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Conservation of dry air, water, and energy in CAM and its impact on tropical rainfall

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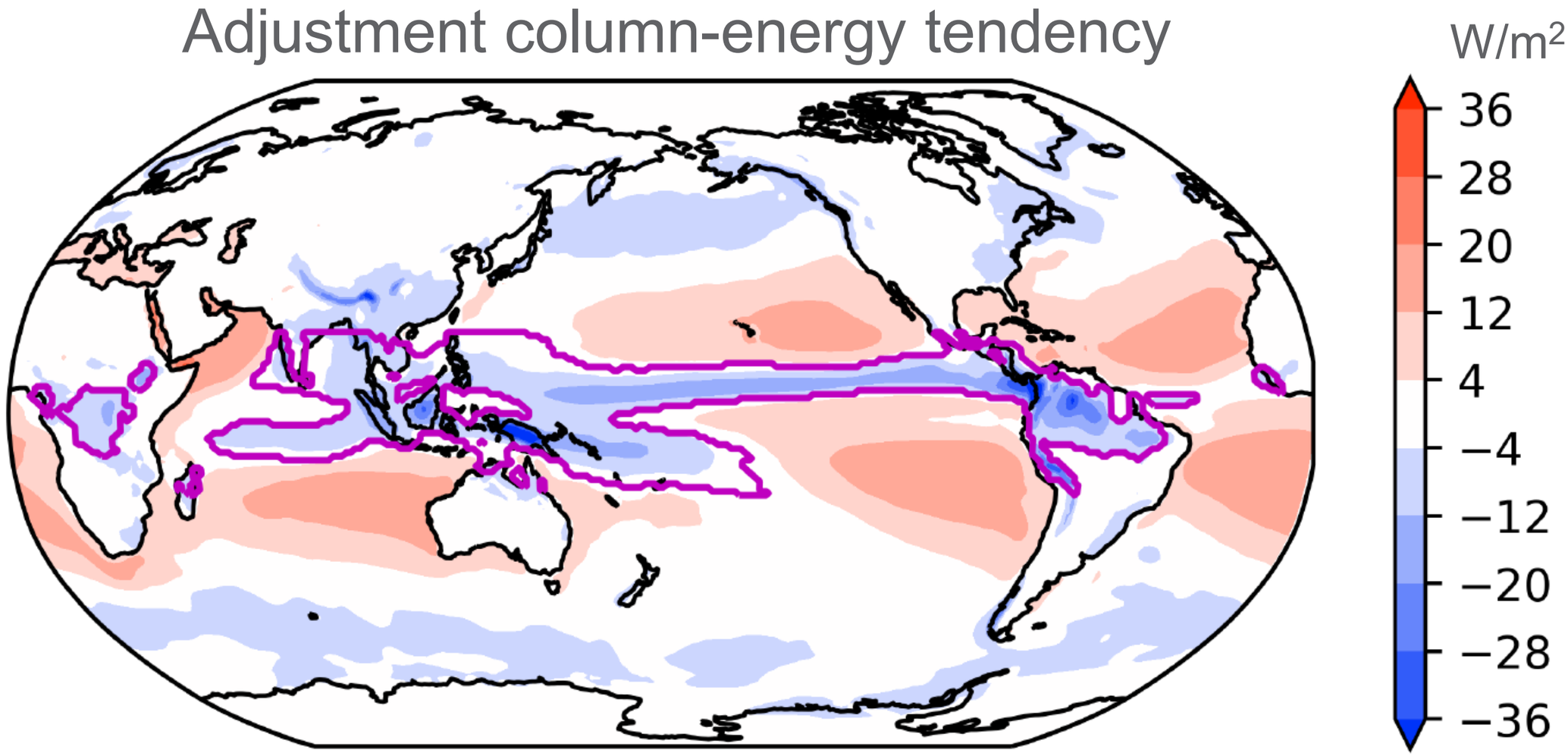
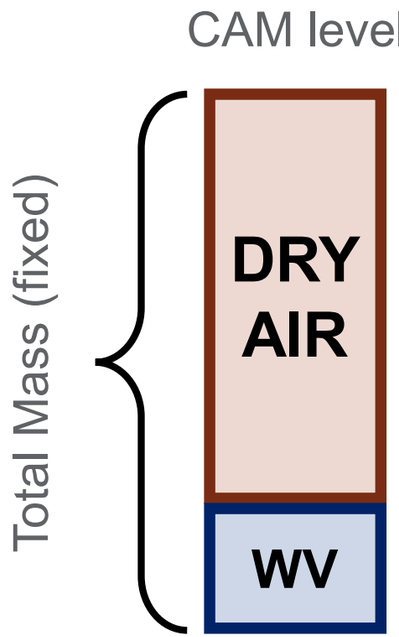
[3]NCAR

Closing the energy budget requires accounting for the column-energy tendency from a mass adjustment routine



Closing the energy budget requires accounting for the column-energy tendency from a mass adjustment routine

CAM use a fixed hydrostatic pressure thickness to compute mass of each vertical layer, which is the sum of dry air and vapor

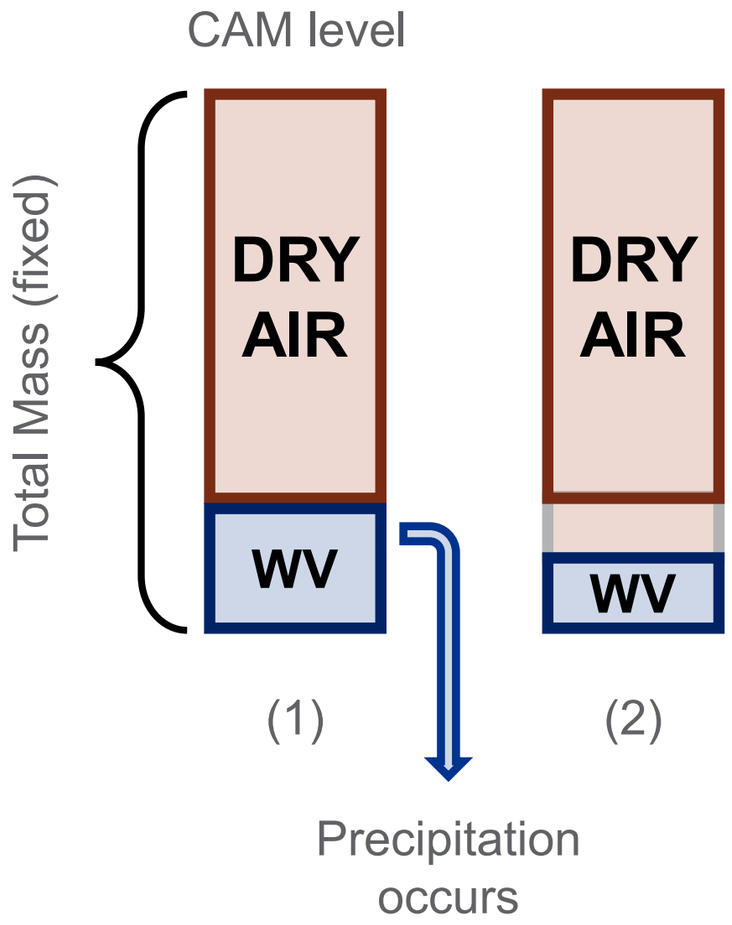


(1)

$$\text{Layer mass} = \frac{\delta^k p}{g} = m_t = m_d + m_v$$

Assumed fixed during physics

Vapor mass can change during the physics, which breaks dry air conservation

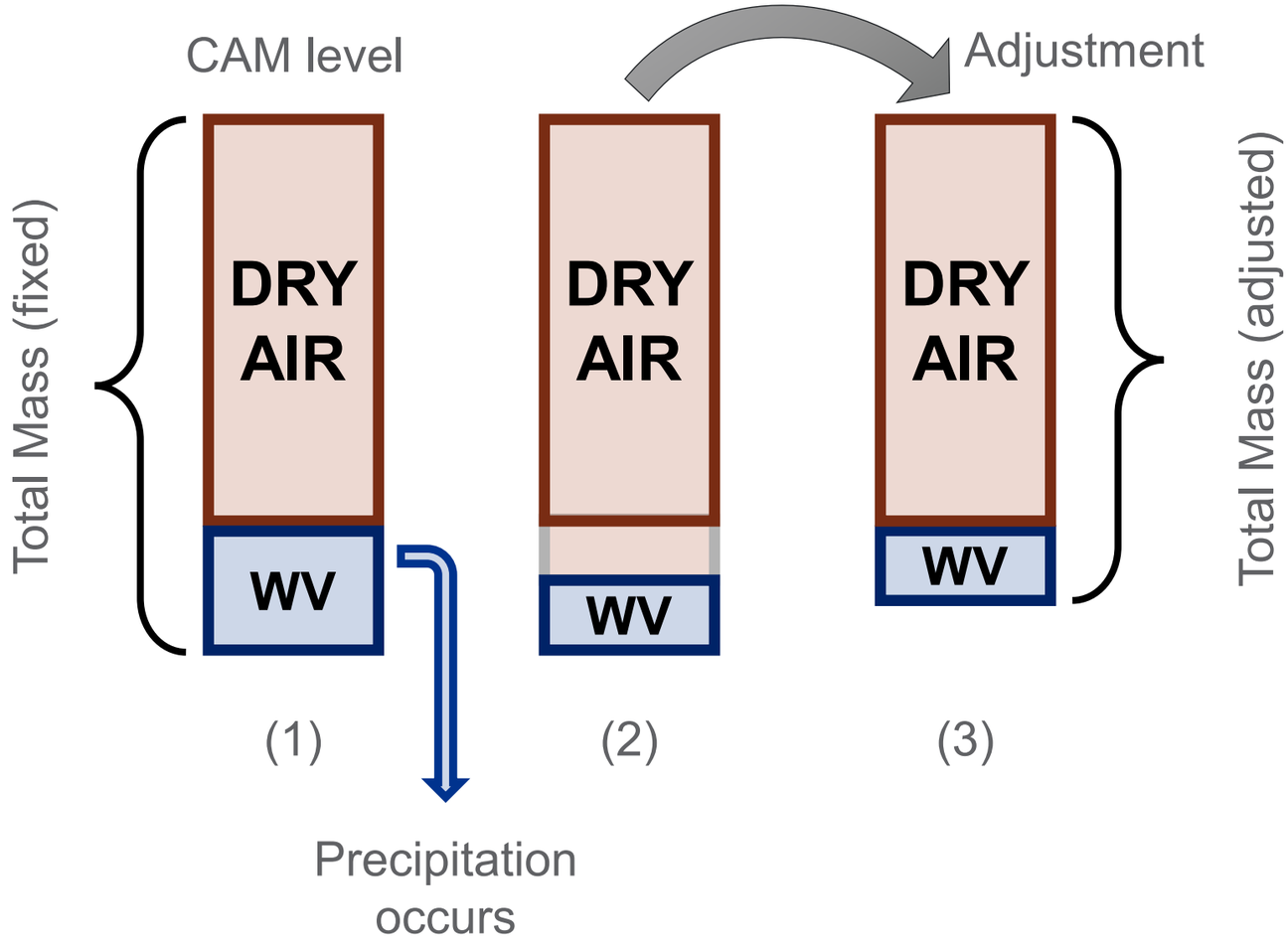


(1) $$m_t = m_d + m_v$$

(2) $$m_t \neq m_d + m^*_v$$

*after physics (m_v)

To avoid spurious dry mass changes, total mass changes to match water vapor mass change



(1) $$m_t = m_d + m_v$$

(2) $$m_t \neq m_d + m^*_v$$

(3) $$m^*_t = m_d + m^*_v$$

*after physics (m_v)
*after adjust (m_t)

This adjustment happens after all of the physics parameterizations have been called.

CAM tracks column-energy budget for conservation purposes

Assumptions

Column-integrated Hydrostatic balance

Sum over *k* levels

$$\varepsilon = \frac{1}{g}\sum_k \underbrace{c_{pd} m_t^k T^k + L_s m_v^k + L_f m_l^k}_{\text{Enthalpy}} + \underbrace{m_t^k \frac{(\mathbf{u}^k)^2}{2}}_{\text{Kinetic Energy}} + \sum_k m_t^k \Phi_s$$

Surface Geopotential

CAM tracks column-energy budget for conservation purposes

Assumptions
Column-integrated
Hydrostatic balance

$$m_t = m_d + m_v$$

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Surface Geopotential

During the adjustment

$$\Delta m_t = \Delta m_v$$

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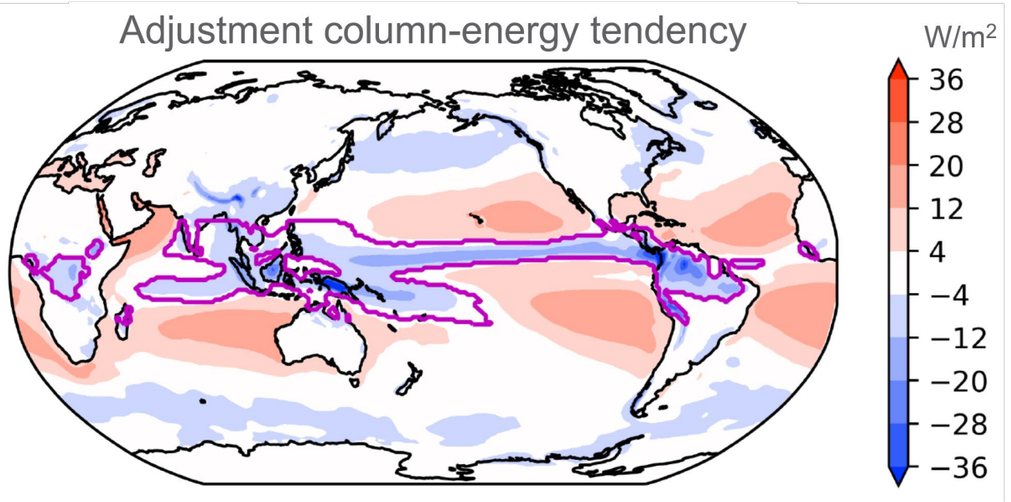
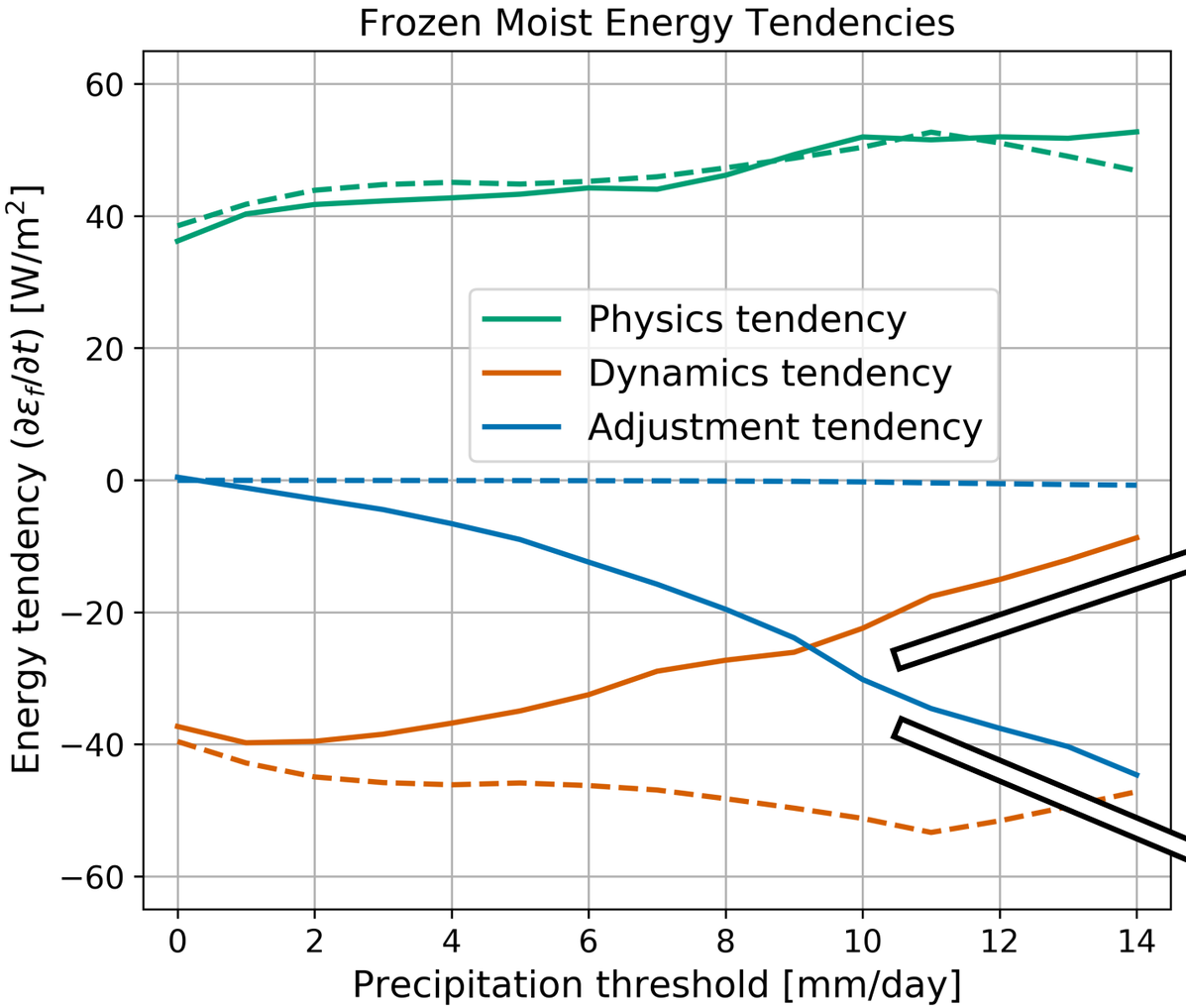
$$\Delta\varepsilon_{\text{adj}} = \sum_k \left(c_{pd}\Delta m_v^k T^k + \Delta m_v^k \frac{\left(\mathbf{u}^k\right)^2}{2} \right) + \sum_k \Delta m_v^k \Phi_s$$



Water vapor is included in the mass used for CAM's energy expression. It has internal, potential, and kinetic energy, just like the dry air. When water vapor changes phase, only its latent energy is retained in the model. The remaining internal, potential, and kinetic energy are left to the global fixer to handle. The remaining local imbalance violates the divergence theorem.

In regions of heavier rainfall, CAM diverges less energy



Physics tendency = SHFLX + LHFLX + RADFLX

Decreasing energy divergence

Increasing energy sink from adjustment

Masking over tropical regions with heavier rainfall

A fix is needed for CAM to satisfy the divergence theorem locally (make atm tendency match TOA + SFC fluxes)

KEY

Lofted water vapor condenses and rains out

Total water vapor energy = Latent energy + Remaining IE + KE + PE

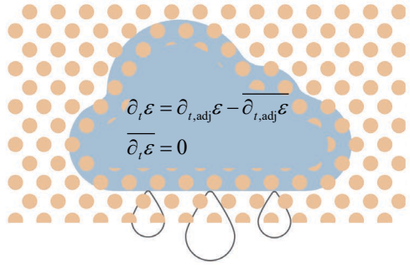
$\partial_t \varepsilon$ = Local time-tendency of column energy

$\overline{\partial_t \varepsilon}$ = Global time-tendency of column energy

PHF = Precipitation heat flux at surface

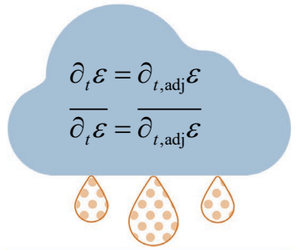
POSSIBLE ENERGY PATHWAYS

DEFAULT CAM6



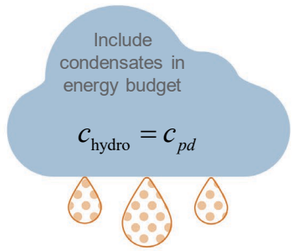
$\mathrm{PHF} = \overline{\mathrm{PHF}} = 0$

A Use adj. energy tend. at surface



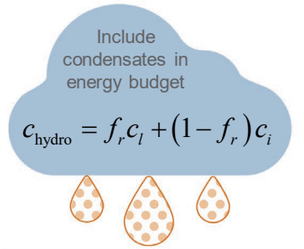
$\mathrm{PHF} = \partial_t \varepsilon_{\mathrm{adj}}$

B Simple enthaply (CAM6)



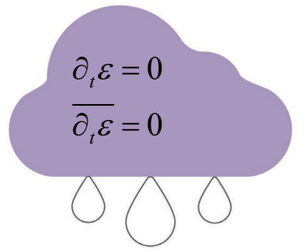
$\mathrm{PHF} = c_{pd} PT_{\mathrm{rain}}$

C Rigorous enthalpy



$\mathrm{PHF} = \left(f_r c_l + (1 - f_r) c_i\right) PT_{\mathrm{hydro}}$

D Local energy fixer



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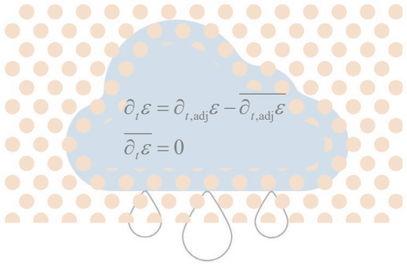

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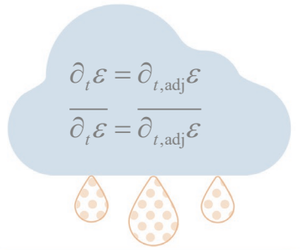

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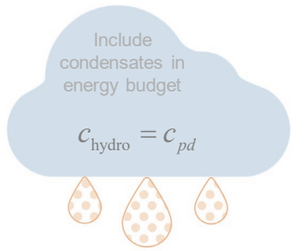

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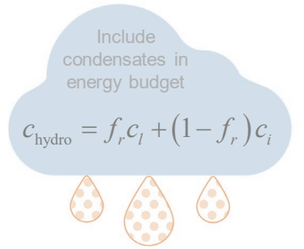
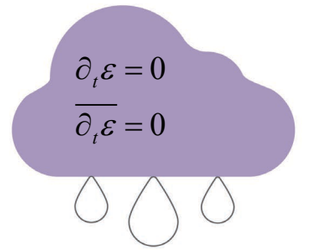


$\mathrm{PHF} = \left(f_r c_l + (1 - f_r) c_i\right) PT_{\mathrm{hydro}}$

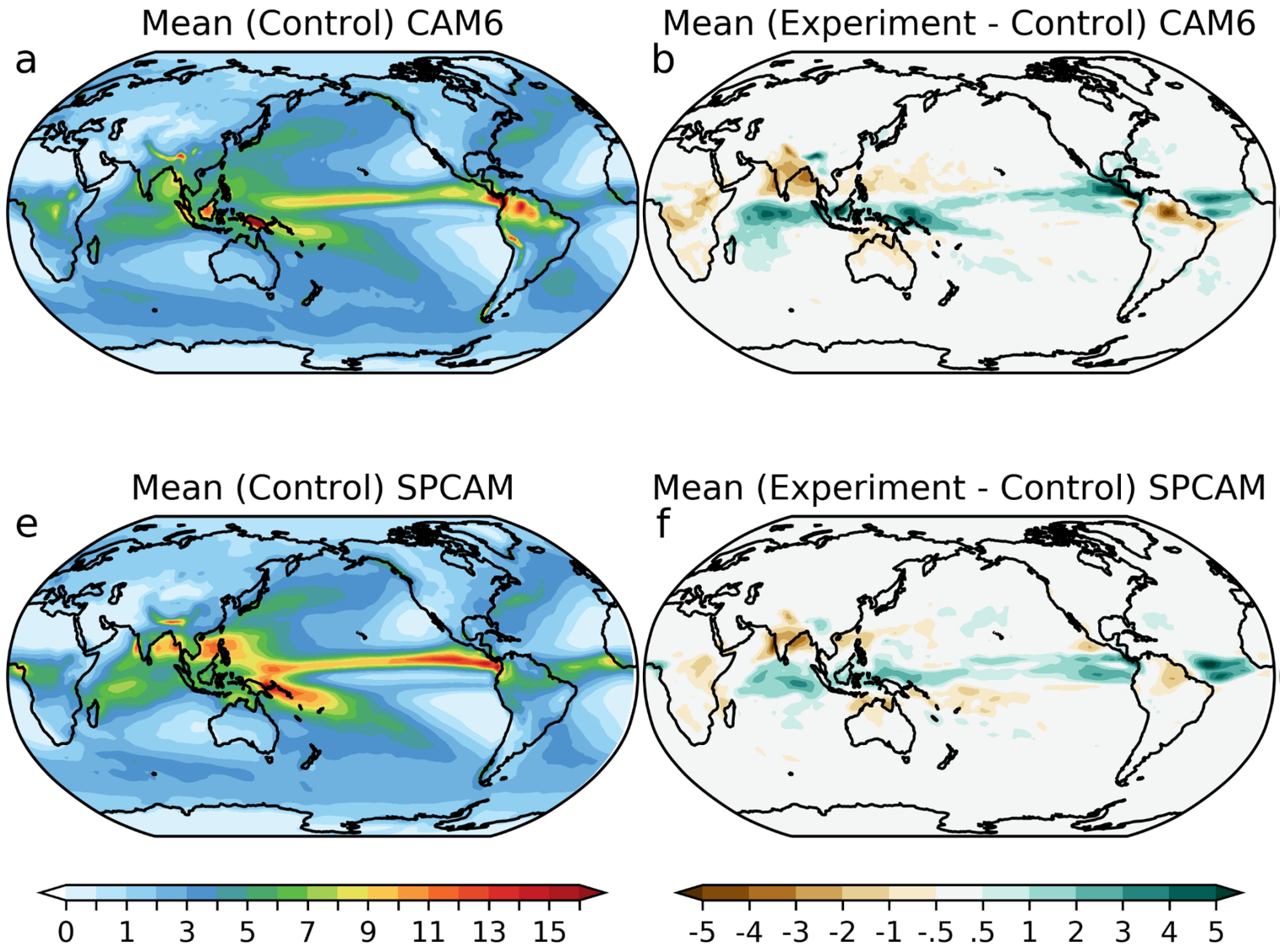
Use the local fixer option for a sensitivity test

D Local energy fixer

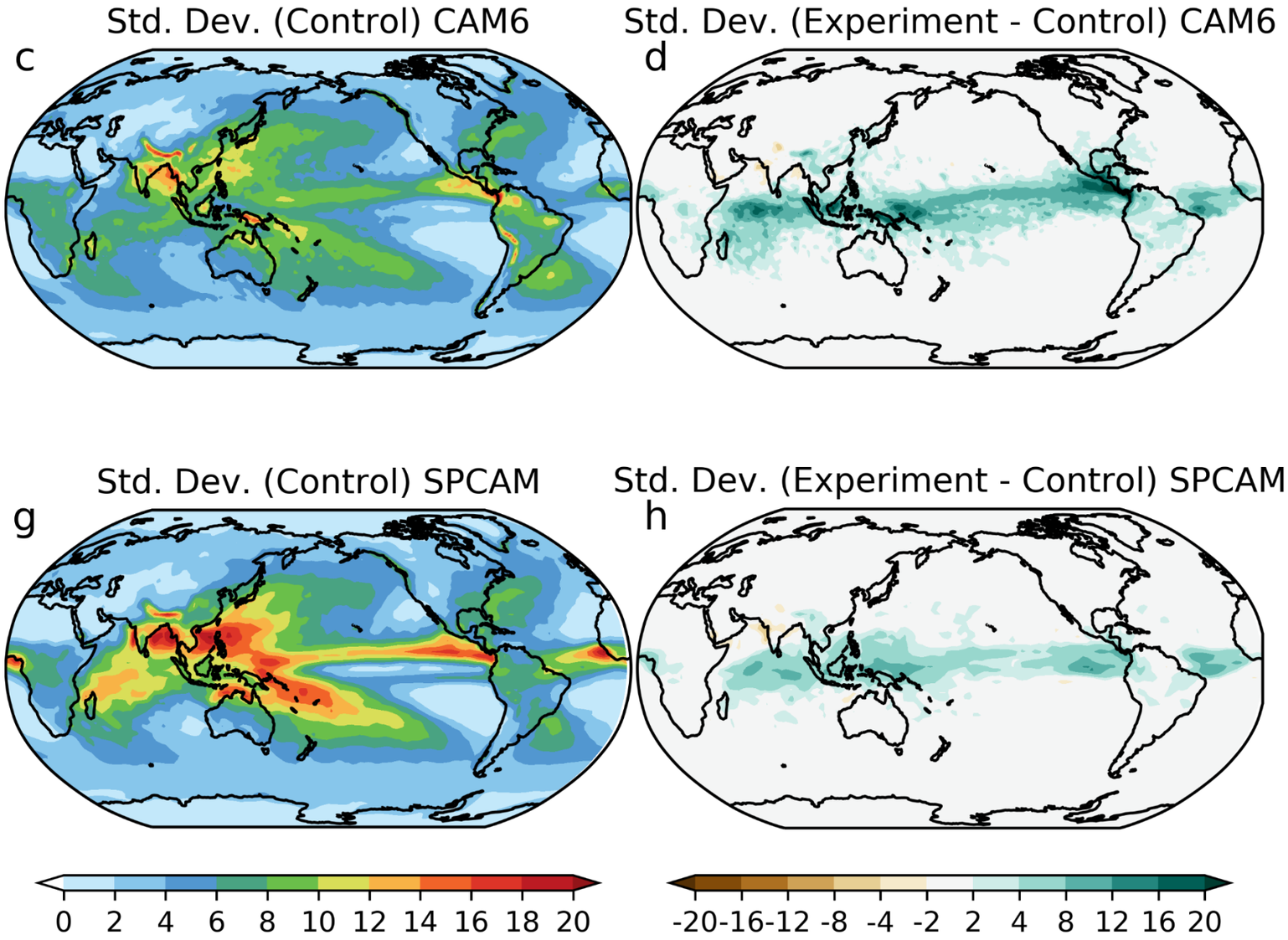


$\mathrm{PHF} = \overline{\mathrm{PHF}} = 0$

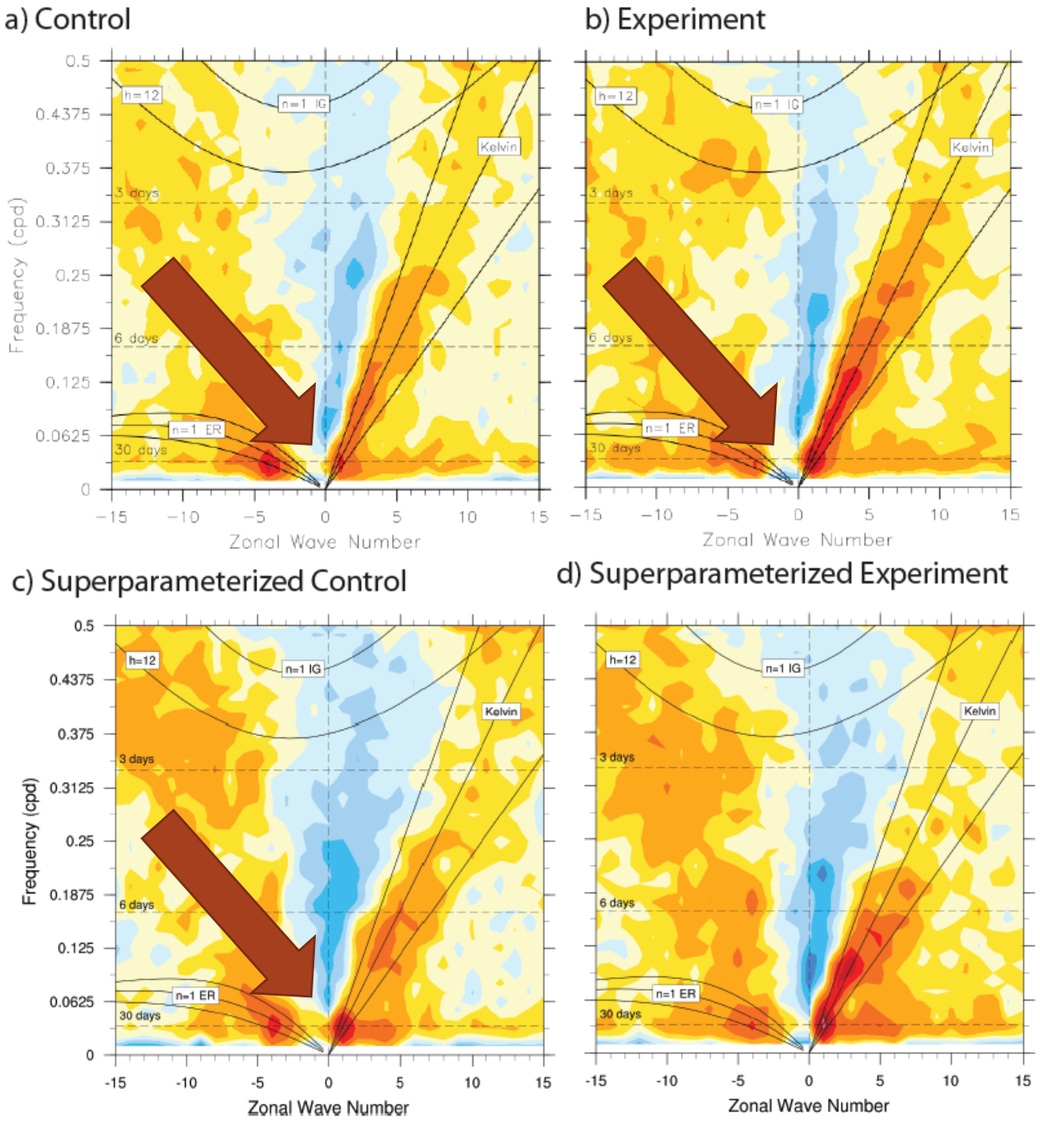
Tested in both parameterized-convection CAM6 and SPCAM. Responses are similar

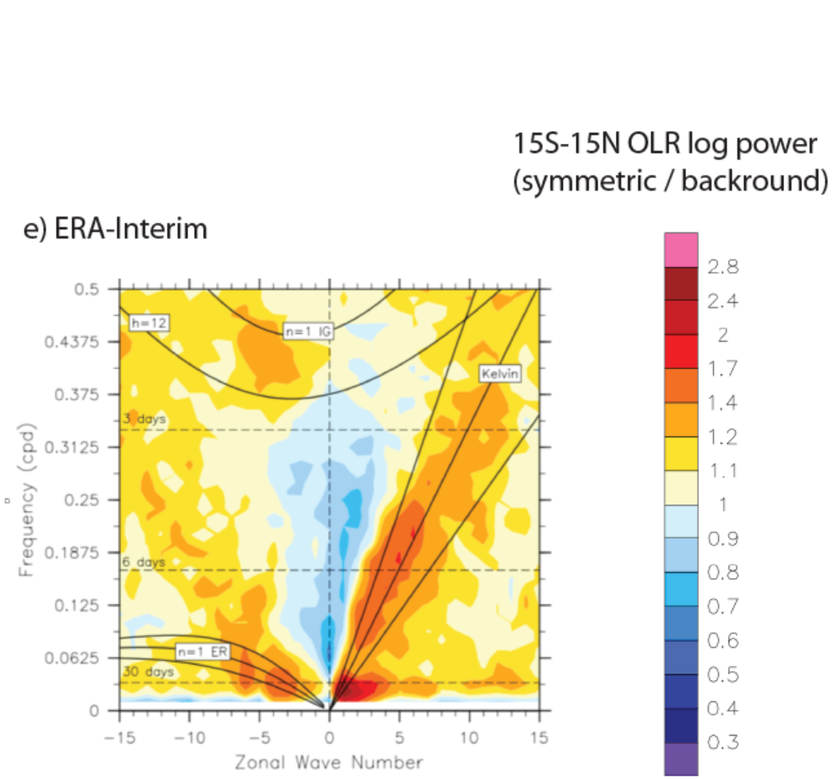


Large increases in daily rainfall variability across the Tropics



Increase in strength of MJO between Experiment and Control similar to the increase between SPCAM and CAM.





What do we takeaway from all of this?

- In CAM, **water vapor has internal, kinetic, and potential energy, but when it condenses only its latent energy is retained by the model,** while the remaining energy is thrown out and left to the global fixer to handle.

- This problem is exposed during a mass adjustment routine, giving it the energy tendency shown

- This **energy error has profound impacts on the hydrologic cycle**, motivating a need to address this issue

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Thank you

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Extra slides

A realistic option that includes all phases of water in the energy budget may have a similar response to our sensitivity experiment, though not as strong