The challenge of Energy budget closure in Earth system models

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CESM Atmosphere Model Working Group Meeting, 19 – 21 February 2019

The challenge of Energy budget

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A total energy error analysis of dynamical cores and physics-dynamics coupling in the Community Atmosphere Model (CAM)

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Research question

How large are the spurious total energy sources/sinks in an atmosphere model and where are they coming from?

The challenge of Energy budget closure in Earth system models

Total energy (TE) equation

- moist atmosphere

Net energy flux calculated by parameterizations

Thermal energy

Dry mass per unit area

Dry mixing ratio

Kinetic energy

$$\frac{d\widehat{E}}{dt} = \widehat{F}_{net},$$

where

$$\frac{d\widehat{E}}{dt} = \frac{d}{dt}\left\{\frac{1}{\Delta S}\int_{\eta=0}^{\eta=1}\iint_S \left(\frac{1}{g}\frac{\partial M^{(d)}}{\partial \eta^{(d)}}\right)\sum_{\ell \in \mathcal{L}_{all}}\left[m^{(\ell)}\left(K + c_p^{(\ell)}T + \Phi_s\right)\right] dA d\eta^{(d)}\right\},$$

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

and

$$\widehat{F}_{net} = \frac{1}{\Delta S}\int_{\eta=0}^{\eta=1}\iint_S \left(\frac{1}{g}\frac{\partial M^{(d)}}{\partial \eta^{(d)}}\right)\sum_{\ell \in \mathcal{L}_{all}}\left[m^{(\ell)}\right] F_{net}\, dA d\eta^{(d)}.$$

where ΔS is the surface area of the sphere, Φ_s is the surface geopotential and $\widehat{(\cdot)}$ refers to the global average.

Lauritzen et al. (2018); https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2017MS001257

Total energy (TE) equation
- moist atmosphere

$$\frac{d\widehat{E}}{dt} = \widehat{F}_{net},$$

The continuous equations of motion on which the dynamical core is based conserve TE globally:

$$\frac{d\widehat{E}}{dt} = 0$$

the global average.

Total energy (TE) equation
- moist atmosphere

$$\frac{d\widehat{E}}{dt} = \widehat{F}_{net},$$

Conserving total energy to within ~0.01 W/m² is considered "good enough" for coupled climate modeling (Boville, 2000; Williamson et al., 2015)

$$\frac{d\widehat{E}}{dt} \leq 0.01 W/m^2$$

Earths energy imbalance is ~1 W/m^2

Total energy (TE) equation
- moist atmosphere

$$\frac{d\widehat{E}}{dt} = \widehat{F}_{net},$$

Column physics: TE change in column should be balanced by fluxes in/out of the top and bottom

$$\frac{d\widehat{E}}{dt} = \frac{1}{\Delta S} \iint_S \left(p_{top} F_{net} - p_s F_{net} \right) dA.$$

Potential spurious sources/sinks of total energy in an atmosphere model:

- **Parameterization errors:** Individual parameterizations may not have a closed energy budget. CAM parameterizations are required to have a closed energy budget under the assumption that pressure remains constant during the computation of the subgrid-scale parameterization tendencies. In other words, the TE change in the column is exactly balanced by the net sources/sinks given by the fluxes through the column.

- **Pressure work:** That said, if parameterizations update specific humidity then the surface pressure changes (e.g., moisture entering or leaving the column). In that case the pressure changes which, in turn, changes TE. This is referred to as pressure work [section 3.1.8 in Neale et al., 2012].

- **Continuous TE formula discrepancy:** If the continuous equations of motion for the dynamical core conserve a TE different from the one used in the parameterizations then an energy inconsistency is present in the system as a whole. In CAM this mismatch arose from the evolutionary nature of the model development and not by deliberate design; and should be eliminated in the future.

- **Dynamical core errors:** Energy conservation errors in the dynamical core, not related to physics-dynamics coupling errors, can arise in multiple parts of the algorithms used to solve the equations of motion.

- **Physics-dynamics coupling (PDC):** Assume that physics computes a tendency. Usually the tendency (forcing) is passed to the dynamical core which is responsible for adding the tendencies to the state.

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CAM-SE dynamical core

$$\widehat{E} = \frac{1}{\Delta S}\int_{\eta=0}^{\eta=1}\iint_S \left(\frac{1}{g}\frac{\partial M^{(d)}}{\partial \eta^{(d)}}\right)\sum_{\ell\in\mathcal{L}_{all}}\left[m^{(\ell)}\left(K + c_p^{(\ell)}T + \Phi_s\right)\right] dA d\eta^{(d)}$$

CAM physics (not by deliberate design!)

$$\widehat{E}_{phys} = \frac{1}{\Delta S}\int_{\eta=0}^{\eta=1}\iint_S \left(\frac{1}{g}\frac{\partial M^{(d)}}{\partial \eta^{(d)}}\right)\left(1 + m^{(wv)}\right)\left[\left(K + c_p^{(d)}T + \Phi_s\right)\right] dA d\eta^{(d)}$$

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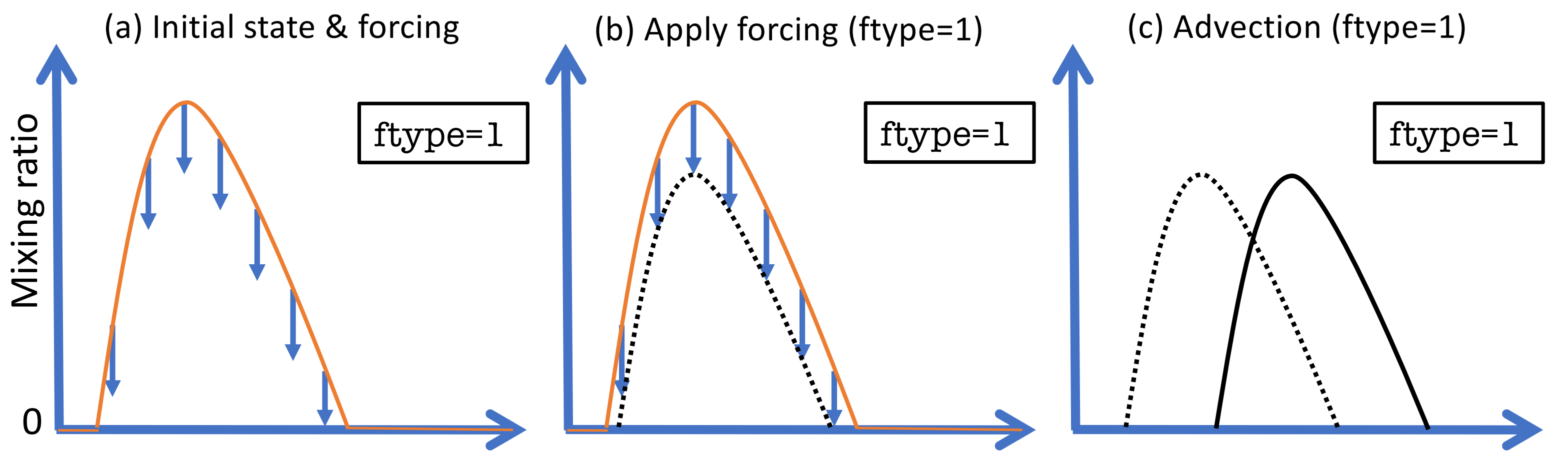
Temporal physics-dynamics coupling methods

State-update method

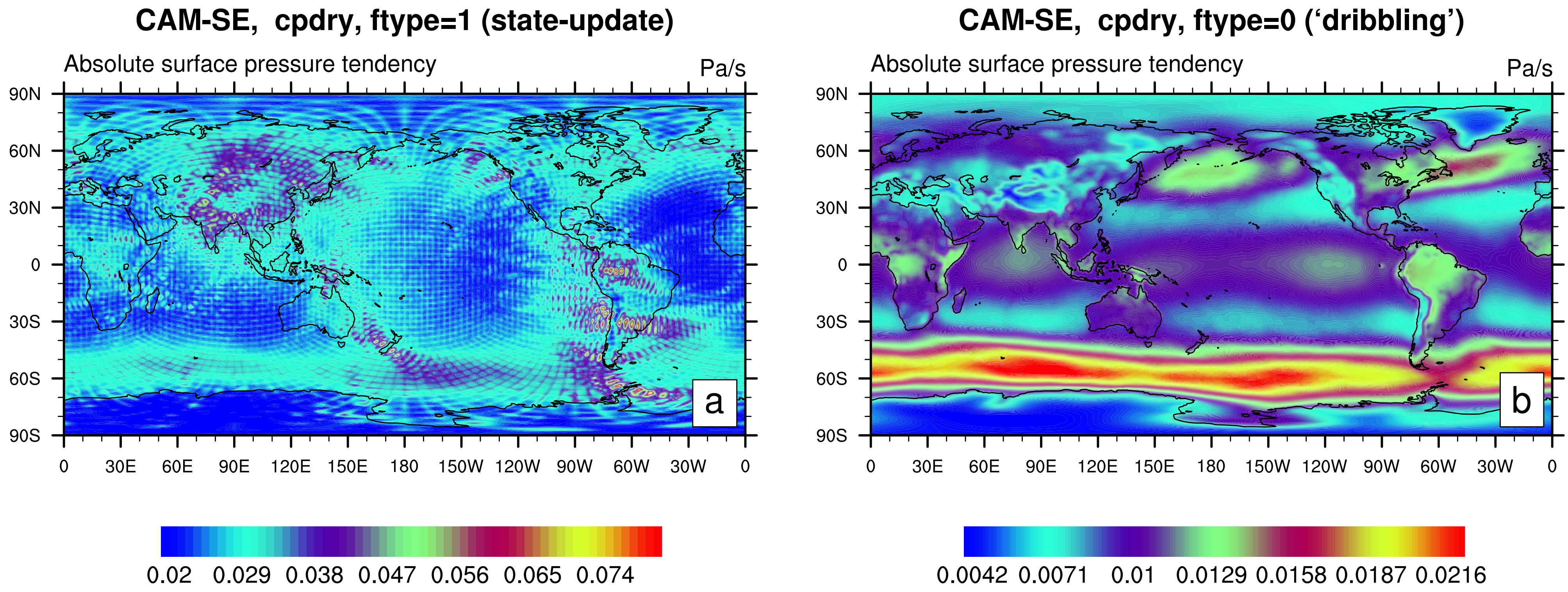


No physics-dynamics coupling error:

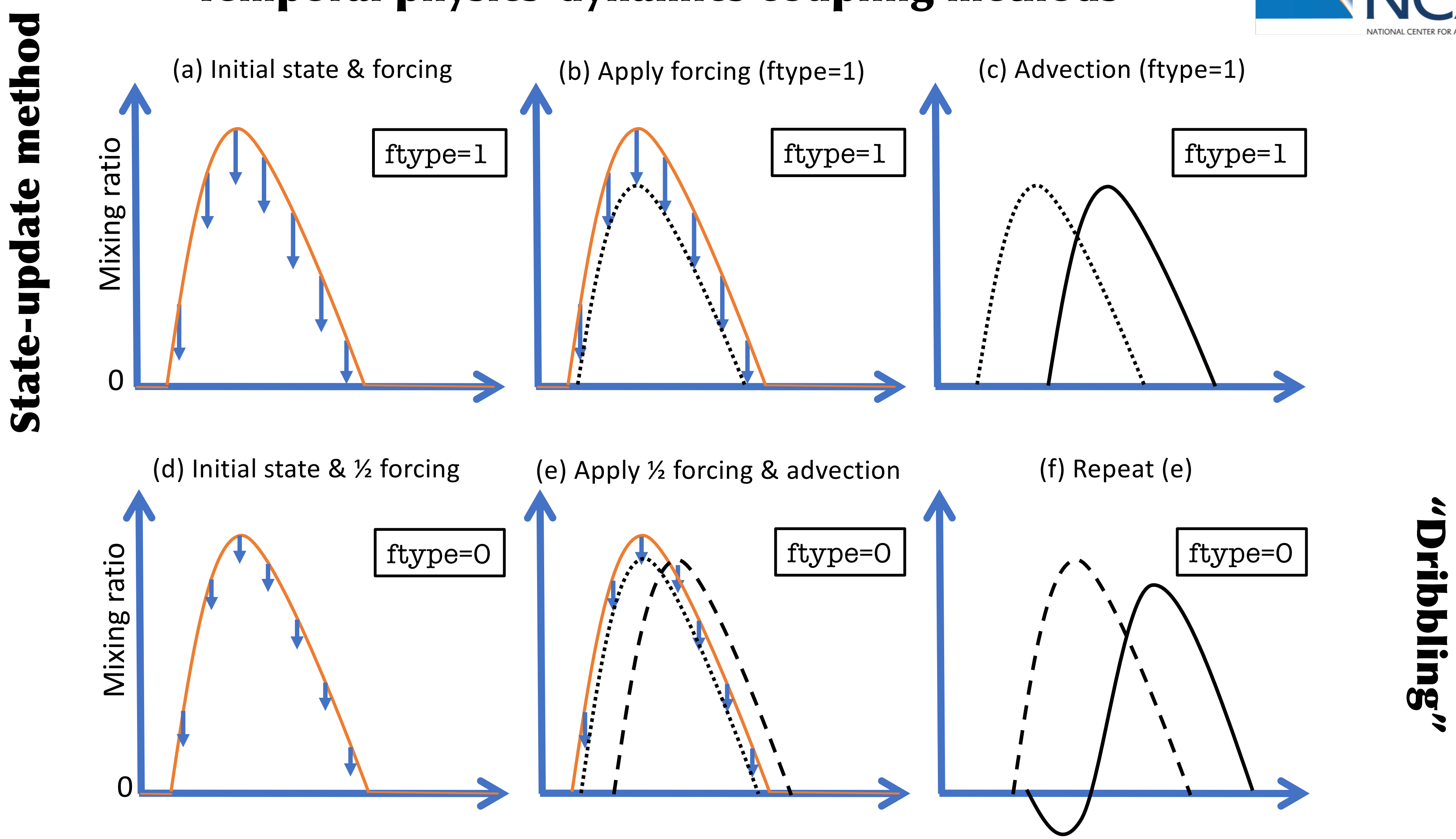
(Dry) Energy change due to physics energy increments

$$\Delta M^{(d)} \Delta T \quad \Delta M^{(d)} \left[(\Delta u)^2 + (\Delta v)^2 \right] \quad \Delta m^{(\ell)} \Delta M^{(d)}$$

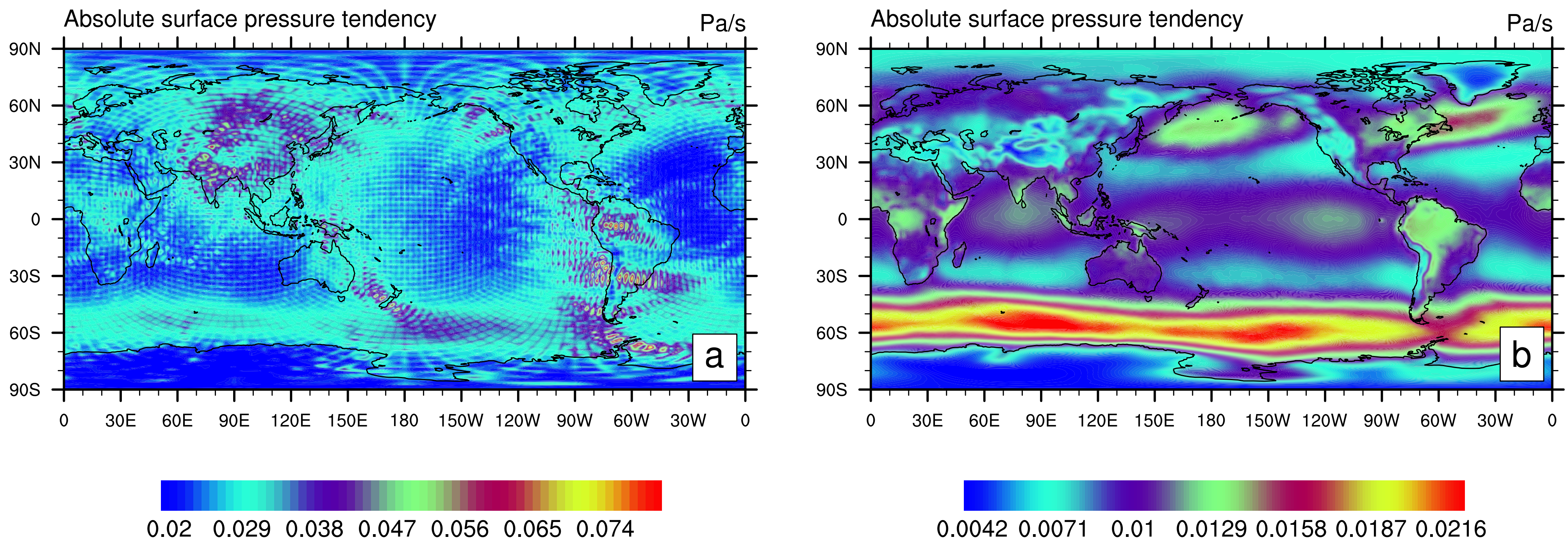
= Dynamics energy change due to physics forcing


CAM-SE, cpdry, ftype=1 (state-update)
Absolute surface pressure tendency
Pa/s
90N
60N
30N
0
30S
60S
90S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
a
0.02
0.029
0.038
0.047
0.056
0.065
0.074
CAM-SE, cpdry, ftype=0 ('dribbling')
Absolute surface pressure tendency
Pa/s
b
0.0042
0.0071
0.01
0.0129
0.0158
0.0187
0.0216

Temporal physics-dynamics coupling methods



CAM-SE, cpdry, ftype=1 (state-update) **CAM-SE, cpdry, ftype=0 (‘dribbling’)**



Temporal physics-dynamics coupling methods

State-update method

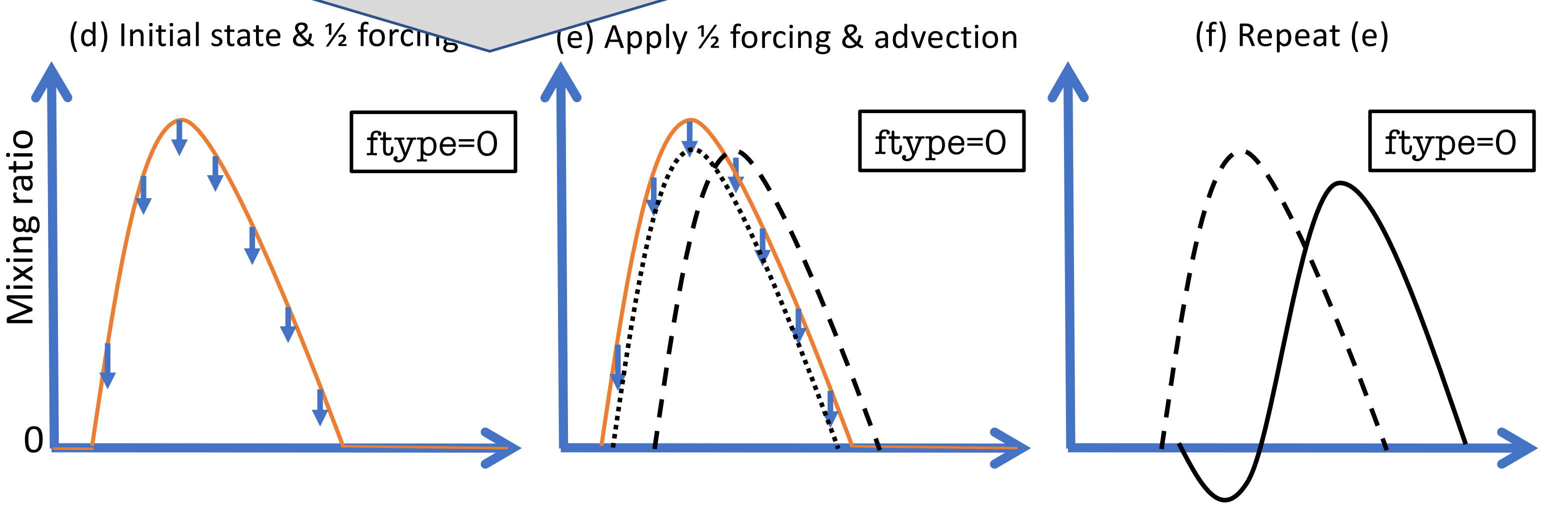
- **Thermal energy "dribbling" error: Thermal energy increment from physics**

$$\Delta M^{(d)} \Delta T$$

does not match thermal energy change in dycore when tendency is added to dycore state.

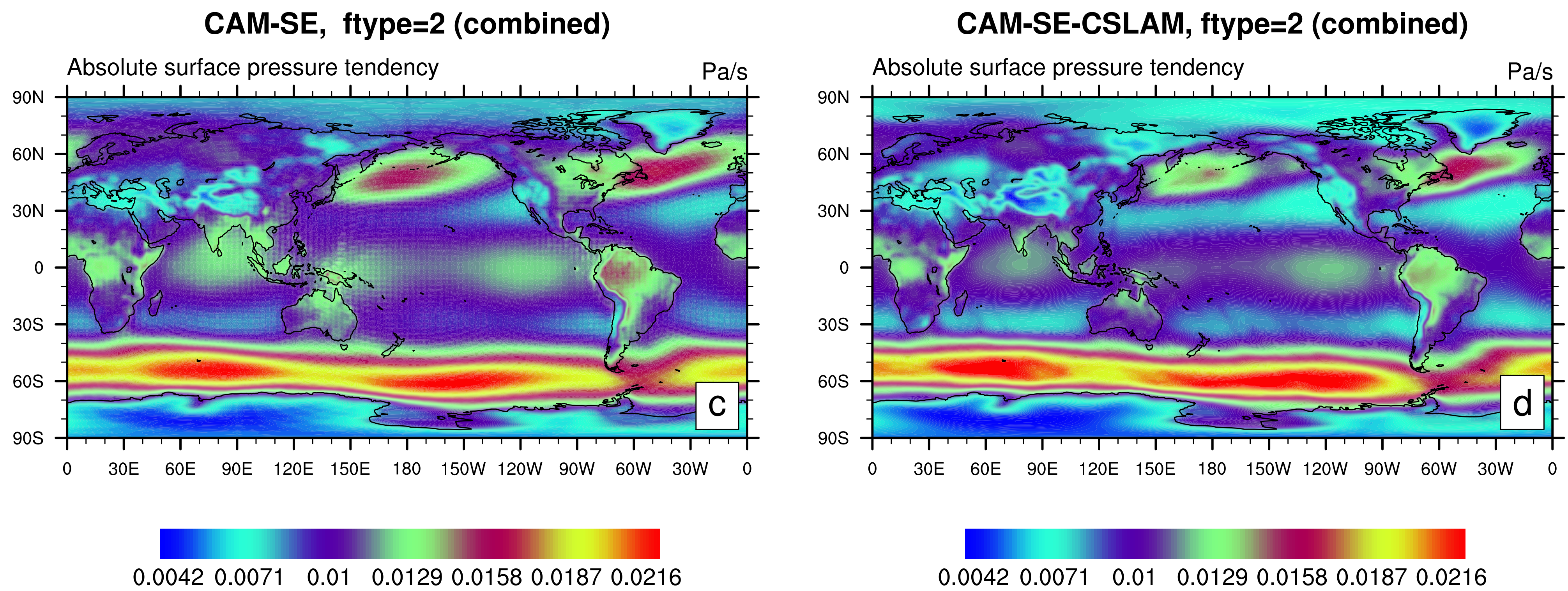
- **Kinetic energy "dribbling" error:** $$\Delta M^{(d)} \left[(\Delta u)^2 + (\Delta v)^2 \right]$$

- **Mass "clipping" error: e.g., if logic in dycore to prevent negative mixing ratios**



"Dribbling"

ftype=2: state-updating (type=1) for tracers (i.e. no mass-clipping errors) and “dribbling” (ftype=0) for u,v, and T.



Potential spurious sources/sinks of total energy in an atmosphere model:

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Fixing spurious sources/sinks of total energy in an atmosphere model:

- **Compensating Energy fixers:** To avoid TE conservation errors which could accumulate and ultimately lead to a climate drift, it is customary to apply an arbitrary energy fixer to restore TE conservation. Since the spatial distribution of many energy errors, in general, is not known, global fixers are used. In CAM a uniform increment is added to the temperature field to compensate for TE imbalance from all processes, i.e. dynamical core, physics-dynamics coupling, TE formula discrepancy, energy change due to pressure work, and possibly parameterization errors if present.

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

Energy fixer

Pressure work

Dynamical core

Physics-dynamics coupling

Continuous TE formula discrepancy

Spurious sources/sinks of total energy in atmosphere model:

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  CAM parameterizations are requi
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  In other words, the TE change in
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  This is referred to as pressure wor

- **Continuous TE formula discr**
  a TE different from the one used i
  as a whole. In CAM this mismatc
  design; and should be eliminated

- **Dynamical core errors:** Energ
  errors, can arise in multiple parts

- **Physics-dynamics coupling (**
  passed to the dynamical core wh

Budget closed in CAM 😀 but …

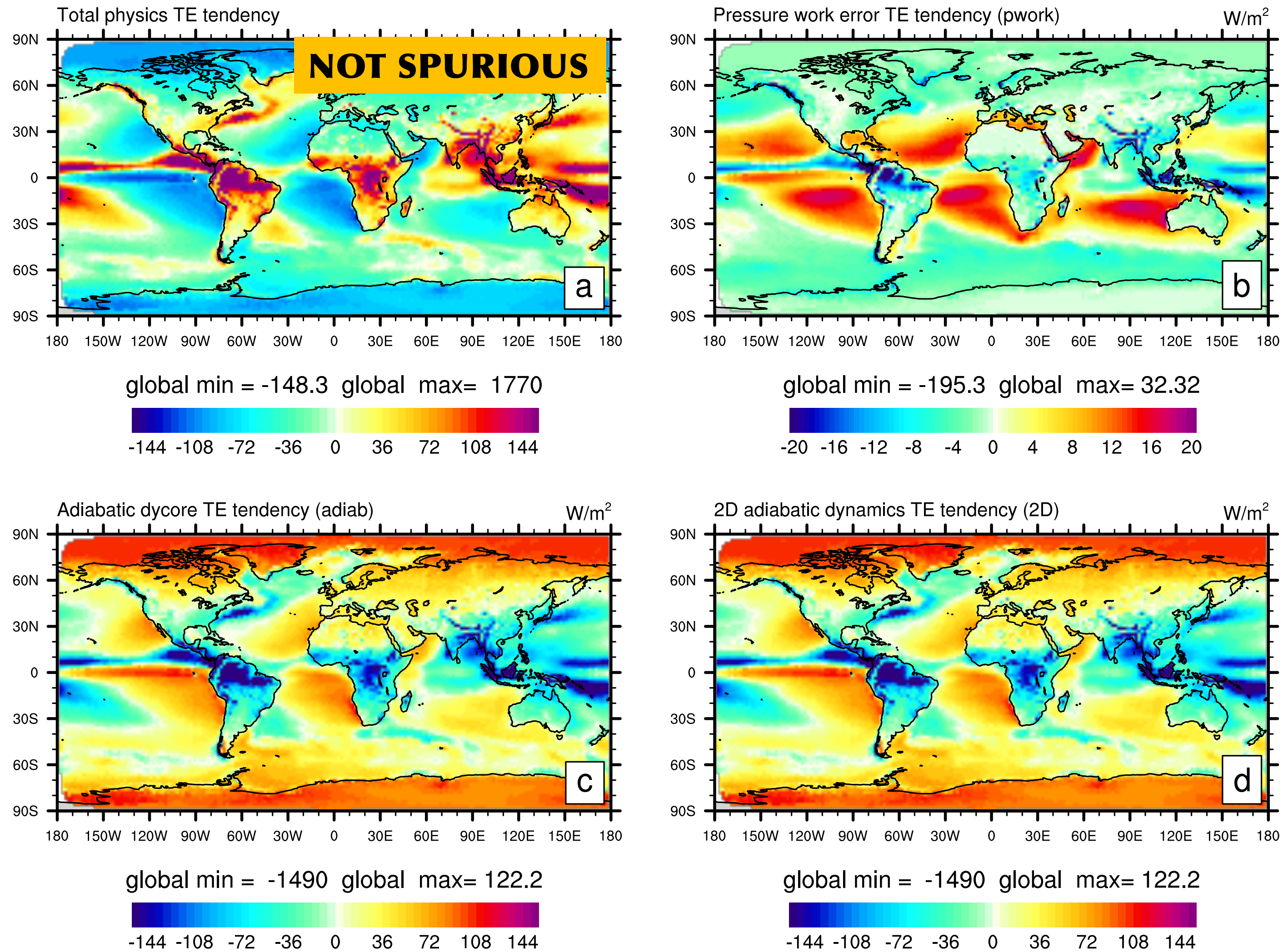
Pressure work: ~0.3 W/m²

TE formula discr. (CAM-SE only): ~0.6 W/m²

CAM-SE: ~-0.6 W/m² (decreases to -0.3W/m² with smoother topography)
CAM-FV and CAM-FV3: ~ 1.1 W/m²

CAM-SE: PDC errors ("dribbling"): ~0.5 W/m²

TE tendencies for the default CAM-SE configuration (AMIP)



Summary

- Total energy errors in numerical discretizations (dynamical core), physics-dynamics coupling and pressure work errors are ~-0.6 – 0.3 W/m^2
- Local errors can be an order of magnitude larger (at least)!

Outlook

- In next-generation models we should consider formulating physics in dry pressure coordinates (so that coordinate surfaces stay fixed during physics updates)
- Can we close the total energy budget locally in models?
- Integrating weather-climate models: parameterizations for weather models are, in general, not formulated to have a closed TE budget. Major challenge?

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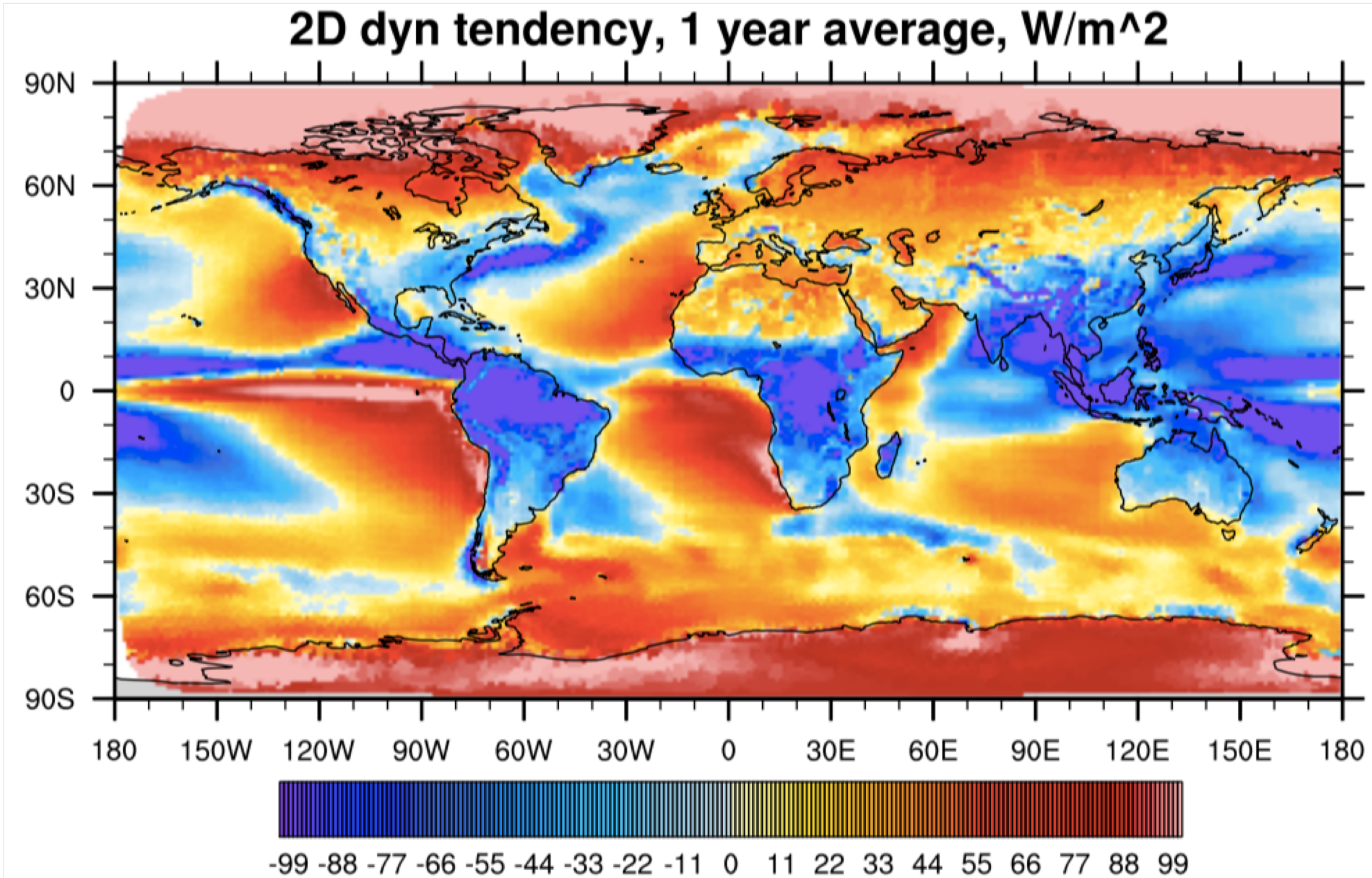
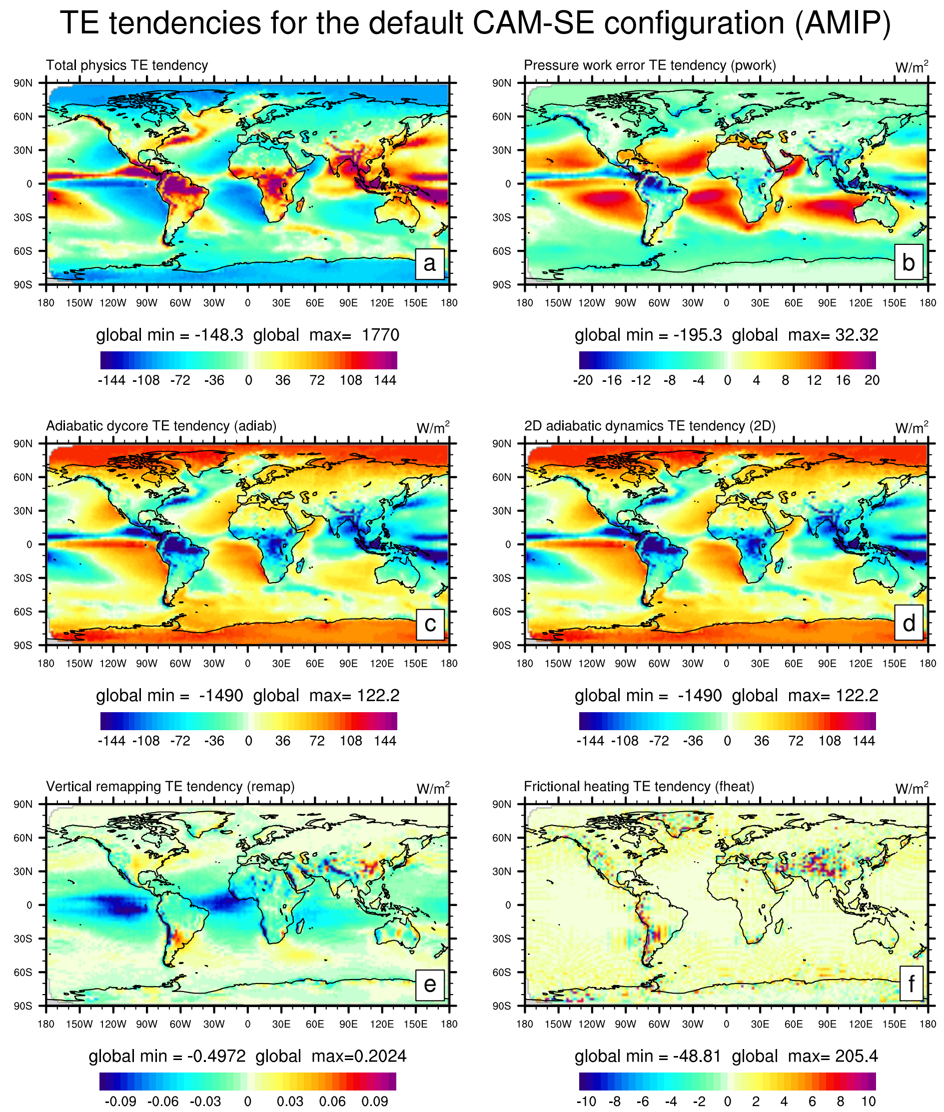


Not SPURIOUS locally – should integrate to 0



TE tendencies for the default CAM-SE configuration (AMIP)
Total physics TE tendency
global min = -148.3 global max= 1770
Pressure work error TE tendency (pwork)
W/m²
global min = -195.3 global max= 32.32
Adiabatic dycore TE tendency (adiab)
W/m²
global min = -1490 global max= 122.2
2D adiabatic dynamics TE tendency (2D)
W/m²
global min = -1490 global max= 122.2
Vertical remapping TE tendency (remap)
W/m²
global min = -0.4972 global max=0.2024
Frictional heating TE tendency (fheat)
W/m²
global min = -48.81 global max= 205.4
a
b
c
d
e
f

```
do nt=1,ntotal

   PARAMETERIZATIONS:

   Last dynamics state received from dynamics
   output 'pBF'
   [efix] Energy fixer
   output 'pBP'
   [param] Physics updates the state and state saved for energy fixer
   output 'pAP'
   [pwork] Pressure work (dry mass correction)
   output 'pAM'
   Physics tendency (forcing) passed to dynamics
   [phys: pBF ... pAM]

   DYNAMICAL CORE

   output 'dED'
   do ns=1,nsplit
      output 'dAF'

      START PHYSICS-DYNAMICS COUPLING
        Update dynamics state with (1/nsplit) of physics tendency (ftype=2)
        if (ns=1) Update dynamics state with entire physics tendency (ftype=1)
      DONE PHYSICS-DYNAMICS COUPLING
      [phys: dAF ... dBD]

      output 'dBD'

      do nr=1,rsplit
         Advance the adiabatic frictionless equations of motion
           in floating Lagrangian layer
         do ns=1,hypervis_subcycle
            output 'dBH'
            Apply hyperviscosity operators
            output 'dCH'
            [fheat] Add frictional heating to temperature
            output 'dAH'
            [hvis: dBH ... dAH]
         end do (ns=1,hypervis_subcycle)
      end do (nr=1,rsplit)
      [2D: dBD ... dAD]
      output 'dAD'
      [remap] Vertical remapping from floating Lagrangian levels to Eulerian levels
      output 'dAR'
      [adiab: dBD ... dAR]
   end do (ns=1,nsplit)
   Dynamics state saved for next model time step and passed to physics
   output 'dBF'

end do (nt=1,ntotal)
```

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Diagnosing TE errors:

Implemented using CAM history infrastructure by computing column integrals of energy at various places in CAM and outputting the 2D energy fields. CAM history internally handles accumulation and averaging in time at each horizontal grid point.