On the development of the NCAR CAM-SE-CSLAM with separate physics grid

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PDEs on the Sphere
April 5, 2017
Paris, France

Overview:

1. Aside: Simpler models in the CESM2
   (=Community Earth System Model version 2; release ~June 2017)

2. Dry-mass vertical coordinate version of NCAR CAM-SE
   (incl. discussion on total energy including condensates)

3. Consistent finite-volume transport with SE dynamics (PDEs 2015)

4. Coupling to physics using a finite-volume grid

Simpler models effort in the CESM

(started by L.Polvani and A.Clement)

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Provide "out-of-the-box" support for:

- **Various DCMIP tests:**
  - several idealized baroclinic waves (Jablonowski, Ullrich and Polvani waves)
  - Kessler Microphysics (Kessler, 1969)
  - Toy terminator chemistry (Lauritzen et al., 2015)
- **Held-Suarez forcing** (Held and Suarez, 1994)
- **Moist Held-Suarez forcing** (Thatcher and Jablonowski, 2016)
- **Aquaplanet configurations** (Medeiros et al., 2016; ...)

Moist baroclinic wave with Kessler Micro Physics

Ullrich et al. (2014) baroclinic with 3 tracers (cloud ice, rain water, water vapor)+Kessler (1969) physics

P.H.Lauritzen, C.Zarzycki
& S.Goldhaber

A. KESSLER PHYSICS

The cloud microphysics update according to the following equation set:

$$\frac{\Delta\theta}{\Delta t} = -\frac{L}{c_p\pi}\left(\frac{\Delta q_{vs}}{\Delta t} + E_r\right) \quad (78)$$

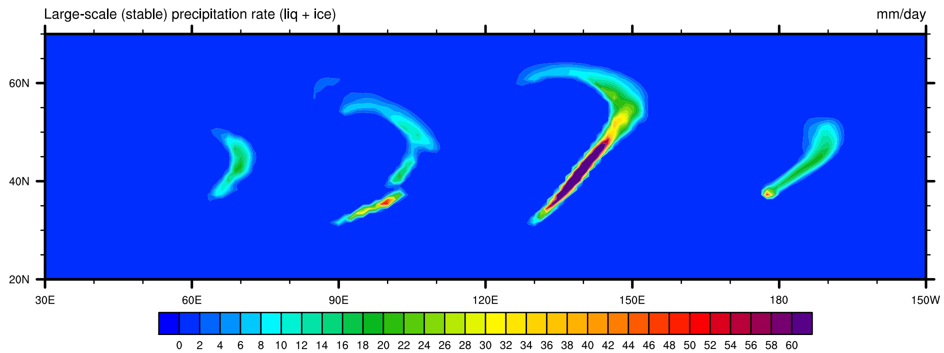
$$\frac{\Delta q_v}{\Delta t} = \frac{\Delta q_{vs}}{\Delta t} + E_r \quad (79)$$

$$\frac{\Delta q_c}{\Delta t} = -\frac{\Delta q_{vs}}{\Delta t} - A_r - C_r \quad (80)$$

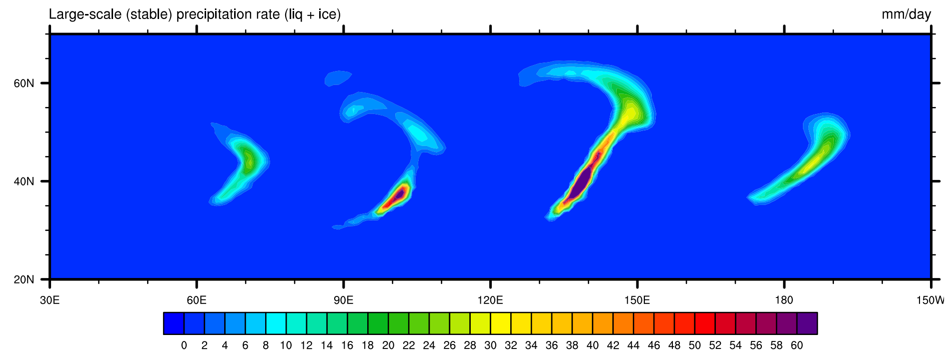
$$\frac{\Delta q_r}{\Delta t} = -E_r + A_r + C_r - V_r\frac{\partial q_r}{\partial z}, \quad (81)$$

where L is the latent heat of condensation, A_r is the autoconversion rate of cloud water to rain water, C_r is the collection rate of rain water, E_r is the rain water evaporation rate, and V_r is the rain water terminal velocity.

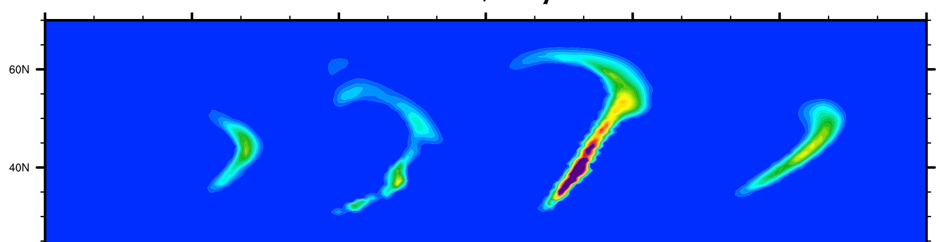
CAM-FV, day 10



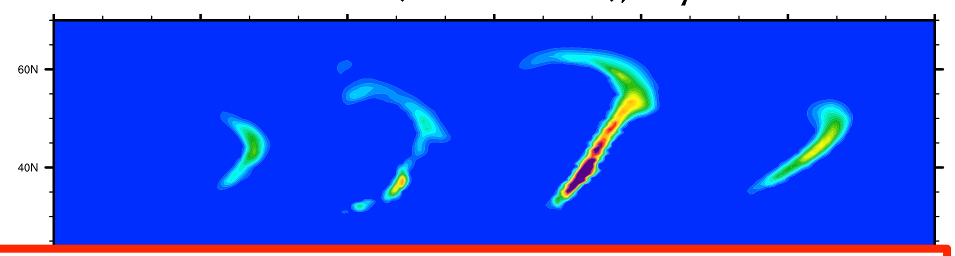
CAM-SE-CSLAM, day 10



CAM-SE, day 10



CAM-SE (dtime = 900s), day 10

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./create_newcase -compset FKESSLER -res ne30_ne30
```

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2. Dry-mass vertical coordinate version of NCAR CAM-SE
   (incl. discussion on total energy including condensates)

   Note: NCAR CAM-SE ≠ DOE ACME CAM-SE ≠ CAM-HOMME

3. Consistent finite-volume transport with SE dynamics (PDEs 2015)

4. Coupling to physics using a finite-volume grid

NCAR CAM-SE : dry-mass eta

Consider a 'moist' η-coordinate system: The pressure is given by

$$p(\eta) = A(\eta)p_0 + B(\eta)ps,$$

where ps is 'moist' surface pressure.

In a floating η-coordinate system, $\dot{\eta} = 0$, the continuity equation for p can be written as

$$\frac{\partial}{\partial t}\left[\left(\frac{\partial p}{\partial \eta}\right)\right] + \nabla \cdot \left[\left(\frac{\partial p}{\partial \eta}\right)\vec{v}\right] = S^p,$$

where $S^p(q_v)$ is the source/sink term for pressure ($q_v \equiv$ specific humidity).

- This source/sink term:
  - makes the handling of tracers more complicated

    An inert tracer will have source/sink terms (i.e. if there are moisture changes all "wet" mixing ratios must be changed accordingly)
  - makes it harder to move towards conserving a more comprehensive total energy

- Complicates CSLAM-SE coupling in a moist atmosphere

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$$\frac{\partial}{\partial t}\left[\left(\frac{\partial p}{\partial \eta}\right)\right] + \nabla \cdot \left[\left(\frac{\partial p}{\partial \eta}\right)\vec{v}\right] = S^p,$$

where $S^p(q_v)$ is the source/sink term for pressure ($q_v \equiv$ specific humidity).

NCAR CAM-SE : dry-mass eta

If one uses a dry mass vertical coordinate

$$p(\eta_d) = A(\eta_d)p_0 + B(\eta_d)ps_d,$$

where ps_d is dry surface pressure, then the continuity equation for pressure does not have sources/sinks

$$\frac{\partial}{\partial t}\left[\left(\frac{\partial p_d}{\partial \eta_d}\right)\right] + \nabla \cdot \left[\left(\frac{\partial p_d}{\partial \eta_d}\right)\vec{v}\right] = 0.$$

Model levels do not move during physics-dynamics coupling!

NCAR CAM-SE : dry-mass eta

The $\eta^{(d)}$-coordinate adiabatic and frictionless atmospheric primitive equations assuming floating Lagrangian vertical coordinates [*Starr*, 1945; *Lin*, 2004] can be written as

$$\frac{\partial \vec{v}}{\partial t} + (\zeta + f)\,\hat{\vec{k}} \times \vec{v} + \nabla_{\eta^{(d)}}\left(\frac{1}{2}\vec{v}^2 + \Phi\right) + \frac{1}{\rho}\nabla_{\eta^{(d)}} p = 0,$$

$$\frac{\partial T}{\partial t} + \vec{v}\cdot\nabla_{\eta^{(d)}} T - \frac{1}{c_p \rho}\omega = 0,$$

$$\frac{\partial}{\partial t}\left(\frac{\partial p^{(d)}}{\partial \eta^{(d)}} m^{(\ell)}\right) + \nabla_{\eta^{(d)}}\cdot\left(\frac{\partial p^{(d)}}{\partial \eta^{(d)}} m^{(\ell)} \vec{v}\right) = 0, \quad \ell = d, v, cl, ci, \ldots$$

where ρ is the full density $\sum_\ell \rho^{(\ell)}$, p is the sum of the partial pressures $p^{(d)} + p^{(v)}$ (dry and water vapor pressure; note that cloud liquid and cloud ice do not exert a pressure), Φ is the geopotential height ($\Phi = g\,z$, where g is the gravitational constant), $\hat{\vec{k}}$ is the unit vector normal to the surface of the sphere, $\zeta = \hat{\vec{k}} \cdot \nabla\times\vec{v}$ is vorticity, f Coriolis parameter, and $\omega = Dp/Dt$ is the pressure vertical velocity.

Staniforth et al. (2006)

NCAR CAM-SE : dry-mass eta

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$$\frac{\partial}{\partial t}\left(\frac{\partial p^{(d)}}{\partial \eta^{(d)}} m^{(\ell)}\right) + \nabla_{\eta^{(d)}}\cdot\left(\frac{\partial p^{(d)}}{\partial \eta^{(d)}} m^{(\ell)} \vec{v}\right) = 0, \quad \ell = d, v, cl, ci, \ldots$$

where ρ is the full density $\sum_\ell \rho^{(\ell)}$, … he sum of the … artial pressures $p^{(d)} + p^{(v)}$ (dry and water vapor pressure; note th… d liquid and c… d ice do not exert a pressure), Φ is the geopotential height (Φ … where g is the gr… ational constant), $\hat{\vec{k}}$ is the unit vector normal to the surfa… sphere, $\zeta = \hat{\vec{k}} \cdot \nabla$… vorticity, f Coriolis parameter, a… elocity.

$$\rho = \rho^{(d)}\left(\sum_\ell m^{(\ell)}\right), \text{where } \ell = \text{‘}d\text{‘, ‘}v\text{‘, ‘}cl\text{‘, ‘}ci\text{‘}$$

$$c_p = \frac{\sum_\ell \left[m^{(\ell)}\, c_p^{(\ell)}\right]}{\sum_\ell m^{(\ell)}}$$

dry air ’d’, water vapor ’v’, cloud liquid ’cl’ and cloud ice ’ci’

Internal Energy

(similarly for total kinetic energy)

The total internal energy integrated over the entire atmosphere is given by

$$I_{tot} = \iiint \rho c_p T\, dz\, \cos(\theta) r\, d\lambda\, d\theta$$

Using the hydrostatic balance this equation can be written as

$$I = \sum_{\ell} I^{(\ell)} = -\frac{1}{g} \sum_{\ell} \iiint c_p^{(\ell)} m^{(\ell)} T \left(\frac{\partial p^{(d)}}{\partial \eta^{(d)}} \right) d\eta^{(d)} \cos(\theta) r\, d\lambda\, d\theta,$$

where $I^{(d)}$ is the total internal energy of dry air, $I^{(v)}$ the total internal energy of water vapor, etc.

Energy diagnostics for NCAR CAM-SE

```
do n=1,nsplit
    do r=1,rsplit
        a. advance adiabatic equations of motion in floating Lagrangian
           layer (Lin, 2004)
        b. advance hyperviscosity operators on u,v,T,dp
        c. add momentum diffusion back as heating
    end do
    do vertical remapping of u,v,T and tracers
end do
```

2D dyn (steps a–c)

1D dyn (vertical remapping)

Energy diagnostics (multi-year average values) from AMIP simulation

dE/dt of 2D dyn	: 0.070 W/m^2
dE/dt of frictional heating from (u,v) diffusion	: 0.757 W/m^2
dE/dt of T diffusion	: 0.074 W/m^2
dE/dt of dp diffusion	: -0.003 W/m^2
dE/dt of 1D dyn	: -0.207 W/m^2
dE/dt dycore	: -0.1367 W/m^2

Internal Energy

The total internal energy integrated over the entire atmosphere is given by

$$I_{tot} = \iiint \rho c_p T \, dz \, \cos(\theta) r \, d\lambda \, d\theta$$

Using the hydrostatic balance th equation can

$$I = \sum_{\ell} I^{(\ell)} \quad \ldots \quad \iiint c_p^{(\ell)} m \quad \ldots \quad \cos(\theta) r \, d\lambda \, d\theta,$$

Discrepancy
~0.5 W/m²

ernal energy

of water vap

The internal energy in CAM physics is defined as

$$I_{tot}^{(CAM)} = -\frac{1}{g} \iiint c_{pd} T \left(1 + m_v\right) \left(\frac{\partial p_d}{\partial \eta_d}\right) d\eta_d \, \cos(\theta) r \, d\lambda \, d\theta$$

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3. **Consistent finite-volume transport with SE dynamics (PDEs 2015)**

4. Coupling to physics using a finite-volume grid

CAM-SE-CSLAM without moisture

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Monthly Weather Review

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

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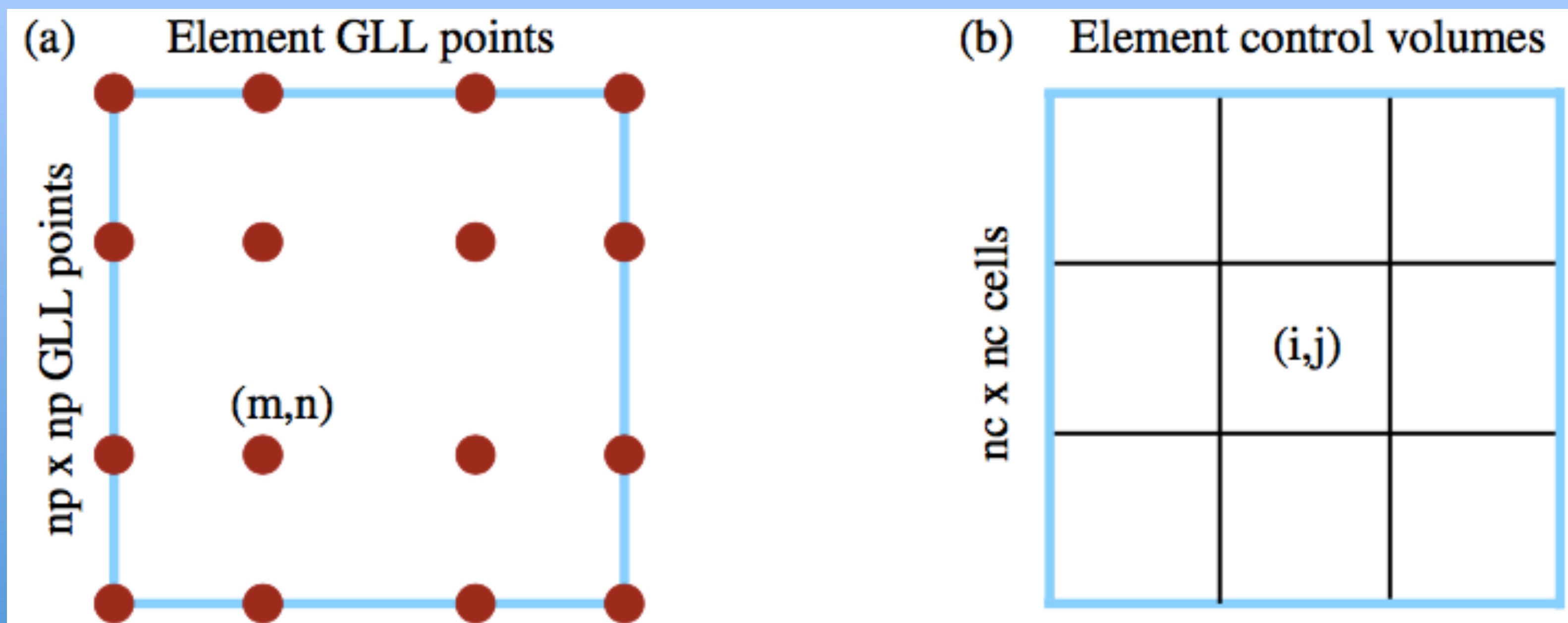
CAM-SE-CSLAM without moisture



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CAM-SE-CSLAM without moisture

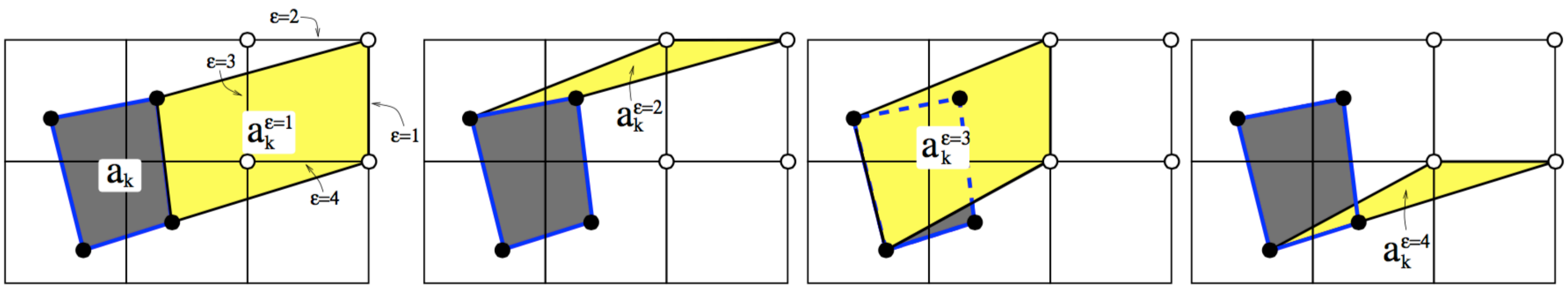
Spectral-Element Method: CAM-SE

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. (2017)

Finite-Volume Method: CSLAM



CSLAM discretization is given by

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

Harris et al. (2011), Lauritzen et al. (2010)

CAM-SE-CSLAM without moisture

Spectral-Element Method: CAM-SE

Mass change over CSLAM control volume A_k implied by SE

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

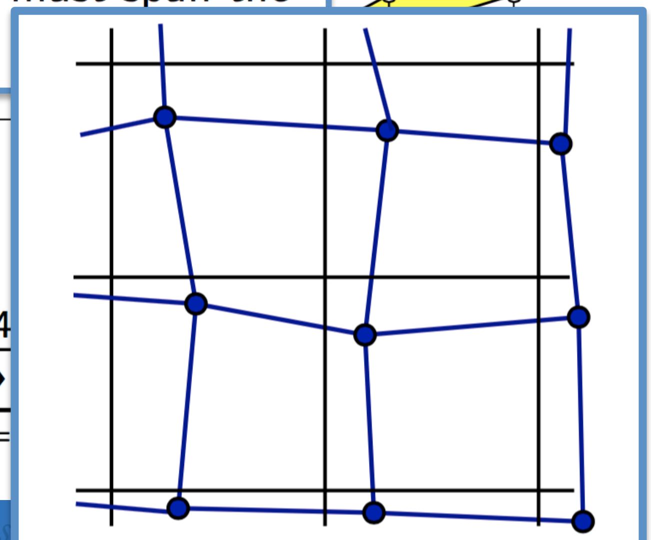
(Lauritzen et al., 2016; in prep).

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

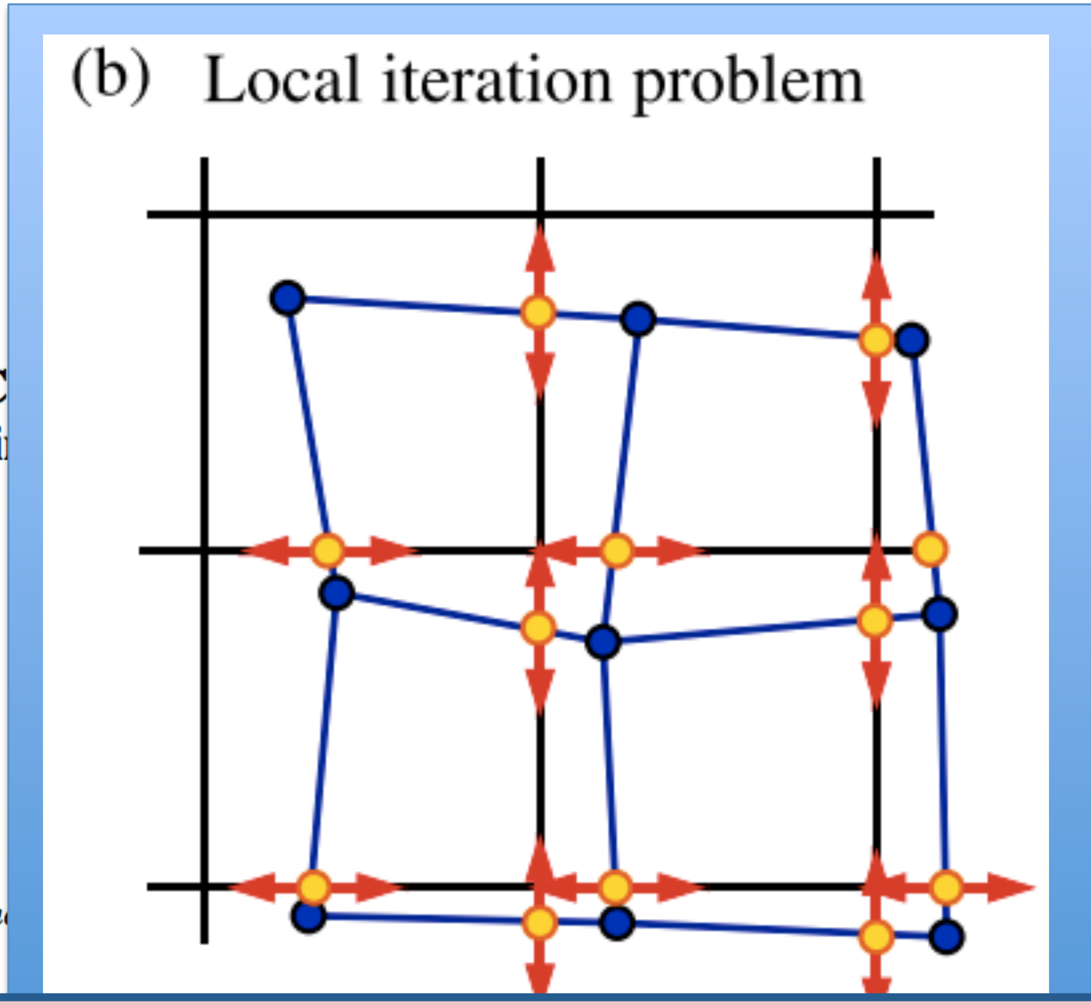


CSLAM discretization is given by

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

CAM-SE-CSLAM without moisture

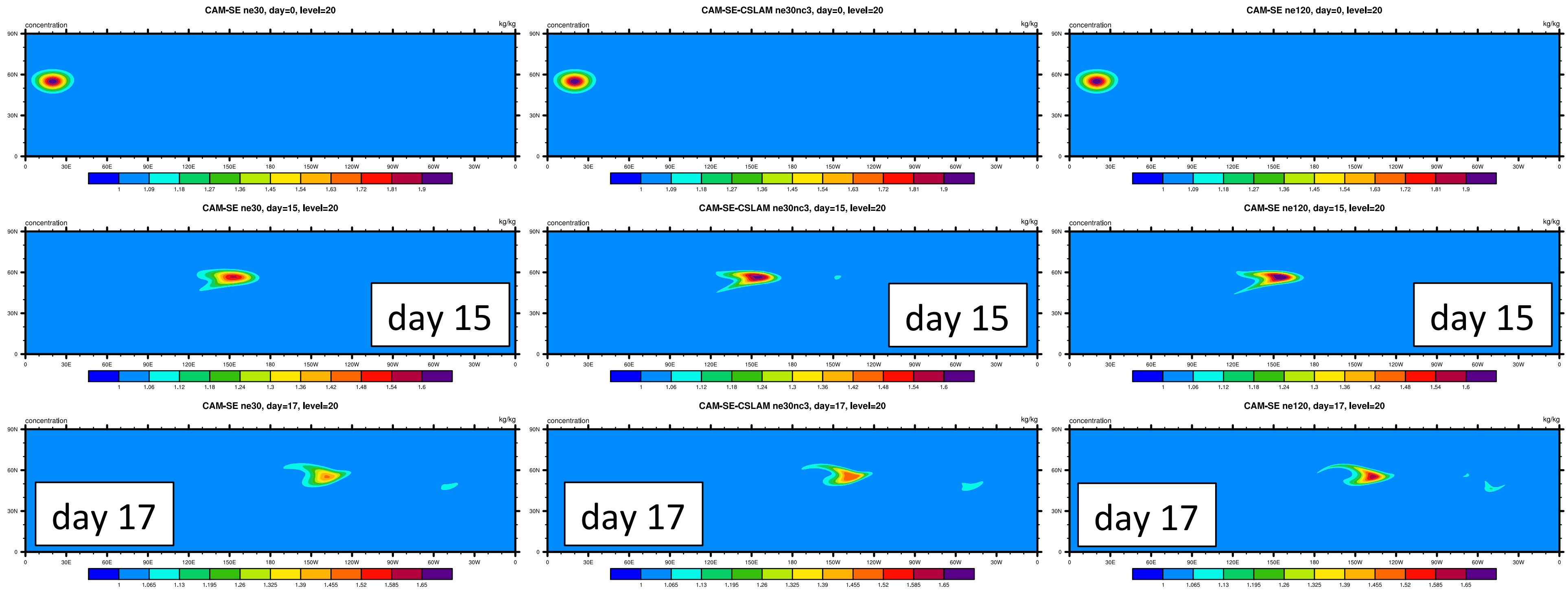
CAM-SE–C ... -Lagrangian
Fi ... cs

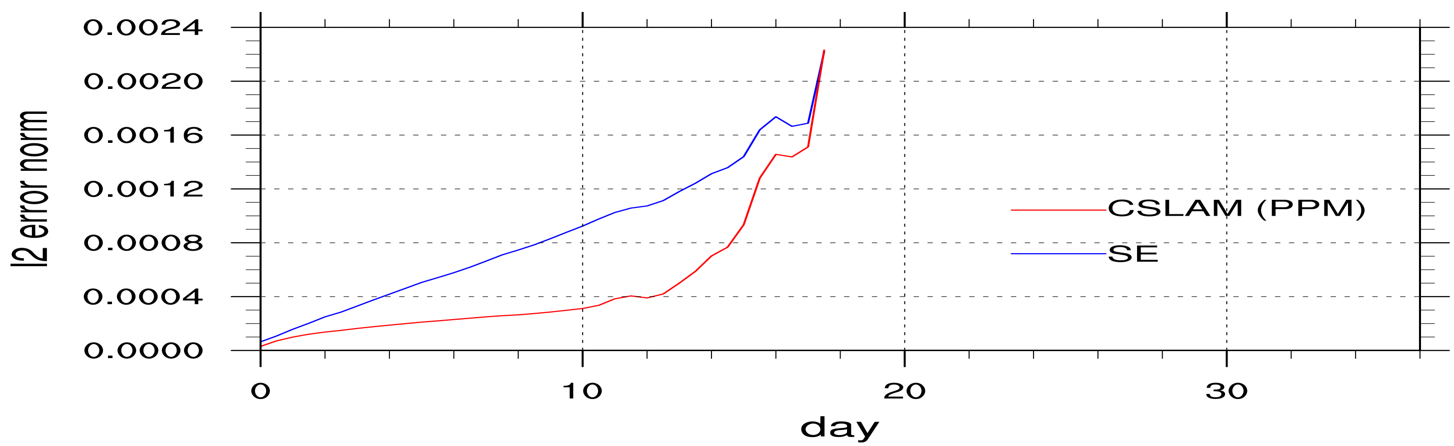


Departm ... California

In principle, the consistent CSLAM algorithm can be used with any fluxes that obey the Lipschitz criterion … and no search algorithm needed anymore!

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

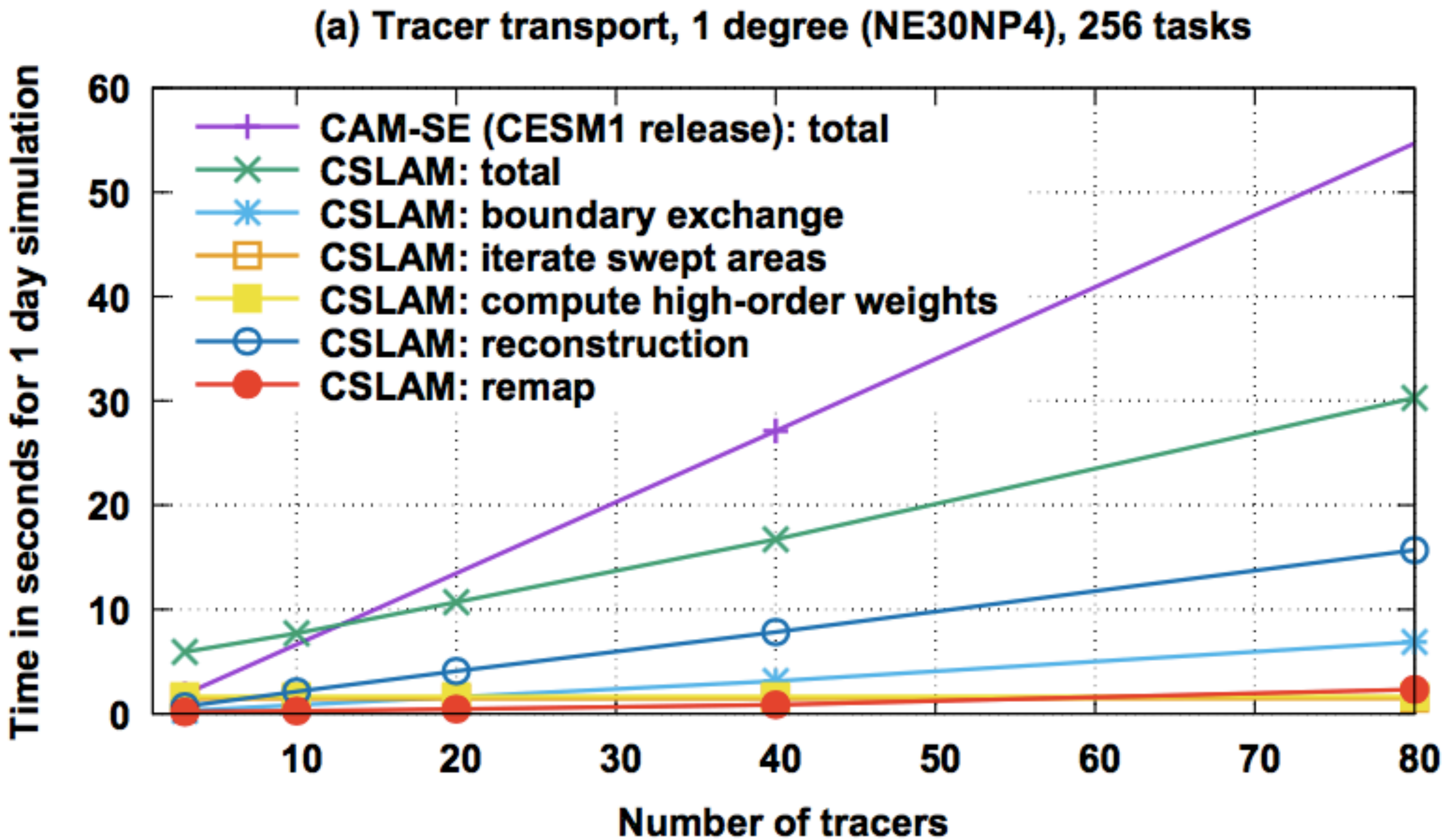




NCAR

Lauritzen et al. (2017)

Throughput



(a) Tracer transport, 1 degree (NE30NP4), 256 tasks
CAM-SE (CESM1 release): total
CSLAM: total
CSLAM: boundary exchange
CSLAM: iterate swept areas
CSLAM: compute high-order weights
CSLAM: reconstruction
CSLAM: remap
Time in seconds for 1 day simulation
Number of tracers
0
10
20
30
40
50
60
70
80

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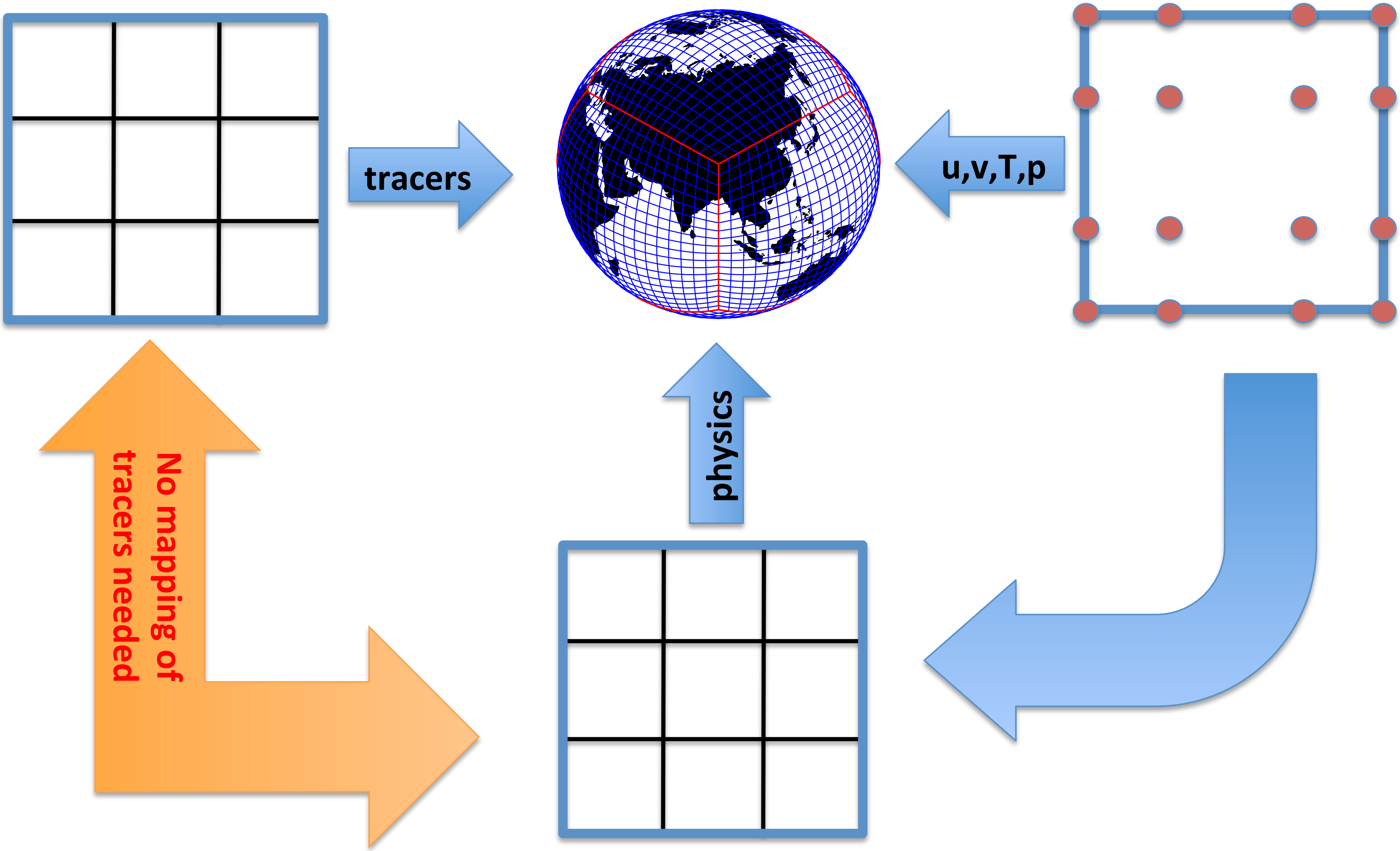
CAM-SE-CSLAM with moisture

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

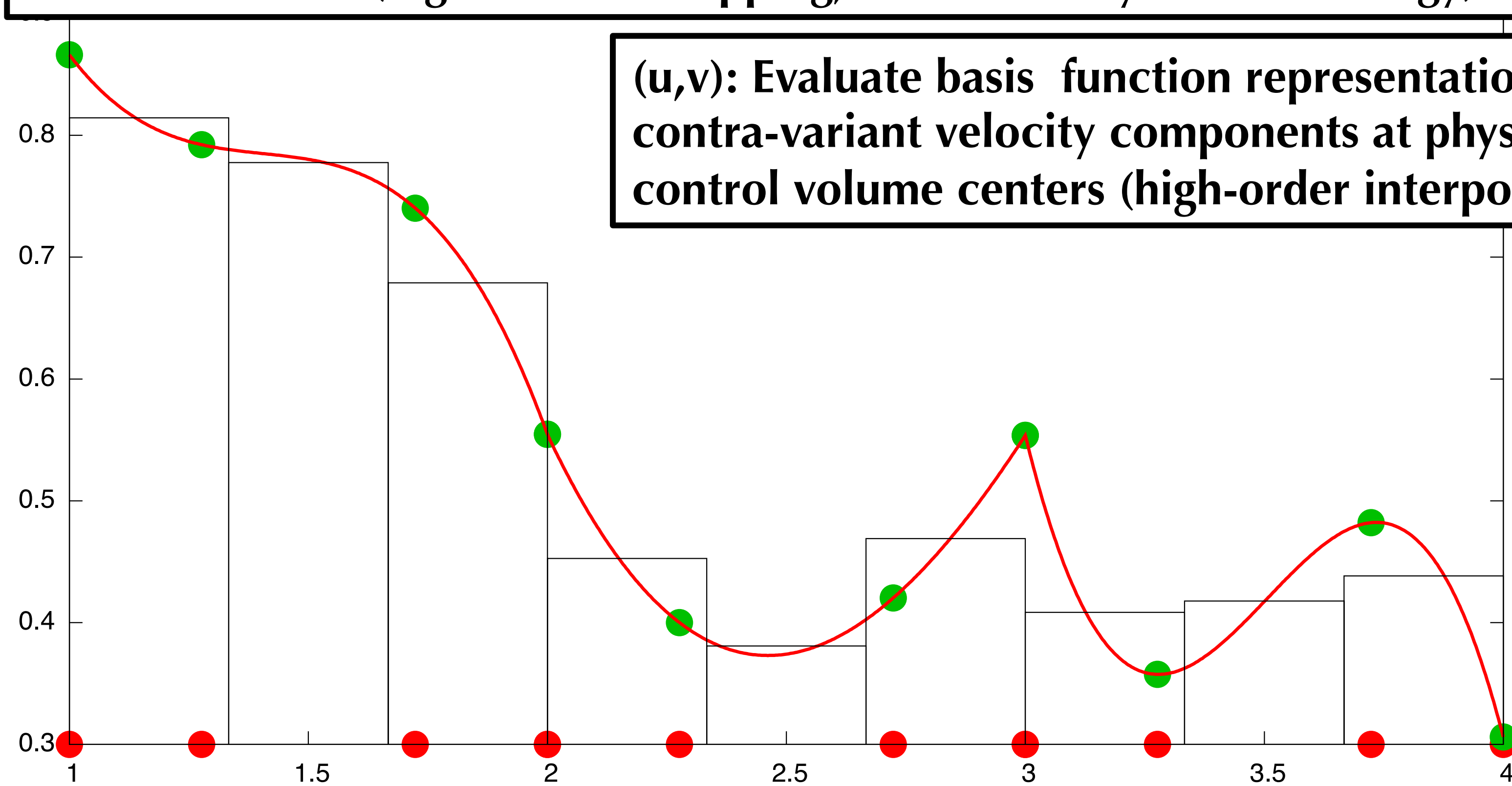


SciDAC
Scientific Discovery through Advanced Computing

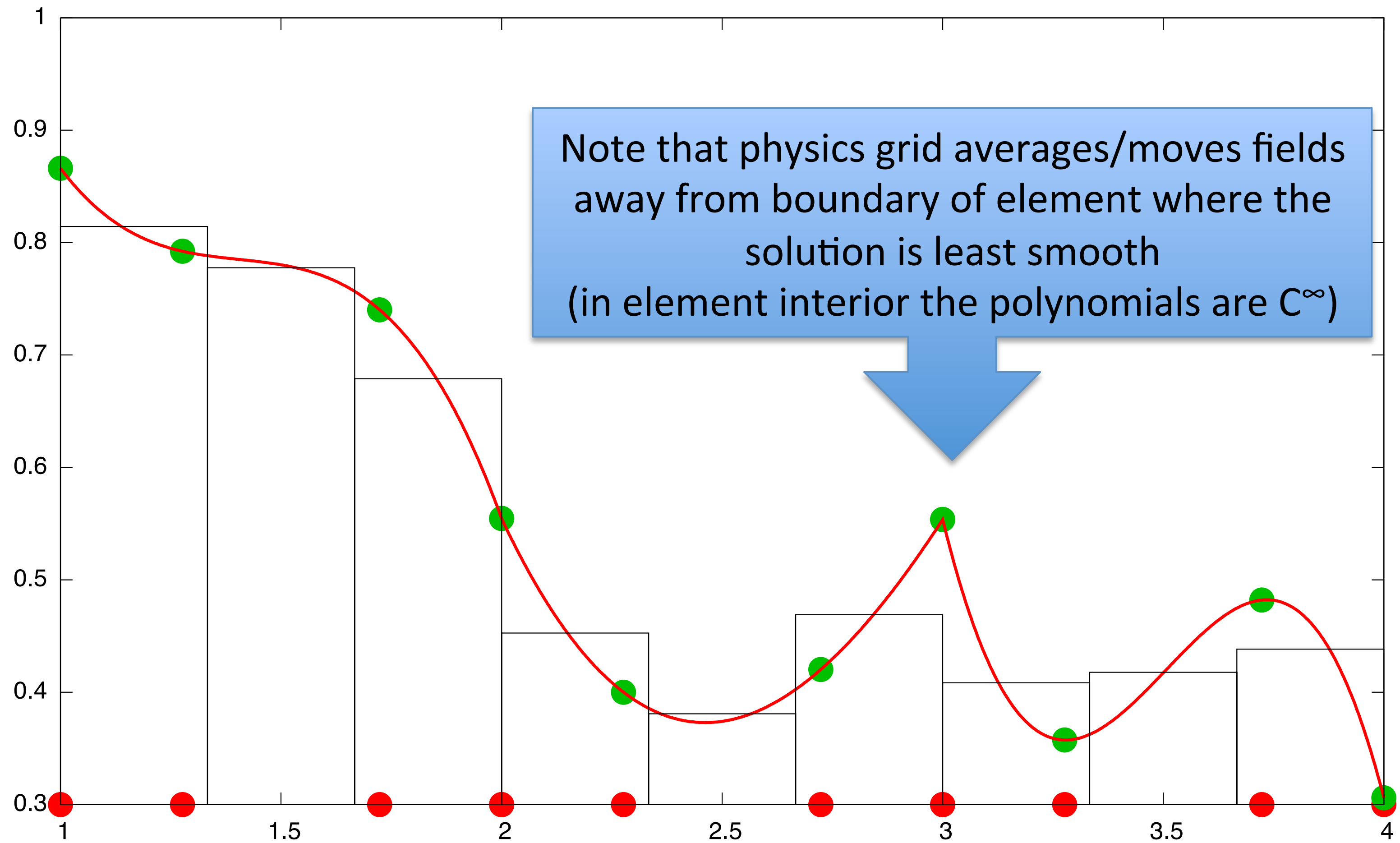
Mapping u,v, T, omega from dynamics grid (GLL) to finite-volume (CSLAM) grid

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)



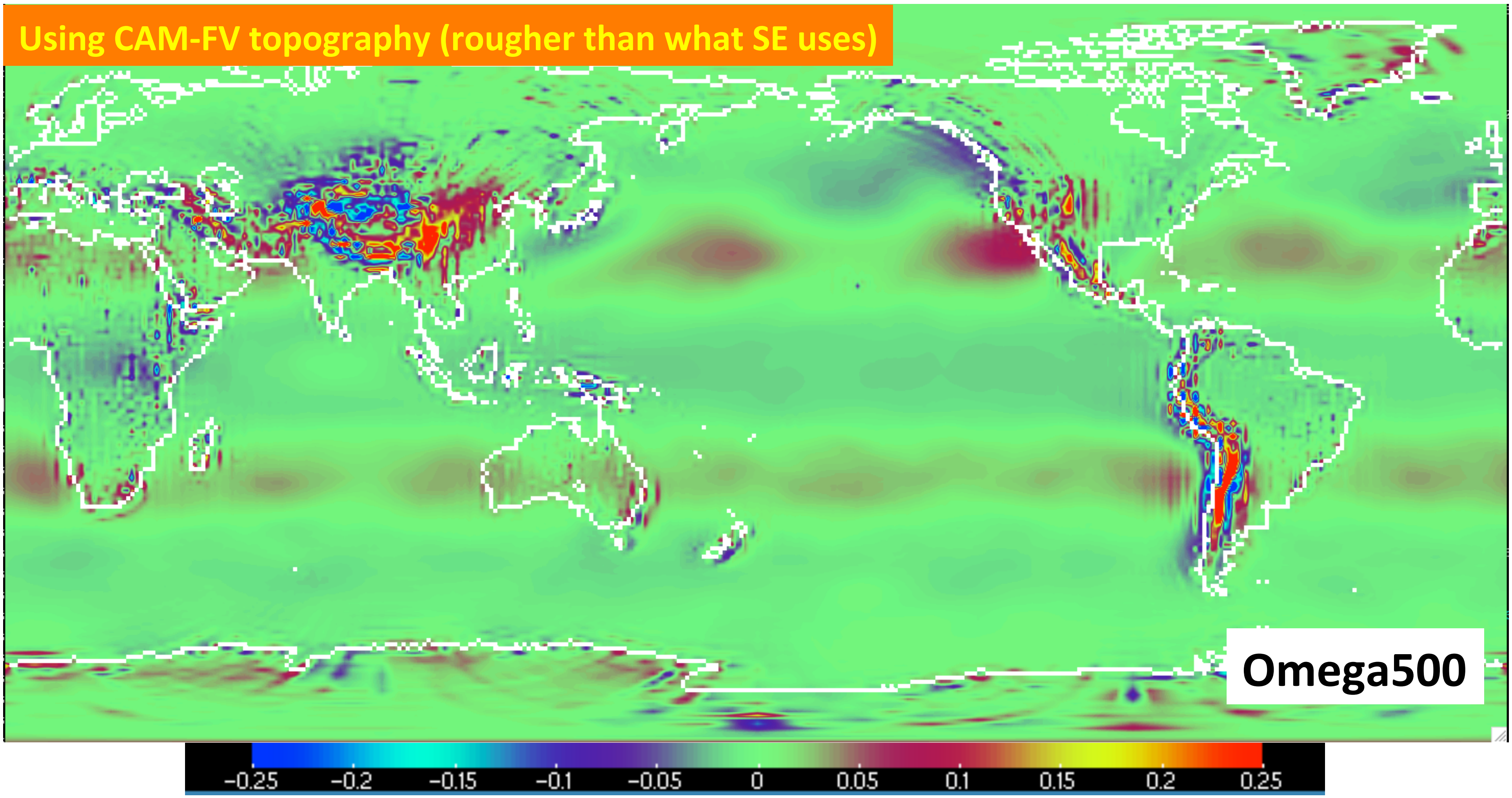
Mapping u,v, T, omega from dynamics grid (GLL) to finite-volume (CSLAM) grid



CAM-SE with "rougher" topography

Held-Suarez forcing with real-world topography (6 months spin-up; 2 years and 9 months average)
Note: dry test so no moist physics feedbacks

bnd_topo = '/home/pel/run_scripts/topo/ne30np4_nc3000_Nsw042_Nrs008_Co060_Fi001_ZR_test_vX_111416.nc



CAM-SE-CSLAM

Held-Suarez forcing with real-world topography (6 months spin-up; 2 years and 9 months average)
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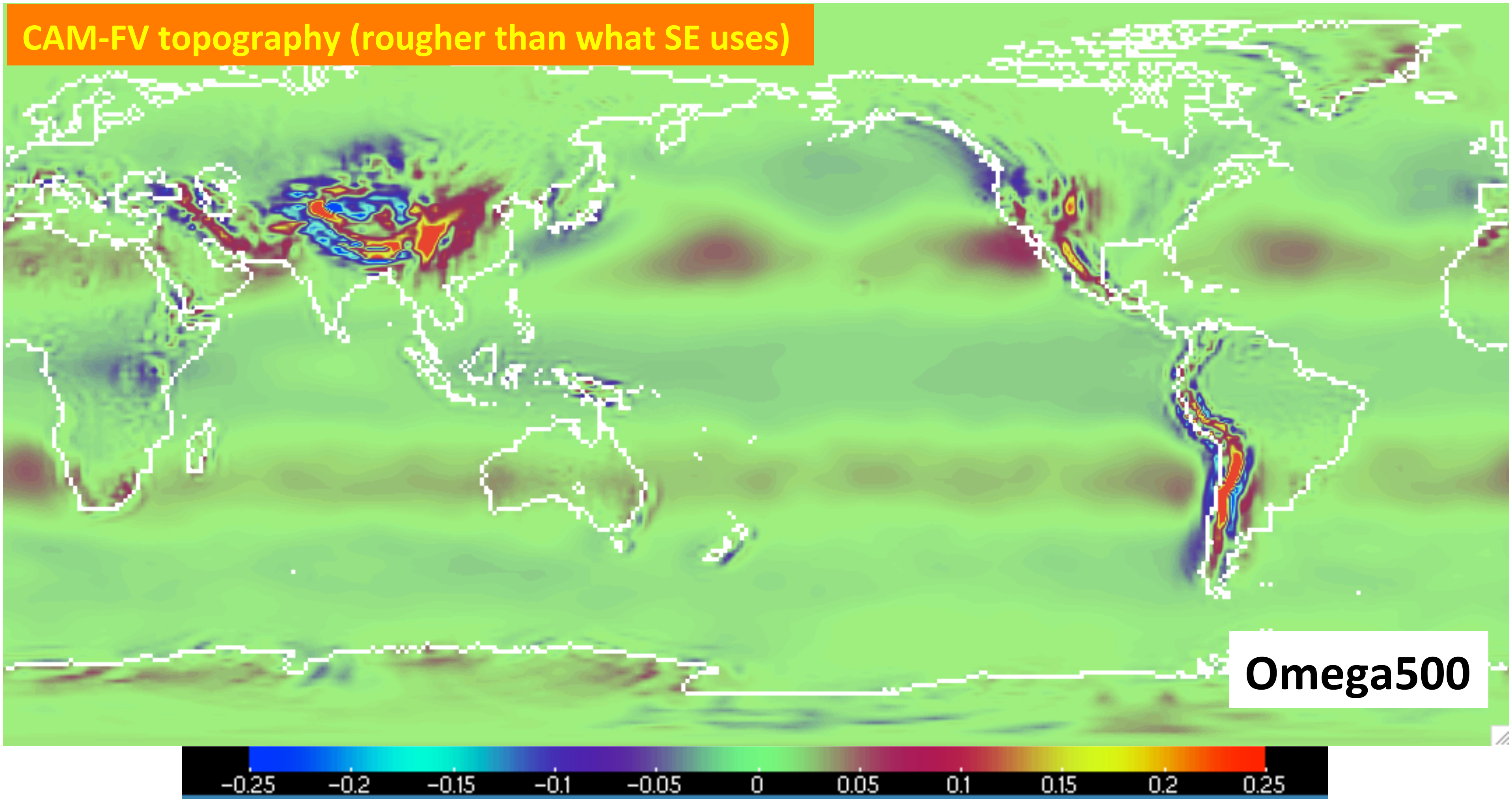
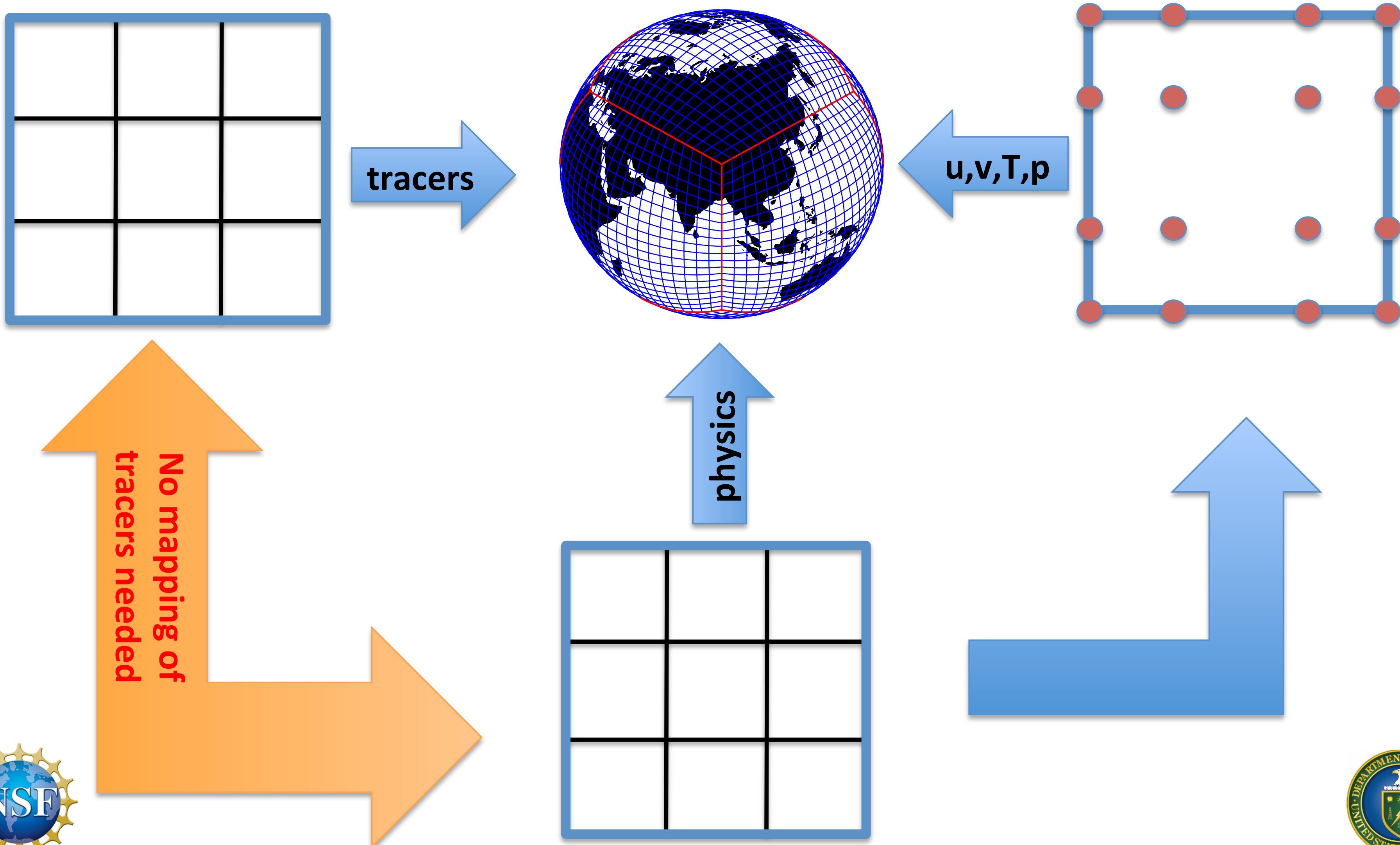
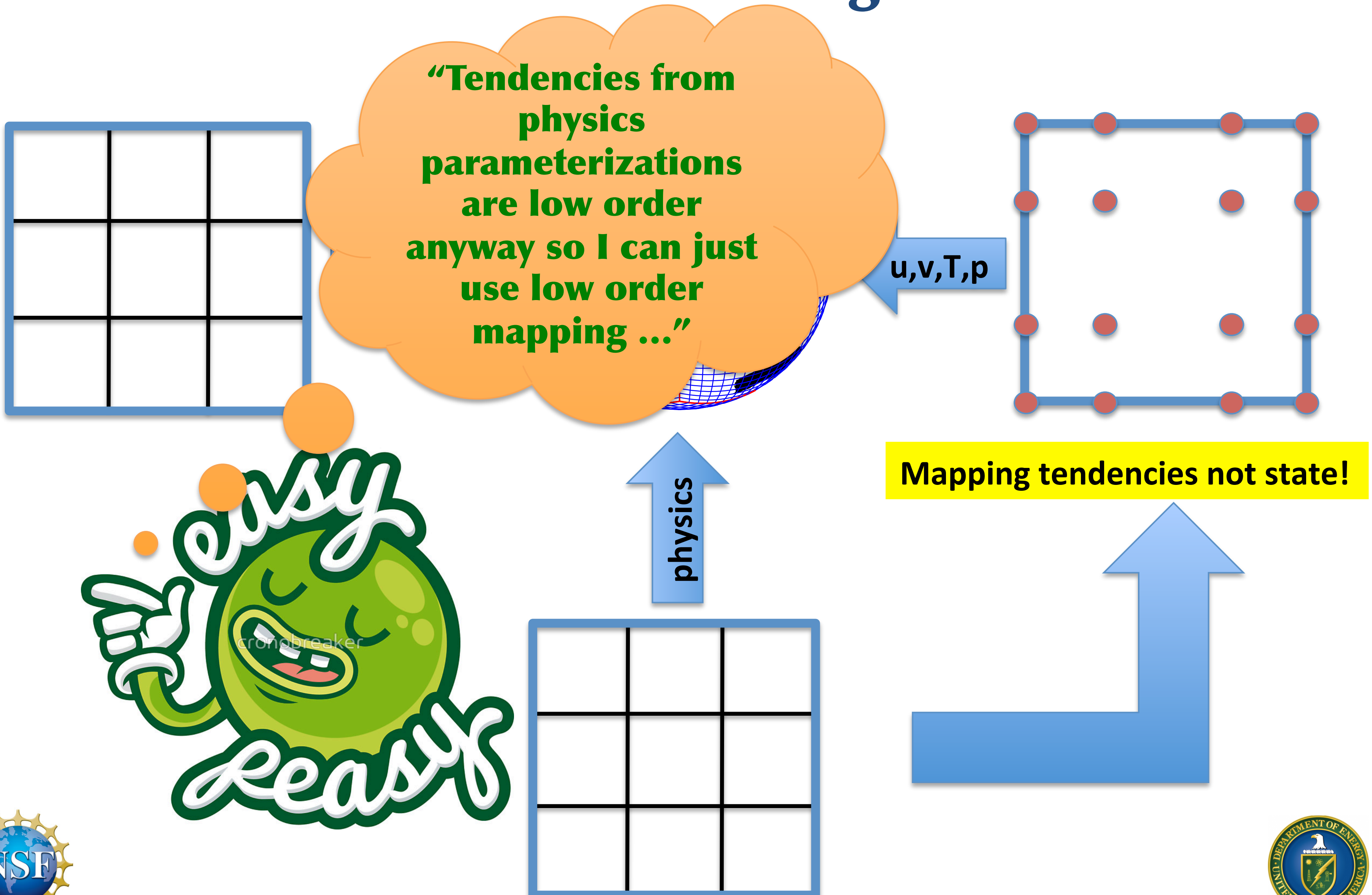


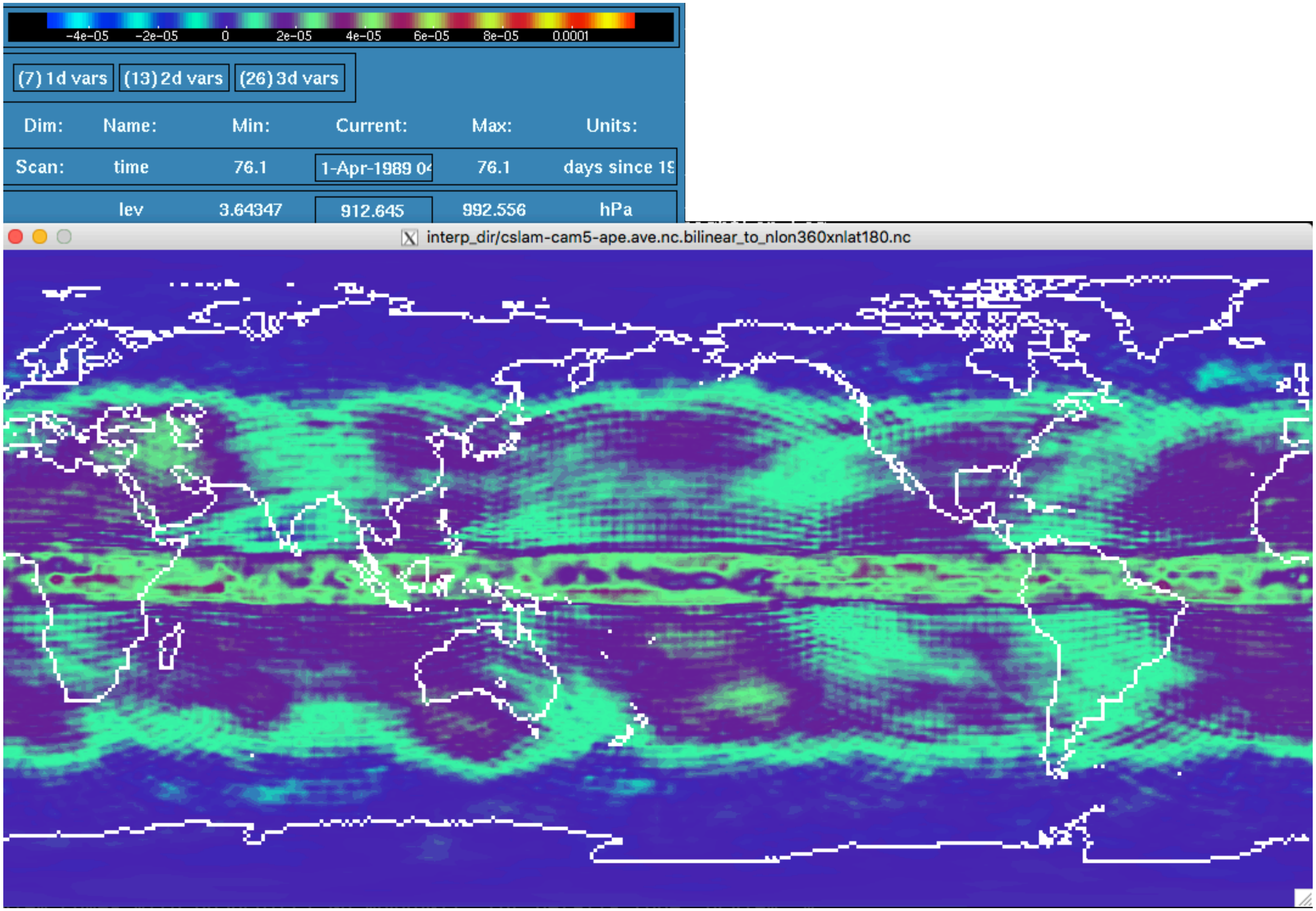
CAM-SE-CSLAM configuration



CAM-SE-CSLAM configuration



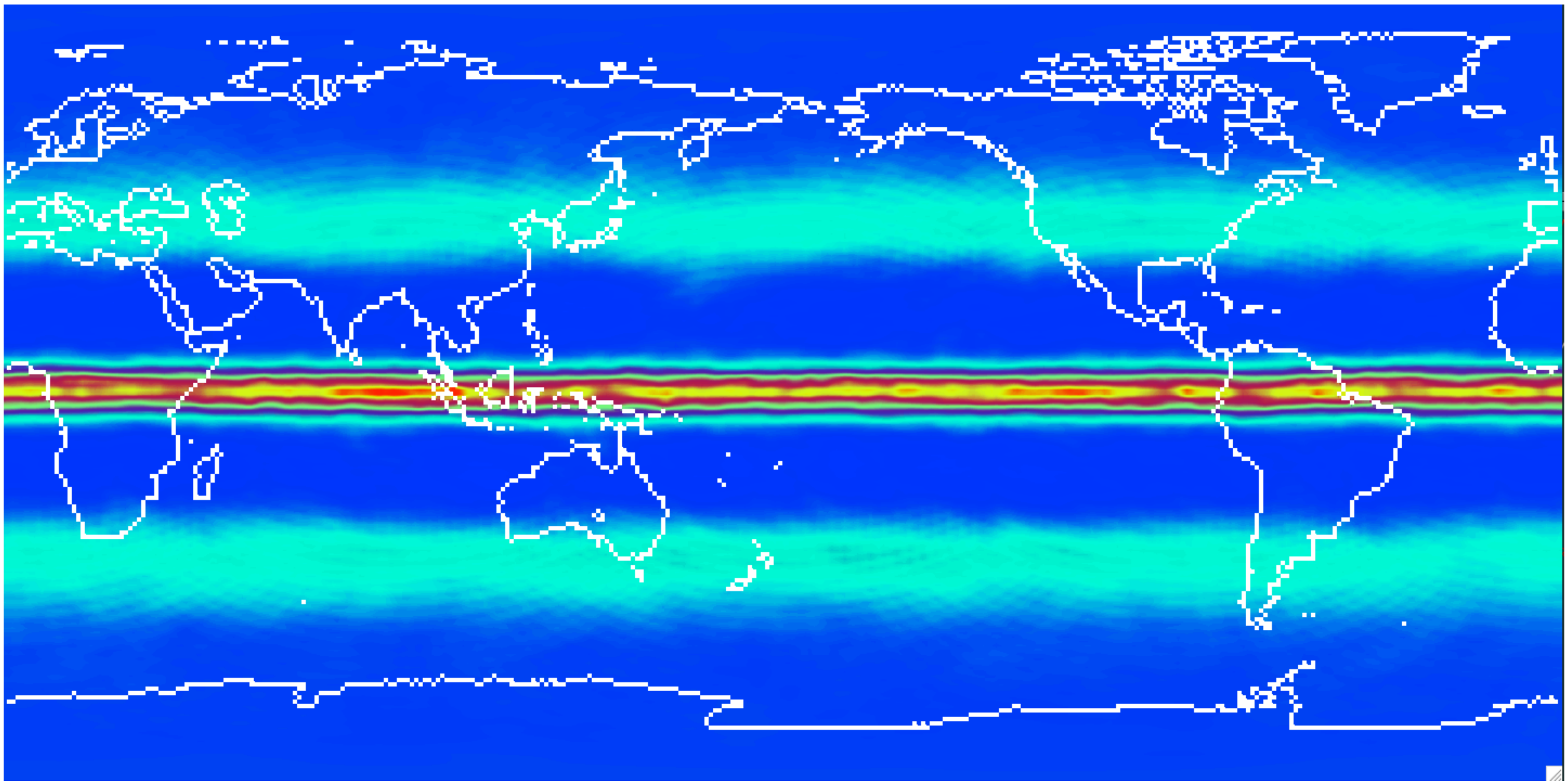
Temperature tendency: FT



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

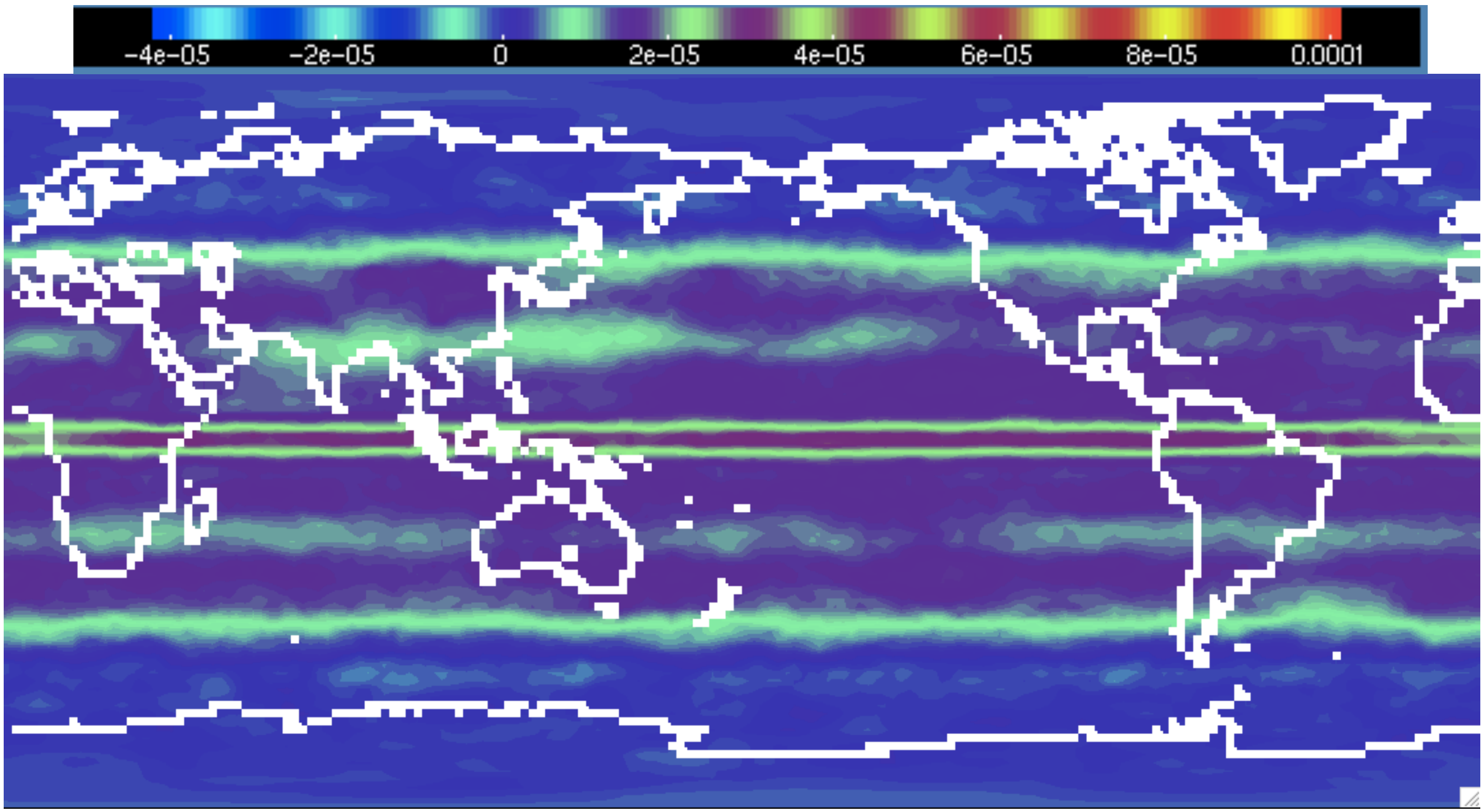
PRECT

(TOTAL PRECIPITATION RATE)



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

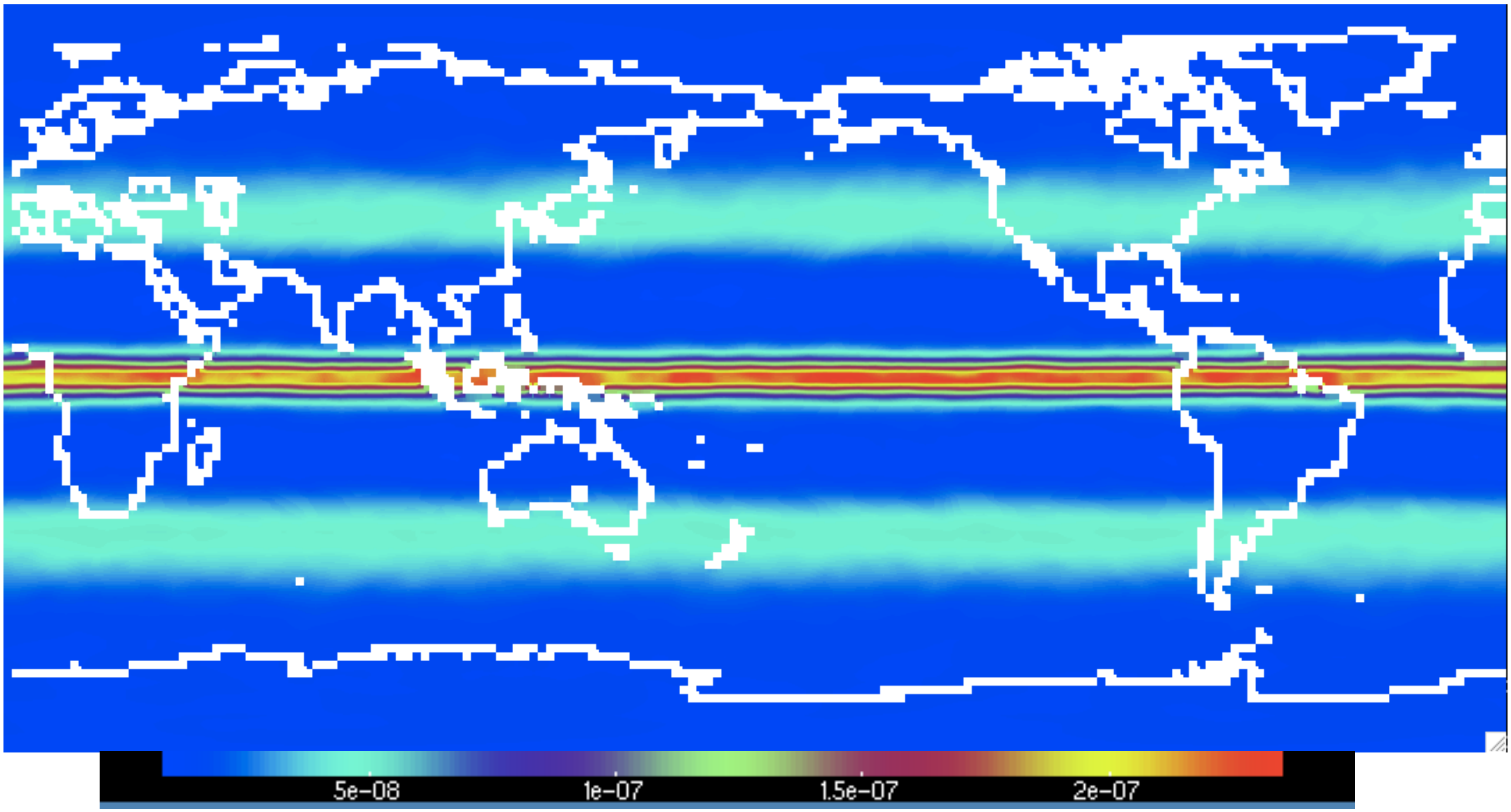
Temperature tendency: FT



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

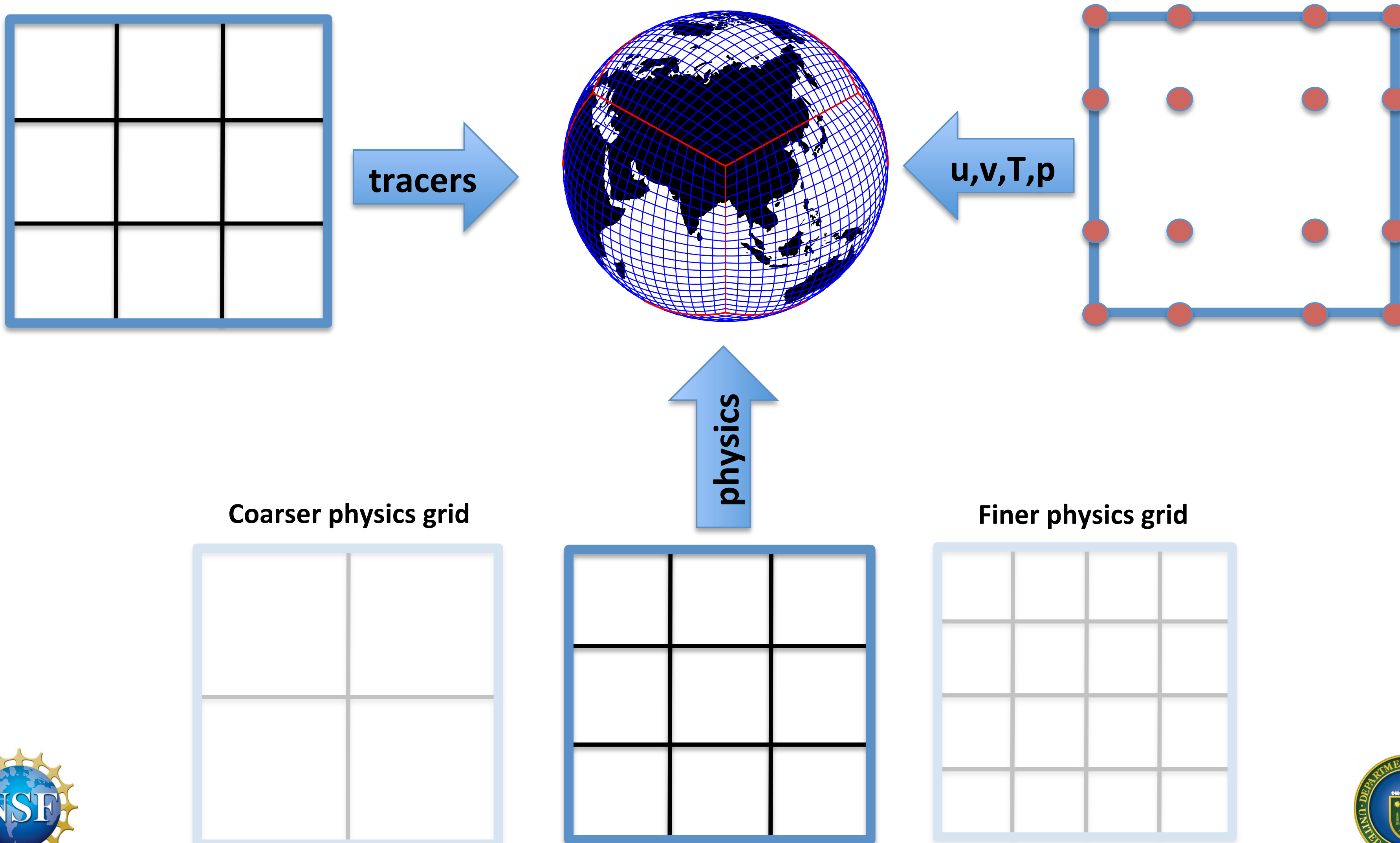
PRECT

(TOTAL PRECIPITATION RATE)



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

CAM-SE-CSLAM configuration

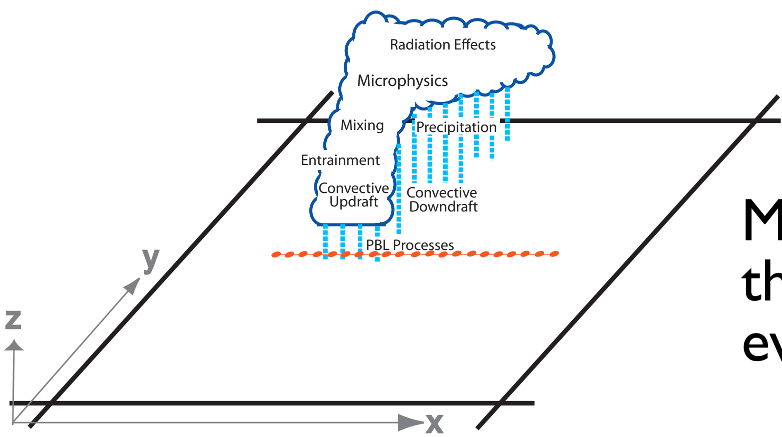


Multiscale Modeling Framework (MMF)

"Cloud Resolving Convective Parameterization" or "Superparameterization"

Approach trying to improve the representation of cloud processes by using the simulated statistics of 2D CRM.

Grabowski & Smolarkiewicz (1999), Khairoutdinov & Randall (2001), and many others.

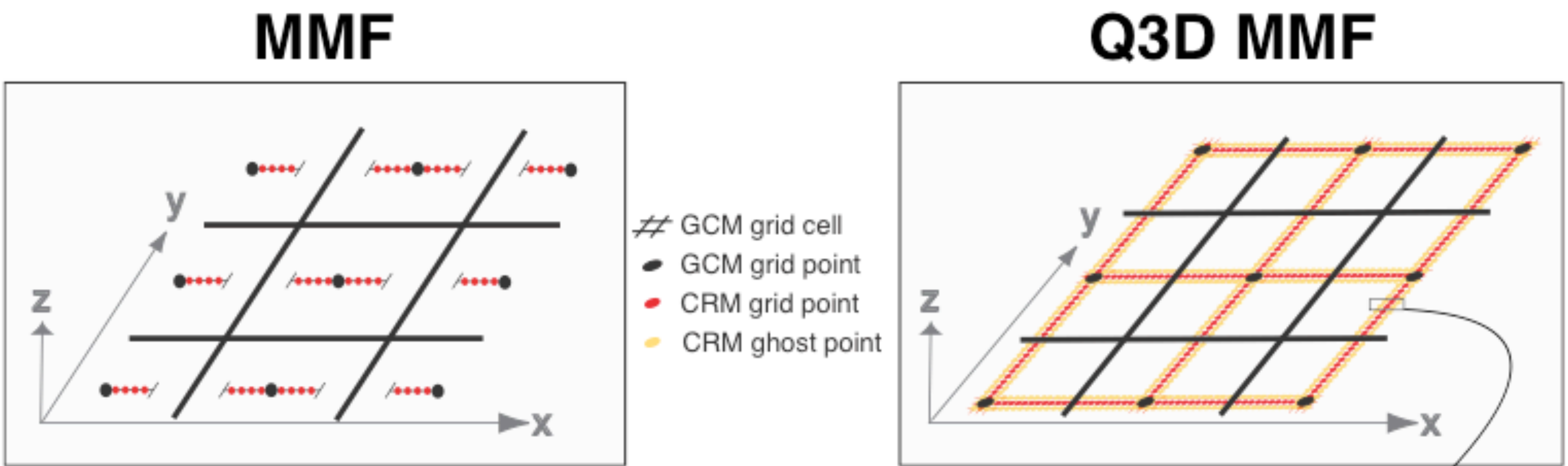


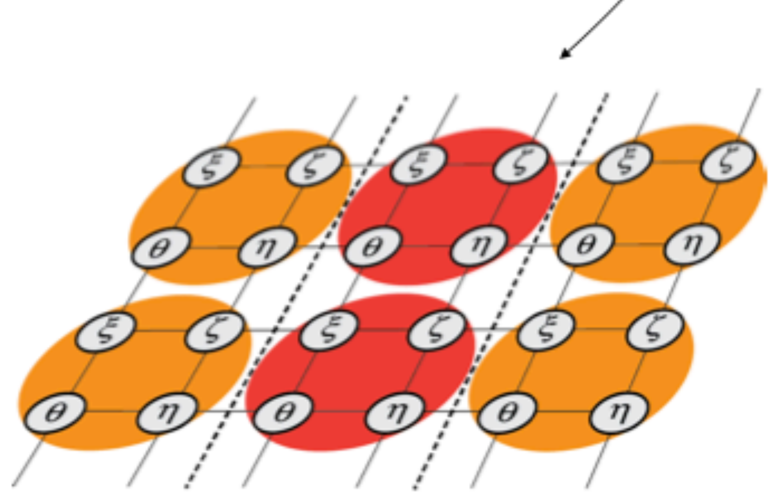
Many studies have shown the ability of the MMF to simulate various atmospheric events with a wide range of time scales.

But, there are inherent limits:

- Confinement of CRMs with cyclic boundary conditions
- Use of 2D CRMs
- Need to choose a particular direction for the 2D CRMs

Quasi-3D Multiscale Modeling Framework





In Q3D MMF

- CRMs are seamlessly connected
- Two perpendicular sets of CRMs are used
- Each CRM is three-dimensional, *(although it is applied to a narrow channel-like domain)*