Enforcing local energy conservation in CAM physics

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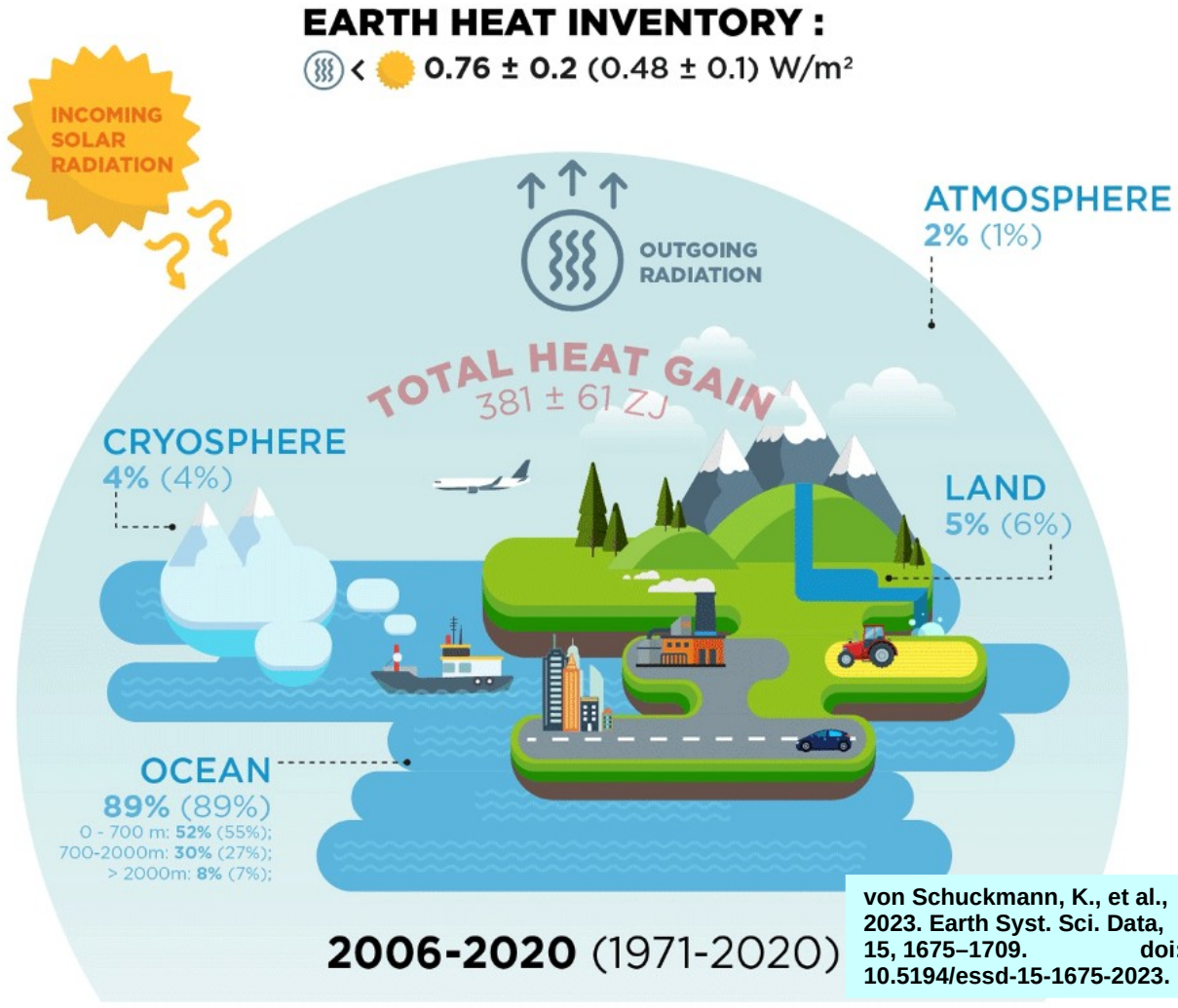
NCAR winter working group meeting, Boulder, 4/2/2026

This work

Energy in the climate system

- Currently absorbing ~400 TW
- ~50% in upper ocean (0-700m), ~40% in deep ocean
- ~2 TW warming up land, ~2 TW melting ice
- ~1 TW warming atmosphere



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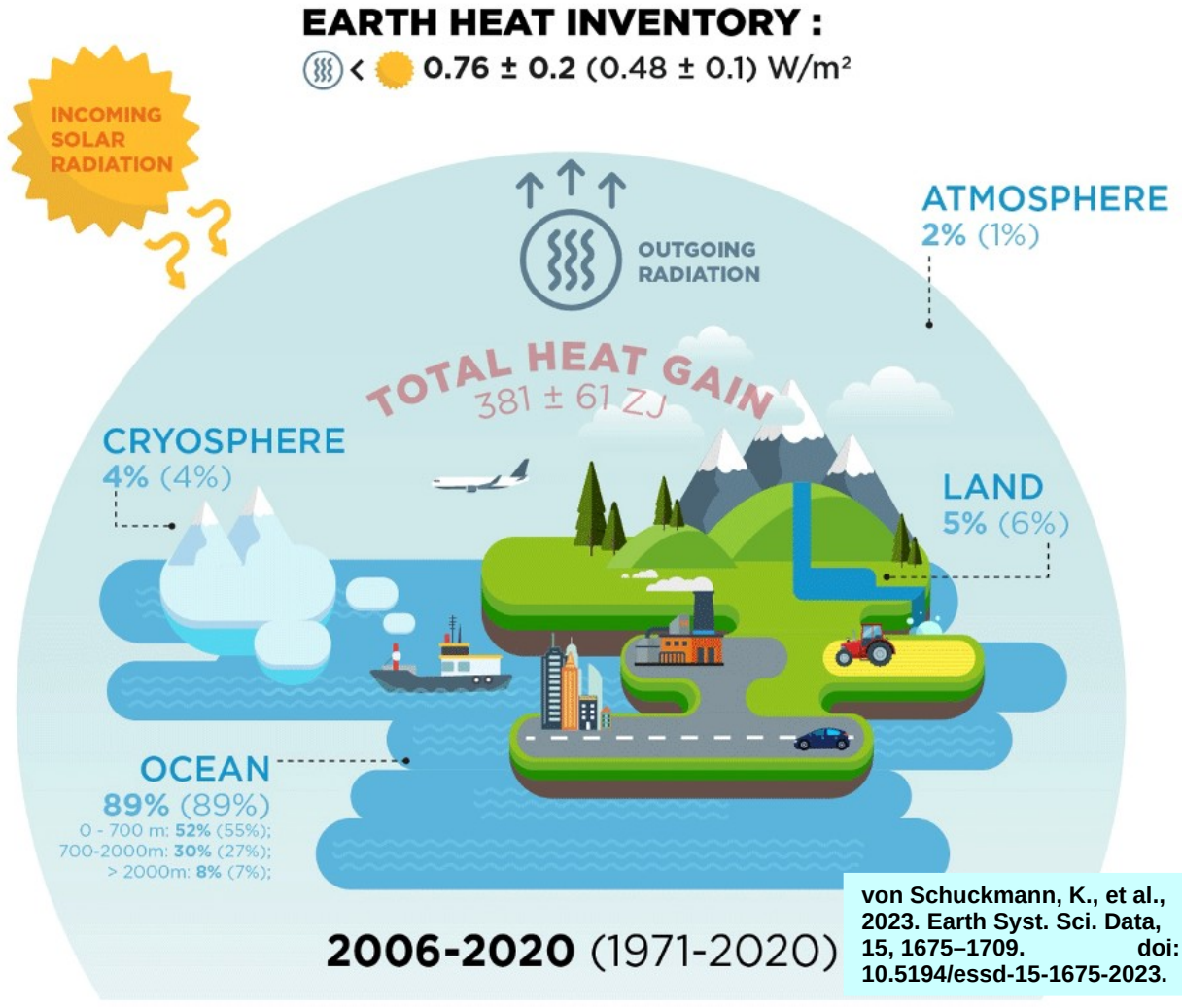

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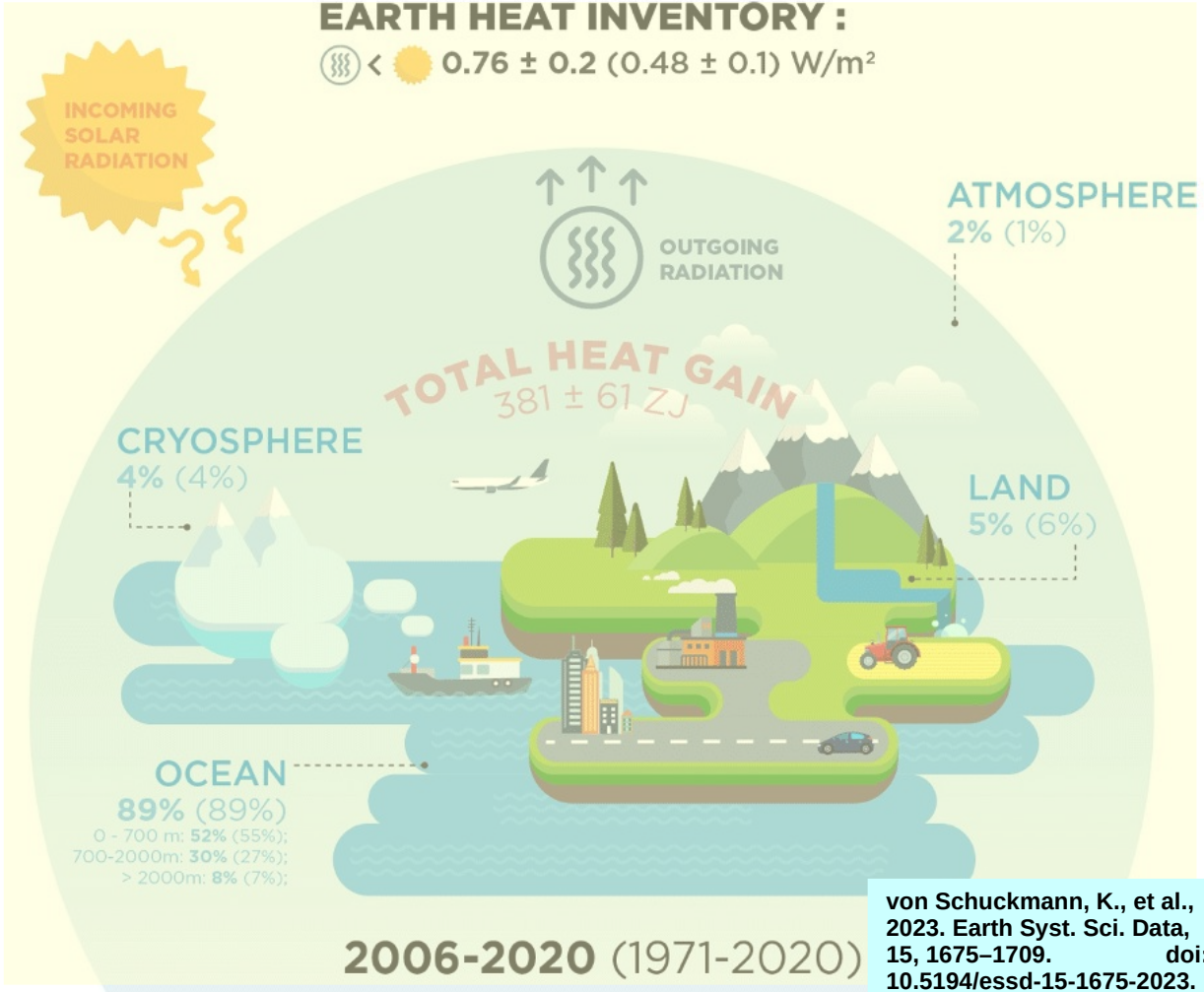

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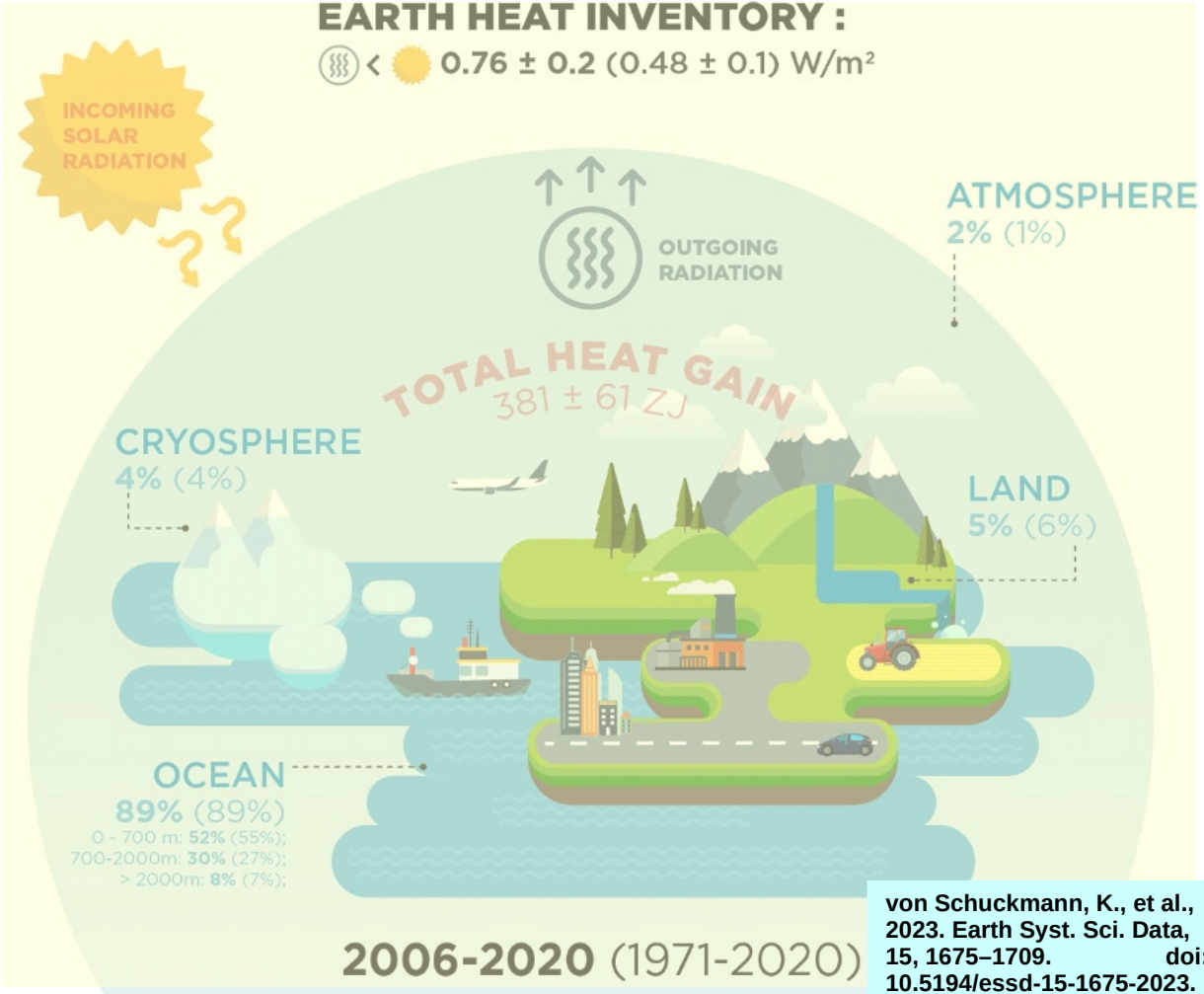

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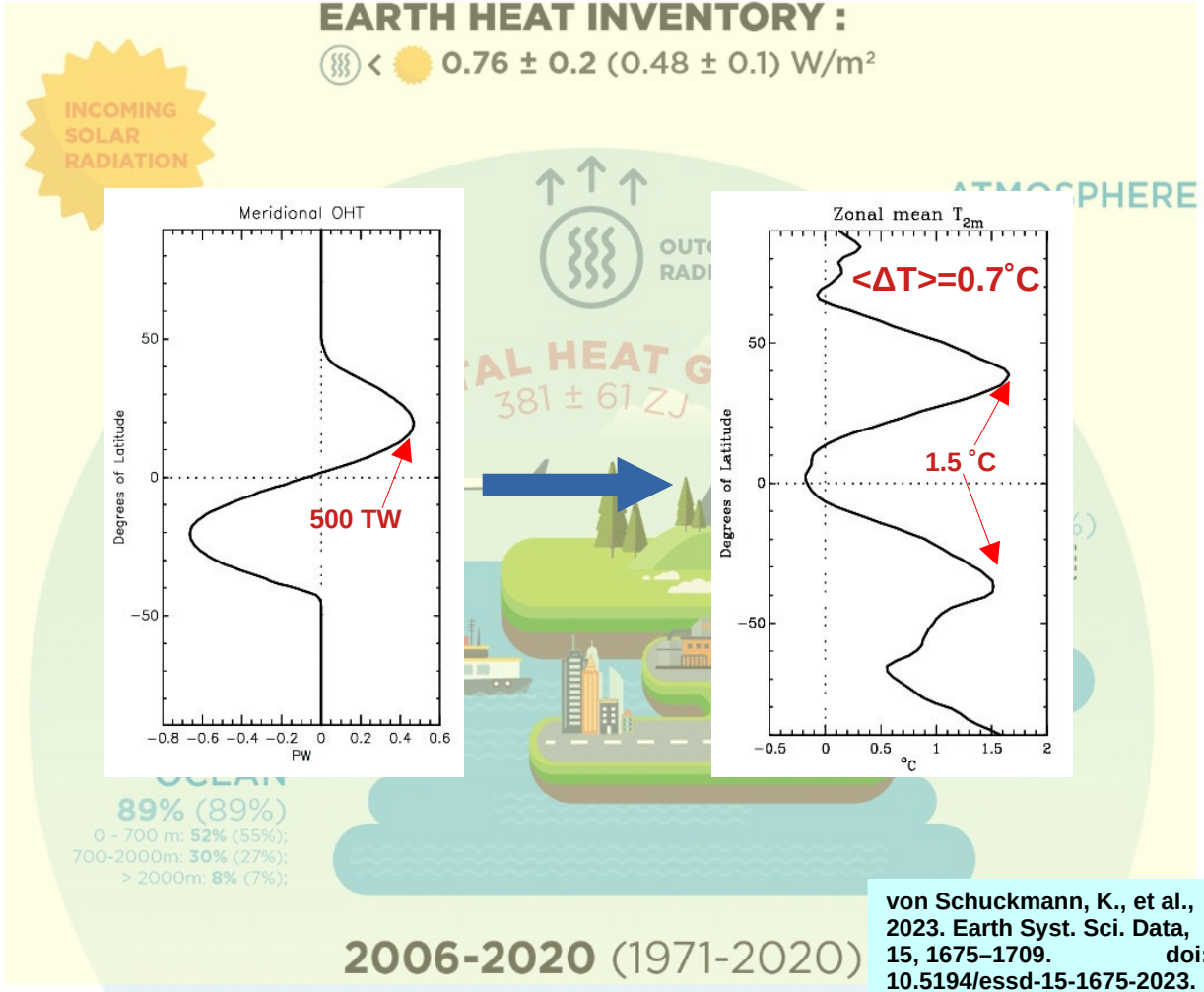

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Fixing energy in CAM

- **2-500 TW *adjusted* by *fixer (physics)***
- caused by ***dme_adjust***, which changes the model state *and* its local enthalpy without any associated boundary fluxes
- => ditch dme_adjust and make an energy-conserving state adjustment instead
- Two possible choices:
  1. **Leave all water consistently mass-less**
  2. **Attach material heat (enthalpy) to water mass**

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1) update CAM's thermodynamic functions using a reference phase f_{ref} and a reference temperature T_0 for the enthalpy of water consistent with reference latent heats, and a zero-point enthalpy h_0 for all water species

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2) adjust the model state at the end of physics conserving enthalpy:

- enthalpy of dry mass adjustment:

$$-\delta h_i^{(dma)} = (\Delta p_i/g)\,\delta q_i^{(f)}\,\left(c_p^d T_i + \phi_s\right)$$

- hydrostatic pressure work:

$$-\delta h_i^{(work)} = -\,(\Delta p_i/g)\,\delta q_i^{(f)}\,(\phi_s - \phi_i)$$

- material enthalpy of water (excl. reference latent heats):

$$\delta h_i^{(mat)} = (\Delta p_i/g)\,\delta q_i^{(f)}\left[c_p^{(f)}\left(T_b^{(f)} - T_0\right) + c_p^{(liq)} T_0 + h_0 + \phi_s\right]$$

- implicit heat due to update of heat capacity of moist air:

$$-\delta h_i^{(imp)} = (\Delta p_i/g)\,\delta q_i^{(f)}\left[\left(c_p^{(f)} - c_p^d\right)(T_i - T_0) + \left(c_p^{(liq)} - c_p^d\right) T_0 + h_0\right]$$

- N.B. all 4 terms are needed to satisfy Eq.(B19) of Lauritzen et al. 2022

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Attach material heat (enthalpy) to water mass

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2) adjust the model state at the end of physics conserving enthalpy:

- all 4 terms are needed to satisfy Eq.(B19) of Lauritzen et al. 2022
- total enthalpy adjustment:

$$\begin{aligned} \delta h_i^{(tot)} &= \delta h_i^{(dma)} + \delta h_i^{(work)} + \delta h_i^{(mat)} + \delta h_i^{(imp)} \\ &= -\left(\Delta p_i / g\right) \delta q_i^{(f)} \left[c_p^{(f)} \left(T_i - T_b^{(f)} \right) + \left(\phi_i - \phi_s \right) \right] \end{aligned}$$

- matches expected material enthalpy boundary flux at potential Φ_s and temperature T_b
- represents heat exchanged between air and water added/removed from the atmospheric column
- ***-> distributed between local height and surface***

Fixing energy in CAM

- **Correct CAM's thermodynamic functions**
- **Conserve hydrostatic energy (=enthalpy) including i.a. hydrostatic pressure work term**
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- **Check that state updates are independent of f_{ref}, T_0, h_0**

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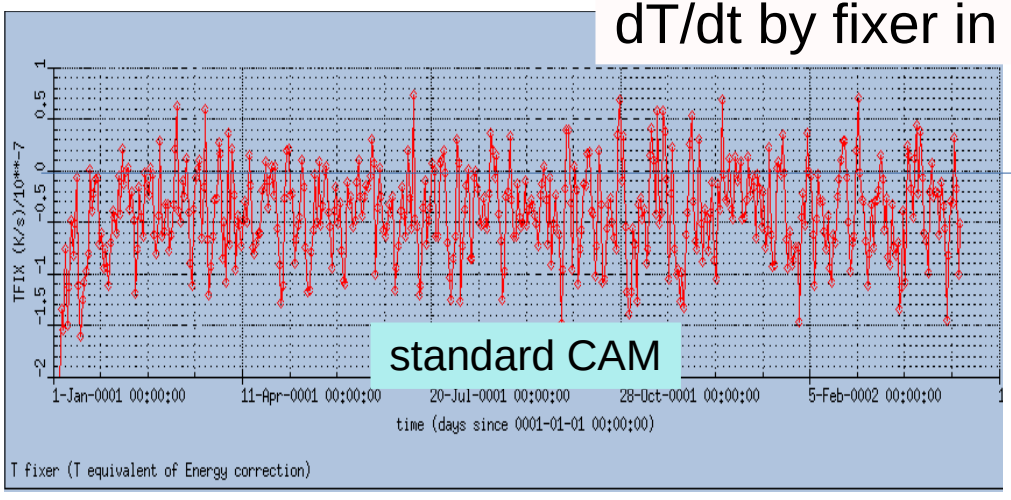
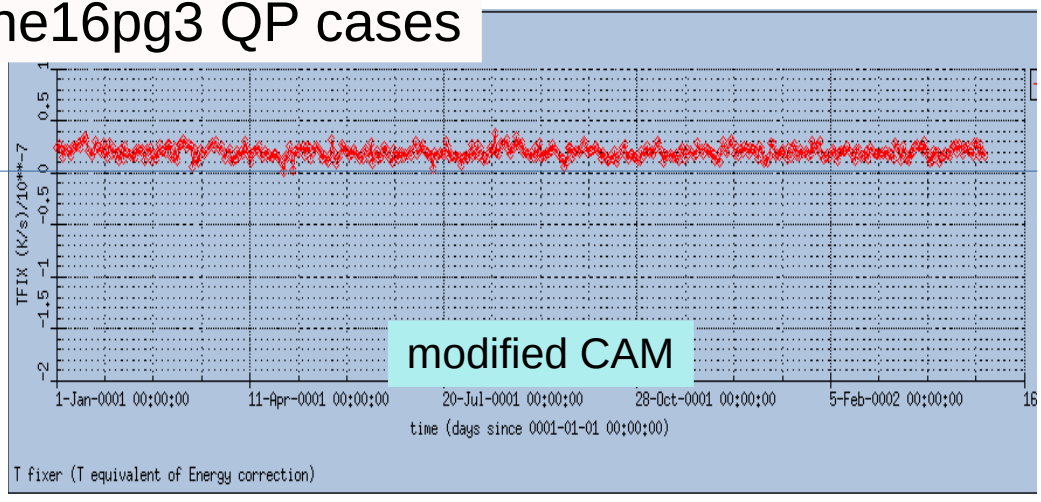
dT/dt by fixer in ne16pg3 QP cases





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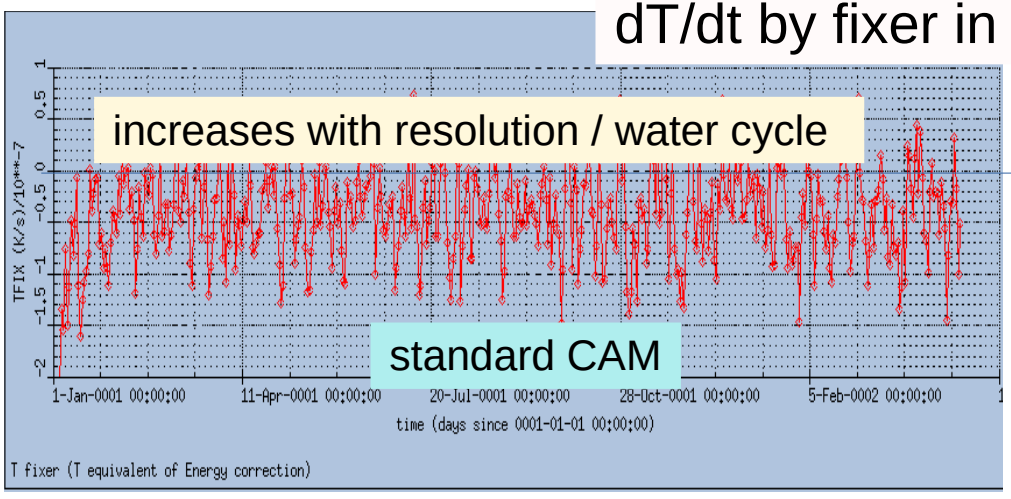

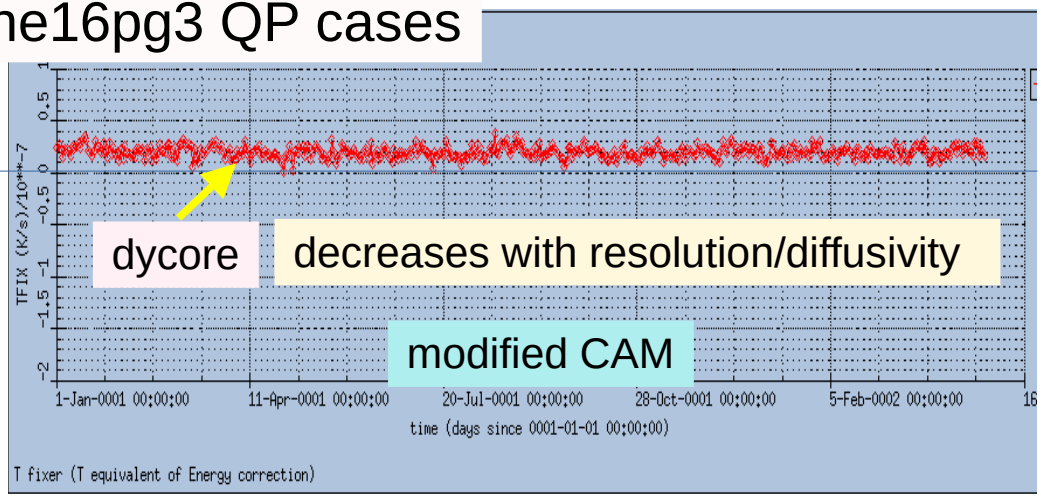

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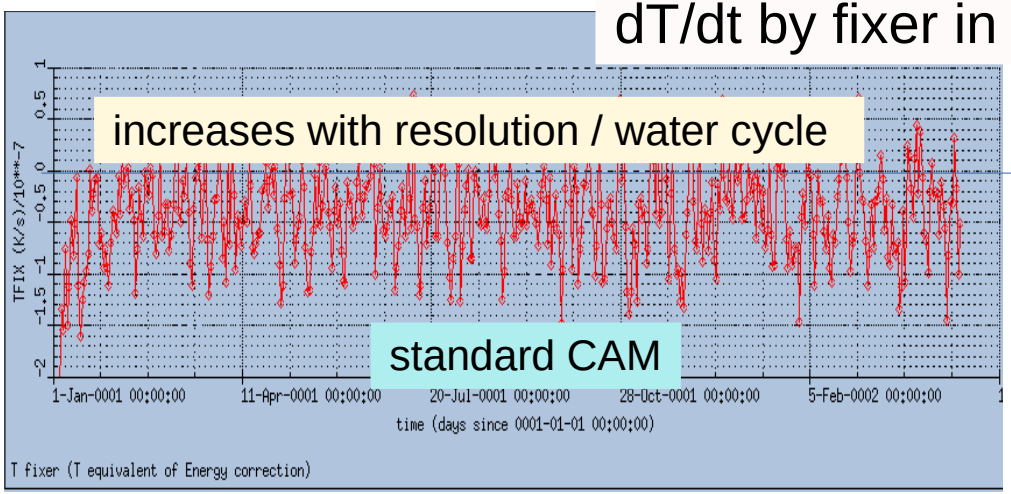

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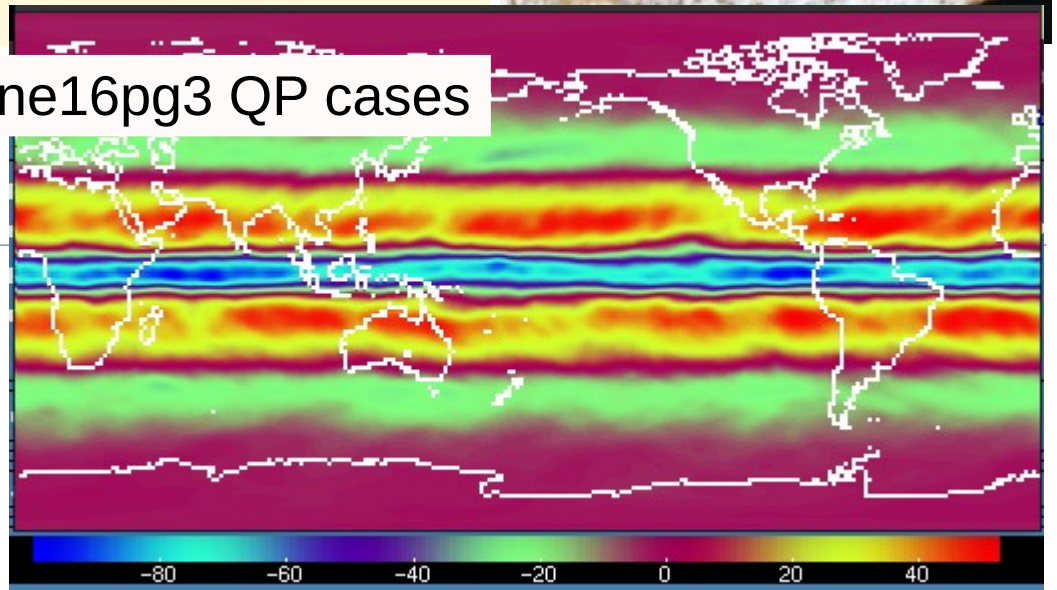

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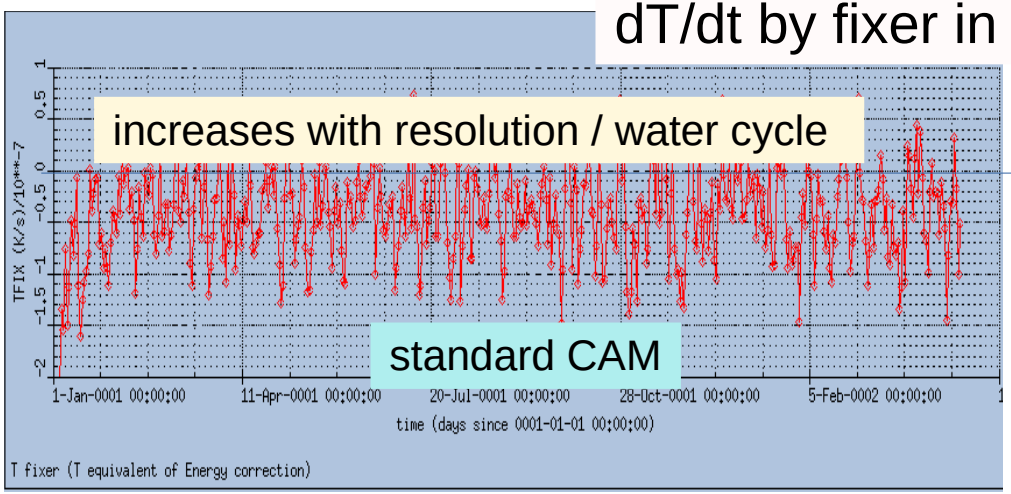

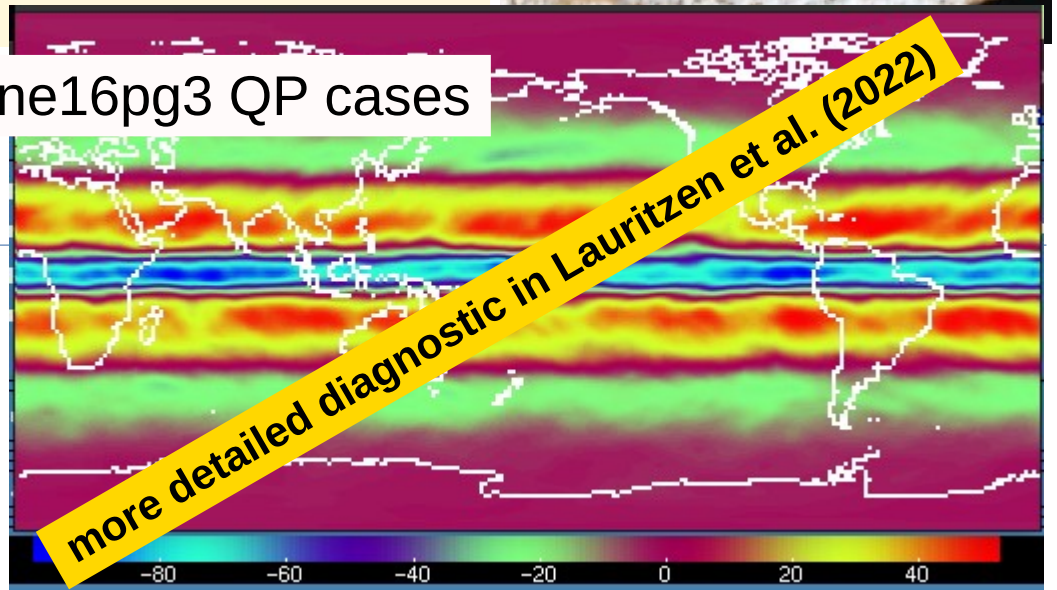

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- standard CAM: 3.4 W m^{-2} K^{-1}
- modified CAM: 2.7 W m^{-2} K^{-1}

a bit preliminary (TOA tuned to ~0 with large CLUBB_C8) but consistent with expectation from increased spurious negative meridional heat transport by nonconservation + fixer.

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currently:

- MOM can accept local material enthalpy fluxes
- BLOM can't, but can accept locally the (dominant) variable latent heat part, and fix the rest
- not sure about CTSM and CISM...

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- ...**if** the time-stepping (or solution-finding) of the state is appropriate
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  - net column heating is unaffected
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- for now, “local conservation” is only achieved column-wise
- even without local conservation, use of global energy fixer may be inappropriate