CESM2 release of CAM-SE (& CAM-SE-CSLAM)

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New SE dynamical core for CESM2

Science changes:

- Dry mass vertical coordinates
- Condensate loading in dynamical core (recommended as default)
- Separate physics grid and CSLAM options (not scientifically supported "yet")
- Eulerian vertical advection no longer supported! Moist vertical coordinates not supported! (to keep code base simpler)

Other:

- Out-of-the-box CESM configurations for idealized setups (Held-Suarez, moist baroclinic wave with Kessler physics, terminator chemistry, …)
- Performance upgrades from CISL (threading, more efficient SE transport)
- Dynamical core is no longer imported from HOMME (High-Order Methods Modeling Environment) ; code must go through CAM code review
- Cleaned up code base: trunk SE has ~61000 lines of code; new SE has ~39000 lines of code (further cleanup in progress …)

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
  - makes it harder to represent condensate loading in the dynamical core
- Complicates CSLAM-SE coupling in a moist atmosphere

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

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

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!

CAM-SE : dry-mass eta

The η_d-coordinate atmospheric primitive equations assuming floating Lagrangian vertical coordinates [*Starr*, 1945; *Lin*, 2004] can be written as

$$\frac{\partial \vec{v}}{\partial t} + (\zeta + f)\,\hat{\vec{k}} \times \vec{v} + \nabla_{\eta_d}\left(\frac{1}{2}\vec{v}^2 + \Phi\right) + \frac{1}{\rho}\nabla_{\eta_d} p = \nu \nabla^4 \vec{u}, \tag{16}$$

$$\frac{\partial T}{\partial t} + \vec{v} \cdot \nabla_{\eta_d} T - \frac{1}{c_p \rho}\omega = \nu \nabla^4_{\eta_d} T, \tag{17}$$

$$\frac{\partial}{\partial t}\left(\frac{\partial p_d}{\partial \eta_d} m_i\right) + \nabla_{\eta_d} \cdot \left(\frac{\partial p_d}{\partial \eta_d} m_i \vec{v}\right) = \nu \nabla^4_{\eta_d}\left(m_i\right), \quad i = d, v, cl, ci, \ldots \tag{18}$$

where Φ is the geopotential height ($\Phi = g\,z$, where g is the gravitational constant), c_p is the specific heat constant for dry air, $\hat{\vec{k}}$ 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.

CAM-SE : dry-mass eta

The η_d-coordinate atmospheric primitive equations assuming floating Lagrangian vertical coordinates [*Starr*, 1945; *Lin*, 2004] can be written as

$$\frac{\partial \vec{v}}{\partial t} + (\zeta + f)\,\hat{\vec{k}} \times \vec{v} + \nabla_{\eta_d}\left(\frac{1}{2}\vec{v}^2 + \Phi\right) + \frac{1}{\rho}\nabla_{\eta_d} p = \nu \nabla^4 \vec{u}, \tag{16}$$

$$\frac{\partial T}{\partial t} + \vec{v}\cdot\nabla_{\eta_d} T - \frac{1}{c_p \rho}\omega = \nu \nabla^4_{\eta_d} T, \tag{17}$$

$$\frac{\partial}{\partial t}\left(\frac{\partial p_d}{\partial \eta_d} m_i\right) + \nabla_{\eta_d}\cdot\left(\frac{\partial p_d}{\partial \eta_d} m_i \vec{v}\right) = \nu \nabla^4_{\eta_d}(m_i), \quad i = d, v, cl, ci, \ldots \tag{18}$$

where Φ is the geopotential height (Φ ... $g z$, where g is the gravitational constant), c_p is the specific heat constant for dr... is the unit ve...r normal to the surface of the sphere, $\zeta = \hat{\vec{k}} \cdot \nabla \times \vec{v}$ is vorticit... ...iolis parameter, ... $\omega = Dp/Dt$ is the pressure vertical velocity.

$$\rho = \rho_d\left(\sum_i m_i\right), i = \text{‘}d\text{‘}, \text{‘}v\text{‘}, \text{‘}cl\text{‘}, \text{‘}ci\text{‘}.$$

$$c_p = \frac{\sum_i \left[m_i\, c_{pi}\right]}{\sum_i m_i}$$

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

"Correct" 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 this equation can be written as

$$I_{tot} = \sum_i I_i,$$

where I_d is the total internal energy of dry air, I_v the total internal energy of water vapor, etc.:

$$\begin{aligned}
I_d &= -\frac{1}{g} \iiint c_{pd} T \left(\frac{\partial p_d}{\partial \eta_d} \right) d\eta_d \, \cos(\theta) r \, d\lambda \, d\theta, \\
I_v &= -\frac{1}{g} \iiint c_{pv} m_v T \left(\frac{\partial p_d}{\partial \eta_d} \right) d\eta_d \, \cos(\theta) r \, d\lambda \, d\theta, \\
I_{cl} &= -\frac{1}{g} \iiint c_{pcl} m_{cl} T \left(\frac{\partial p_d}{\partial \eta_d} \right) d\eta_d \, \cos(\theta) r \, d\lambda \, d\theta, \\
I_{ci} &= -\frac{1}{g} \iiint c_{pci} m_{ci} T \left(\frac{\partial p_d}{\partial \eta_d} \right) d\eta_d \, \cos(\theta) r \, d\lambda \, d\theta.
\end{aligned}$$

“Correct” 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 ... equation can be written as

$$I_{tot} = \sum_i I_i,$$

where I_d is the total inter... ...ry air, I_v the total internal energy of water vapor, etc.:

The internal energy in CAM physics is defined as

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

$$I_{cl} = -\frac{1}{g} \iiint c_{pcl} m_{cl} T \left(\frac{\partial p_d}{\partial \eta_d}\right) d\eta_d \, \cos(\theta) r \, d\lambda \, d\theta,$$

$$I_{ci} = -\frac{1}{g} \iiint c_{pci} m_{ci} T \left(\frac{\partial p_d}{\partial \eta_d}\right) d\eta_d \, \cos(\theta) r \, d\lambda \, d\theta.$$

"Correct" Internal Energy

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

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

Enforcing the correct energy in CAM physics is NON-TRIVIAL:

- **If a parameterization alters water vapor, cloud liquid, and/or cloud ice then internal energy (and kinetic energy) changes**
- **The assumption that pressure levels stay fixed during physics updates is violated unless we switch to dry pressure levels**

y of water vapor,

$$I_v = -\frac{1}{g} \iiint c_{pv} m_v T \left(\frac{\partial p_d}{\partial \eta_d}\right) d\eta_d \, \cos(\theta) r \, d\lambda \, d\theta,$$

$$I_{cl} = -\frac{1}{g} \iiint c_{pcl} m_{cl} T \left(\frac{\partial p_d}{\partial \eta_d}\right) d\eta_d \, \cos(\theta) r \, d\lambda \, d\theta,$$

$$I_{ci} = -\frac{1}{g} \iiint c_{pci} m_{ci} T \left(\frac{\partial p_d}{\partial \eta_d}\right) d\eta_d \, \cos(\theta) r \, d\lambda \, d\theta.$$

Two SE configurations

controlled with namelist: `qsize_condensate_loading = 1,3`

1. Set $c_p = c_{pd}$ and $\rho = \rho_d + \rho_v$
2. Use 'correct' c_p and $\rho = \rho_d + \rho_v + \rho_{ci} + \rho_{cl}$

In dynamics-physics coupling we pass $\Delta p = \Delta p_d(1 + m_v)$ to remain consistent with the physics definition of total energy.

Both configurations have pros and cons:

1a. Only difference between #1 and trunk is vertical coordinate

1b. The continuous equations of motion conserve the same "wrong" energy as CAM physics.

1c. The adiabatic momentum equations and thermodynamic equations do not "feel" the condensates

2a. The continuous equations of motion conserve the "correct" energy but CAM physics will (through the energy fixer) enforce the "wrong" energy

2b. The adiabatic momentum equations and thermodynamic equations "feel" the condensates (a.k.a. condensate loading; may be significant at higher resolution)

Energy budgets in CAM-FV (0.9x0.9)

CAM5.3 physics; 10 year run

pEFIX = dE/dt energy fixer (pBP-pBF) : -0.8103 W/m^2
pDMEA = dE/dt dme_adjust (pAM-pAP) : 0.2636 W/m^2

Energy fixer fixes dme_adjust (pDMEA), lack of energy conservation in adiabatic dynamical core (dADIA) and energy lost/gained in physics-dynamics coupling (dPDC):

-pEFIX = pDMEA+dADIA+dPDC

CAM-FV uses updated state (no "drippling" of tendencies) from physics so dPDC=0

⇒ dADIA = dE/dt adiabatic dynamical core = -pEFIX-pDMEA : -1.0739 W/m^2

Aside:

At 2 degree horizontal resolution dE/dt adiabatic dynamical : -1.2738 W/m^2

Energy budgets in CAM-SE configuration 1

CAM5.9999 physics; 6 year run; qsize_condensate_loading = 1

http://webext.cgd.ucar.edu/FCLIMO/f.e20.F2000_DEV.ne30_ne30.physgrid25_cam5_4_96_se_qsize_1/atm/

pEFIX = dE/dt energy fixer (pBP-pBF) : -0.1913 W/m^2

pDMEA = dE/dt dme_adjust (pAM-pAP) : 0.3064 W/m^2

Energy fixer fixes dme_adjust (pDMEA), lack of energy conservation in adiabatic dynamical core (dADIA) and energy lost/gained in physics-dynamics coupling (dPDC):

-pEFIX = pDMEA+dADIA+dPDC

dADIA = dE/dt adiabatic dynamical core = -0.0732 W/m^2

(-0.1604 W/m^2 vertical remapping, 0.0872 W/m^2 Lagrangian dyn, hypervis V added as heating = 0.7110 W/m^2)

dPDC = dE/dt physics-dynamics coupling (ftype=0) = -0.0419 W/m^2

dADIA (SE configuration 1) = -0.0732 W/m^2 << dADIA (FV) = -1.0739 W/m^2

pDMEA is about the same for CAM-FV and CAM-SE

Energy budgets in CAM-SE configuration 2

CAM5.9999 physics; 6 year run; qsize_condensate_loading = 3

http://webext.cgd.ucar.edu/FCLIMO/f.e20.F2000_DEV.ne30_ne30.physgrid25_cam5_4_96_se_qsize_3/atm/

pEFIX = dE/dt energy fixer (pBP-pBF) : -0.7070 W/m²

pDMEA = dE/dt dme_adjust (pAM-pAP) : 0.3102 W/m²

Energy computations in dynamical use "correct" energy formula
Energy computations in physics use "wrong" energy formula

=> We can not mix computations done in physics and dynamics but ....

dADIA = dE/dt adiabatic dynamical core = -0.0928 W/m²
pEFIX configuration 2 – pEFIX configuration 1 = 0.5257 W/m²
i.e. the inconsistency in energy formula is ca. 0.5 W/m² consistent with Mark Taylors findings.

Even with this inconsistency the energy fixer fixes less than for CAM-FV
=> I recommend configuration 2 as default in CESM2

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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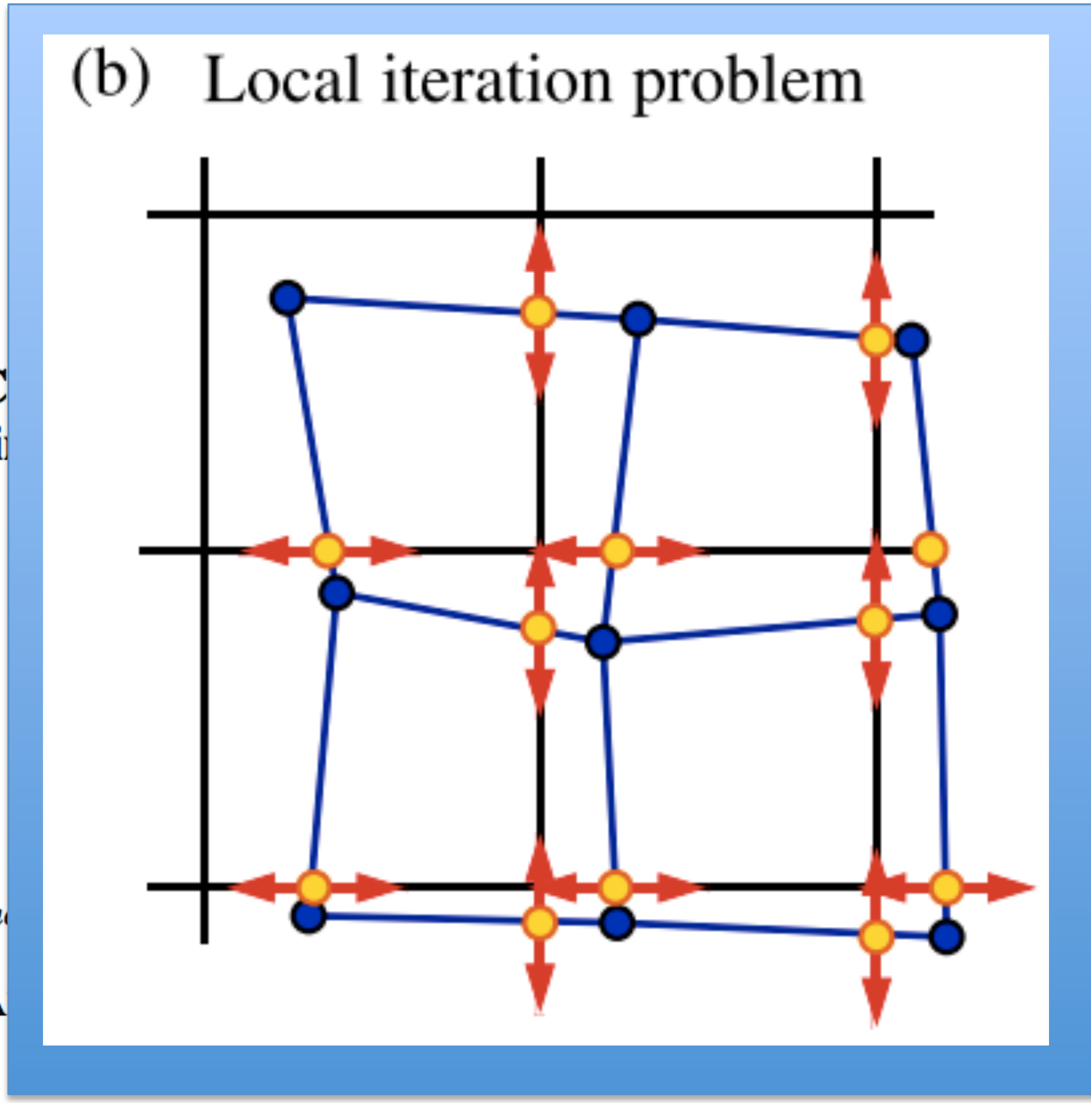
CAM-SE-CSLAM without moisture



CAM-SE–C **-Lagrangian**
Fi **cs**

Departm *alifornia*

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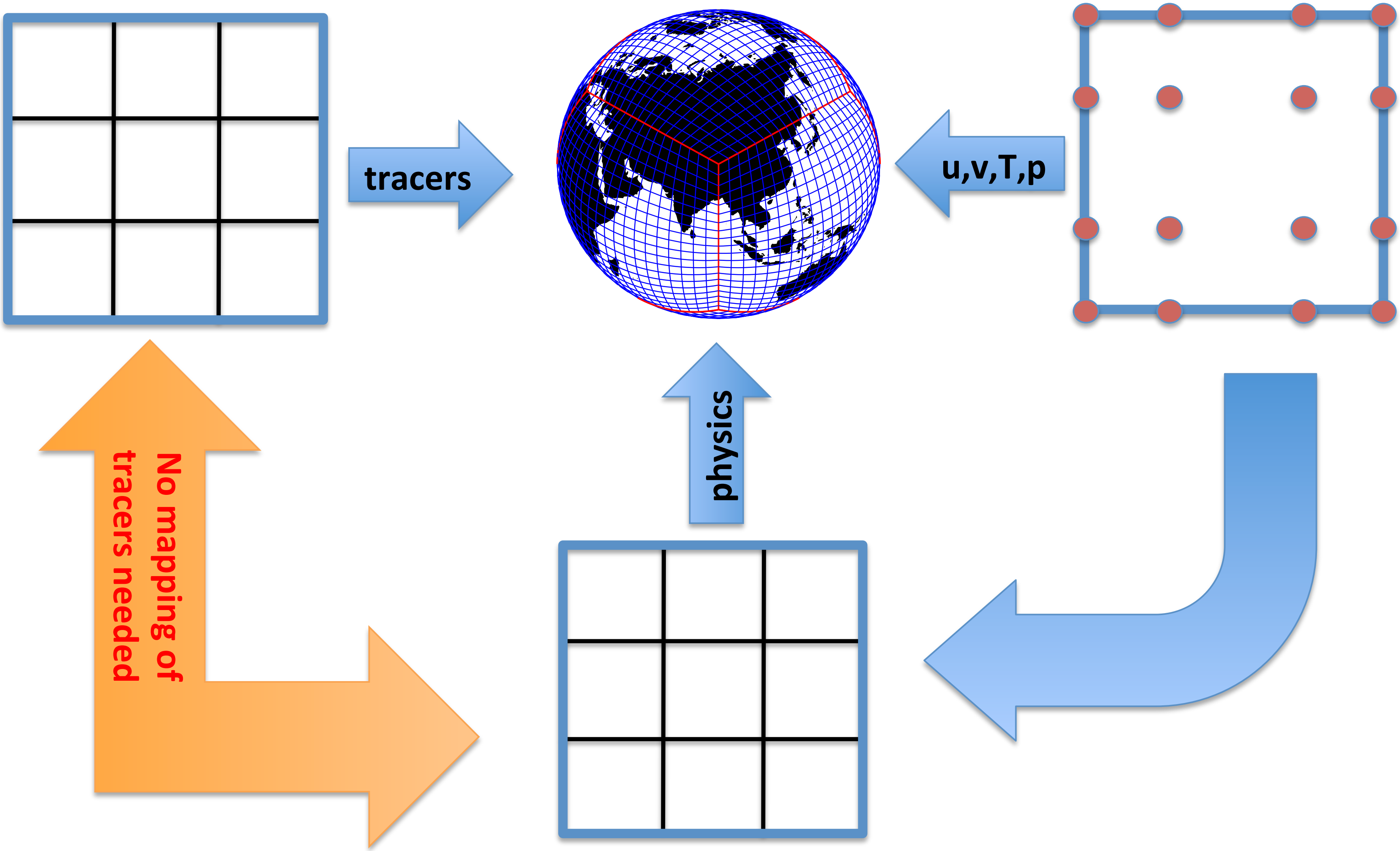
CAM-SE-CSLAM with moisture

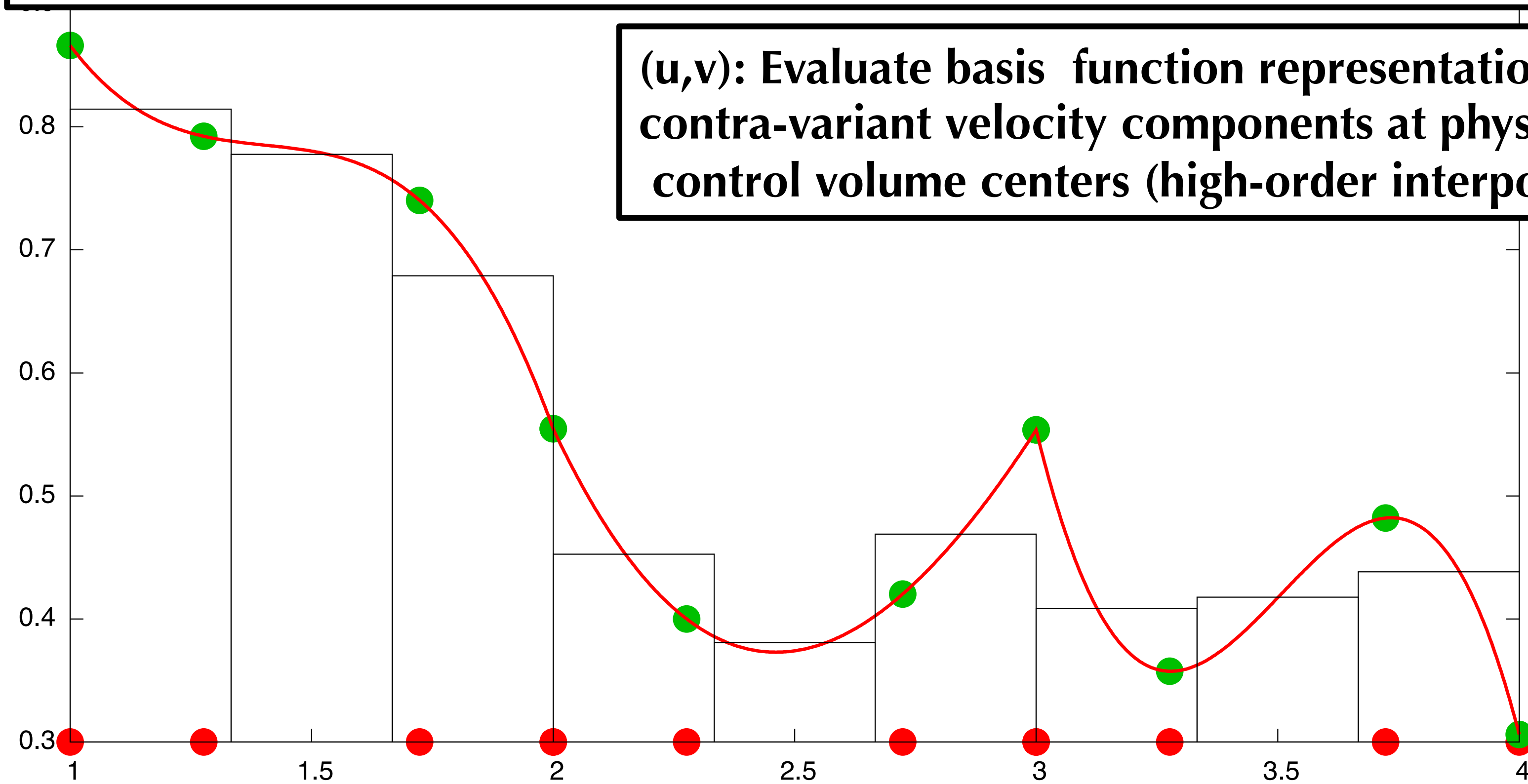
"This is where the fun begins!" – Staniforth et al. (2006)



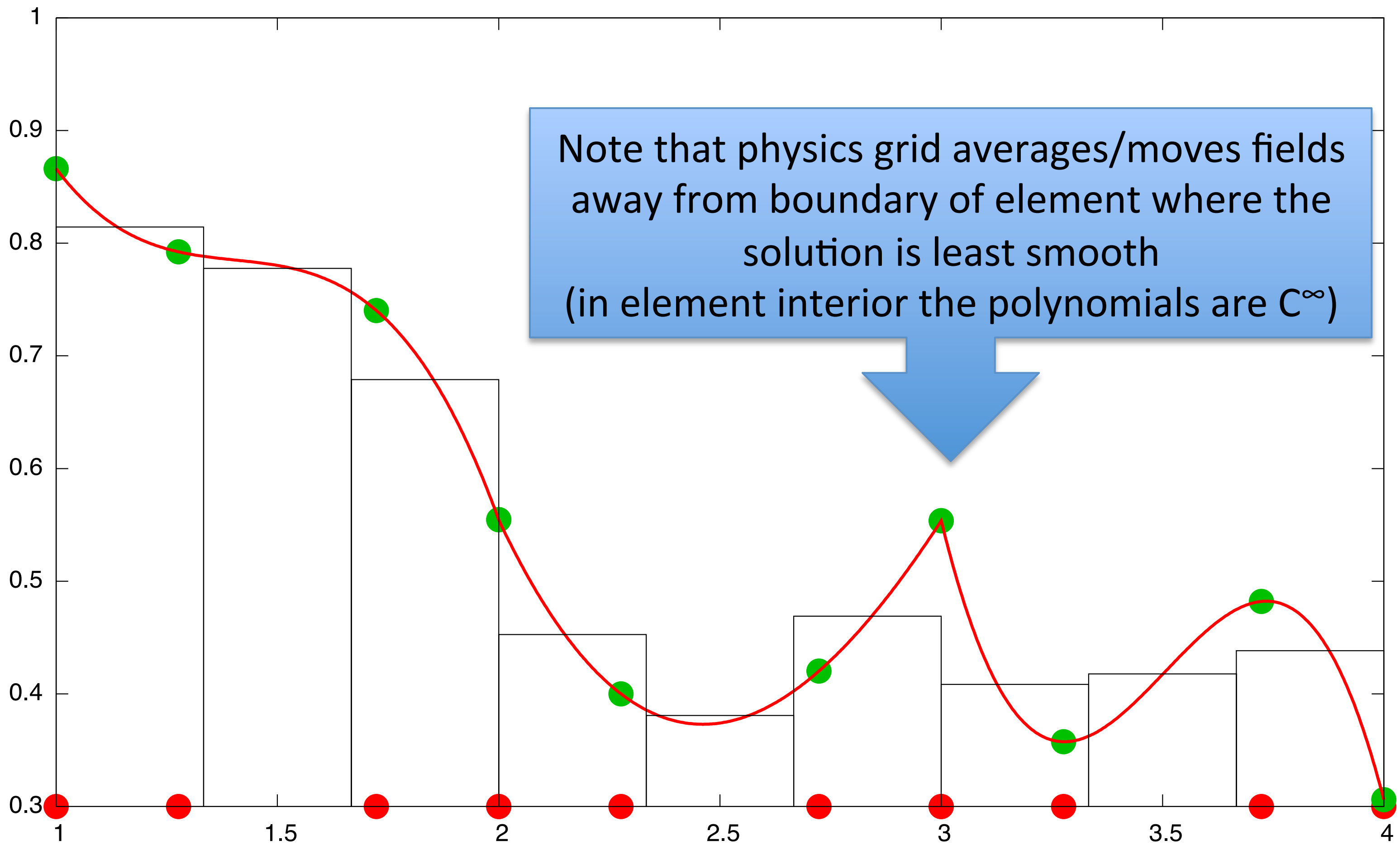
Mapping u,v, T, omega from dynamics grids (GLL) to finite-volume (CSLAM) grid

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

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



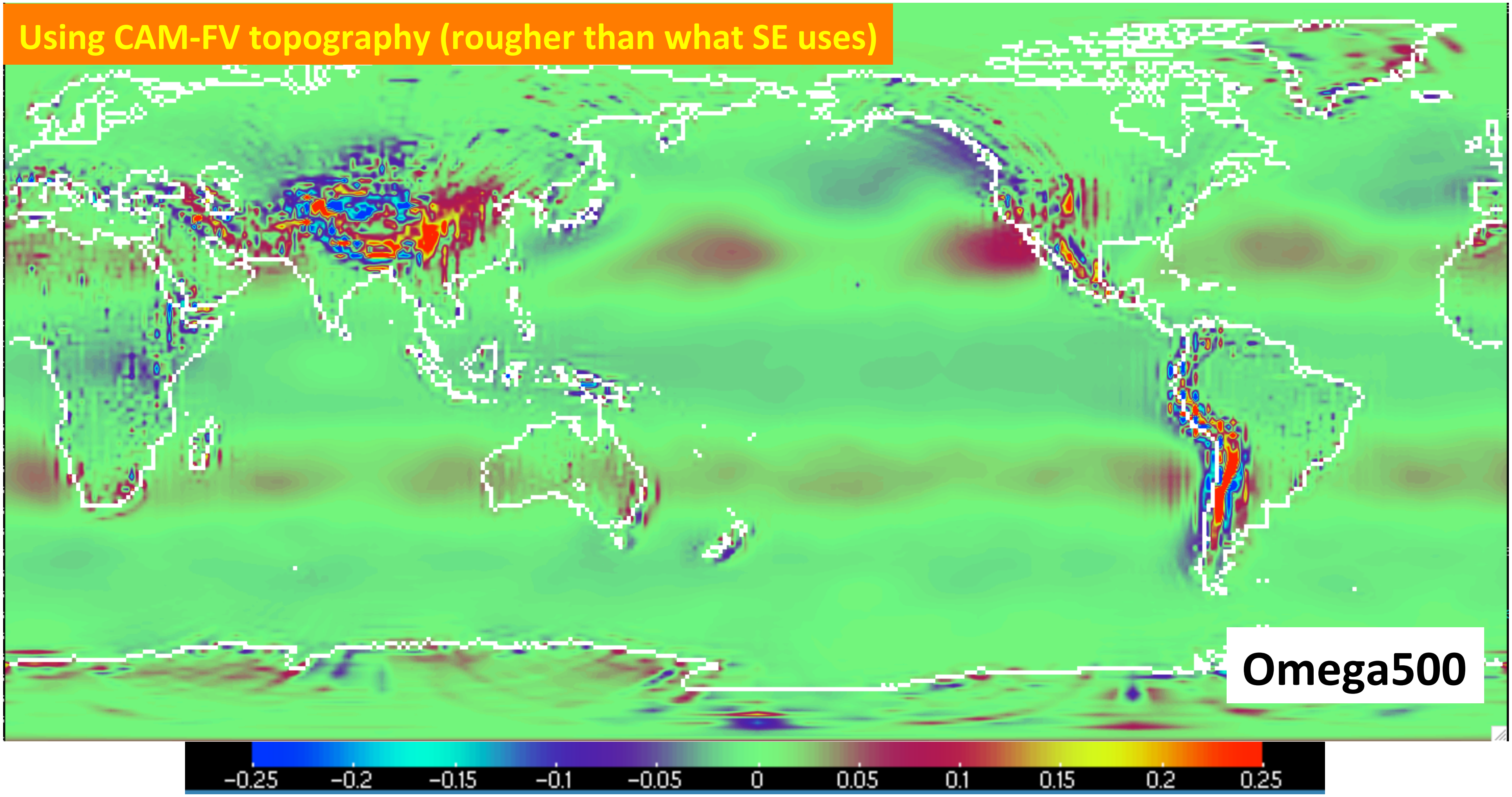
Mapping u,v, T, omega from dynamics grids (GLL) to finite-volume (CSLAM) grid



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 feedback

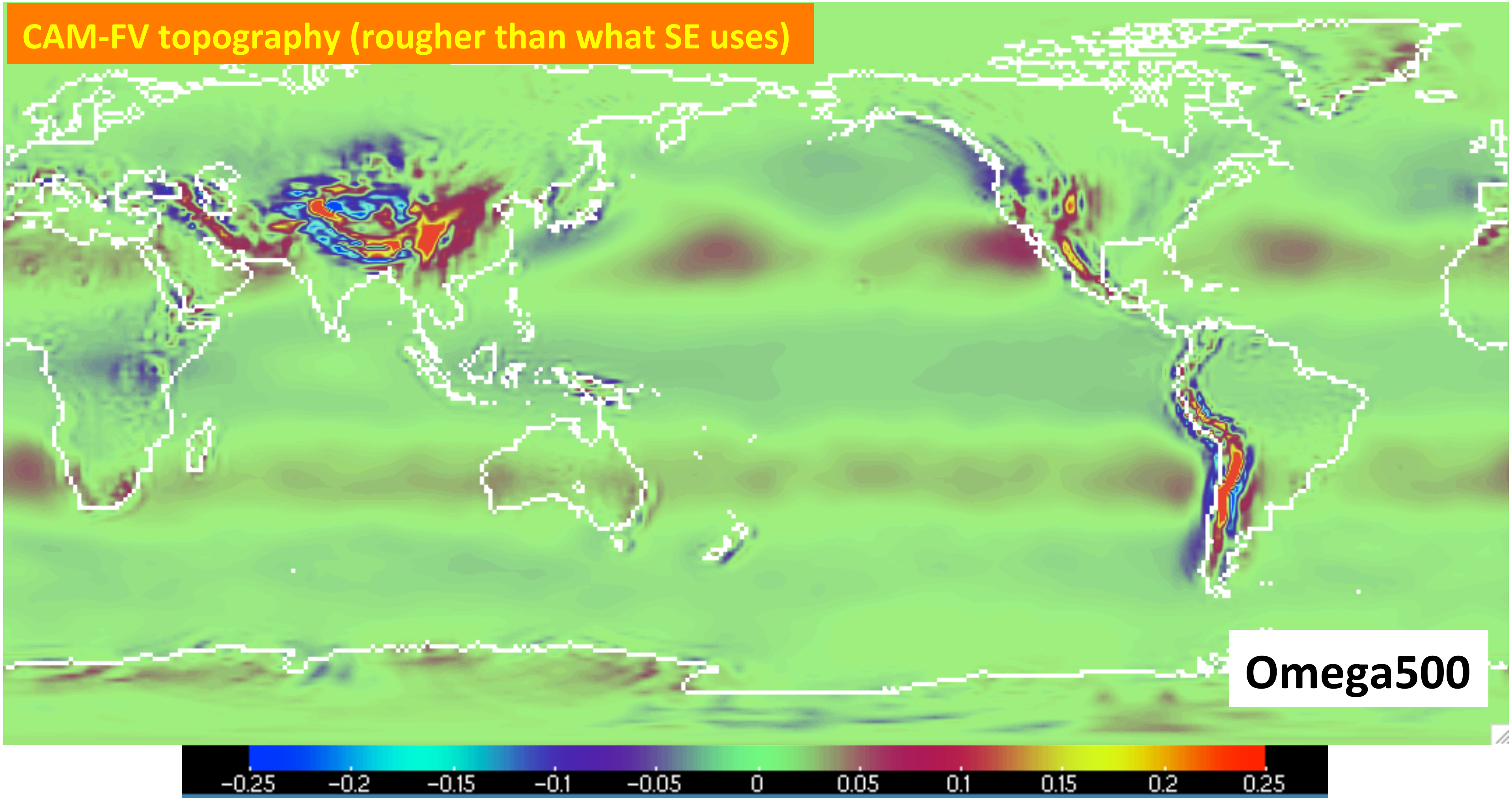
bnd_topo = /home/pel/run_scripts/topo/ne30np4_nc3000_Nsw042_Nrs008_Co060_Fi001_ZR_test_vX_111416.nc



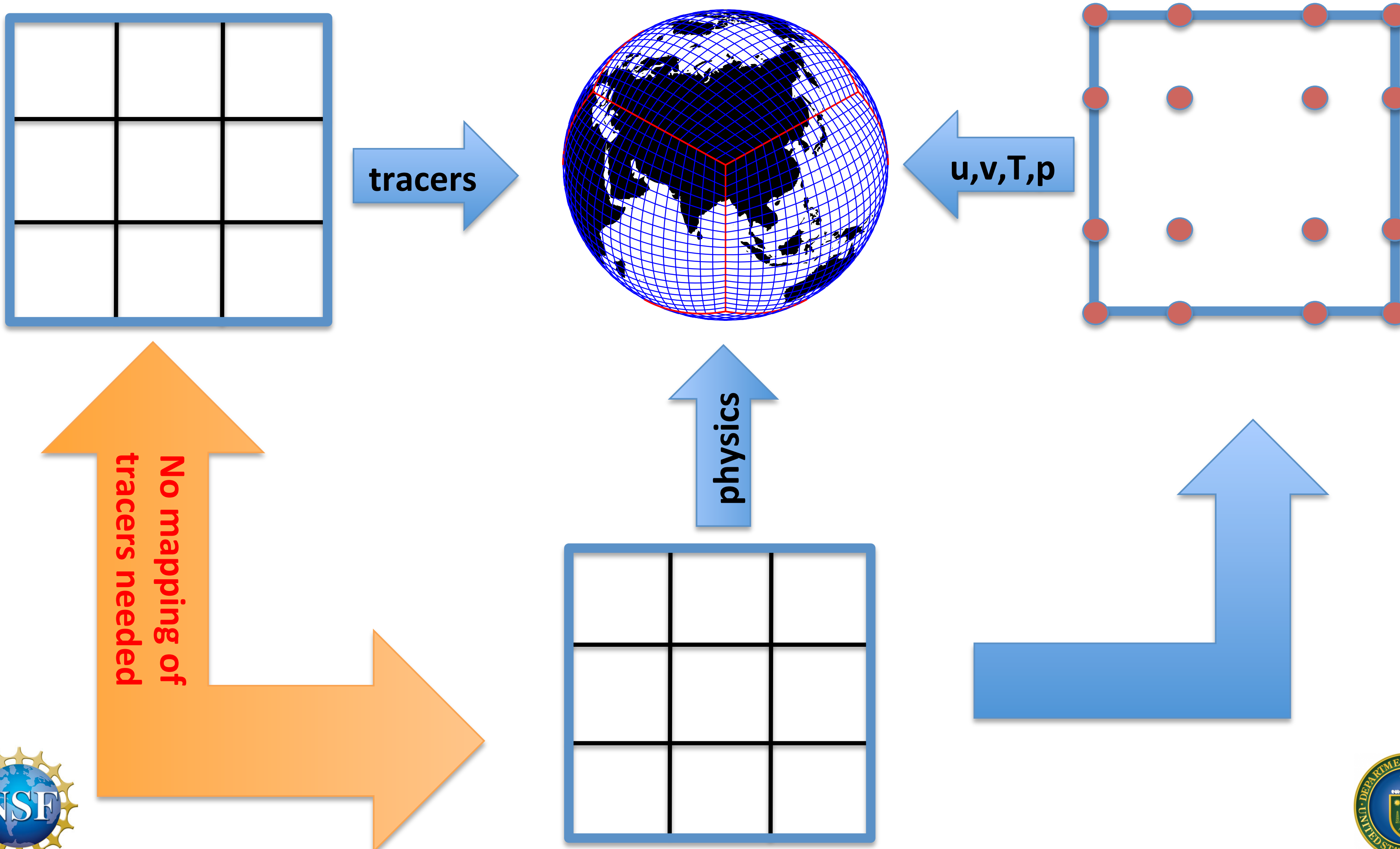
CAM-SE-CSLAM

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

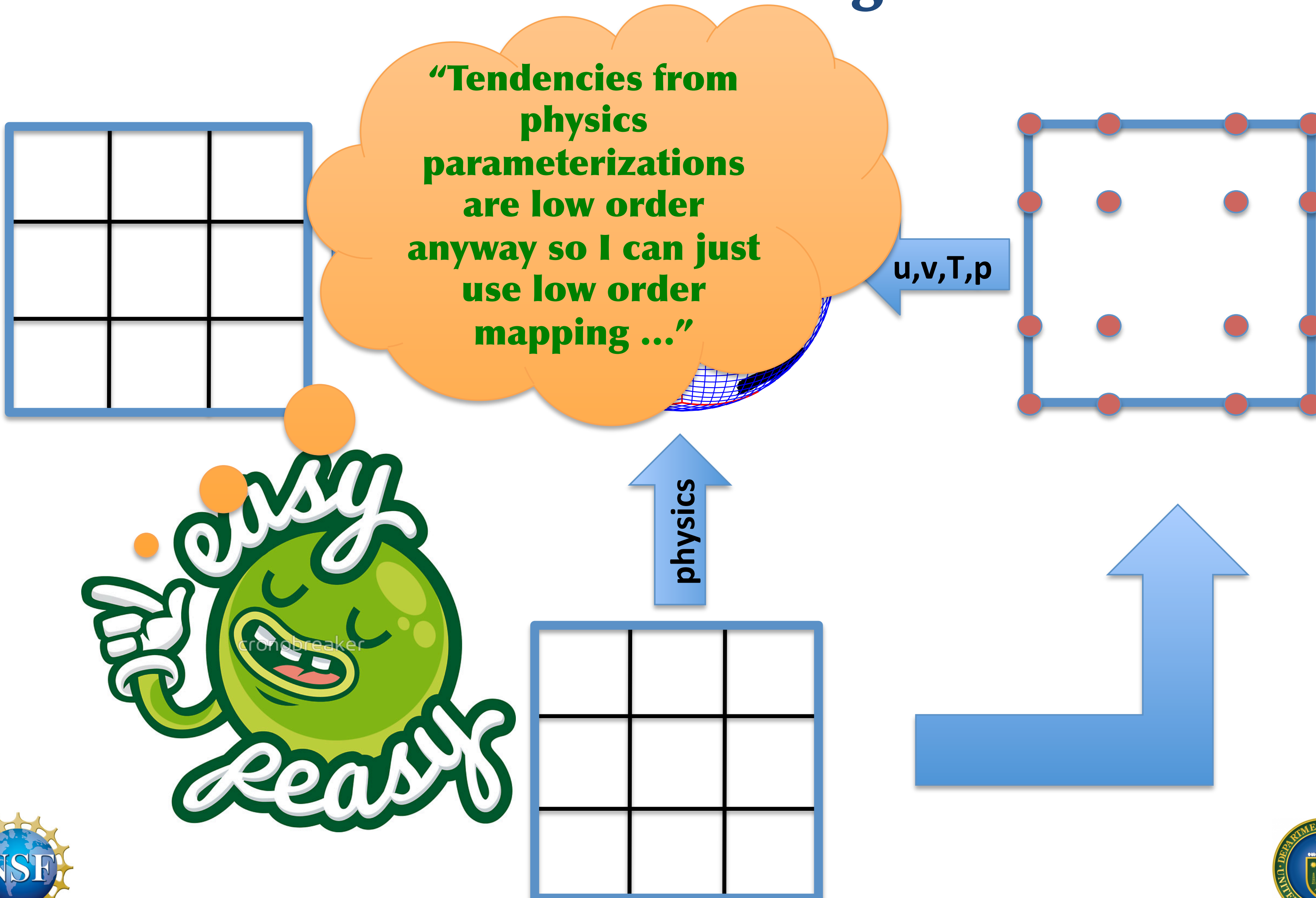
bnd_topo = '/home/pel/run_scripts/topo/ne30np4_nc3000_Nsw042_Nrs008_Co060_Fi001_ZR_test_vX_111416.nc



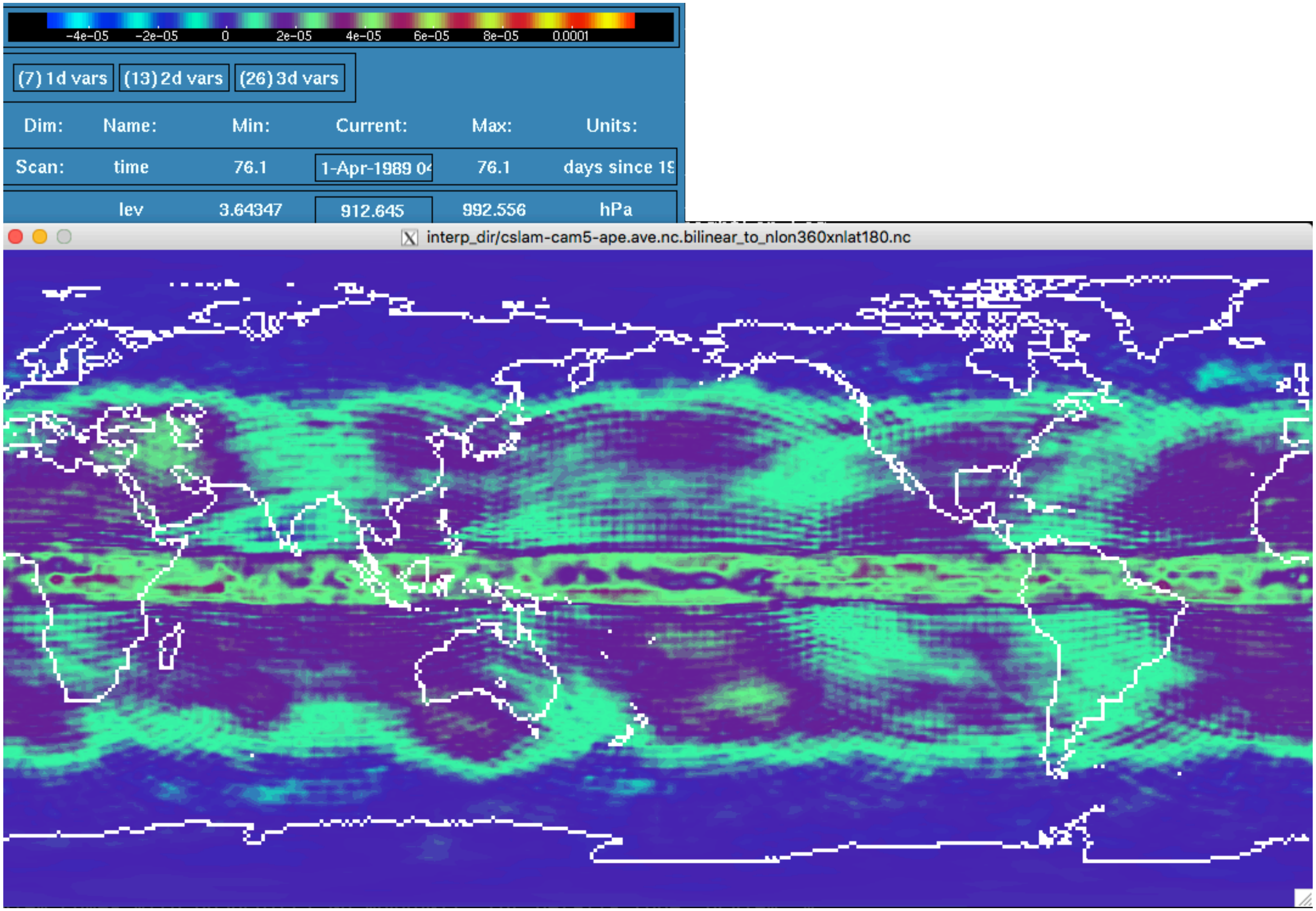
CAM-SE-CSLAM configuration



CAM-SE-CSLAM configuration

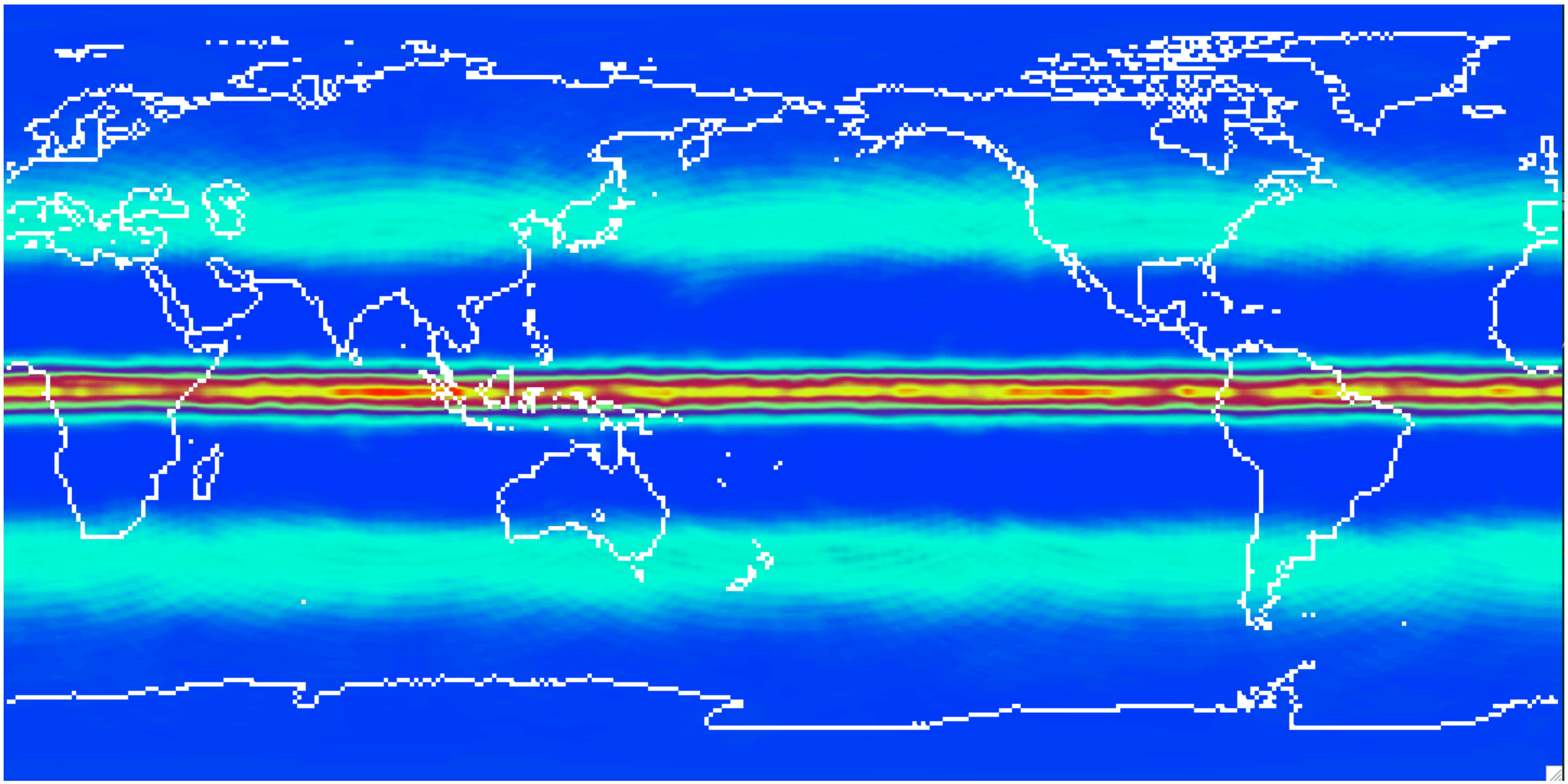


Temperature tendency: FT



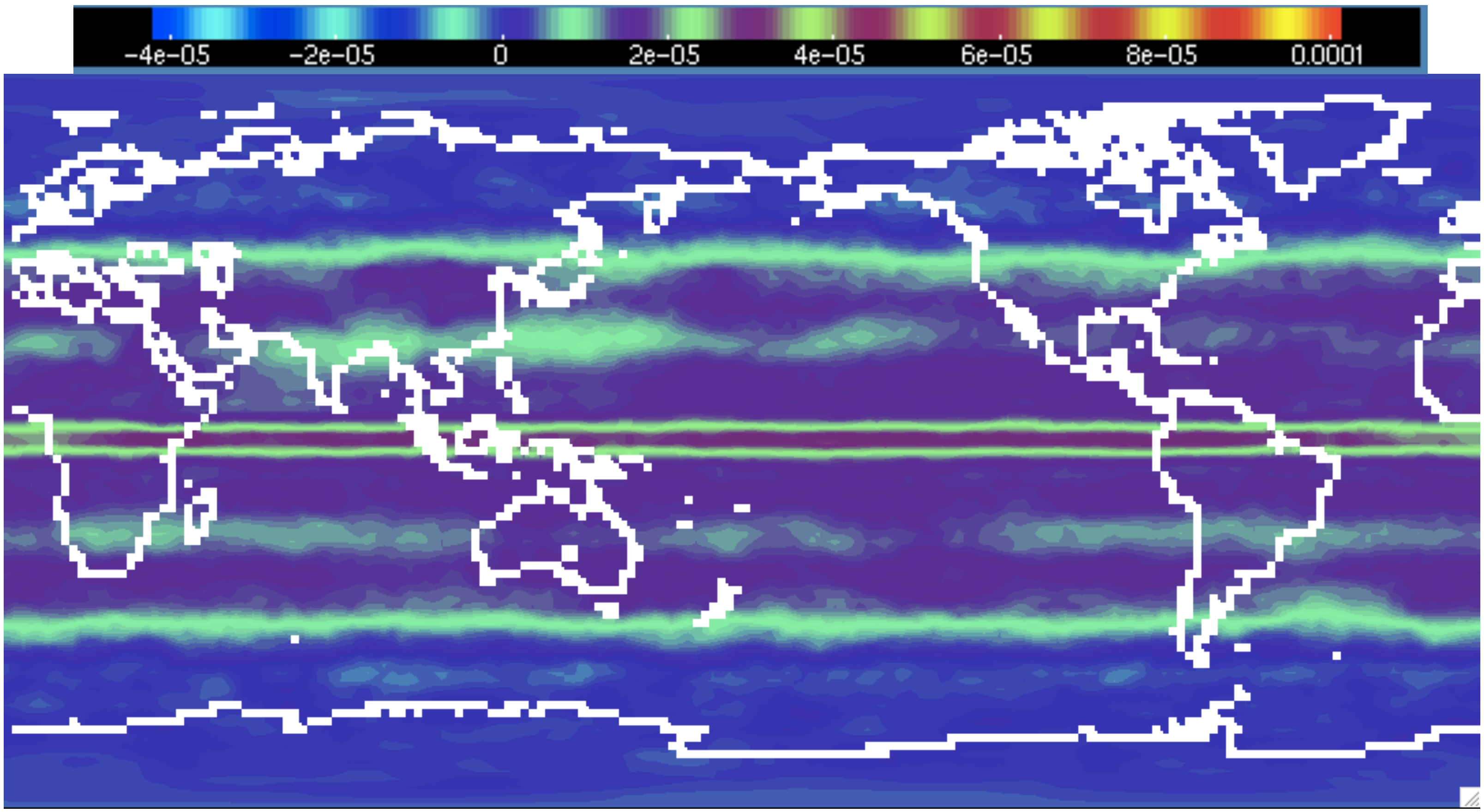
CAM-SE-CSLAM with linear interpolation from phys to dyn: 5 month average

PRECT



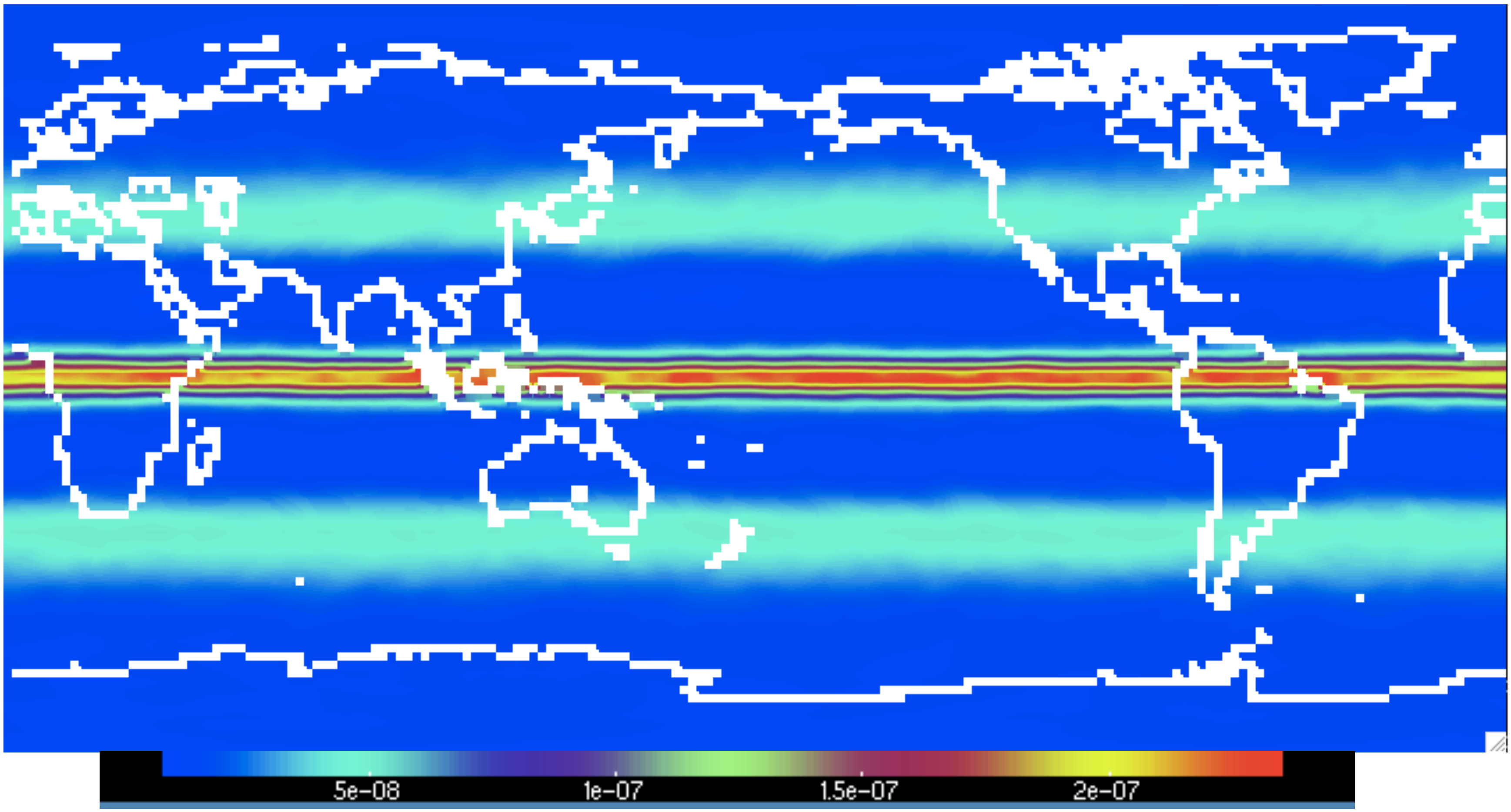
CAM4 SE-CSLAM-physgrid: linear interpolation phys to dyn: 5 month average
Plot looks similar for standard SE (but less noisy)

Temperature tendency: FT



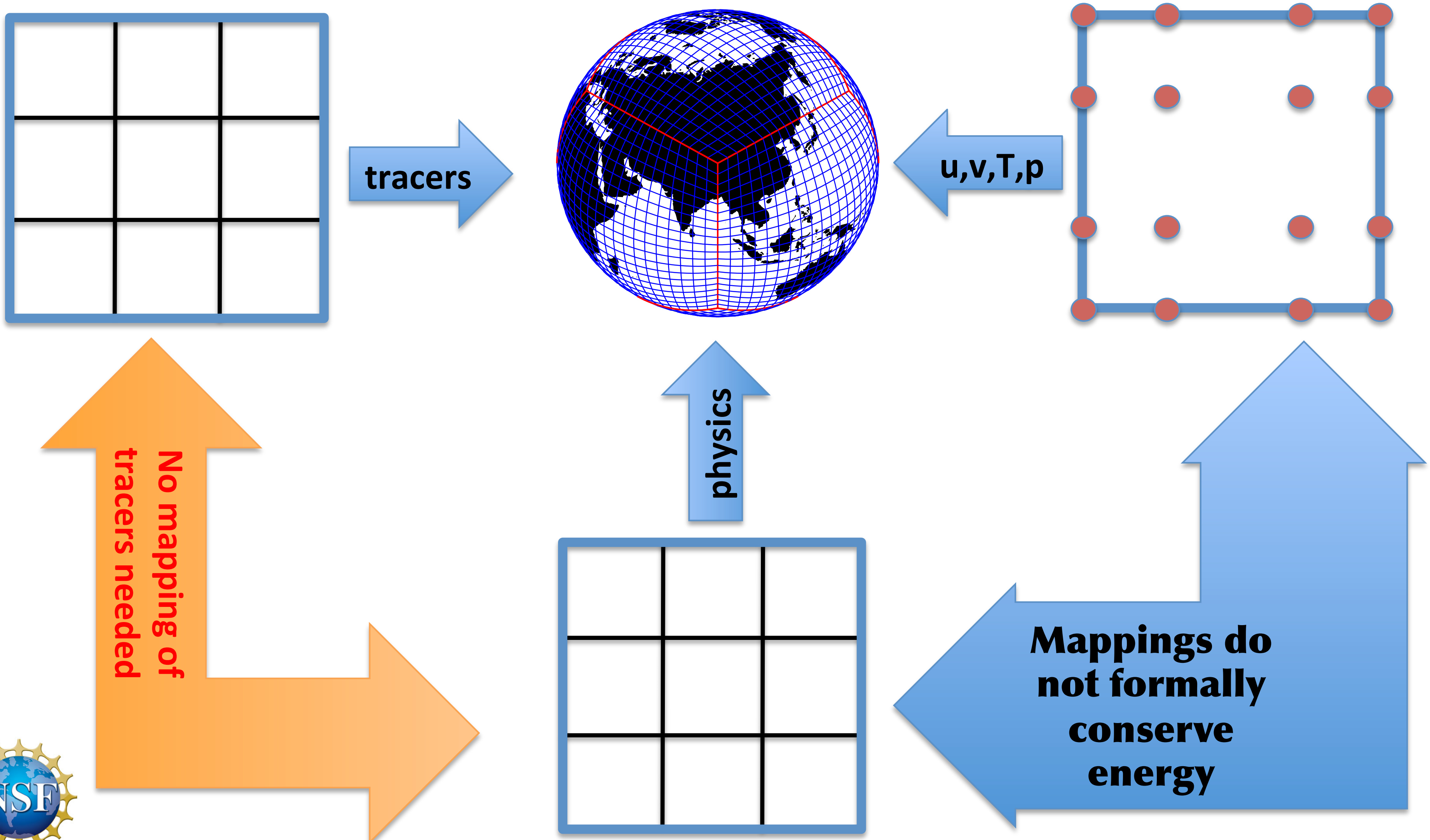
CAM-SE-CSLAM with cubic tensor product interpolation from phys to dyn: 18 month average

PRECT

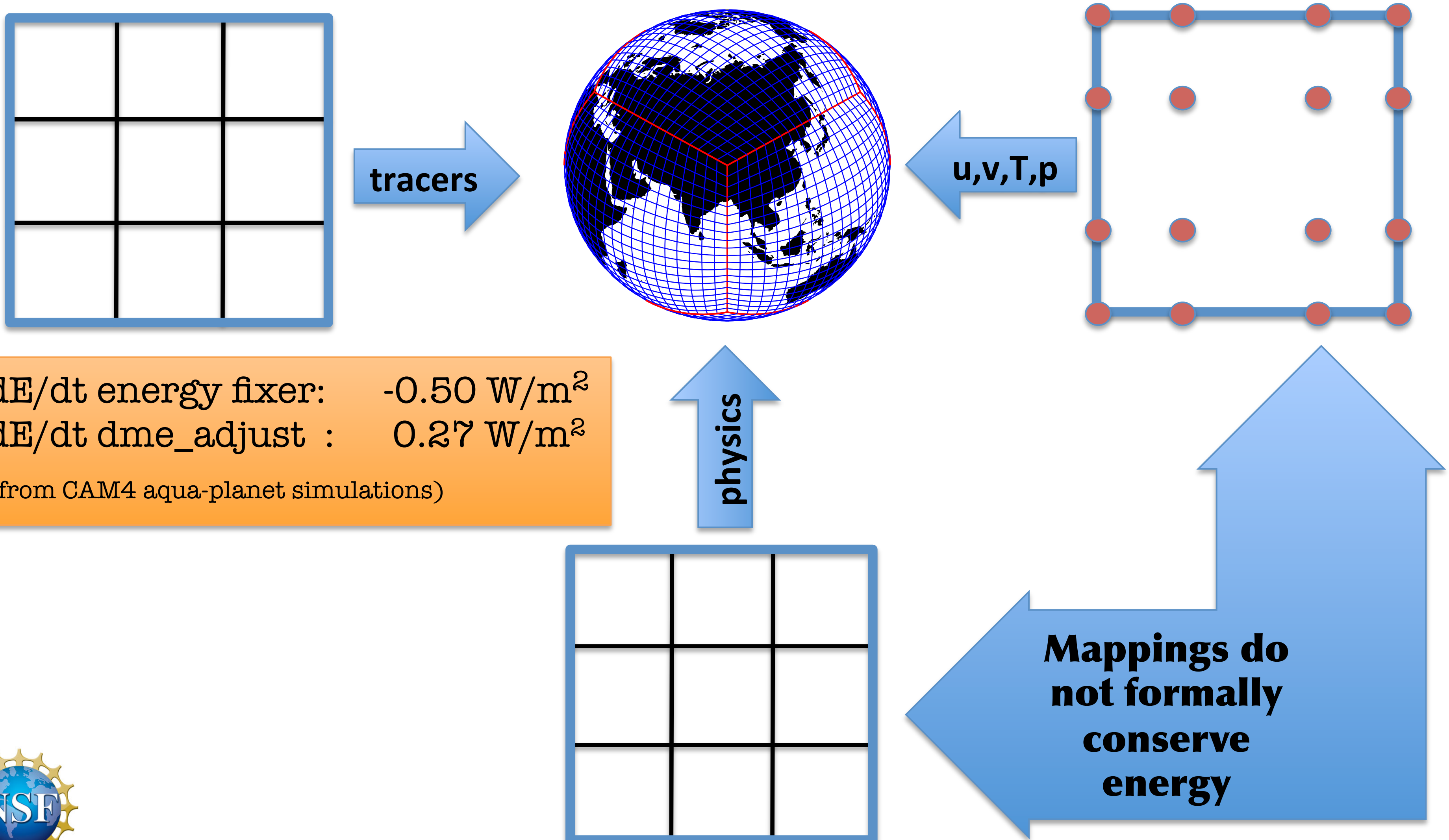


CAM-SE-CSLAM with cubic tensor product interpolation from phys to dyn: 18 month average

CAM-SE-CSLAM configuration



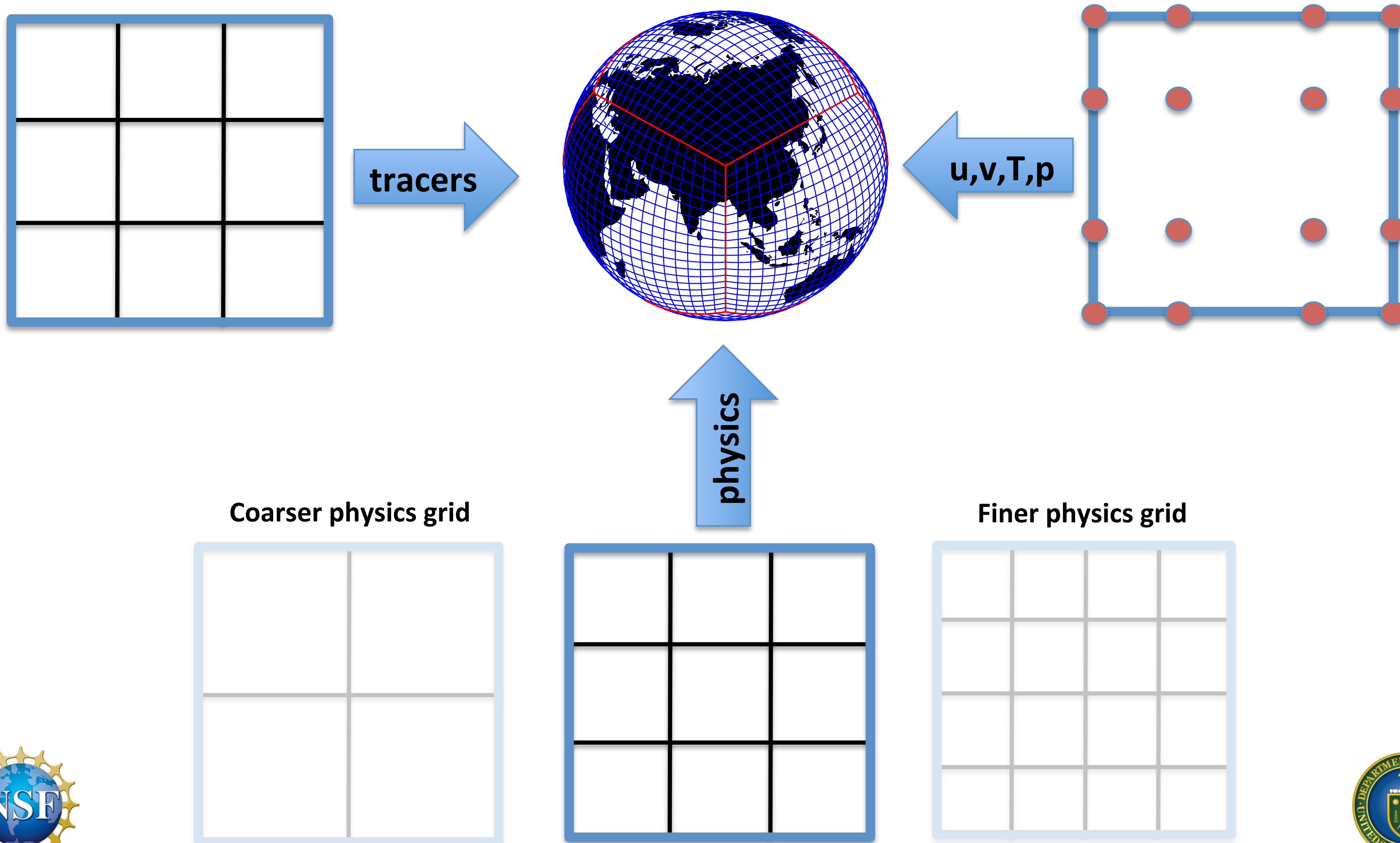
CAM-SE-CSLAM configuration



dE/dt energy fixer: -0.50 W/m^2
dE/dt dme_adjust : 0.27 W/m^2

(from CAM4 aqua-planet simulations)

CAM-SE-CSLAM configuration



CAM-S[...]CSLAM c[...]guration

We are getting very close to finally do science (beyond numerical methods research) with CAM-SE-CSLAM