SIMA dynamical core update

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Thanks to AMP software engineering group for code reviews etc. (Goldhaber, Craig, Nusbaumer, …)
Thanks to Mariana Vertenstein and Jim Edwards for CIME/CESM support

MPAS part of this talk : *Miles Curry, Michael Duda and Bill Skamarock (MMM, NCAR)*
Spectral-element part of this talk : *Mark Taylor and Oksana Guba (SNL, DOE), Francis Vitt and Hanli Liu (HAO, NCAR)*
FV3 part of this talk : *C. Jablonowski (UMICH) and Lukas Harris (GFDL)*

NCAR

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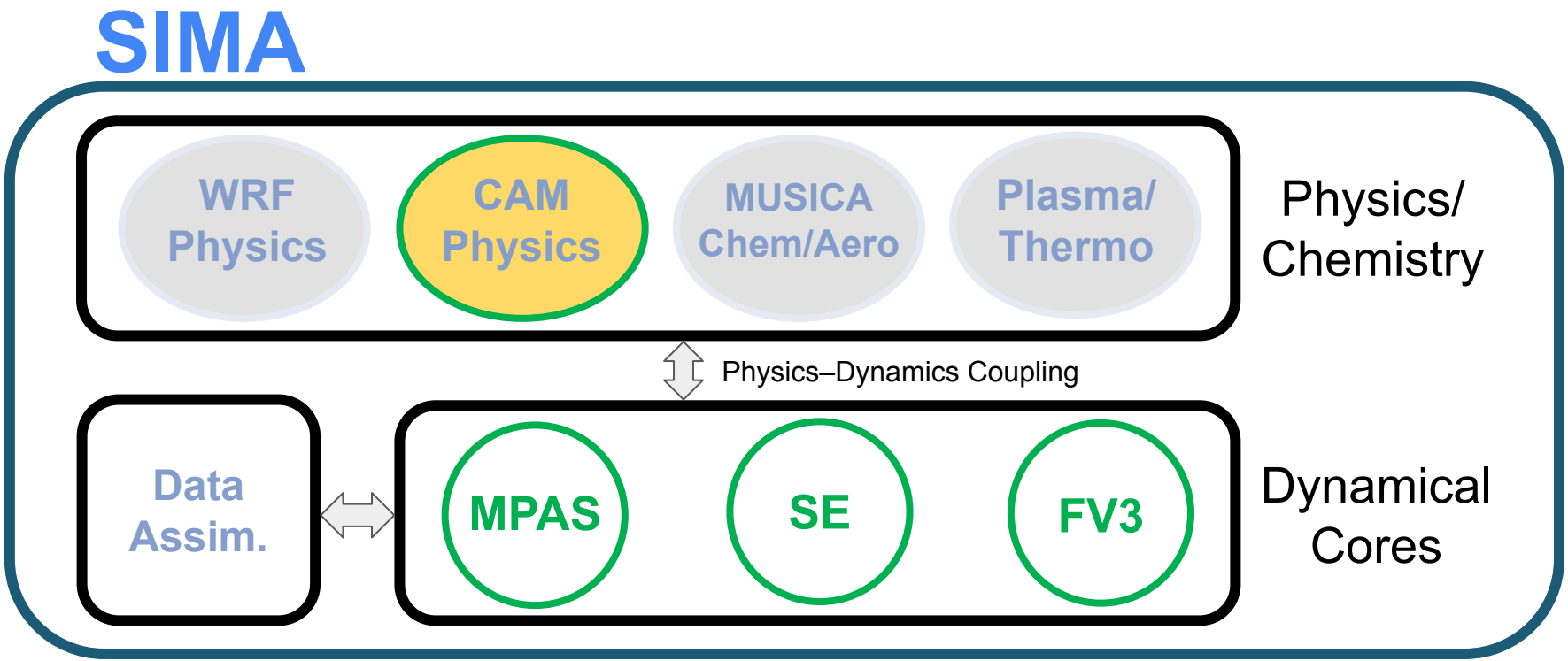
SIMA is a set of interoperable modeling components and infrastructure

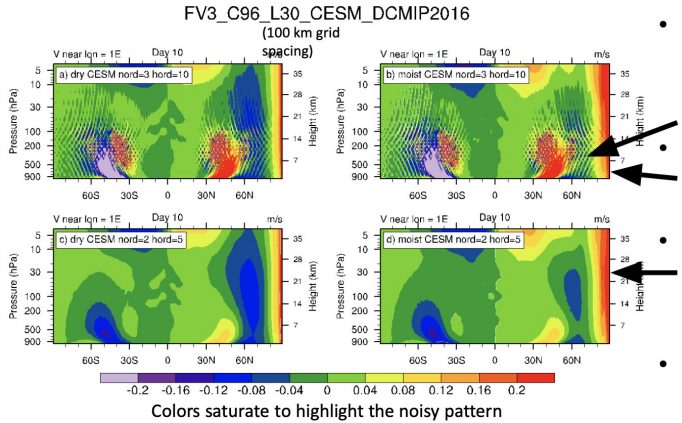


Slide courtesy of SIMA leads

Finite-volume cubed-sphere (FV3) dynamical core update

- Released with CESM2.2; in the process of updating FV3 dynamical core from GFDL
- Working with Lukas Harris and Christiane Jablonowski (NOAA funded effort evaluating CAM-FV3) on “final” configuration for the CESM dynamical core evaluation effort

Impact of the FV3 Divergence Damping on the Circulation



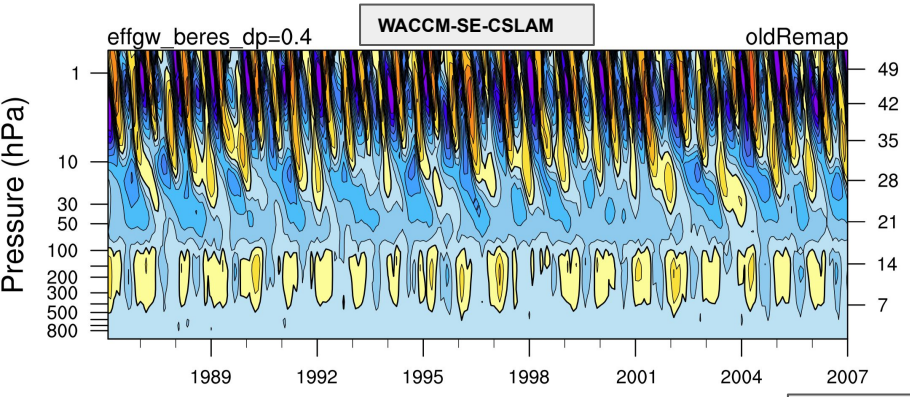
- Insufficient explicit diffusion with FV3’s 8th-order divergence damping (nord=3): Lots of numerical noise
- Enhanced diffusion in advection scheme (hord=10) cannot control this noise
- Slightly more explicit diffusion (6th-order div damping, nord=2) restores smooth solution
- Effect independent of moisture (dry/moist irrelevant)

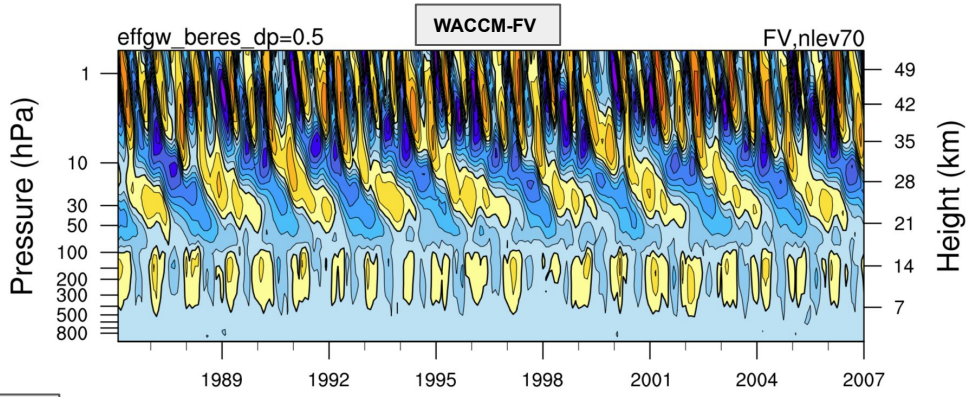
Ullrich et al. (2014) baroclinic wave test case (dry and moist) without topography

Slide courtesy of C. Jablonowski (UMICH)

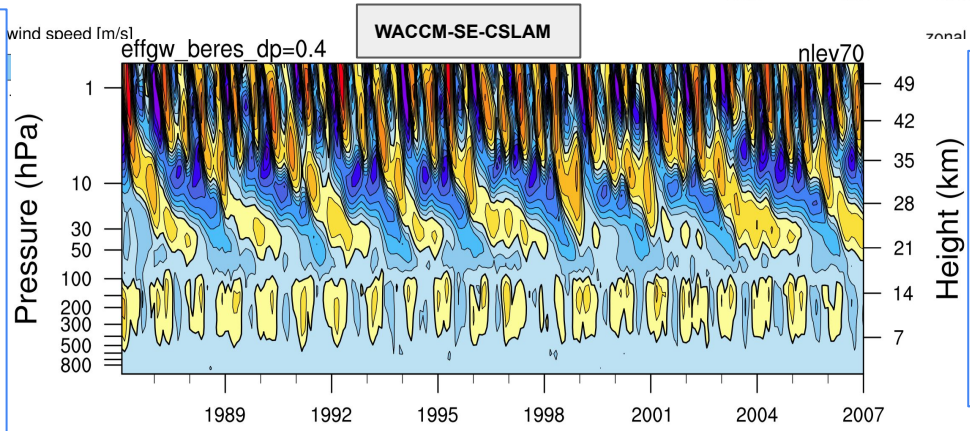
Spectral-element (SE) dynamical core updates

- Switched to FV3 vertical remapping algorithm in SE (improved QBO simulation!)





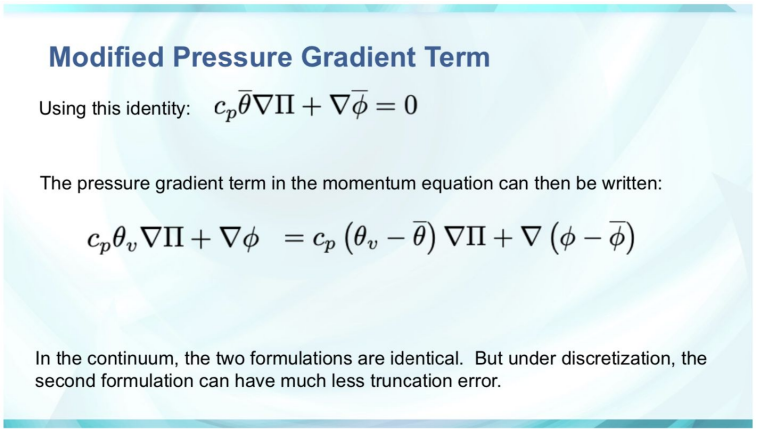
Having several dynamical cores in SIMA and gaining experience with them has significant synergetic effects! (e.g., assess structural uncertainty, algorithm research etc.)

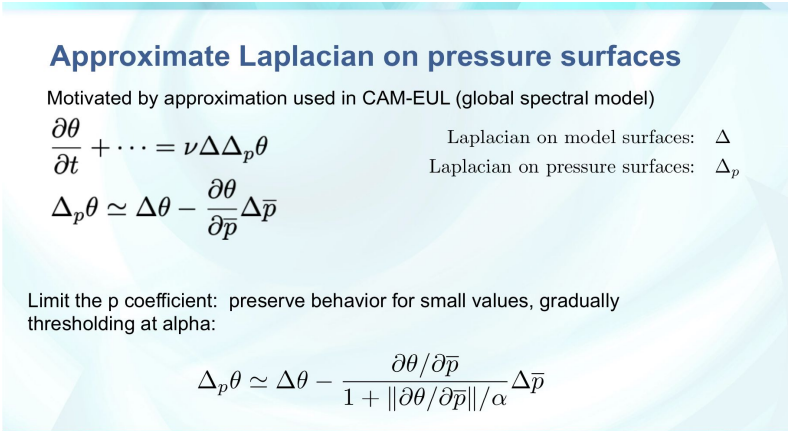


Less diffusive vertical remapping significantly improves QBO; that said, slightly higher vertical resolution needed in both models for “good” QBO ...

Spectral-element (SE) dynamical core updates

- Changes to pressure-gradient force discretization and hyperviscosity



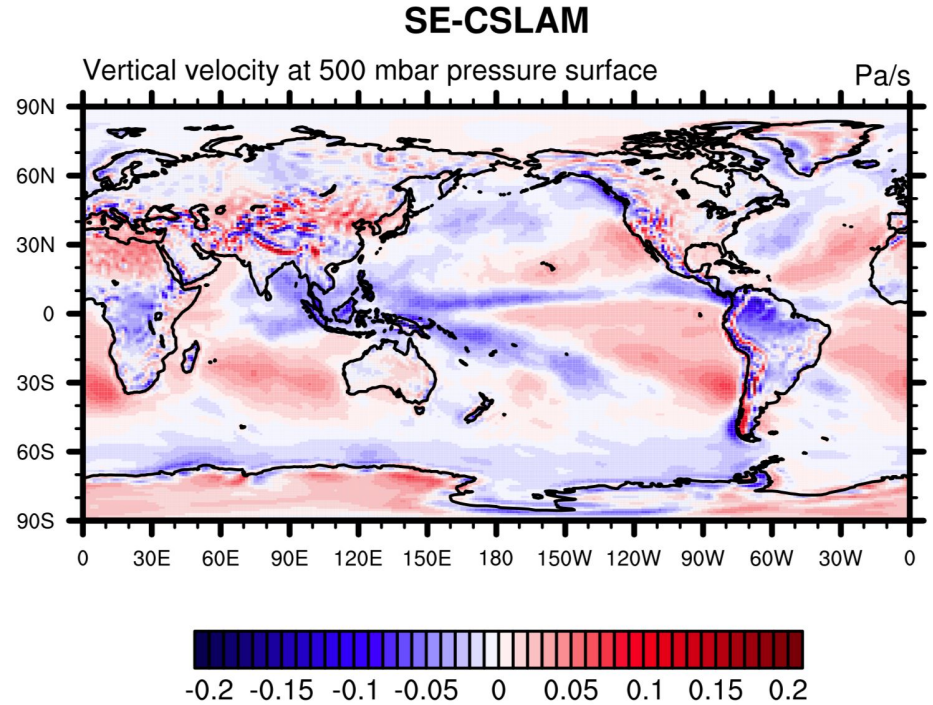


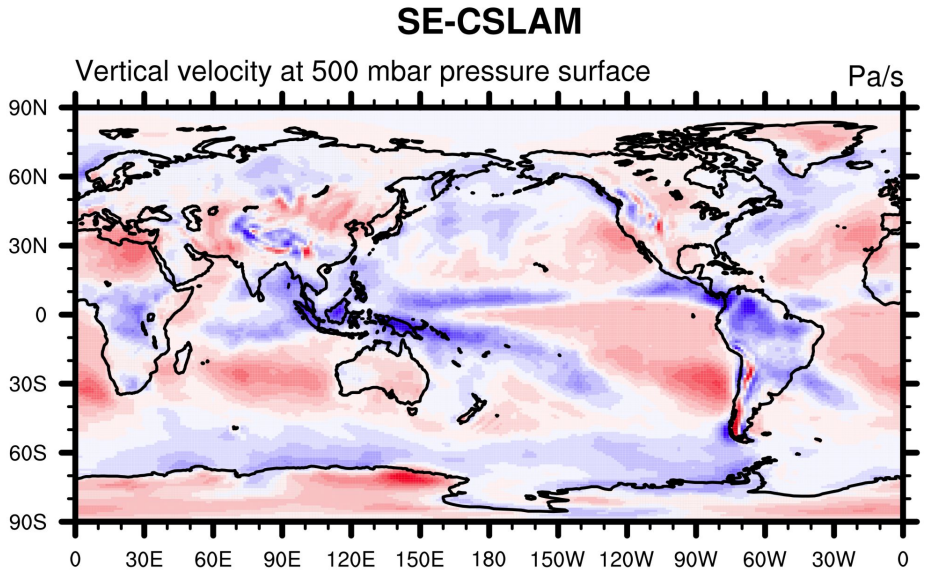
Slides courtesy of M. Taylor (SNL, DOE); note CAM-SE uses T and not theta!

- WACCM-x: Species dependent thermodynamics, “horizontal” thermal conductivity and molecular viscosity operators in the dynamical core + sponge layer modifications.

Improvement of flow over topography

1 year average, AMIP-like (F2000CLIMO): (left) CESM2.2 version of SE, (right) CESM2.2 + topo mods





M.A. Taylor (DOE) and P.H. Lauritzen (NCAR)

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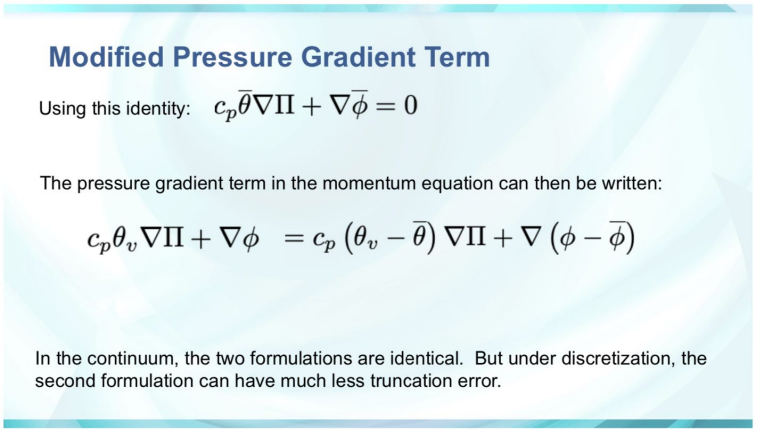
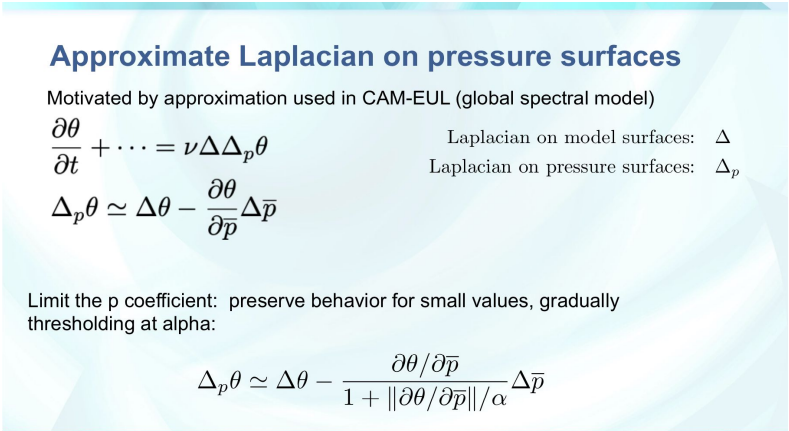
Spectral-element (SE) dynamical core updates

- Changes to pressure-gradient force discretization and hyperviscosity





Slides courtesy of M. Taylor (SNL, DOE); note CAM-SE uses T and not theta!

- WACCM-x: Species dependent thermodynamics, “horizontal” thermal conductivity and molecular viscosity operators in the dynamical core + sponge layer modifications.

A generalized implementation of thermodynamics for species dependent air (dry air composition and condensates) in CAM-WACCM

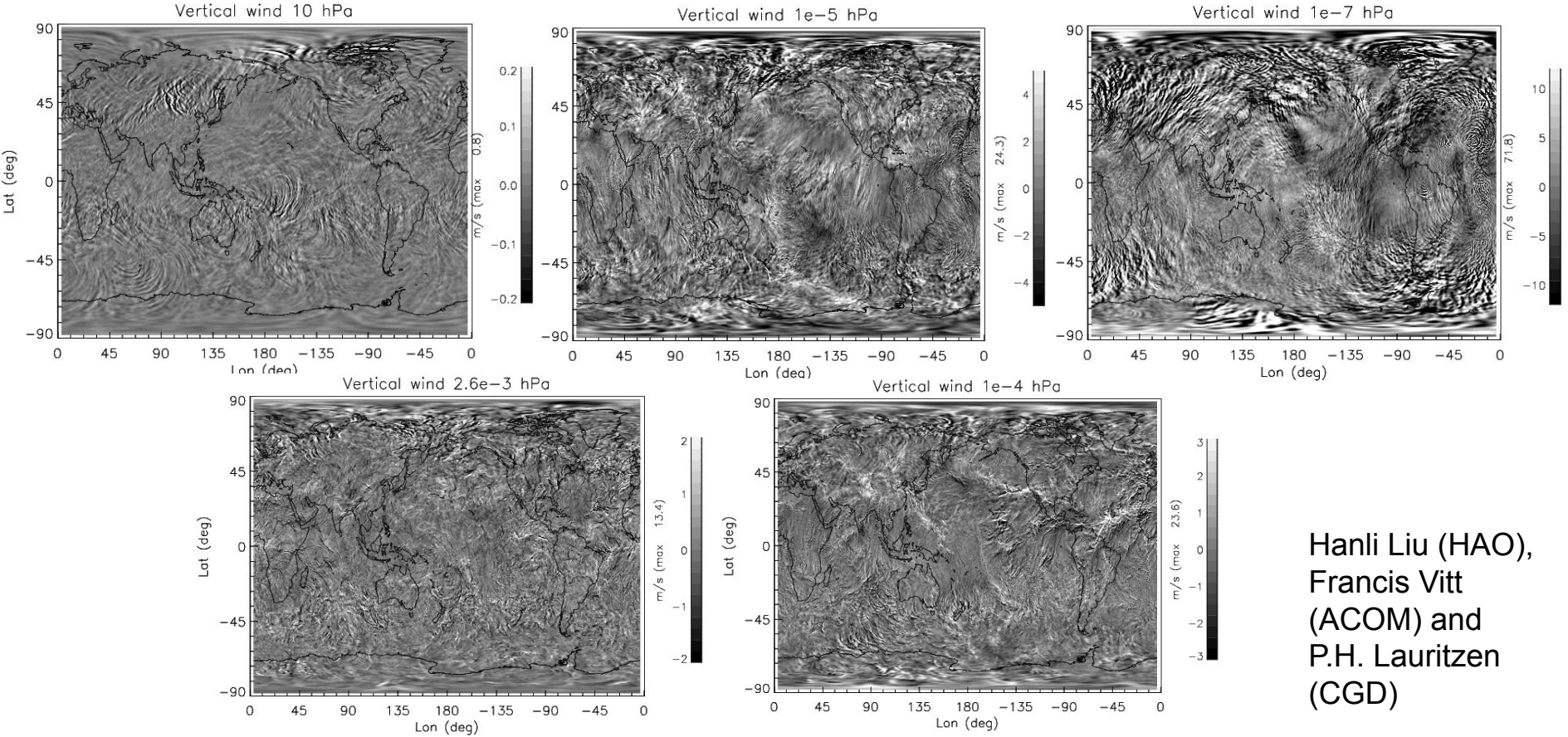
```
<!-- ========================================================================= -->
<!-- Defaults for composition of air                                           -->
<!-- ========================================================================= -->

<dry_air_composition                          >''                                          </dry_air_composition>
<dry_air_composition waccmx="1"               >'O     ','O2    ','H     ','N2    '</dry_air_composition>

<moist_air_composition                        >'Q     '                                    </moist_air_composition>
<moist_air_composition phys="cam4"            >'Q     ','CLDLIQ','CLDICE'                  </moist_air_composition>
<moist_air_composition phys="cam5"            >'Q     ','CLDLIQ','CLDICE'                  </moist_air_composition>
<moist_air_composition phys="cam6"            >'Q     ','CLDLIQ','CLDICE','RAINQM','SNOWQM'</moist_air_composition>
```

Namelist specification of the composition of air, i.e. one can “easily” change composition of air and thermodynamically active water species (note: also applicable to other planets)

SE dynamical core and CAM-WACCM physics call the same module to get molecular viscosity and thermal conductivity coefficients, generalized cp and R, pressure (incl. weight of condensates if applicable), etc.

P.H. Lauritzen (CGD, NCAR), Hanli Liu, and Francis Vitt (HAO, NCAR)

Vertical Winds from ~25km, 273 level WACCM-x using SE-CSLAM (Spectral-elements with CSLAM)



Hanli Liu (HAO), Francis Vitt (ACOM) and P.H. Lauritzen (CGD)

Model for Prediction Across Scales dynamical core (MPAS): Consistent coupling with the CAM physics package

$$\theta_m, \vec{v}, \rho_k^{(d)}, m^{(\ell)} \rightarrow T, \vec{v}, \Delta p, q^{(\ell)}$$

2.2 MPAS prognostic variables

MPAS prognostic variables are (omitting horizontal index):

- $\theta_k^{(m)}$: layer mean modified potential temperature
- $\rho_k^{(d)}$: mid-level dry density
- $z_{k+1/2}$: interface height; layer thickness is $\Delta z_k = z_{k-1/2} - z_{k+1/2}$
- $m_k^{(\ell)}$: layer mean dry mixing ratio of constituent ℓ
- velocity components at mid-level

where k is level index. It is furthermore assumed that the mid-level is located at

$$z_k \equiv \frac{1}{2}\left(z_{k+1/2} + z_{k-1/2}\right). \tag{1}$$

The modified potential temperature in MPAS is defined as

$$\theta_k^{(m)} = \left[1 + \frac{1}{\epsilon} m_k^{(wv)}\right] \theta_k, \text{ where } \epsilon \equiv \frac{R^{(d)}}{R^{(wv)}} \tag{2}$$

(Skamarock et al., 2012, see equation 2) where

$$\theta_k \equiv T_k \left(\frac{P_0}{p_k}\right)^{\kappa}, \tag{3}$$

2.1 CAM physics state variables

Not including state variables in specific parameterization, the CAM physics prognostic state variables are (omitting horizontal index):

- T_k: mid-level temperature
- Δp_k: pressure level thickness
- $q_k^{(\ell)}$: layer mean specific/moist mixing ratio of constituent ℓ
- velocity components at mid-level

where k is level index.

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Constraints:

- Mass conservation (straight forward assuming hydrostatic balance)

$$\Delta p_k = g \Delta z_k \rho_k = g \Delta z_k \rho_k^{(d)} \sum_{\ell \in \mathcal{L}} m_k^{(\ell)}$$

$$\mathcal{L} = \{'d', 'wv', 'cldice', 'cldliq', 'rain', 'snow'\}$$

$$\Delta p_k = g \Delta z_k \rho_k^{(d)} \left(1 + m_k^{(wv)}\right). \text{ (CAM physics)}$$

$$\theta_m, \vec{v}, \rho_k^{(d)}, m^{(\ell)} \rightarrow T, \vec{v}, \Delta p, q^{(\ell)}$$

Constraints:

- Energy conservation: as a first step assume MPAS hydrostatic for energy purposes, assume heat capacity of water vapor is that of dry air:

$$\iiint \left(K + c_p^{(d)} T + \Phi_s\right) dA \frac{dp}{g}$$

Total energy CAM physics (not incl. latent heat terms)

$$\iiint \left(K + c_v^{(d)} T + gz\right) \rho dA\, dz$$

Total energy MPAS (not incl. latent heat terms) assuming MPAS hydrostatic

$$\theta_m, \vec{v}, \rho_k^{(d)}, m^{(\ell)} \rightarrow T, \vec{v}, \Delta p, q^{(\ell)}$$

Note: pressure diagnostic in MPAS (constant volume model); model top pressure not constant as in CAM physics

Half-level pressures are straight-forward to compute using MPAS prognostic state (assuming hydrostatic balance)

$$\Delta p_k = g \Delta z_k \rho_k = g \Delta z_k \rho_k^{(d)} \sum_{\ell \in \mathcal{L}} m_k^{(\ell)}$$

but full level pressure needs to be computed carefully for consistency. For example, choosing

$$p_k = \frac{1}{2}\left(p_{k+1/2} - p_{k-1/2}\right)$$

is NOT consistent with MPAS where mid-level is defined by

$$z_k \equiv \frac{1}{2}\left(z_{k+1/2} + z_{k-1/2}\right)$$

Instead we use the equation of state to compute full-level pressure (and Exner pressure/function)

$$\left\langle \frac{1}{p_k} \right\rangle \equiv \left(\frac{\theta_k^{(v)} \rho_k R^{(d)}}{P_0^{\kappa}} \right)^{(1-\kappa)}$$

$$\begin{aligned} \Pi_k &= \left\{ \frac{p_k}{p_0} \right\}^{R^{(d)}/c_p^{(d)}}, \\ &= \left\{ \left[\rho_k^{(d)} R^{(d)} \theta_k^{(m)} / p_0 \right]^{c_p^{(d)}/c_v^{(d)}} \right\}^{R^{(d)}/c_p^{(d)}}, \\ &= \left[\rho_k^{(d)} R^{(d)} \theta_k^{(m)} / p_0 \right]^{R^{(a)}/c_v^{(d)}}, \end{aligned}$$

=> height computed from CAM physics state (diagnostic) is consistent with MPAS height (fixed)

$$\Delta z_k = \left\langle \frac{1}{p_k} \right\rangle \frac{R^{(d)} T_k^{(v)}}{g} \Delta p_k$$

$$z_k = z_{k+1/2} + \frac{1}{2}\Delta z_k = z_{k+1/2} + \frac{1}{2}\left\langle \frac{1}{p_k} \right\rangle \frac{R^{(d)} T_k^{(v)}}{g} \Delta p_k$$

Temporal evolution of total energy

3.0.0.1 CAM energy equation The total energy equation used in CAM physics (omitting surface fluxes and latent heat terms associated with phase transformations) is given by

$$\frac{\partial}{\partial t} \iiint \left(K + c_p^{(d)} T + \Phi_s \right) dA \, \frac{dp}{g} = \iiint \left[Q + \vec{v} \cdot \vec{F} \right] \, dA \, \frac{dp}{g} \tag{30}$$

(Kasahara, 1974) where Q is the heating rate per unit mass per unit time and $\vec{F}$ is the frictional force per unit mass. This energy equation assumes that the model top pressure is constant in time and that all water species use the same heat capacity $c_p^{(\ell)} = c_p^{(d)}$.

3.0.0.2 MPAS energy equation Assuming hydrostatic balance, constant z model top and $c_p^{(\ell)} = c_p^{(d)}$, MPAS conserves

$$\frac{\partial}{\partial t} \iiint \left(K + c_v^{(d)} T + gz \right) \rho dA \, dz = \iiint \left[Q + \vec{v} \cdot \vec{F} \right] \, dA \, \rho dz \tag{32}$$

(Kasahara, 1974) in the absence of surface fluxes and latent heat terms associated with phase transformations.

```
do nt=1,ntotal

  Transformation from MPAS state to CAM physics state: We have made sure that mass is conserved and that z derived from hydrostatic
  integral in CAM physics using physics state exactly equals z from MPAS. Energies in MPAS and CAM physics match exactly
  before/after d_p_coupling
  call d_p_coupling !(θ_k^(m), v_k, ρ_k^(d), m_k^(ℓ) → T_k, v_k, Δp_k, q_k^(ℓ))

  PARAMETERIZATIONS:

  output 'pBF': State passed to parameterizations, before energy fixer
  call check_energy_fix !Apply energy fixer
  output 'pBP': State after energy fixer, before parameterizations
  call all physics packages sequentially
  call save state for energy fixer
  output 'pAP': state after last physics update in parameterizations
  call dme_adjust !dry mass correction / moisture update
  output 'pAM': state after dry mass correction (only diagnostic for MPAS)

  call p_d_coupling
  Update tracers with physics increment before dynamics starts integration

  SOME DIAGNOSTICS USING MPAS ENERGY FORMULATION:

  output 'dBF': State before physics tendencies are added to dynamical core state
  output 'dAP': Update state with heating increment
  output 'dAM': Update dAP state with water vapor changes

  DYNAMICAL CORE:


  do dycore_step = 1, dycore_steps_per_physics_step (=2 default)

    do dynamics_split=1, dynamics_split_steps (=3 default)
      do rk3_step = 1, 2, 3
        compute large-time-step tendency
        do acoustic_step = 1,num_acoustic_steps
          [default is (rk3_step, num_acoustic_steps) = (1,1), (2,1), (3,2)]
          acoustic step, includes physics heating tendency on RHS of PDEs
        end do
      end do
    end do

    do rk3_tracers_step = 1, 2, 3
      tracer transport RK3 integration
    end do

  end do (dycore_steps_per_physics_step)

  call wshist !write all history (physics, dynamics) from cam_run4
              !time stamp increment

end do
```

Total energy fixer in CAM

2.5. A Few Observations Regarding the Energy Budget Terms

It is useful to note that the energy fixer "fixes" energy errors for the dynamical core, pressure work error, PDC, and TE discrepancy

$$-\partial \widehat{E}^{(\mathrm{efix})}_{\mathrm{phys}} = \partial \widehat{E}^{(\mathrm{pwork})}_{\mathrm{phys}} + \partial \widehat{E}^{(\mathrm{adiab})}_{\mathrm{dyn}} + \partial \widehat{E}^{(\mathrm{pdc})} + \partial \widehat{E}^{(\mathrm{discr})}. \qquad (23)$$

If the energy fixer uses a total energy formula different than the dynamical core's energy formula then the energy fixer is not fixing what it is supposed to fix which is

- "Actual" energy dissipation in dynamical core
- "Actual" energy errors in physics dynamics coupling
- Moisture adjustment as "seen" by dycore

```
do nt=1,ntotal

  call write_dynvar !outfld calls for writing dycore variables (on dycore grid)
                    !to history file; actual file write at end of loop

  call d_p_coupling !(θ_k^(m), v_k, ρ_k^(d), m_k^(l) → T_k, v_k, Δp_k, q_k^(l))

  PARAMETERIZATIONS:

  output 'pBF': State passed to parameterizations, before energy fixer
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  DYNAMICAL CORE:


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        do acoustic_step = 1,num_acoustic_steps
          [default is (rk3_step, num_acoustic_steps) = (1,1), (2,1), (3,2)]
          acoustic step, includes physics heating tendency on RHS of PDEs
        end do
      end do
    end do

    do rk3_tracers_step = 1, 2, 3
      tracer transport RK3 integration
    end do

  end do (dycore_steps_per_physics_step)

  call wshist !write all history (physics, dynamics) from cam_run4
              !time stamp increment

end do
```

Level 0 consistency:

Energy fixer that fixes dynamical core, physics-dynamics coupling and water adjustment energy errors, should use a total energy formula consistent with z-vertical coordinate, i.e. energy fixer should be using

$$\frac{\partial}{\partial t}\iiint \left(K + c_v^{(d)}T + gz\right)\rho dA\, dz$$

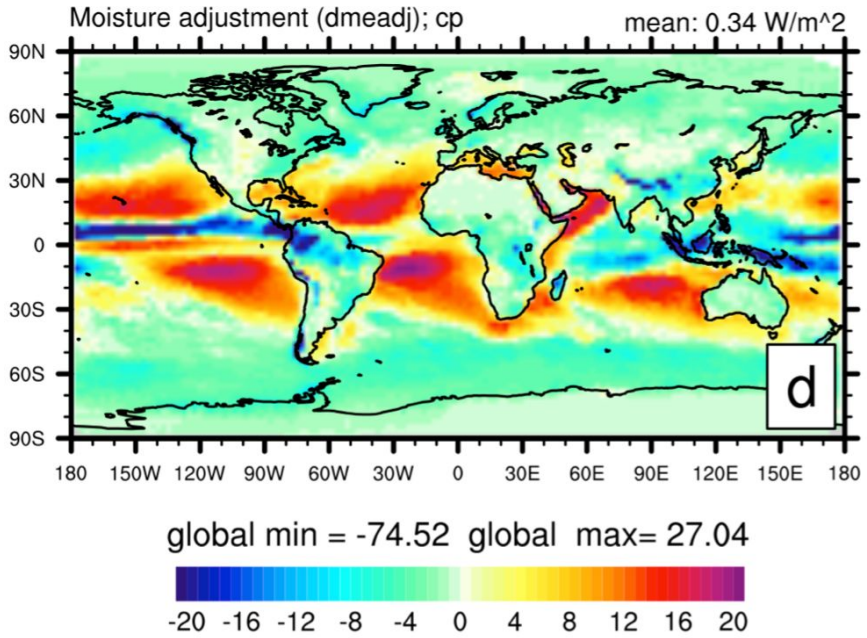
CAM physics parameterizations satisfy

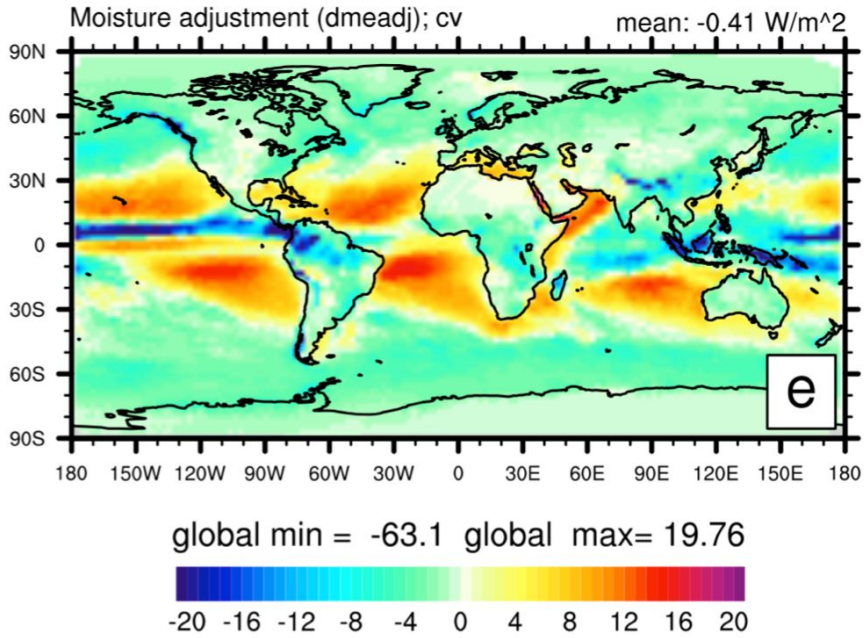
$$\frac{\partial}{\partial t}\iint \left(K + c_p^{(d)}T + \Phi_s\right) dA\, \frac{dp}{g}$$

Temperature increments in CAM physics are for constant pressure and are converted to heating increments under constant volume so that energy increments in the two coordinate systems are the same:

$$\Delta T_k|_p = \frac{c_v^{(d)}}{c_p^{(d)}}\Delta T_k|_V$$

Water adjustment energy tendency (dme_adjust)





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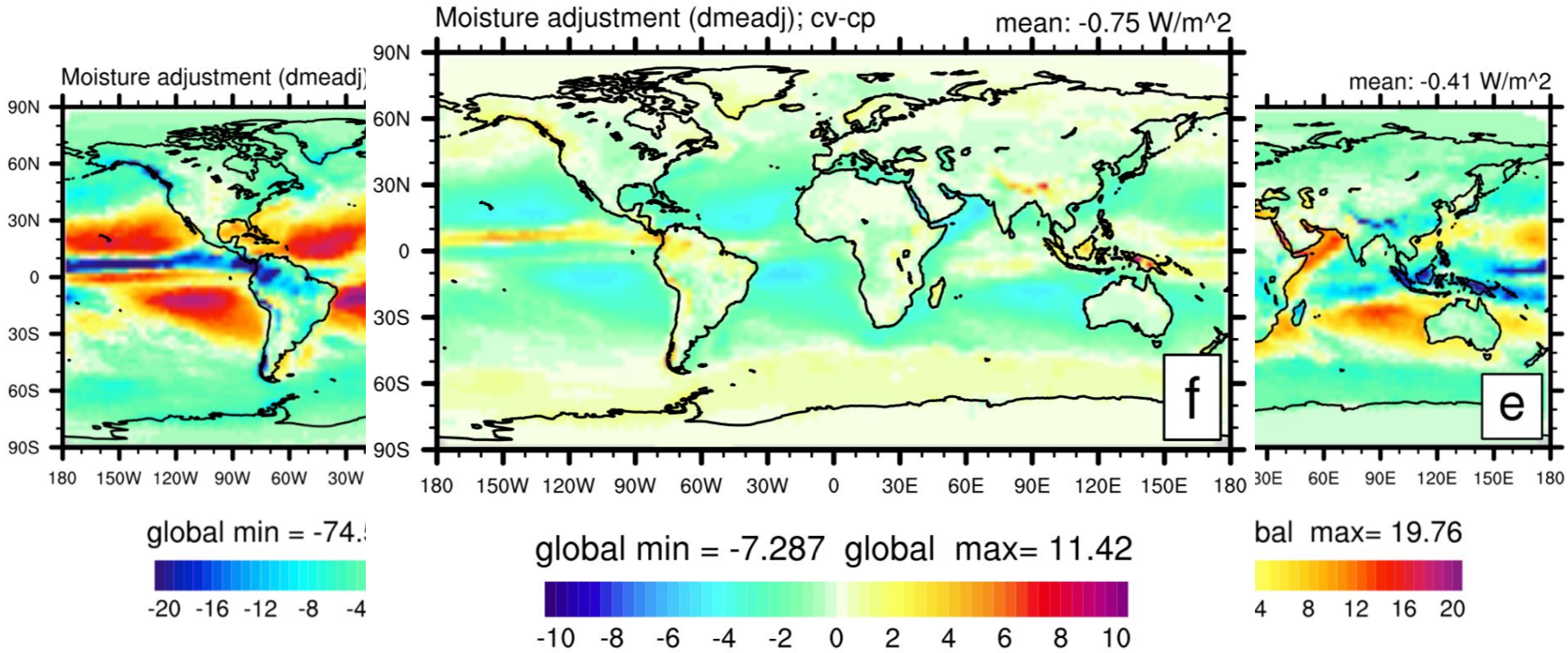
Water adjustment energy tendency (dme_adjust)



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Still inconsistencies:

```
!-----------------------------------------------------------------------------------------------------------
! Update temperature from dry static energy (moved from above for WACCM-X so updating after cpairv_loc update)
!-----------------------------------------------------------------------------------------------------------

if(ptend%ls) then
   do k = ptend%top_level, ptend%bot_level
      state%t(:ncol,k) = state%t(:ncol,k) + ptend%s(:ncol,k)*dt/cpairv_loc(:ncol,k)
      if (present(tend)) &
           tend%dtdt(:ncol,k) = tend%dtdt(:ncol,k) + ptend%s(:ncol,k)/cpairv_loc(:ncol,k)
   end do
end if

! Derive new geopotential fields if heating or water tendency not 0.

if (ptend%ls .or. ptend%lq(1)) then
   call geopotential_t  (                                                                    &
        state%lnpint, state%lnpmid, state%pint  , state%pmid  , state%pdel  , state%rpdel  , &
        state%t     , state%q(:,:,1), rairv_loc(:,:), gravit  , zvirv                       , &
        state%zi    , state%zm      , ncol        )
   ! update dry static energy for use in next process
   do k = ptend%top_level, ptend%bot_level
      state%s(:ncol,k) = state%t(:ncol,k)*cpairv_loc(:ncol,k) &
                       + gravit*state%zm(:ncol,k) + state%phis(:ncol)
   end do
end if
```

1. Static energy potential:

   S = gz + dp*cp*T+gz

We made our heating increments consistent (equivalent to using dp*cv*T in static energy) but z varies in CAM physics (updated after each physics call so the parameterization"see" height changing whereas the MPAS vertical coordinate, height, stays fixed)

2. Related: Top boundary condition in CAM assumes constant pressure (with MPAS pressure at model top varies but not height)
3. Assuming hydrostatic total energy formula (i.e. vertical velocity term missing)
4. Energy formula does not incl. condensates (inconsistency with SE and FV3 as well)

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