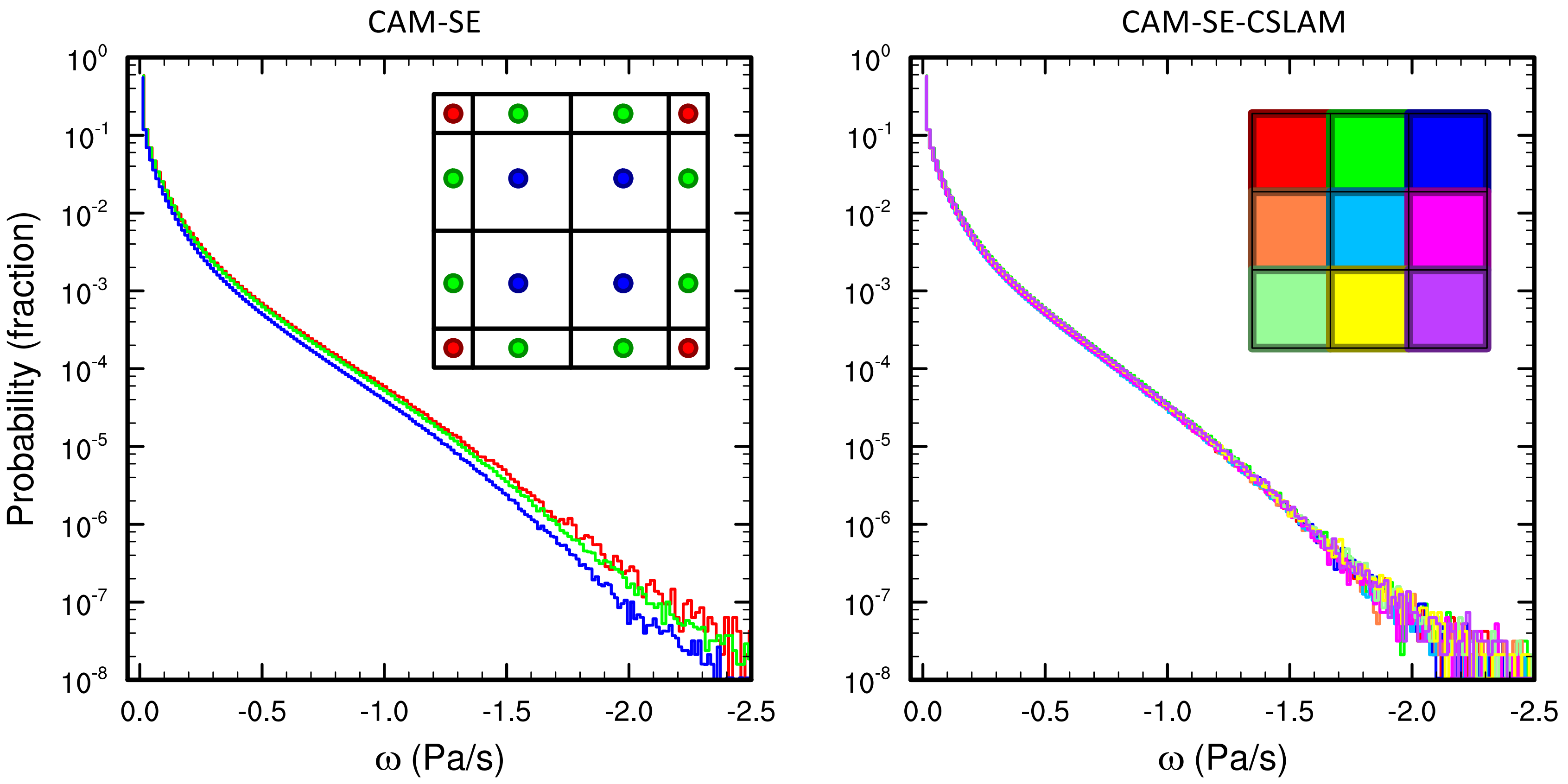
CAM4 Aqua-planet simulation



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

Results – CAM4 Aqua-planets

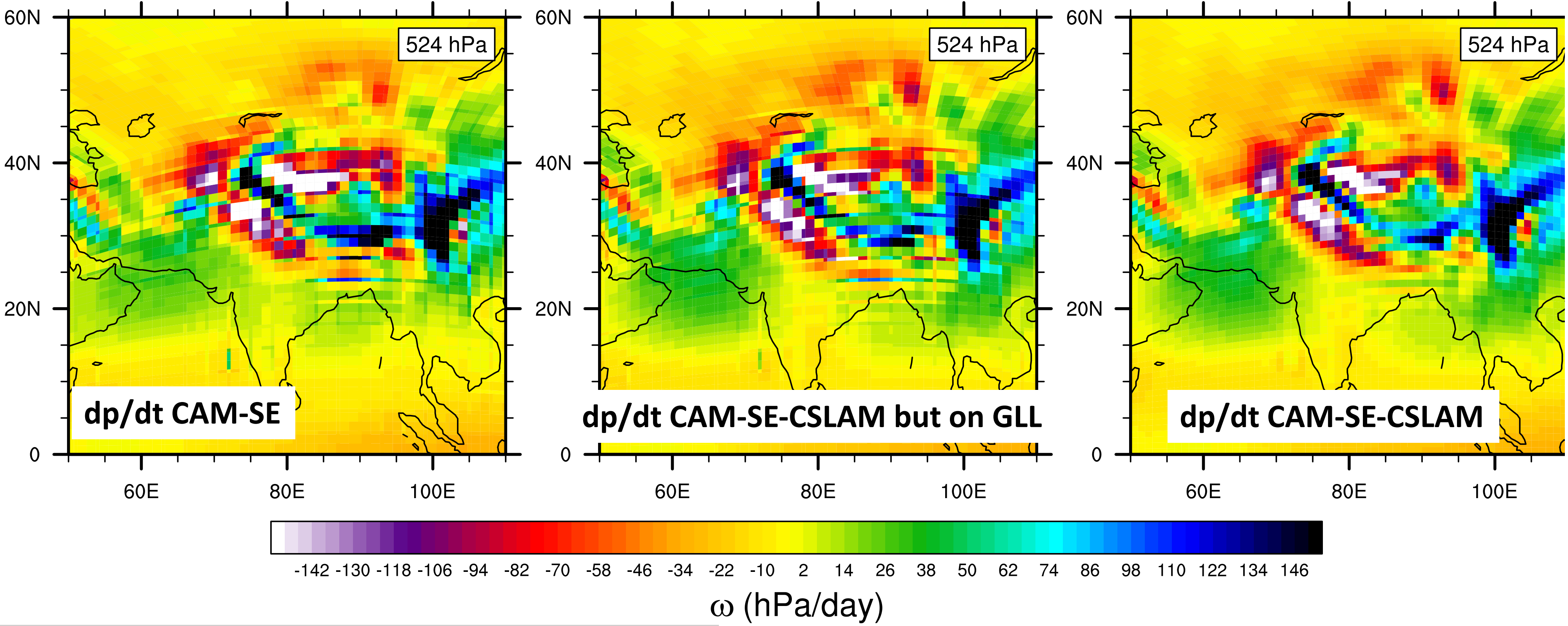
CAM4 Aqua-planet simulation



State the physics ‘sees’ is now independent of location within element!

Herrington et al. (MWR, 2018)

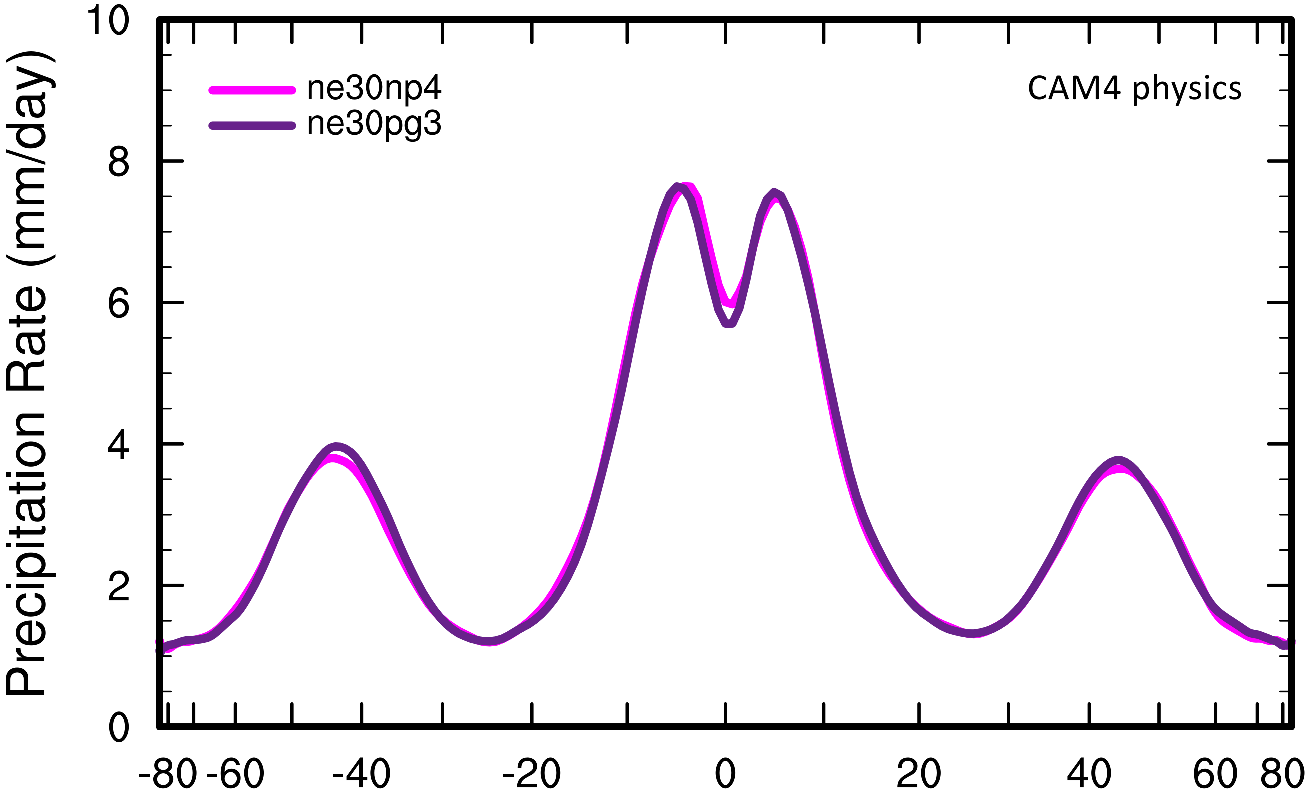
Held-Suarez simulation with real-world topography



Most of spurious noise will not be "seen" by physics (though still present on GLL grid)

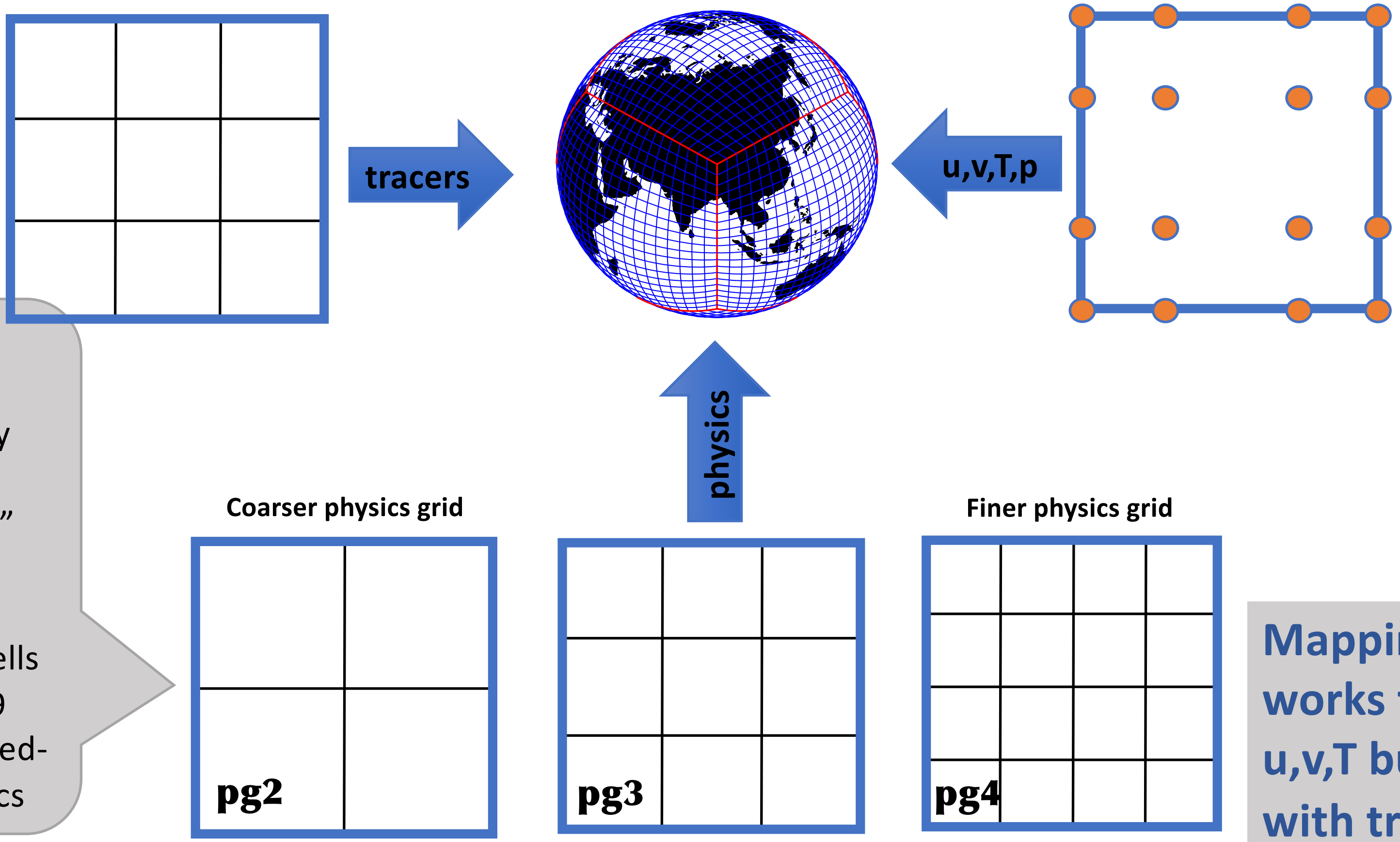
Herrington et al. (MWR, 2018)

That said, the zonal means look very similar …



Lower (or higher) 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 => 2x+ speed-up of physics

Mapping method works the same for u,v,T but “problem” with tracers …

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),

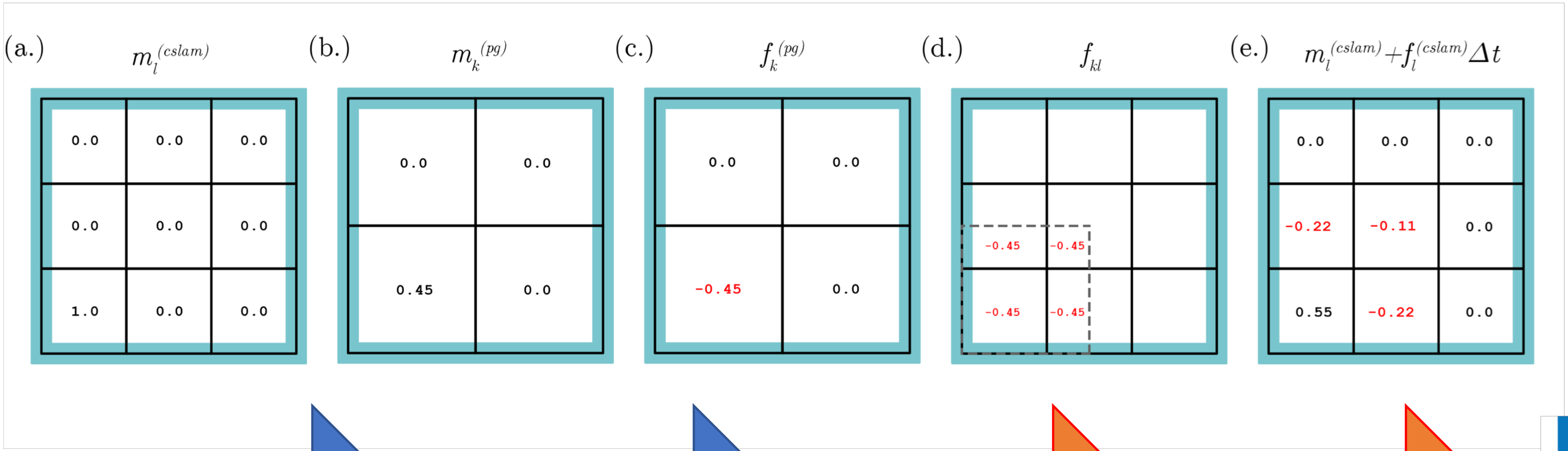
3. linear correlation preservation,

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.

CONVENTIONAL MAPPING METHODS FAIL – SEE Herrington et al. (2019,submitted) for detailed explanation

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



Finite-volume (CSLAM) mapping

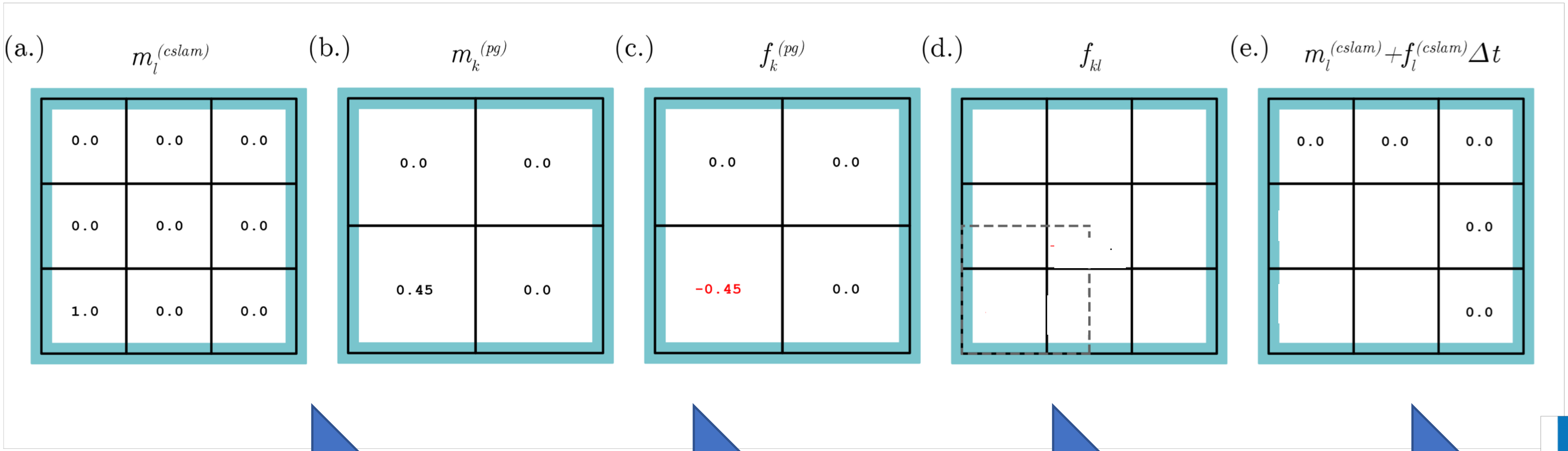
Physics computes tendencies

Area average tendencies back to CSLAM grid

Leads to negative mixing ratios ☹

Herrington et al. (2019, submitted)

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



Finite-volume (CSLAM) mapping

Physics computes tendencies

Scale tendency with mass available in overlap area

$$\sum_{\ell} \Delta m_{k\ell}^{(excess)} \overline{\Delta p_{k\ell}} \delta A_{k\ell}$$

Conserves mass, correlations, consistent, ….

Herrington et al. (2019, submitted)

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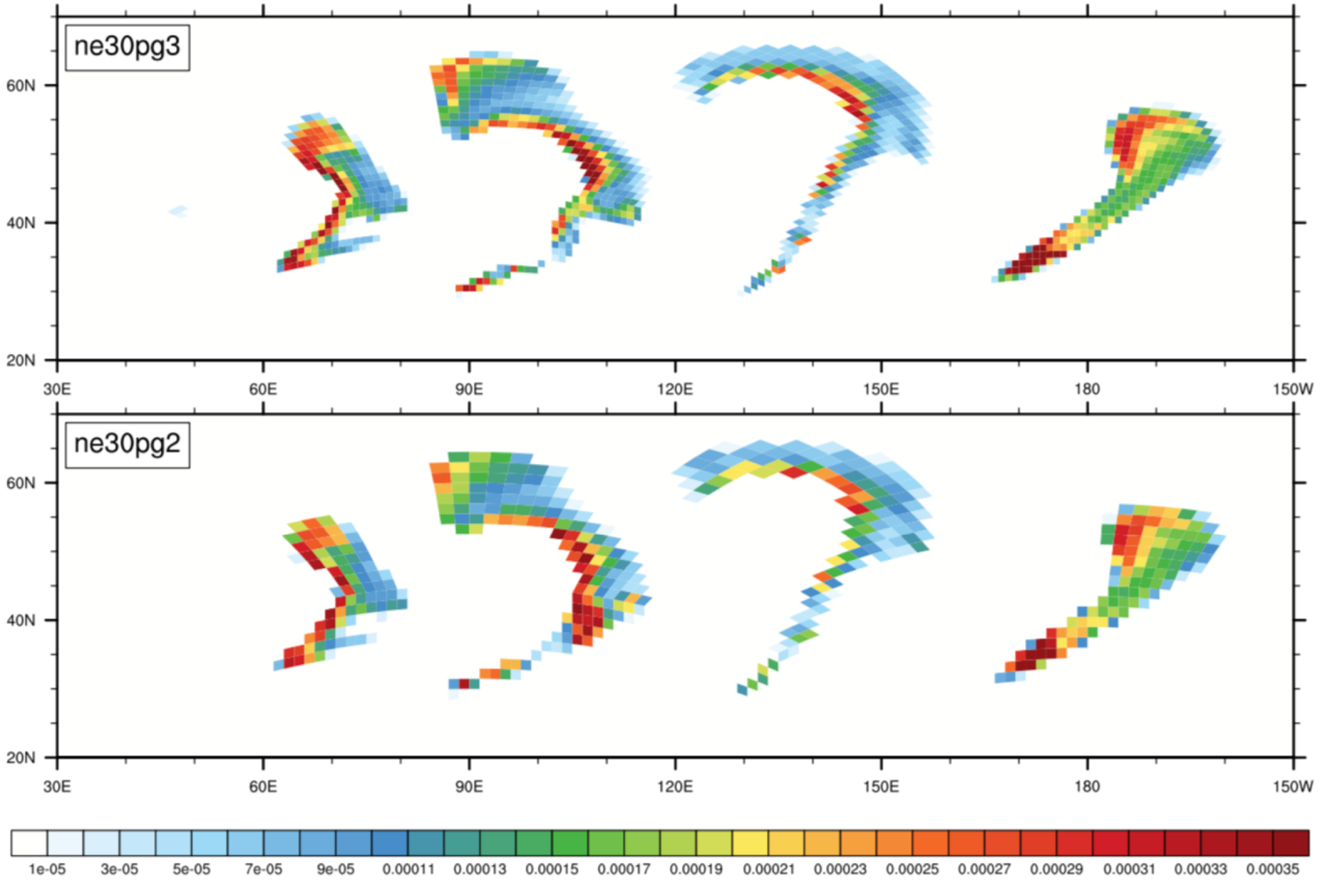
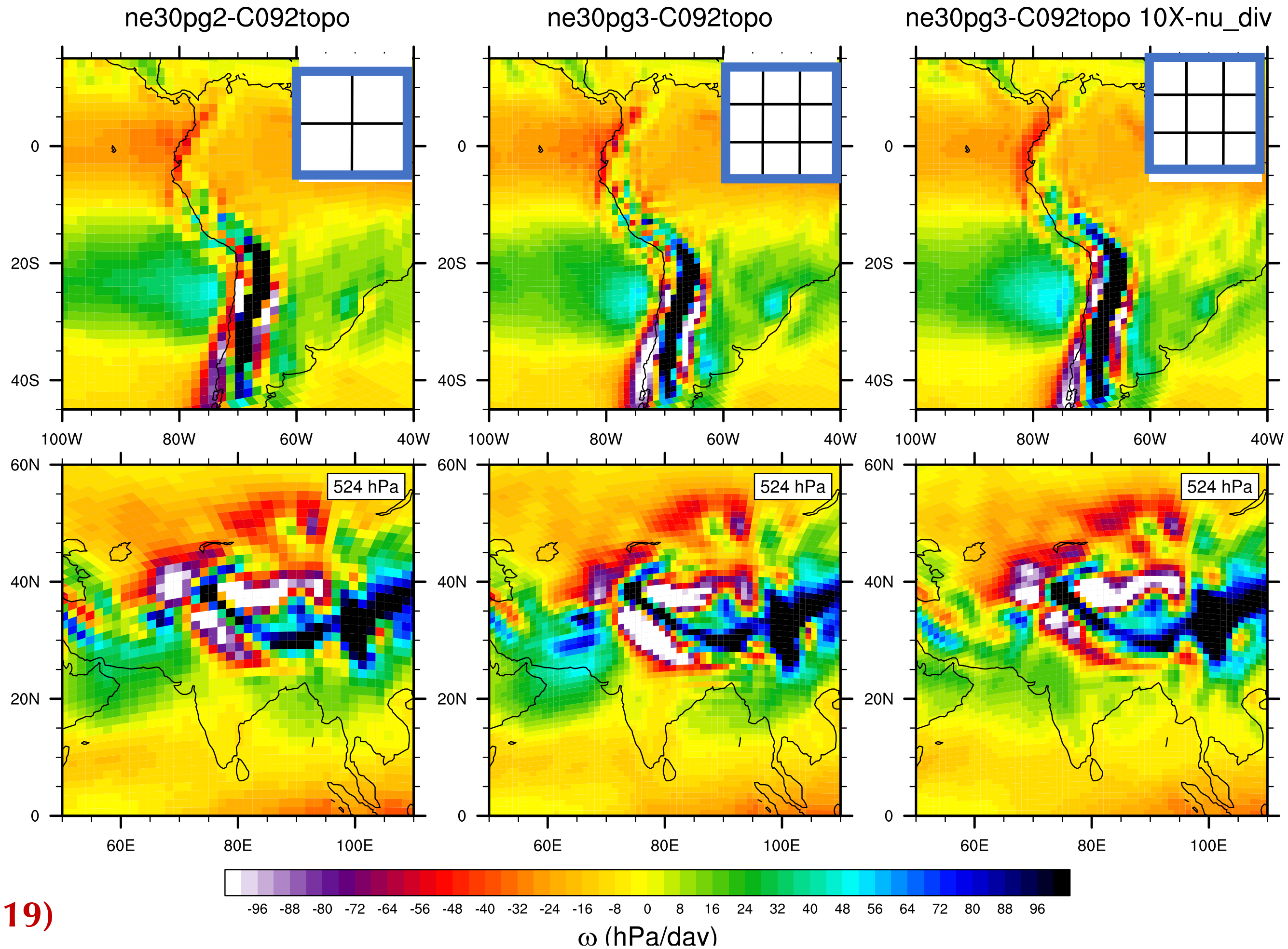


Figure 5. Snapshot of the cloud liquid field in kg kg^{-1} near the $700hPa$ level, on day 10 of the moist baroclinic wave test in the $ne30pg3$ and $ne30pg2$ configurations, displayed on the upper and lower panels, respectively. The fields are shown as a raster plot on their respective physics grids.

Fix Dynamics, change physics grid resolution

(but, same topography smoothing)



Herrington et al. (2019)

Fix Dynamics, change physics grid resolution

(but, same topography smoothing)

We can run with rougher topography without extra damping in the dynamical core when using lower resolution physics grid!

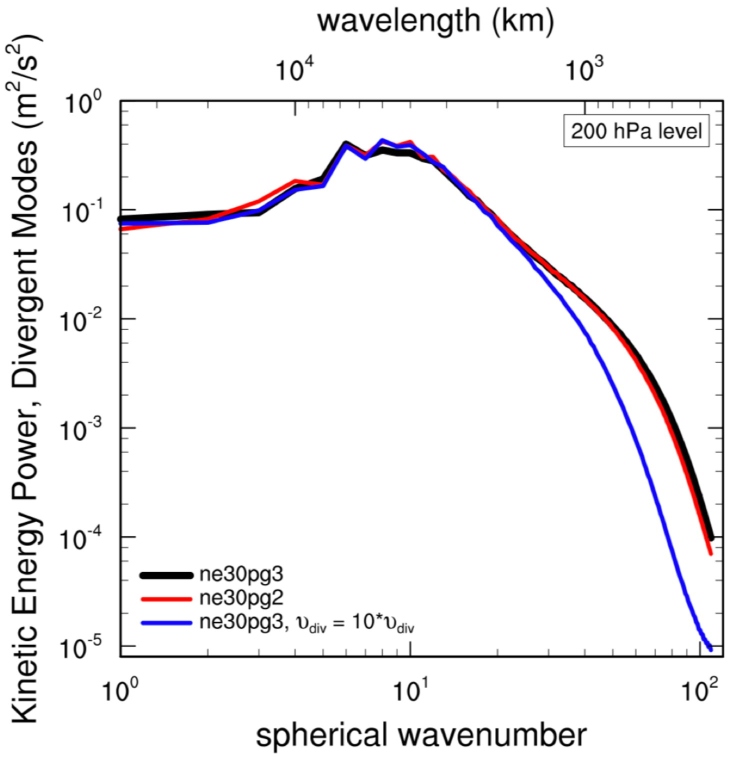


Figure 8. Kinetic energy power spectrum arising from divergent modes in *ne*30*pg*3, *ne*30*pg*2 and *ne*30*pg*3 with the divergence damping coefficient, ν_{div}, increased by an order of magnitude, in the Held-Suarez with topography simulations. Spectra computed from five months of six-hourly winds.

Herrington et al. (2019, submitted)

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)

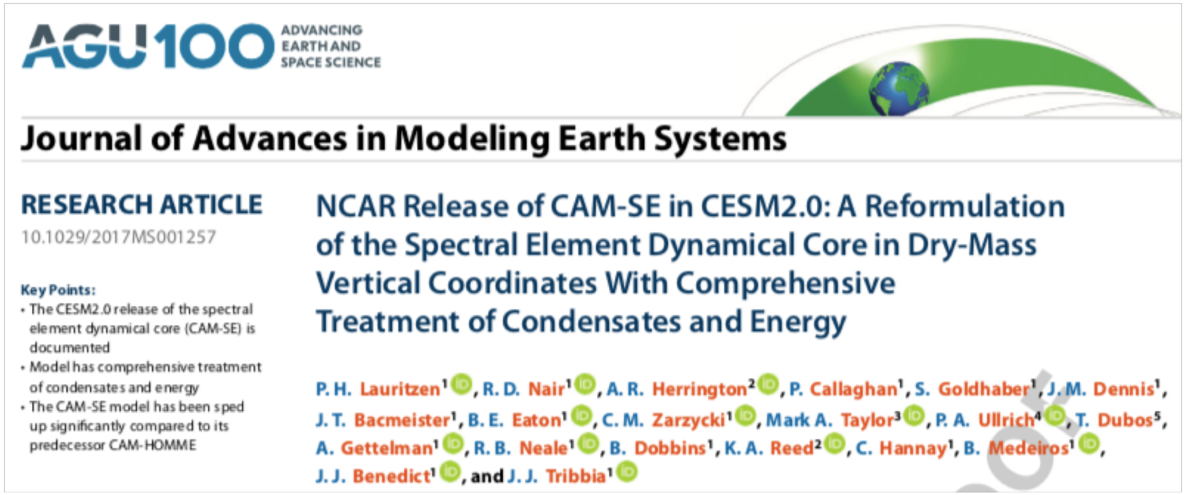
(referred to as CAM-HOMME in this talk)

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

DOE E3SM

(Energy Exascale Earth System Model)

repository



AGU100 ADVANCING EARTH AND SPACE SCIENCE

Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE

10.1029/2017MS001257

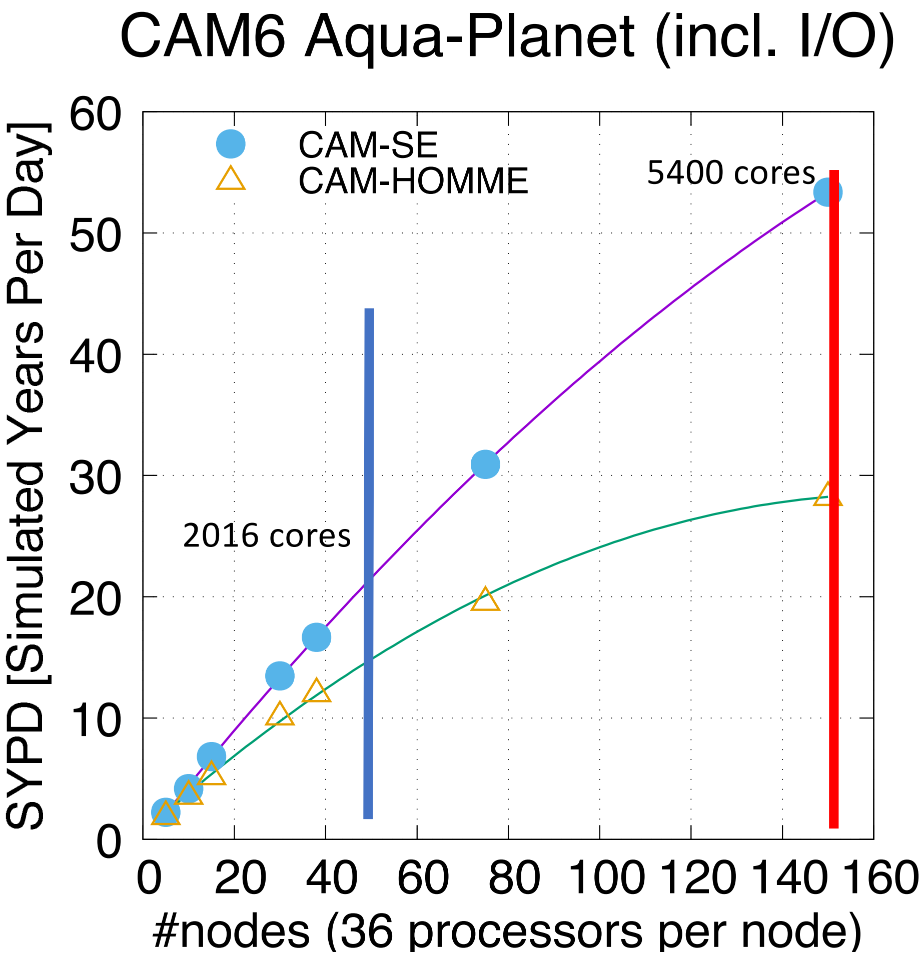
Key Points:

- 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:

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

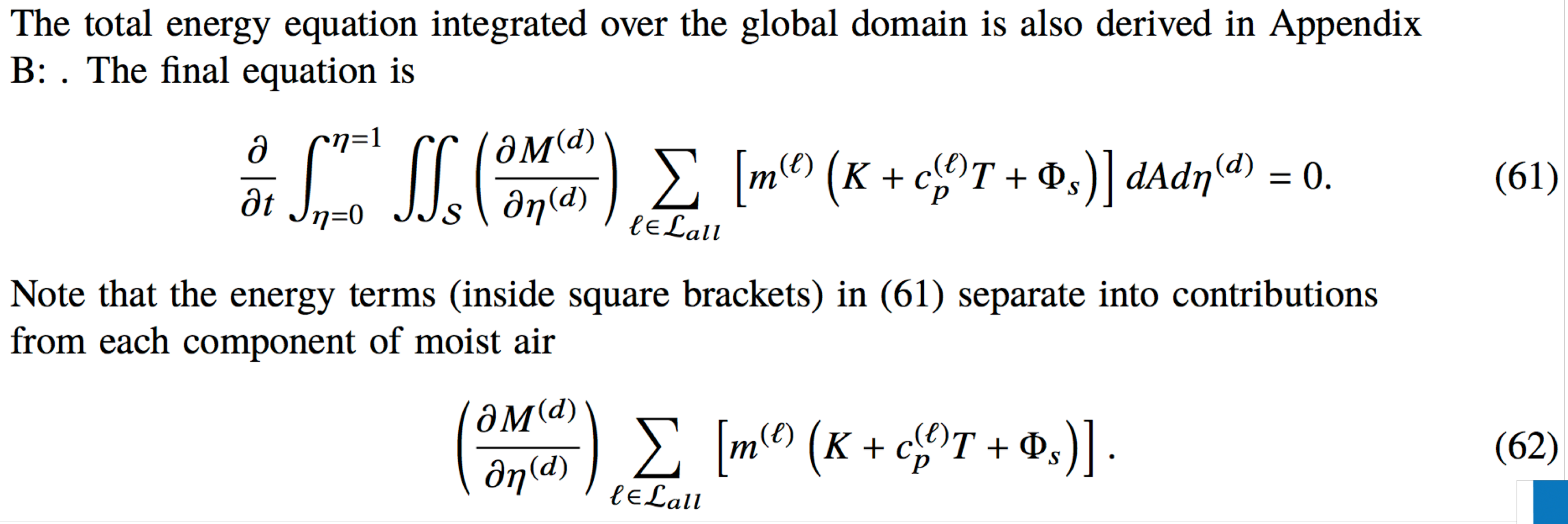
where

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

Lauritzen et al. (2018)

What changed? 2. More comprehensive energy equation

(CAM-HOMME -> CAM-SE)

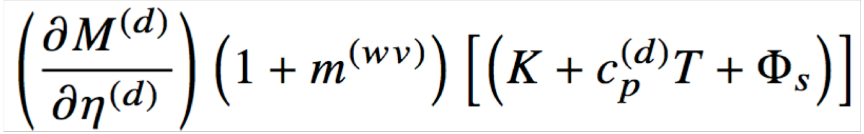


The total energy equation integrated over the global domain is also derived in Appendix B: . The final equation is

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

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

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



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

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

Lauritzen et al. (2018)

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)

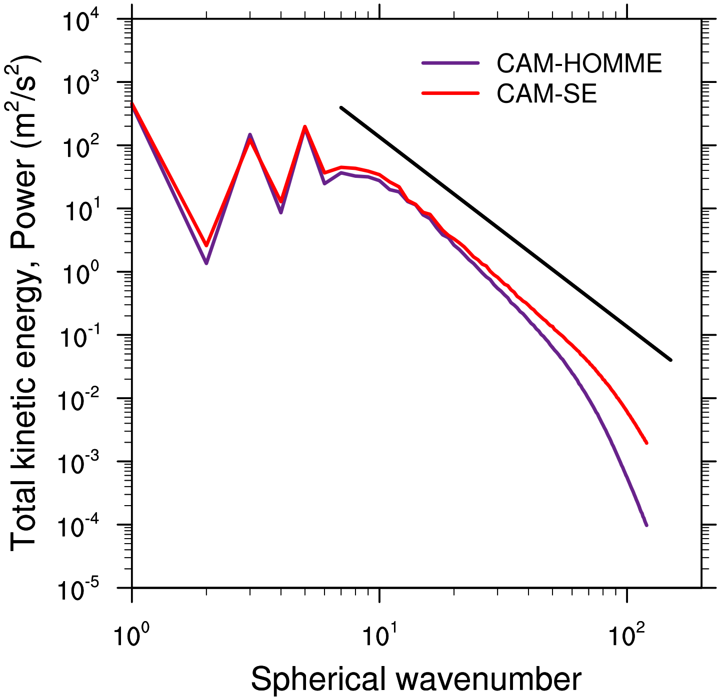
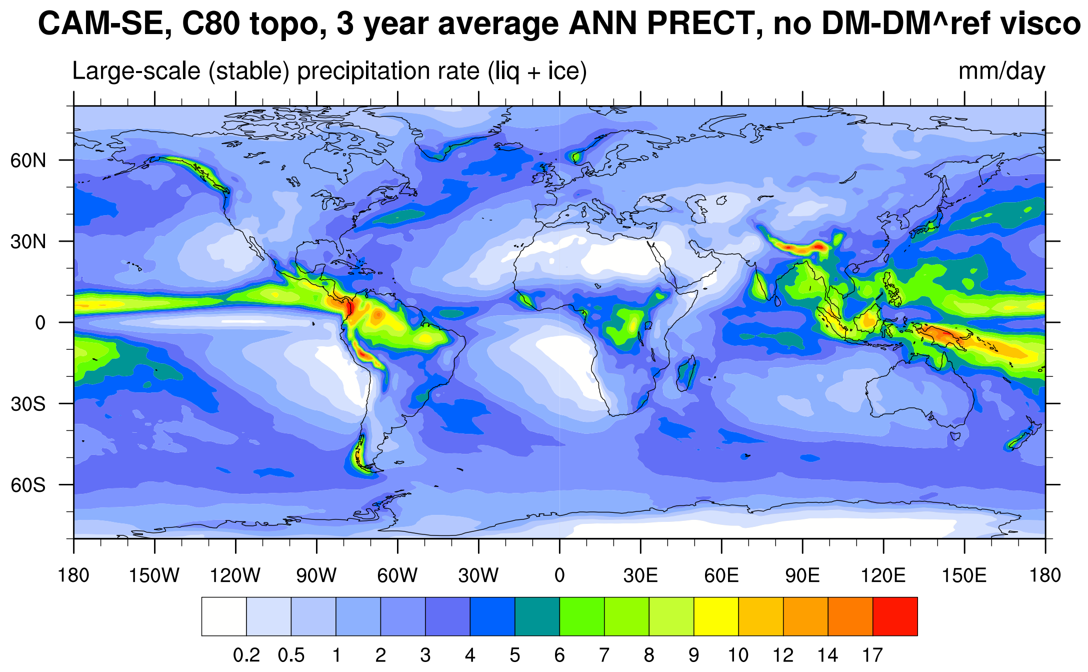


Figure 6. Total kinetic energy spectrum of the horizontal winds at the 200 hPa level in CAM-HOMME and CAM-SE at 1° horizontal resolution ($N_e = 30$ and $N_p = 4$), computed as the mean spectra from 30 days of 6-hourly instantaneous spectra. Black line is the κ^{-3} reference scaling, where κ is wave-number.

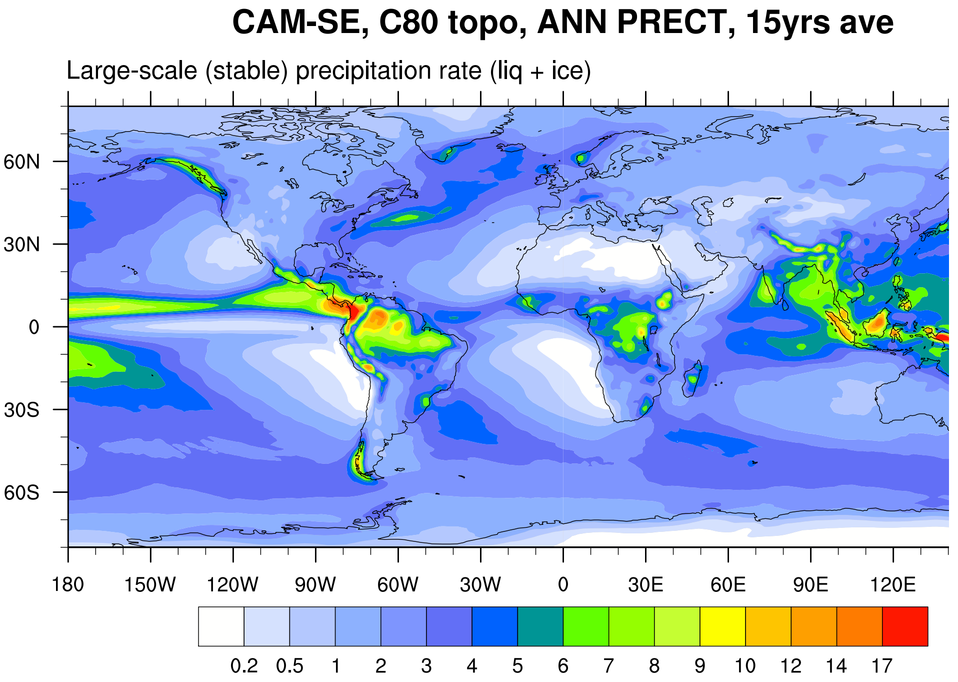
Lauritzen et al. (2018)

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

(CAM-HOMME -> CAM-SE)



CAM-SE, C80 topo, 3 year average ANN PRECT, no DM-DM^ref visco

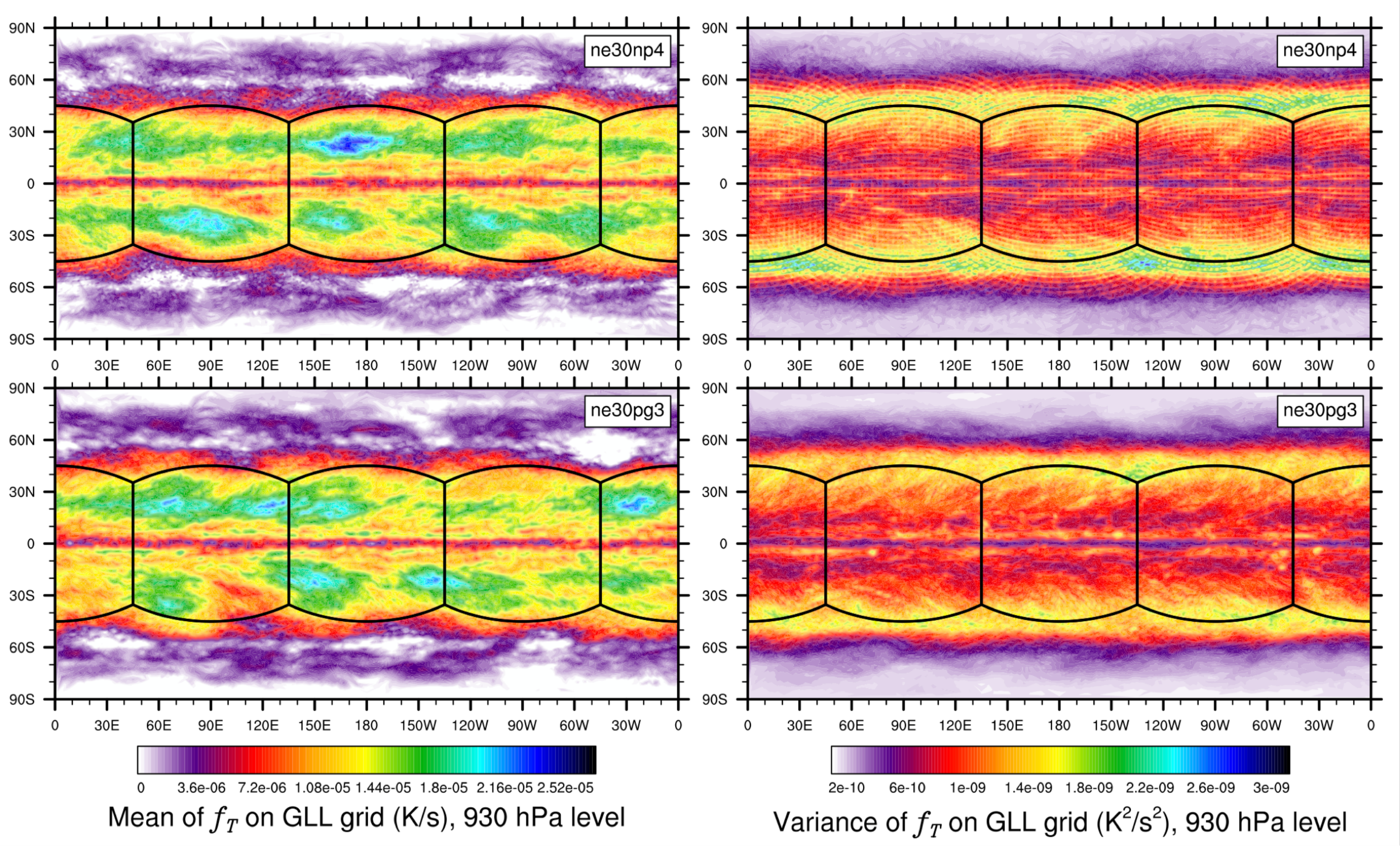


CAM-SE, C80 topo, ANN PRECT, 15yrs ave

Lauritzen et al. (2018)

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

Results – CAM4 Aqua-planets



CAM-SE

CAM-SE-CSLAM

Herrington et al. (MWR, 2018)

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