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Scientific Discovery through Advanced Computing

NCAR
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Conservation and coupling in CAM-SE

(CAM=Community Atmosphere Model; SE=Spectral Elements)

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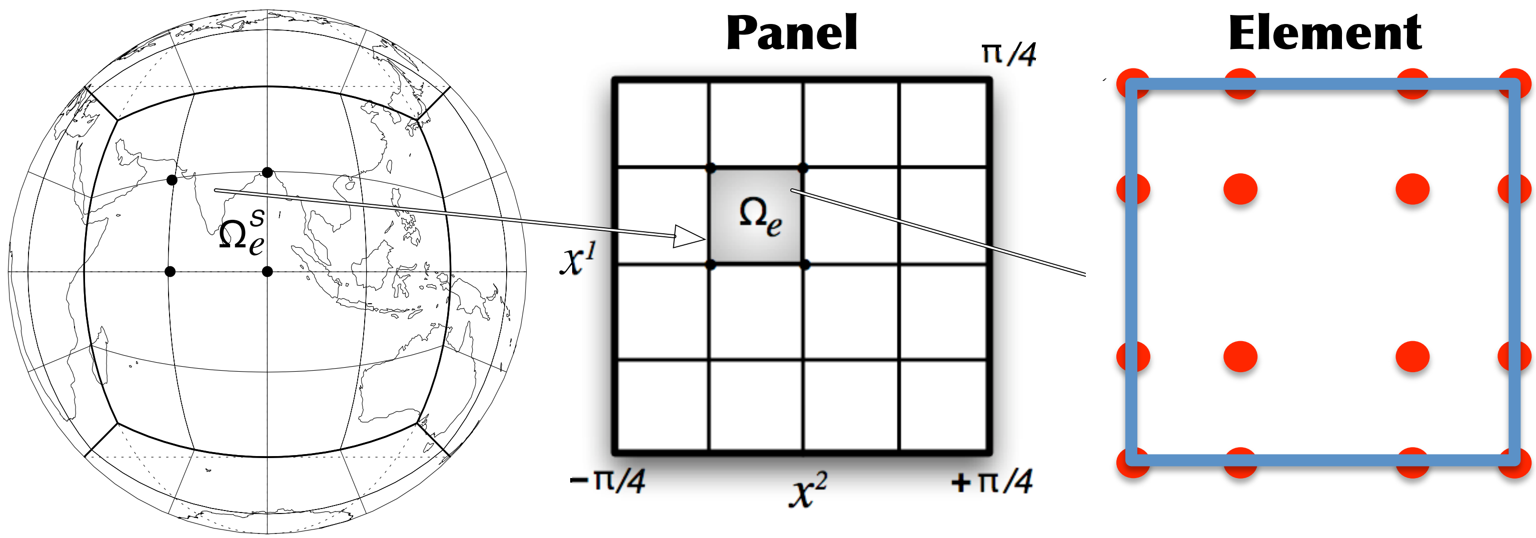
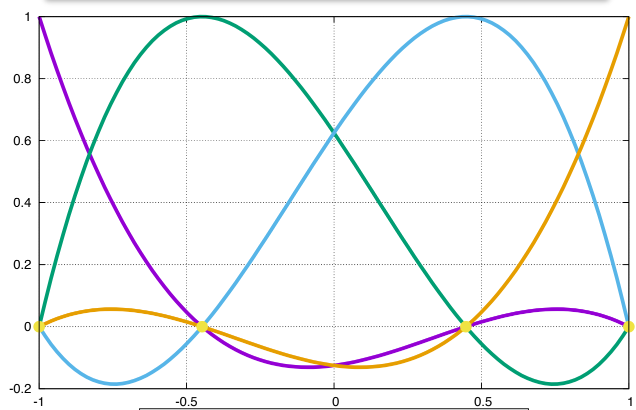
The spectral-element (SE) method: discretization grid



Physical Domain **Computational Domain** **GLL Quadrature Grid**

Nodal 1D polynomial basis functions



GLL=Gauss-Lobatto-Legendre

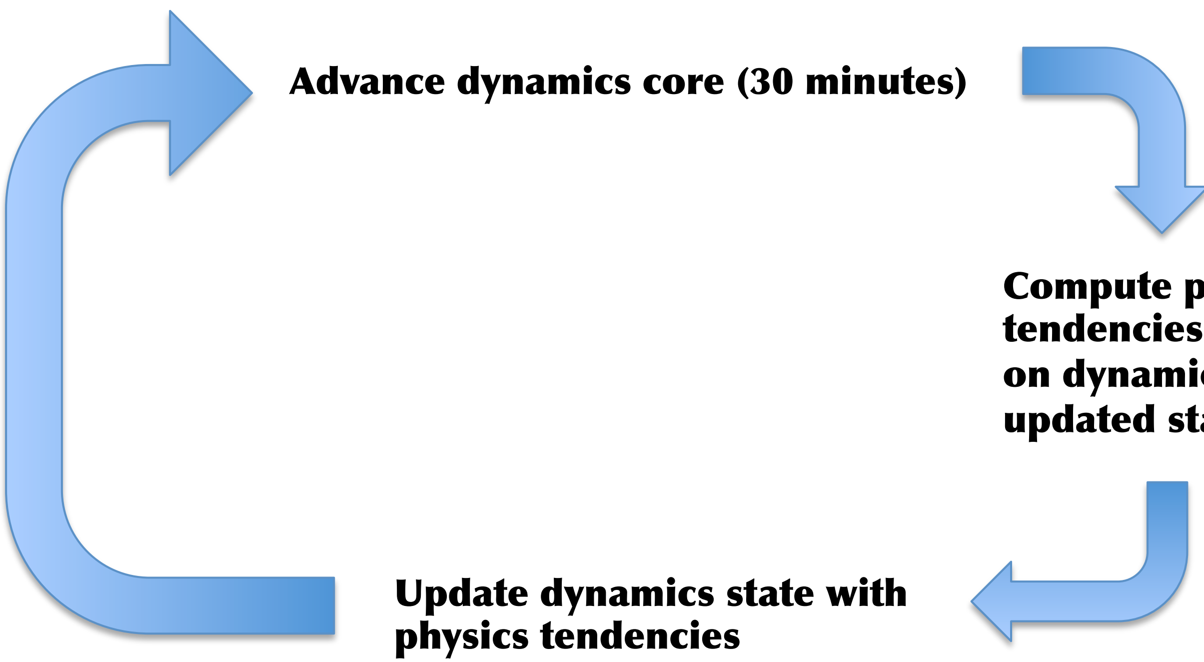
Conservation and coupling

- **Mass-conservation in dynamical core: In the absence of sources and sinks, dry air mass and tracer mass should be conserved**
- **Mass-conservation in physics-dynamics coupling: When adding physics tendencies to tracers in the dynamical core, the mass budget should be closed (not necessarily strictly enforced!)**
- **Closed energy budget: Atmospheric component as a whole should have a closed energy budget (no spurious sources and sinks)**
- **Closed energy budget in physics-dynamics coupling: When adding physics tendencies to the state, the energy change in tendencies should match the energy change in the atmospheric state when tendencies have been added (not necessarily strictly enforced!)**

Conservation and coupling: default CAM-SE

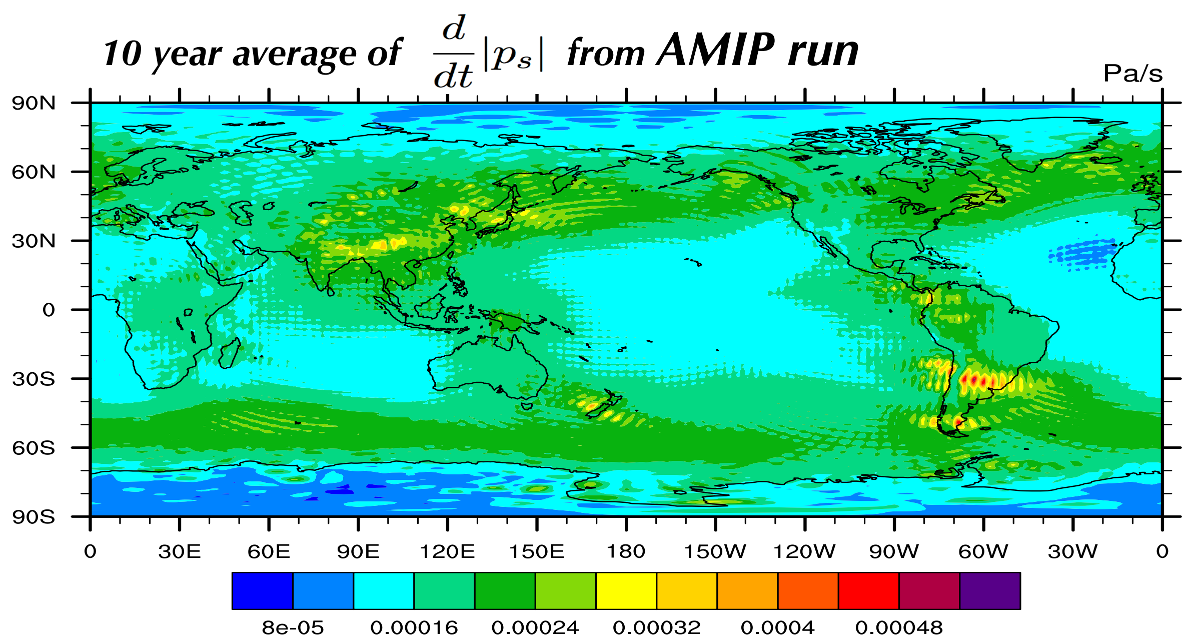
- **Mass-conservation in dynamical core: YES!**
- **Mass-conservation in physics-dynamics coupling: YES if "ftype=1"**

1. Physics updates state ("ftype=1"): mass budget closed but …



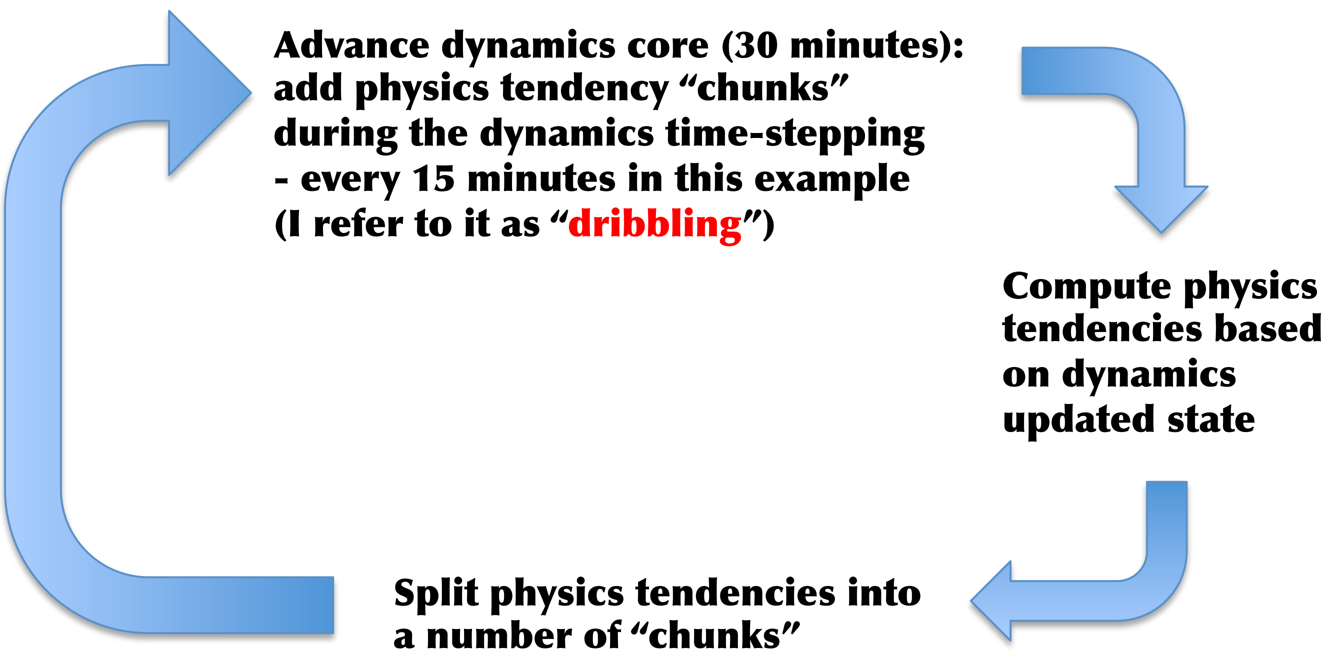
Conservation and coupling: default CAM-SE

- **Mass-conservation in dynamical core: YES!**
- **Mass-conservation in physics-dynamics coupling: YES if "ftype=1"**
- **1. Physics updates state ("ftype=1"): mass budget closed but ...**



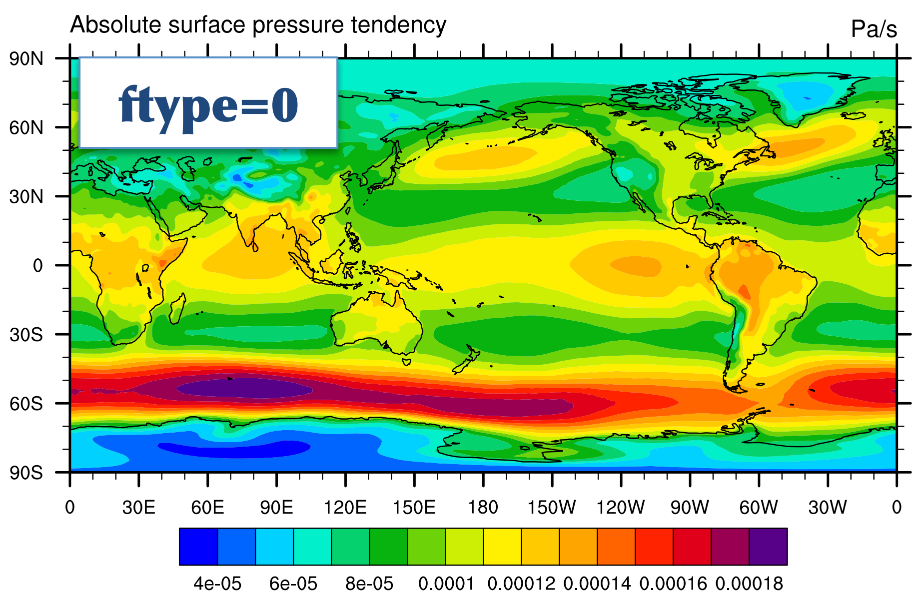
Conservation and coupling: default CAM-SE

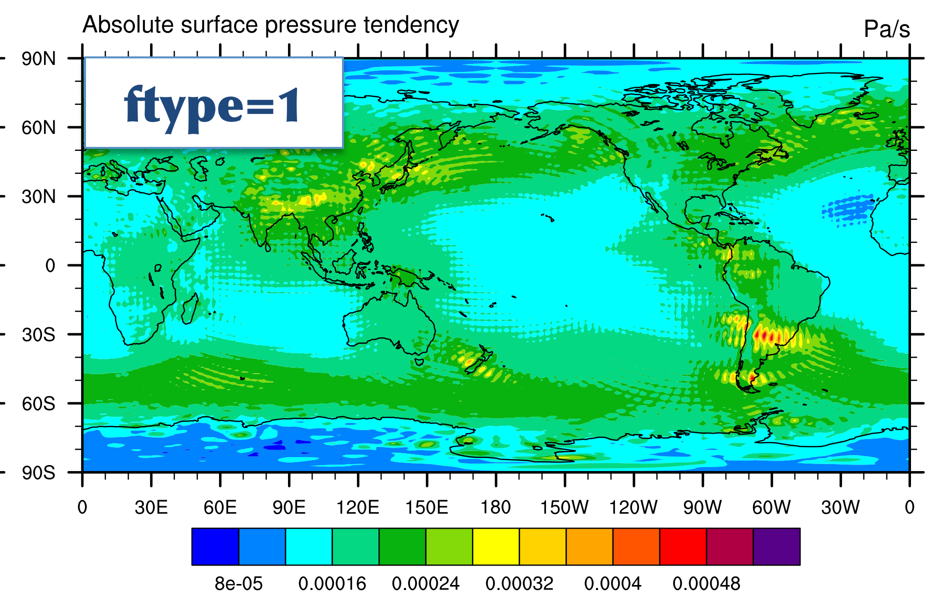
- **Mass-conservation in dynamical core: YES!**
- **Mass-conservation in physics-dynamics coupling:**



Conservation and coupling: default CAM-SE

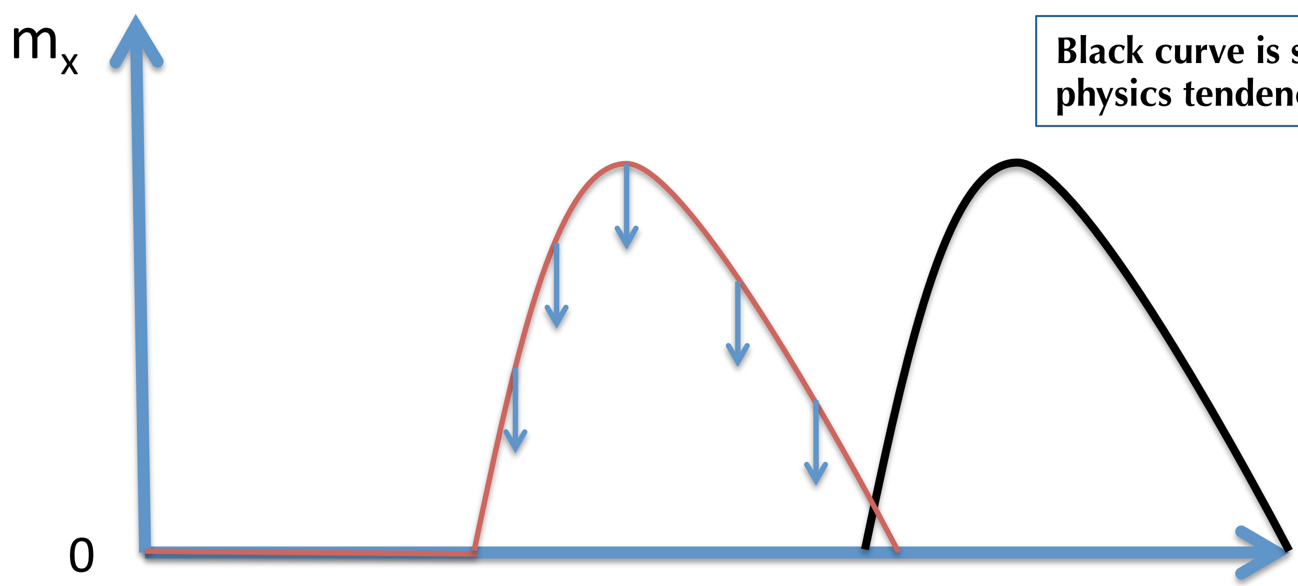
- **Mass-conservation in dynamical core: YES!**
- **Mass-conservation in physics-dynamics coupling:**





Conservation and coupling: default CAM-SE

- Mass-conservation in dynamical core: **YES!**
- Mass-conservation in physics-dynamics coupling: **No!**
- **2. "Dribbling" ("ftype=0"): mass budget not always closed!**

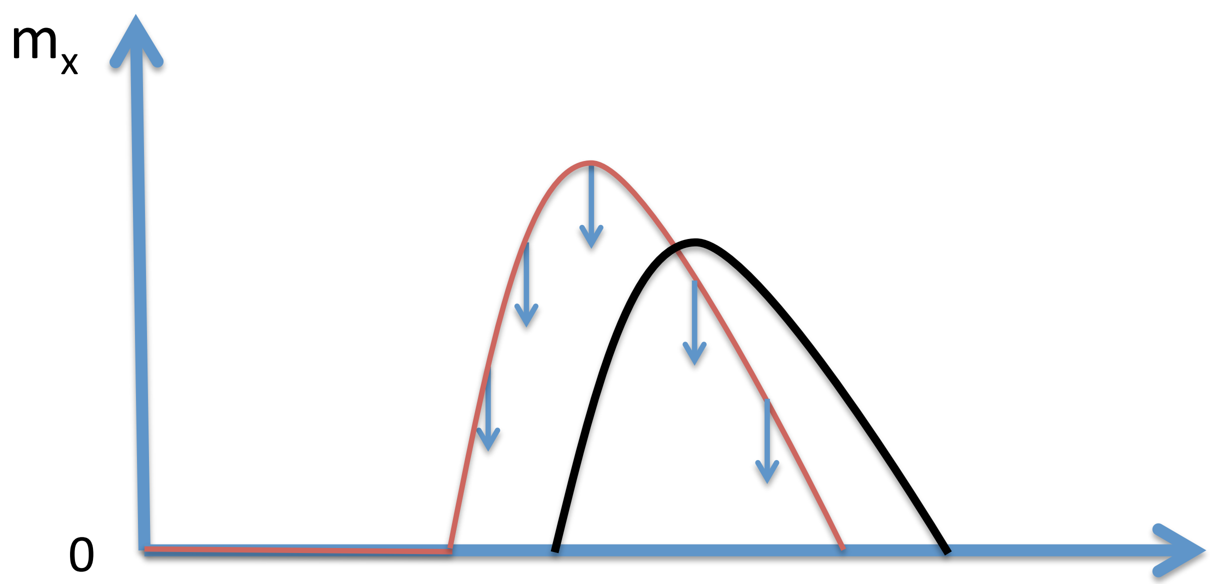


Black curve is solution without physics tendencies

Conservation and coupling: default CAM-SE

- **Mass-conservation in dynamical core: YES!**
- **Mass-conservation in physics-dynamics coupling: No!**

2. "Dribbling" ("ftype=0"): mass budget not always closed!



Conservation and coupling: default CAM-SE

- **Mass-conservation in dynamical core: YES!**
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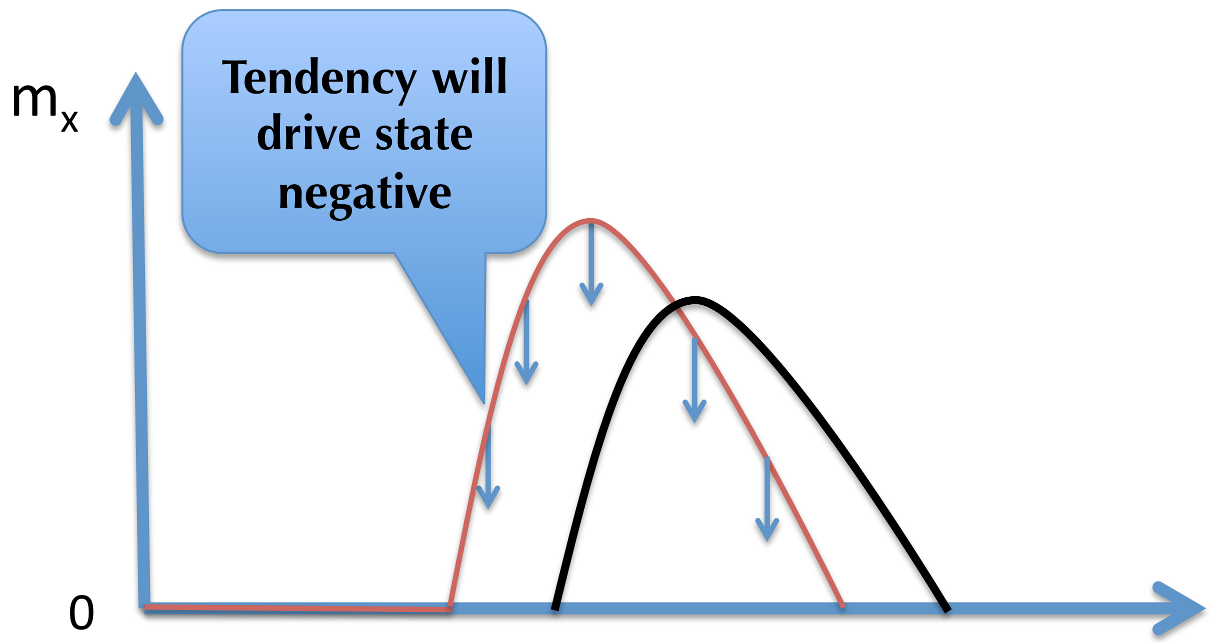
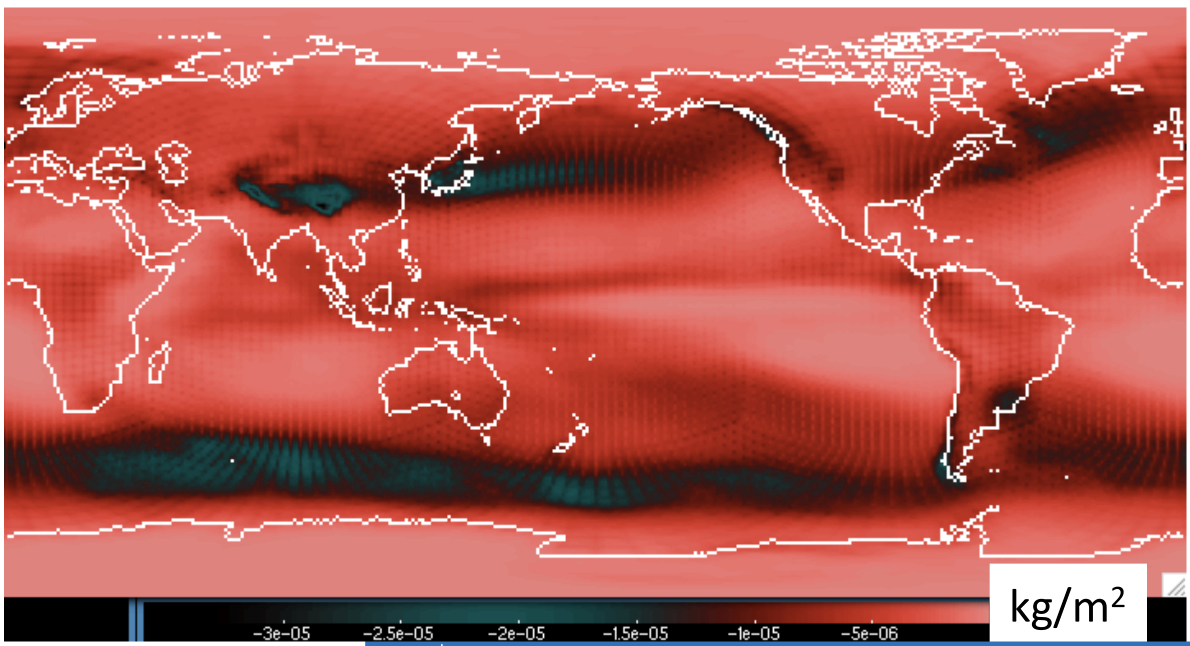


Conservation and coupling: default CAM-SE

- **Mass-conservation in dynamical core: YES!**
- **Mass-conservation in physics-dynamics coupling: No!**

2. "Dribbling" ("ftype=0"): mass budget not always closed!

10-year average of column integrated cloud ice (CLDICE) gained in physics-dynamics coupling



O(5E-7hPa) vertically integrated CLDICE gained in PDC

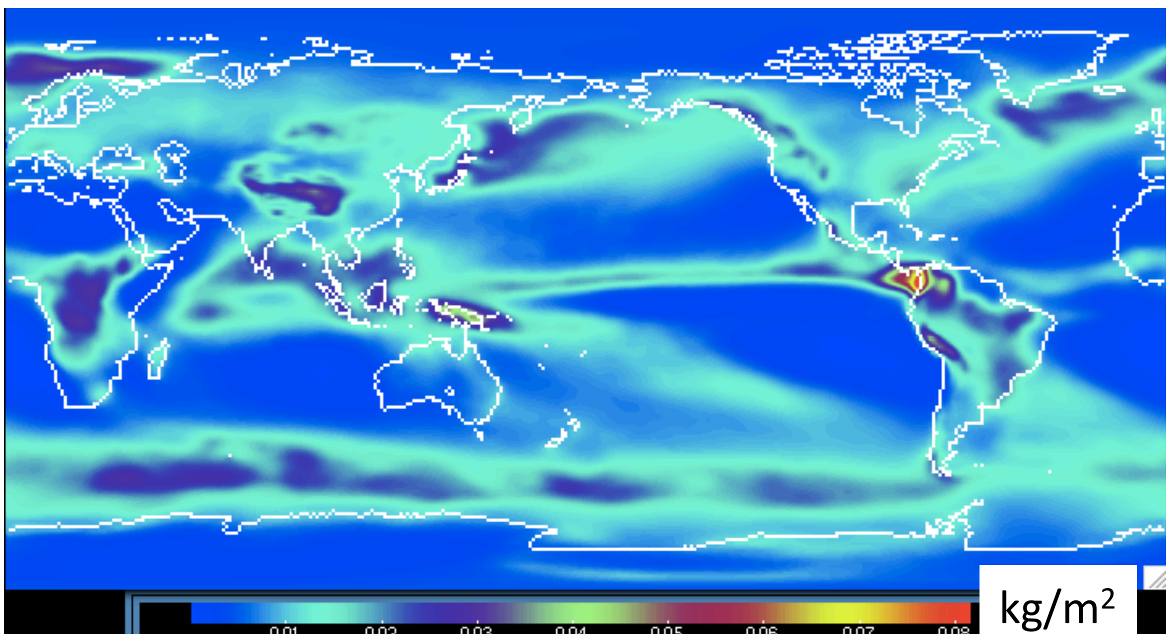
=> tendencies added every 15 minutes so in a 10 year simulation tendencies are added O(3.5E5) times
=> accumulated CLDICE gained in PDC is O(0.175hPa).

Conservation and coupling: default CAM-SE

- **Mass-conservation in dynamical core: YES!**
- **Mass-conservation in physics-dynamics coupling: No!**

2. "Dribbling" ("ftype=0"): mass budget not always closed!

10-year average of column integrated cloud ice (CLDICE)



Global integral if CLDICE corresponds to approximately 1E-3hPa

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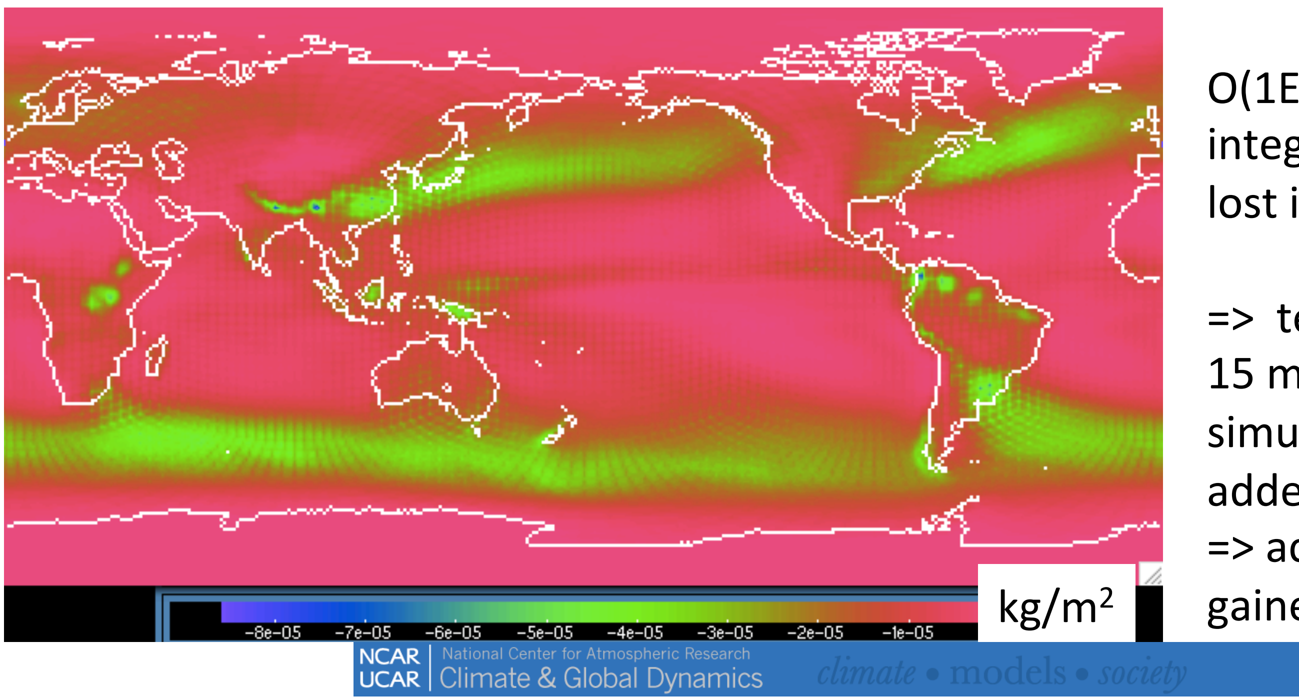
Conservation and coupling: default CAM-SE

- **Mass-conservation in dynamical core: YES!**
- **Mass-conservation in physics-dynamics coupling: No!**

2. "Dribbling" ("ftype=0"): mass budget not always closed!

10-year average of column integrated cloud liquid (CLDLIQ) gained in physics-dynamics coupling



O(1E-6hPa) vertically integrated CLDLIQ lost in PDC

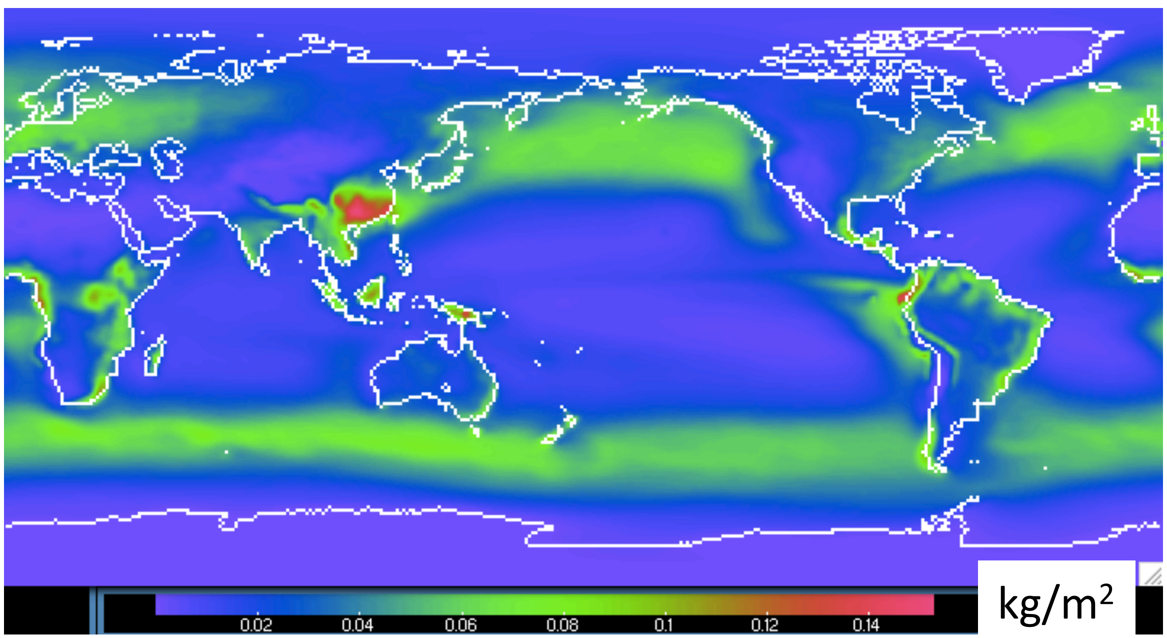
=> tendencies added every 15 minutes so in a 10 year simulation tendencies are added O(3.5E5) times
=> accumulated CLDLIQ gained in PDC is O(0.35hPa).

Conservation and coupling: default CAM-SE

- **Mass-conservation in dynamical core: YES!**
- **Mass-conservation in physics-dynamics coupling: No!**

2. "Dribbling" ("ftype=0"): mass budget not always closed!

10-year average of column integrated cloud liquid (CLDLIQ)



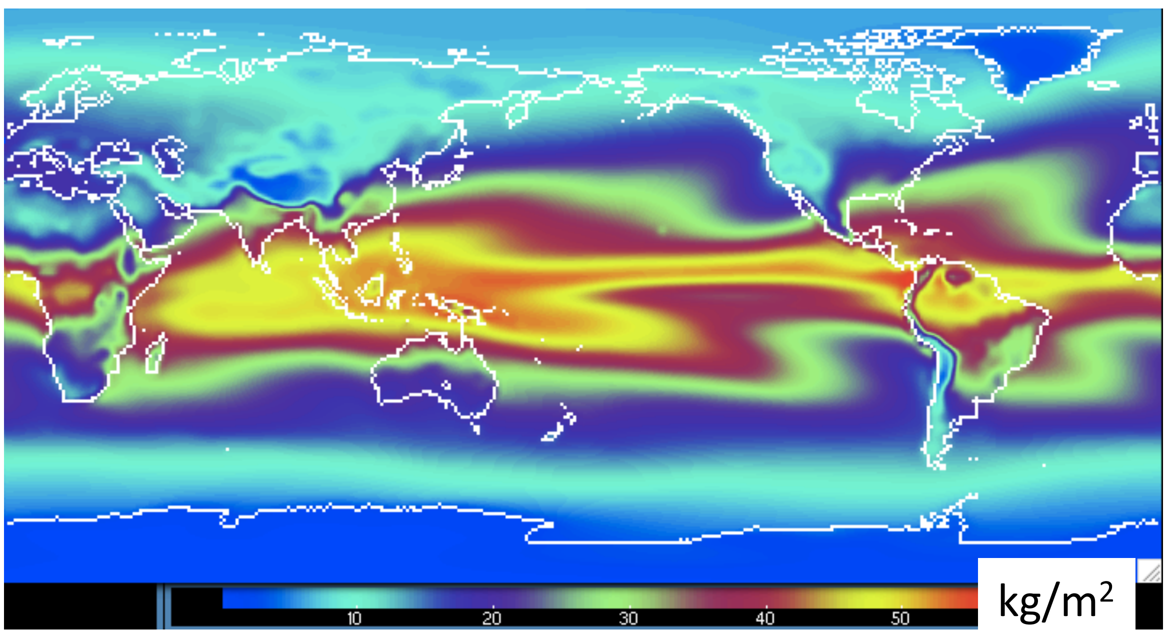
Global integral if CLDLIQ corresponds to approximately 2.6E-4hPa

Conservation and coupling: default CAM-SE

- **Mass-conservation in dynamical core: YES!**
- **Mass-conservation in physics-dynamics coupling: No!**

2. "Dribbling" ("ftype=0"): mass budget not always closed!

10-year average of column integrated water vapor (WV)



O(1E-8hPa) vertically integrated CLDLIQ gained in PDC

=> tendencies added every 15 minutes so in a 10 year simulation tendencies are added O(3.5E5) times
=> accumulated WV gained in PDC is O(1E-3hPa).

Conservation and coupling: default CAM-SE

- **Mass-conservation in dynamical core: YES!**
- **Mass-conservation in physics-dynamics coupling: No!**

2. "Dribbling" ("ftype=0"): mass budget not always closed!

Solution(s):

- **Advect tendencies (expensive….!)**
- **Other?**

Conservation and coupling: CAM-SE

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  (not necessarily strictly enforced!)

Energy Conservation and coupling in CAM-SE

10 year averages from AMIP simulation (specified SSTs cycling over same year)

Dynamical core module

- **Rate of energy change due to explicit dissipation (hyperviscosity)**

  dE/dt = 0.0729 W/m²

- **Frictional heating rate is calculated from K tendency produced from momentum diffusion and added to T:**

  dE/dt = 0.6997 W/m²

- **Vertical remapping**

  dE/dt = -0.1547 W/m²

Total loss of energy in dynamics

dE/dt = -0.0723 W/m²

Rate of energy change due to "dribbling" physics tendencies in the dynamics

dE/dt = 0.056 W/m²

Physics-dynamics coupling layer

Physics module

- **"physical" changes in energy due to water change**

  dE/dt = -0.0016 W/m²

- **Change in energy due to change in pressure due to water vapor change ("dme_adjust")**

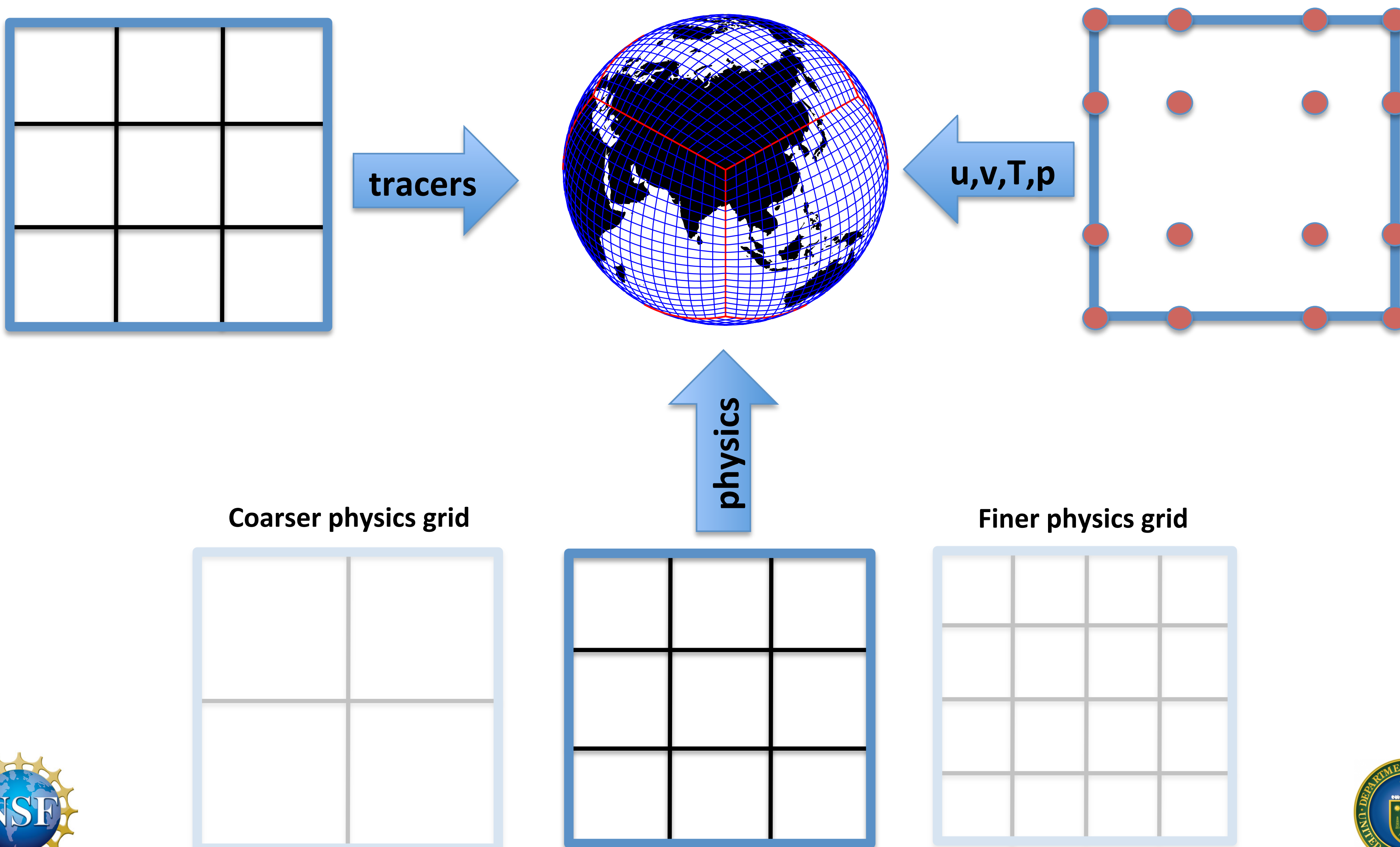
  dE/dt = 0.2667 W/m²

- **Energy fixer**

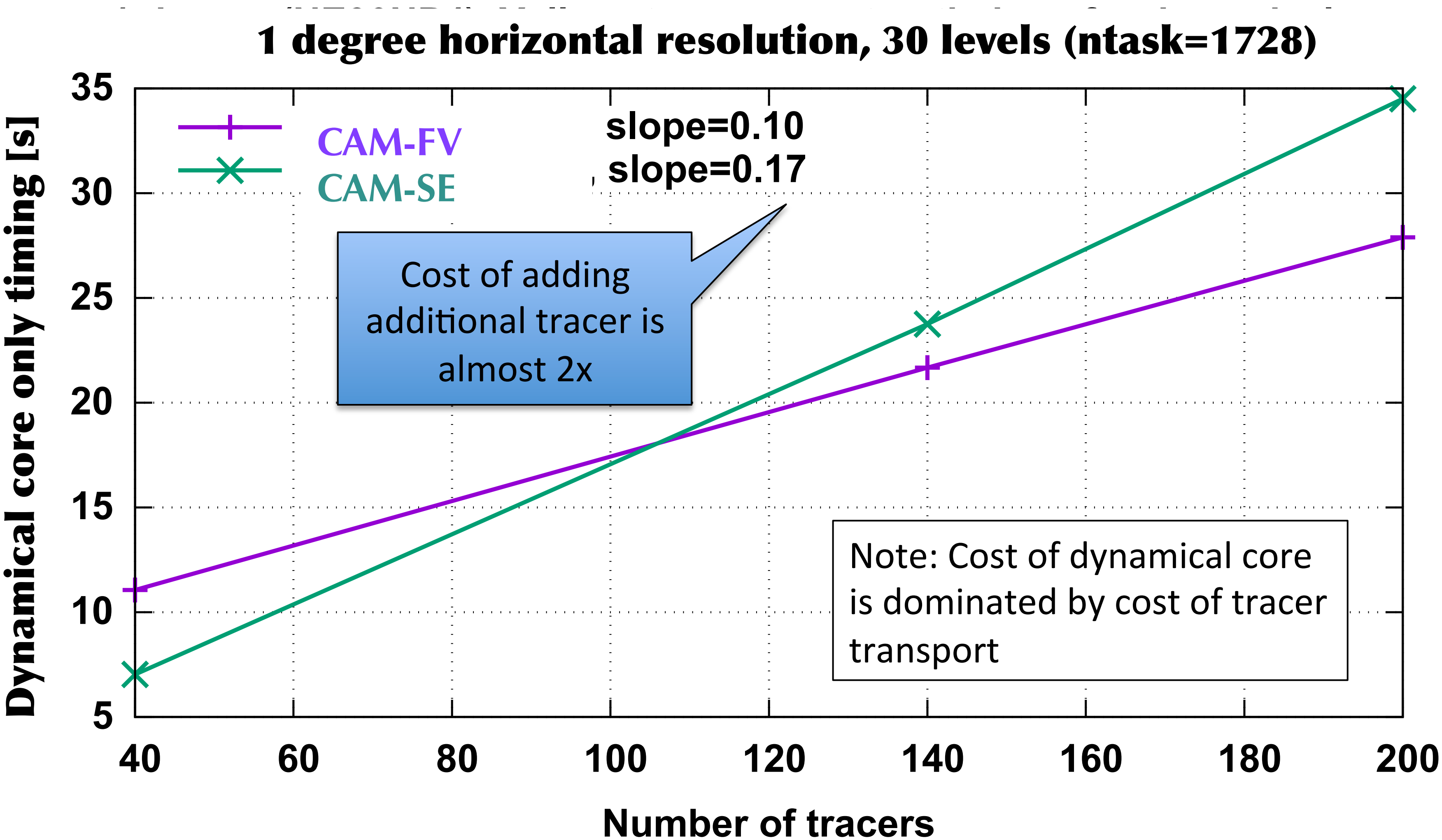
  dE/dt = -0.1843

  (= loss in dynamics + dme_adjust)

Separating dynamics, tracer and physics grids in CAM-SE



1. Why separate tracer grid? SE tracer transport cost

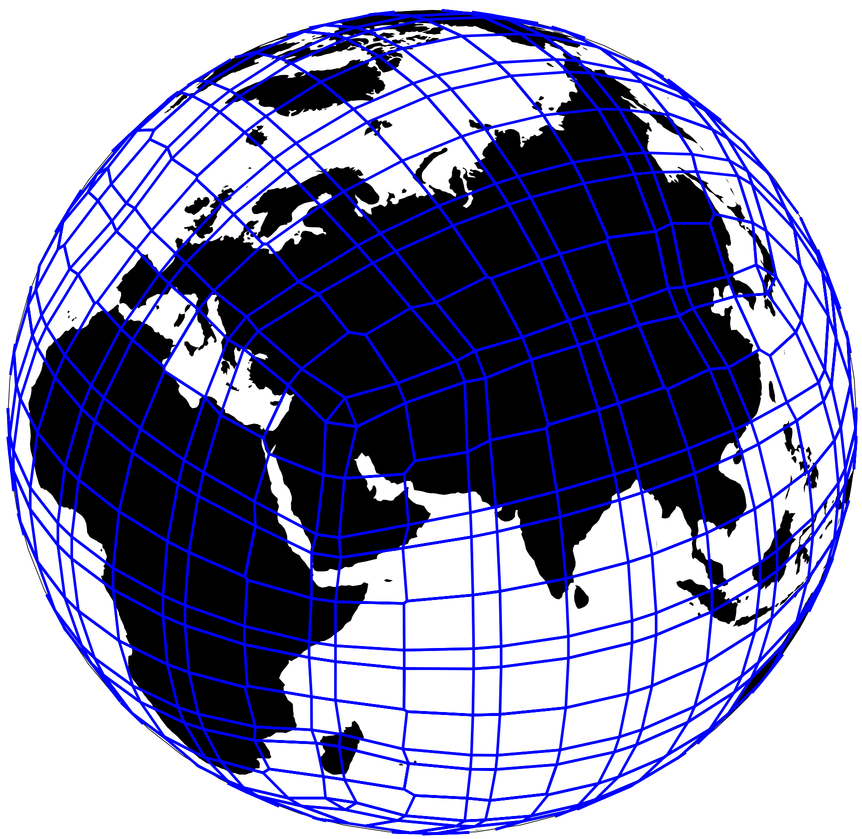


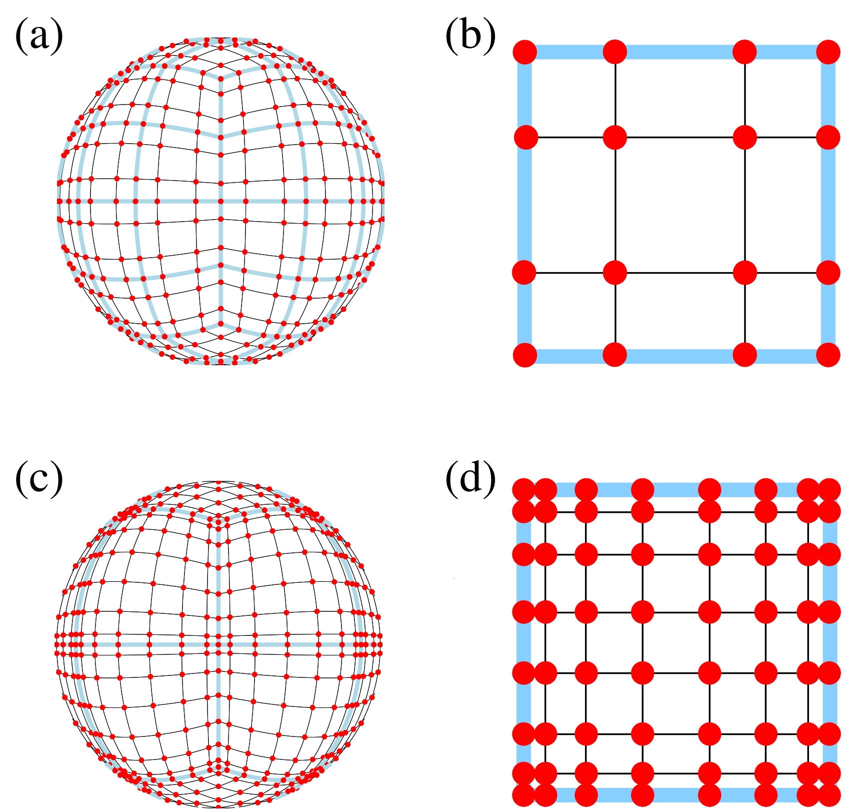
Lauritzen et al.,(2016)

2. Why separate physics grid?
Non-uniform sampling of atmospheric state

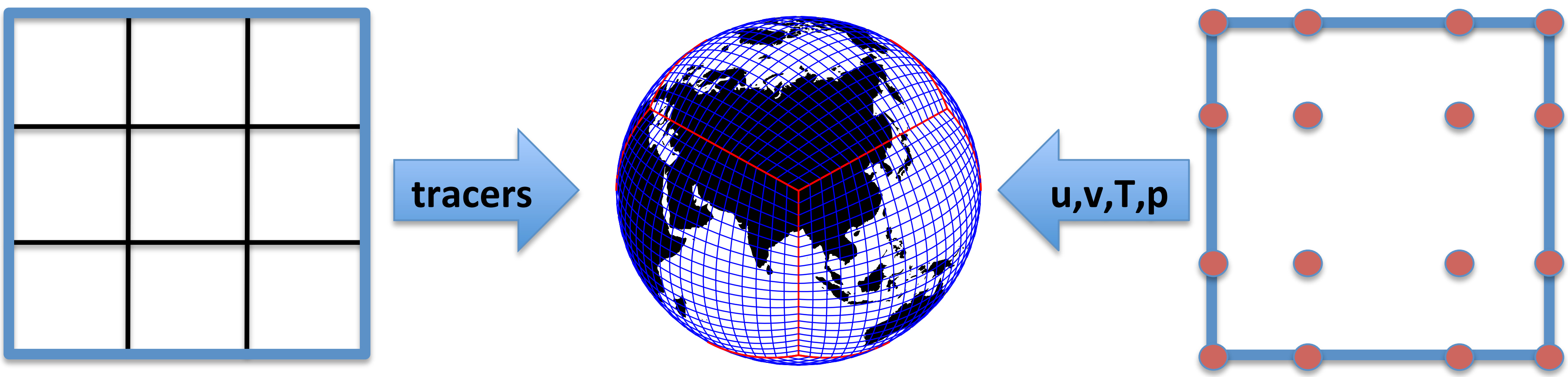
Gets worse with increasing order!

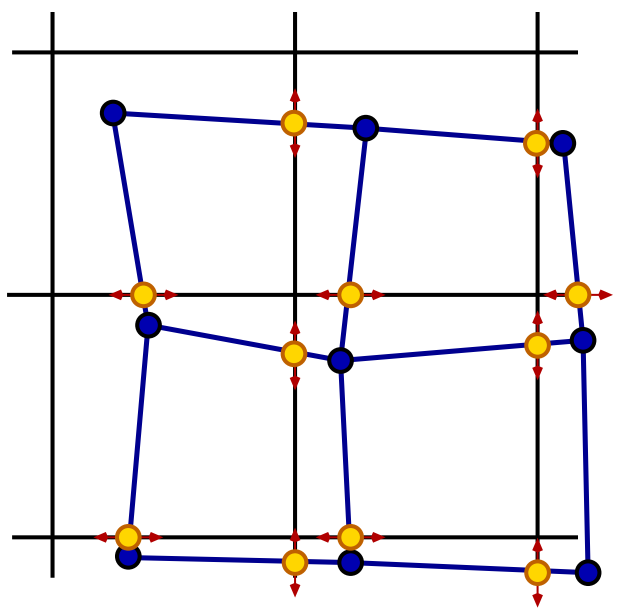
Current physics/“coupler” grid





Separating transport and dynamics grids/ methods in CAM-SE

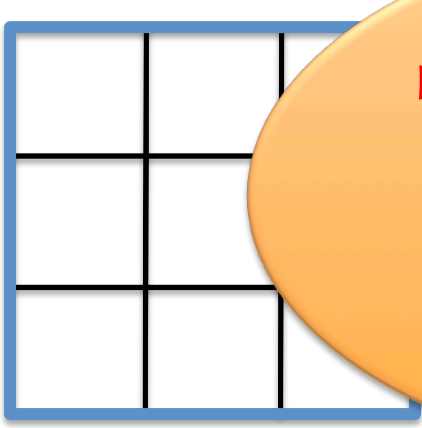




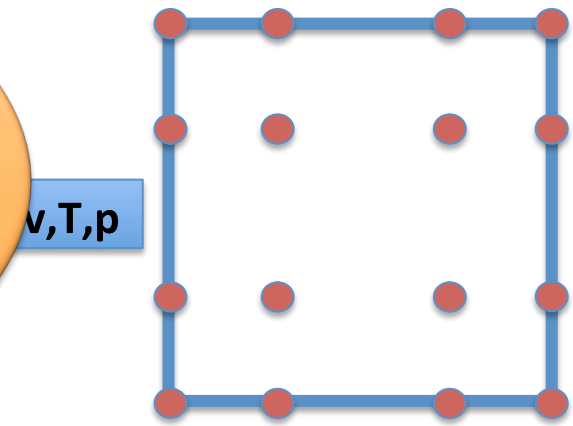
Coupling cell-integrated semi-Lagrangian scheme (CSLAM) with spectral-element dynamics

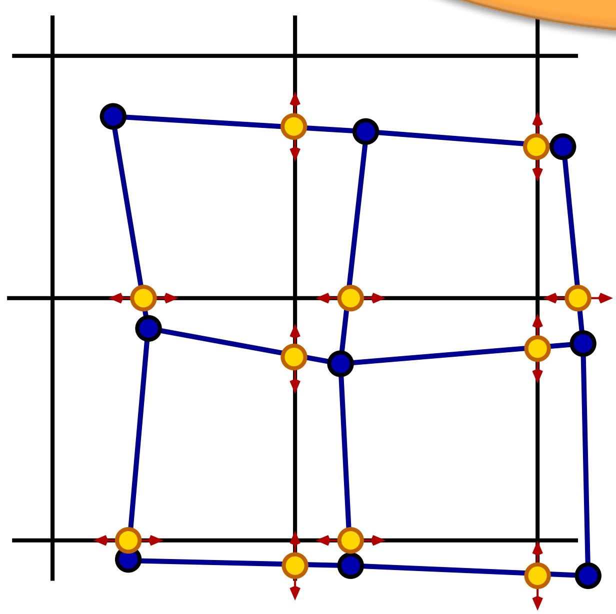
- **Find upstream Lagrangian grid so that air mass-change in CSLAM cell exactly matches air mass change in the same cell but by integrating SE basis functions (see Lauritzen et al., 2016 for details)**
- **Inherent mass-conservation, consistency, shape-preservation as described in Lauritzen et al., (2010)**

Separating transport and dynamics grids/ methods in CAM-SE



Note: coupling algorithm is general - it can be used with any dynamical core that can provide fluxes for CSLAM control volumes!



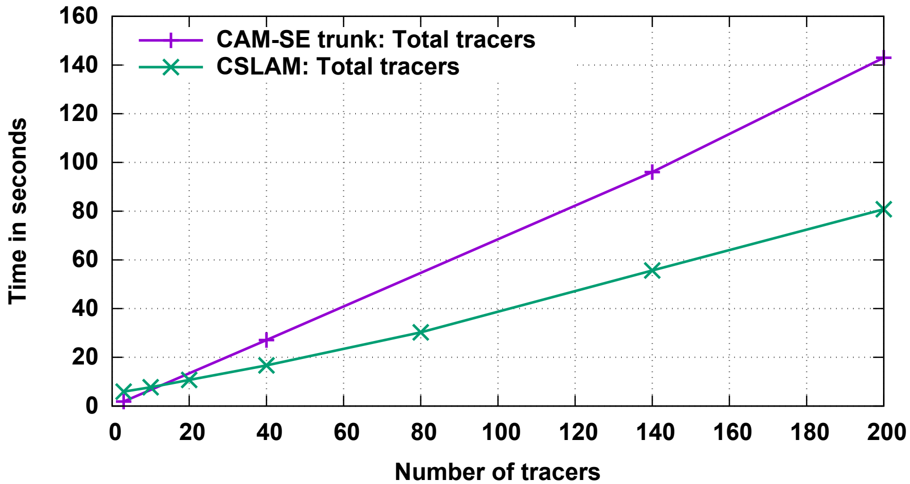


Coupling cell-integrated semi-Lagrangian scheme (CSLAM) with spectral-element dynamics

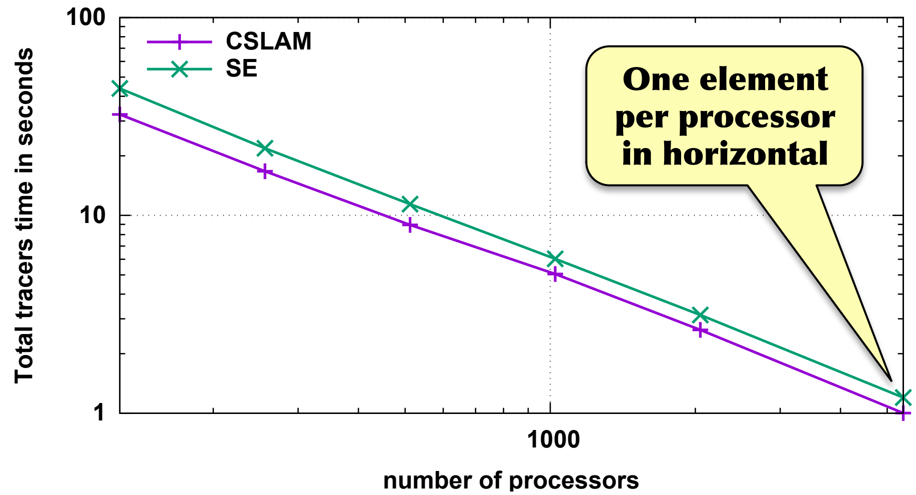
- **Find upstream Lagrangian grid so that air mass-change in CSLAM cell exactly matches air mass change in the same cell but by integrating SE basis functions (see Lauritzen et al., 2016 for details)**
- **Inherent mass-conservation, consistency, shape-preservation as described in Lauritzen et al., (2010)**

CSLAM transport is (a) faster than, (b) as scalable as and (c) more accurate than CAM-SE transport

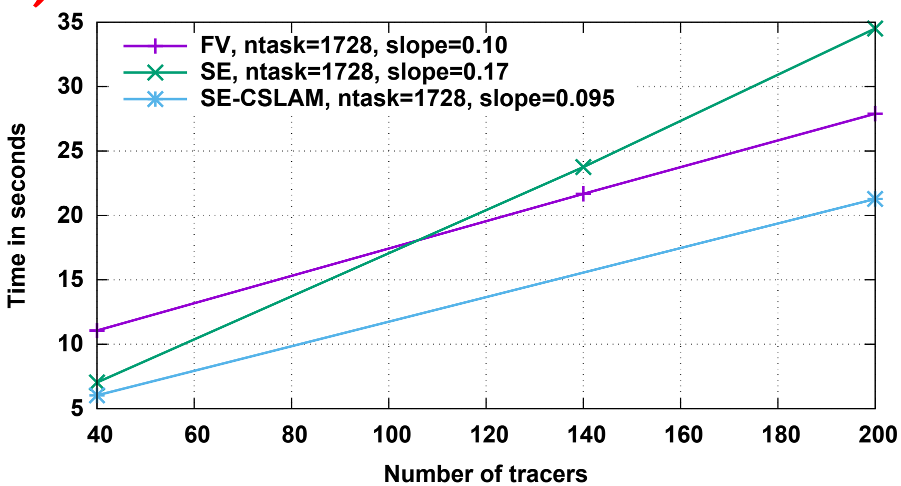
(a) 1 degree horizontal resolution, 30 levels, 256 tasks



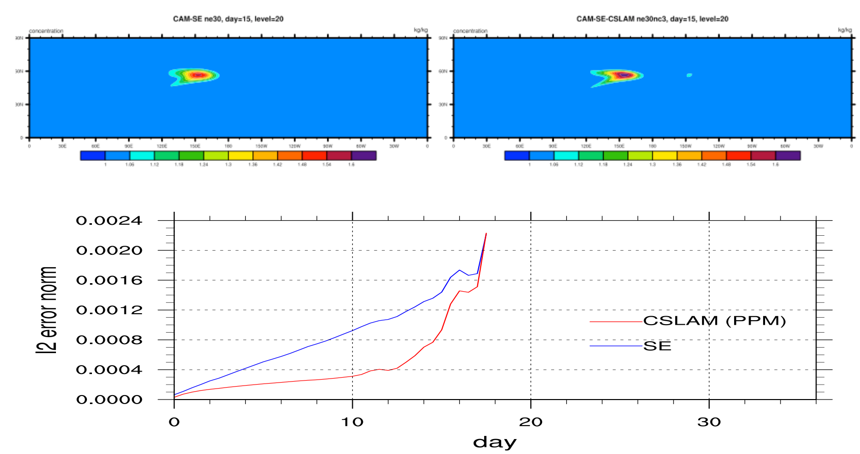
(b) 1 degree horizontal resolution, 30 levels, 40 tracers



(a) 1 degree horizontal resolution, 30 levels, 1728 tasks

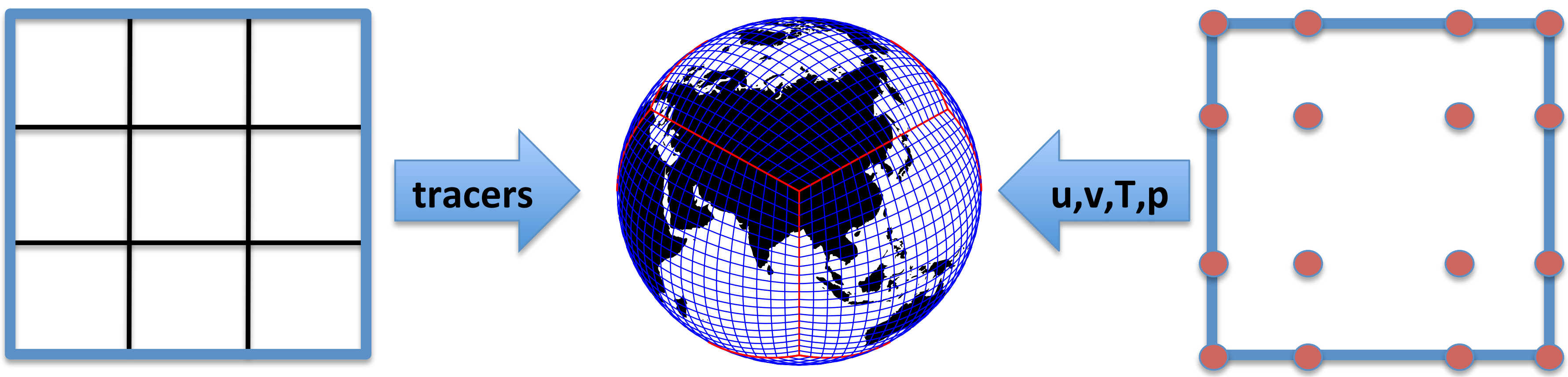


(c) Inert & passive tracer in dry baroclinic wave flow



Lauritzen et al.,(2016)

Separating transport and dynamics grids/ methods in CAM-SE with moisture



Most global models used a moist pressure vertical coordinate

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

=> If there is a change in water vapor then levels move (problematic when coupling CSLAM and SE)

Solution: dry mass vertical coordinates (also makes it straight forward to add water loading in dynamical core)

Dry mass vertical coordinates

1.4. **Primitive equations.** The η_d-coordinate atmospheric primitive equations assuming floating Lagrangian vertical coordinates, neglecting dissipation and forcing terms can be written as

$$\frac{\partial \vec{u}}{\partial t} + (\zeta + f)\,\hat{k}\times\vec{u} + \nabla\left(\frac{1}{2}\vec{u}^2 + \Phi\right) + \frac{1}{\rho}\nabla p = 0 \tag{17}$$

$$\frac{\partial T}{\partial t} + \vec{u}\cdot\nabla T - \frac{1}{c_p\rho}\omega = 0 \tag{18}$$

$$\frac{\partial}{\partial t}\left(\frac{\partial p_d}{\partial \eta}\right) + \nabla\cdot\left(\frac{\partial p_d}{\partial \eta}\vec{u}\right) = 0 \tag{19}$$

$$\frac{\partial}{\partial t}\left(\frac{\partial p_d}{\partial \eta}m_i\right) + \nabla\cdot\left(\frac{\partial p_d}{\partial \eta}m_i\vec{u}\right) = F_i, \quad i = v, cl, ci, \ldots \tag{20}$$

Let m_i be the amount of water substance, chemical species, etc. of type i associated with unit mass of dry air:

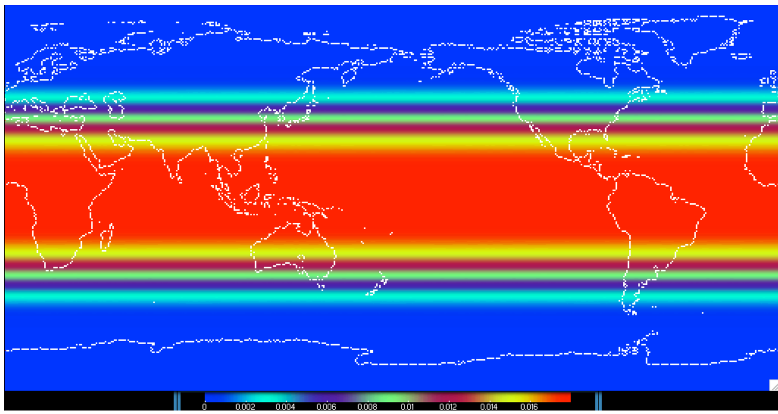
$$m_i \equiv \frac{\rho_i}{\rho_d}, \tag{3}$$

where ρ_d is the mass of dry air per unit volume of moist air and ρ_i the mass of water substance of type i per unit volume of moist air. Here we consider the water substances water vapor m_v, cloud

Adding condensate loading is straight forward!

Initialization of idealized moist baroclinic wave (Ullrich et al., 2013) with dry-mass vertical coordinates

Relative humidity at level 30, day 0

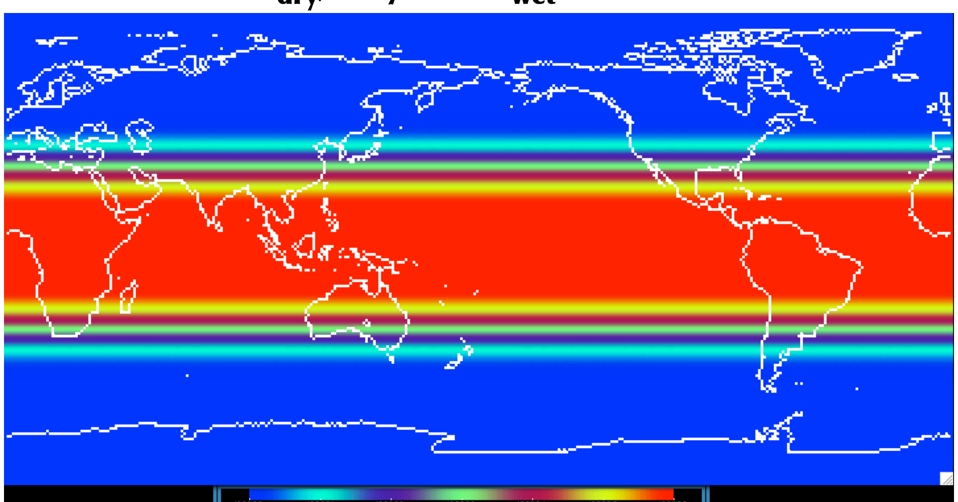


Dry surface pressure is obtained by high-order Gaussian quadrature integration of analytic moisture profile to get water vapor pressure (WVP):

$$ps_{dry} = ps_{wet} - wvp$$

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

PS_{dry}, day 0 (PS_{wet} = 1000hPa)

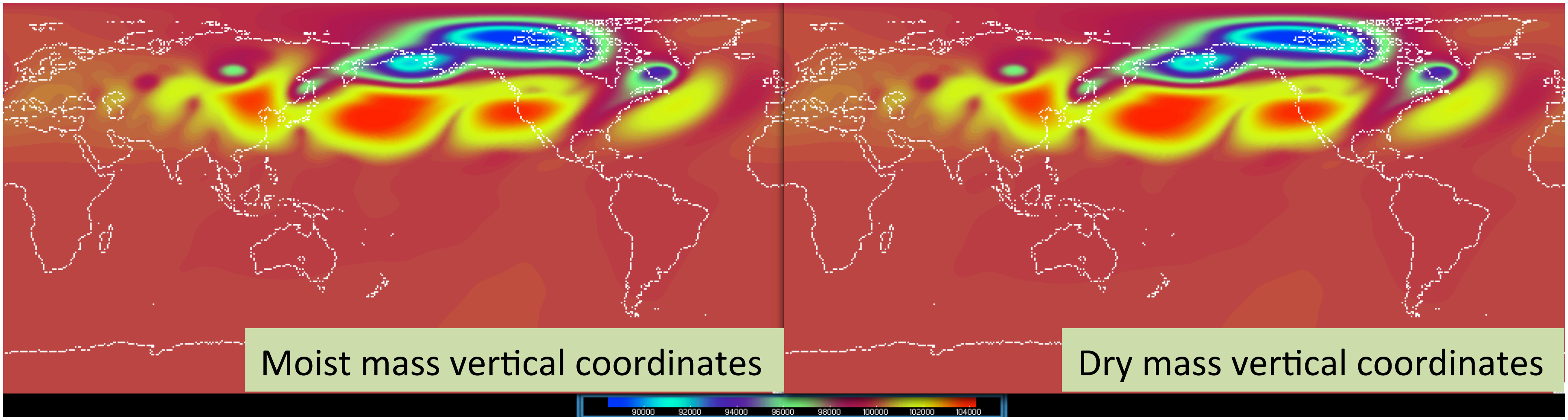


For the dry-mass vertical coordinate ps_{dry} and q (dry mixing ratio for water vapor) must be initialized carefully to get a balanced initial state:

Ps_{wet} matches 1000hPa to 1E-10!

Initialization of idealized moist baroclinic wave (Ullrich et al., 2013) with dry-mass vertical coordinates

Full (moist) surface pressure at day 15



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