



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

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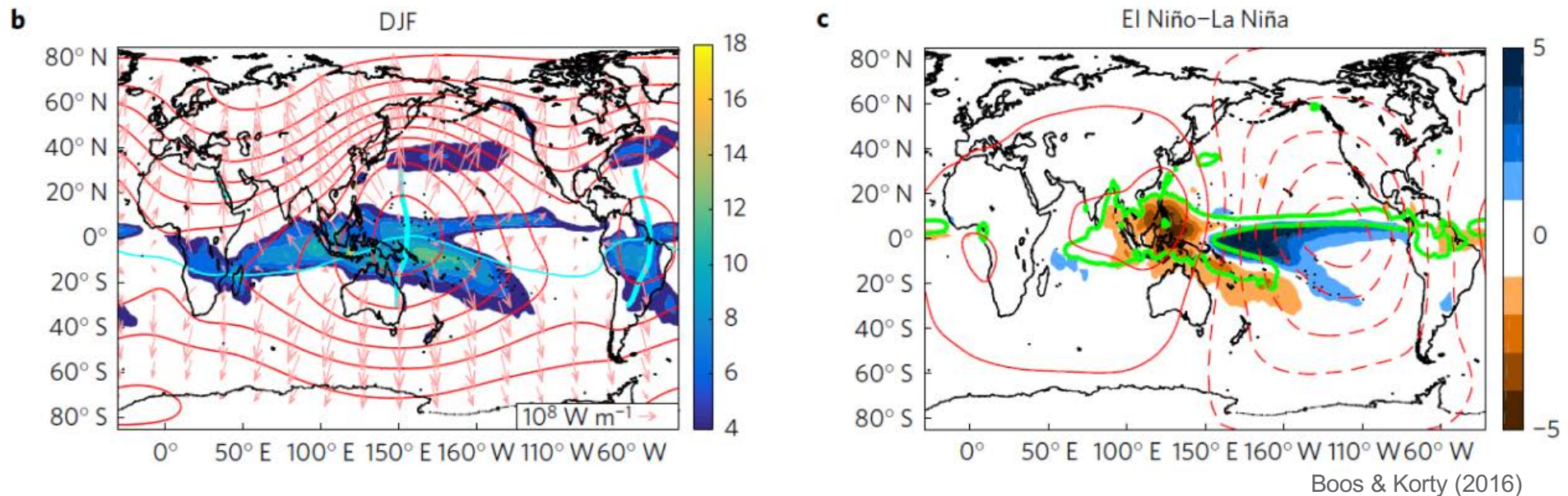
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Regional energy and precipitation budgets linked to create diagnostic and predictive measures of rainfall changes.



Energy flows away from centers of tropical deep convection. Both the flow of energy and the rainfall distribution shift with some climate features like ENSO.

Tried closing the energy budget in CAM, but came up short



The energy budget isn't closing in my CAM runs. What's wrong?

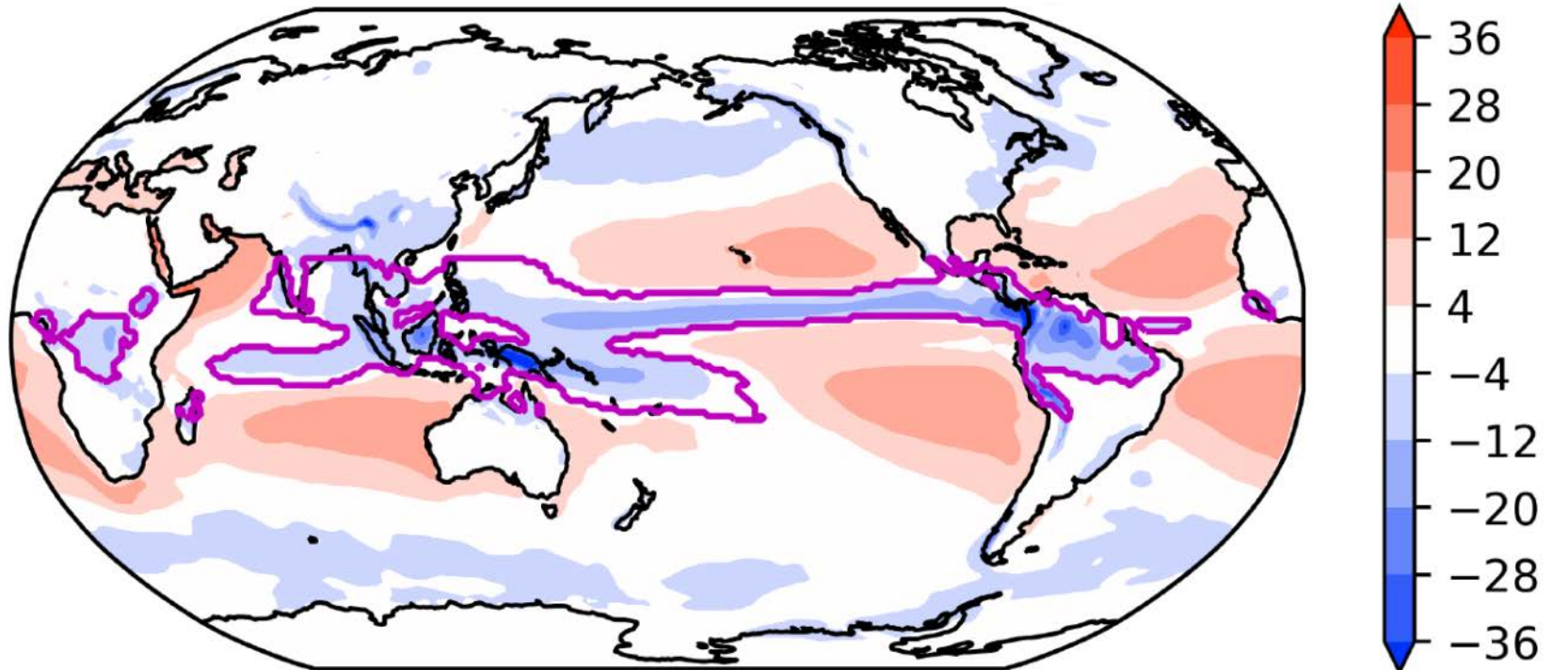
Did you include the adjustment energy tendency?

No. What is that?



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

Adjustment column-energy tendency



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The three big questions that we are going to answer here

1. What is the adjustment process and why does it produce an energy tendency?
2. What impact does this energy tendency have on the simulated hydrologic cycle?
3. How can we make things better?

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An inconsistency in how water is treated in the energy budget

2. What impact does this energy tendency have on the simulated hydrologic cycle?

Dramatic changes to tropical rainfall variability

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Fix the inconsistency with a more rigorous energy budget

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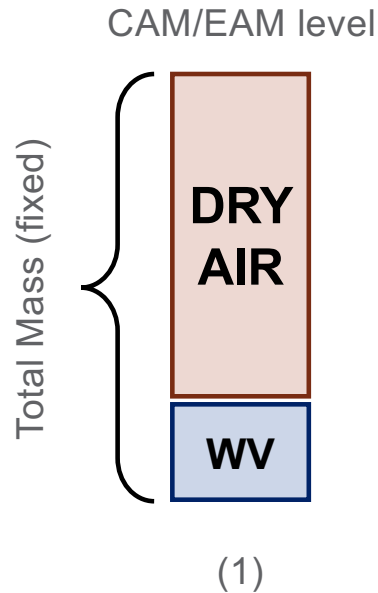
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Fix the inconsistency with a more rigorous energy budget

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

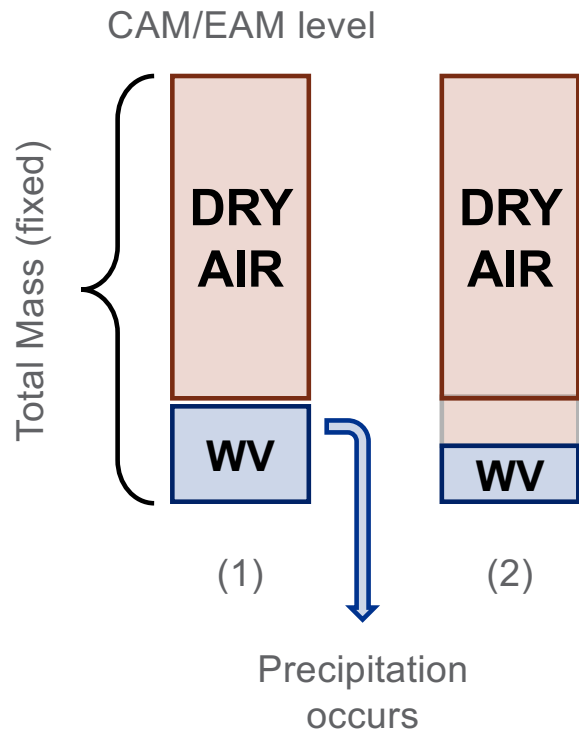


Layer mass = $\frac{\delta^k p}{g} = m_t$

(1)
$$\begin{aligned} p &= d + e \\ m_t &= m_d + m_v \end{aligned}$$

Assumed fixed during physics

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

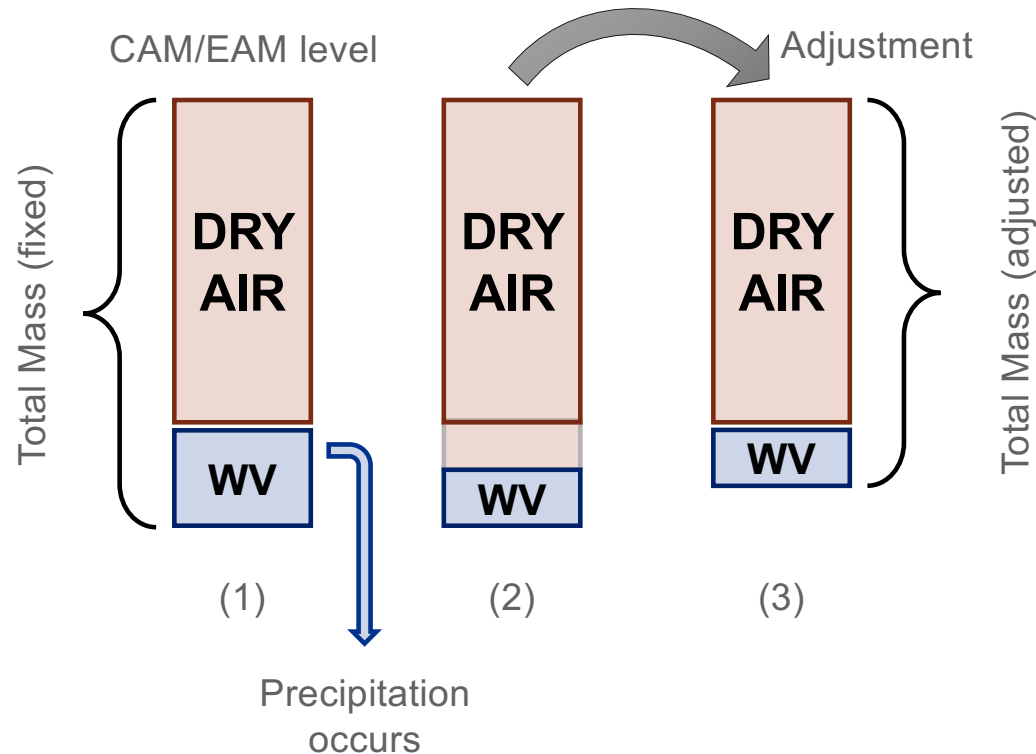


$$(1) \quad m_t = m_d + m_v$$

$$(2) \quad m_t \neq m_d + m_v^*$$

*after physics (m_v)

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



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

$$(2) \quad m_t \neq m_d + m_v^*$$

$$(3) \quad m_t^* = m_d + m_v^*$$

*after physics (m_v)

*after adjust (m_t)

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

CAM (and EAM) tracks column-energy budget for conservation purposes

Assumptions

Column-integrated
Hydrostatic balance

Sum over
 k levels

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

Simple example: Ignore kinetic energy for an oceanic column

Assumptions

Column-integrated
Hydrostatic balance

Sum over
 k levels

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

Enthalpy

$\mathbf{u}^k = 0, \forall k$
 $\Phi_s = 0$

Heating/Cooling is applied to the “total mass” which is held fixed at its initial value during the physics parameterizations

$$\varepsilon = \sum_k c_{pd} m_t^k T^k + L_s m_v^k + L_f m_l^k$$

Changes during physics

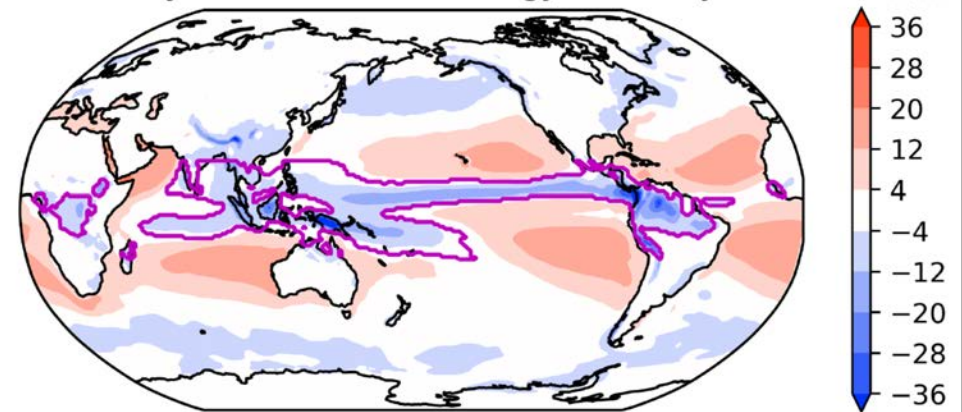
Changes during adjustment

$$\Delta \varepsilon_{\text{phys}} = \sum_k c_{pd} m_t^k \Delta T^k + L_s \Delta m_v^k + L_f \Delta m_l^k$$

$$\Delta \varepsilon_{\text{adj}} = \sum_k c_{pd} \Delta m_t^k T^k$$

$$\Delta \varepsilon_{\text{adj}} = \sum_k c_{pd} \Delta m_v^k T^k$$

Adjustment column-energy tendency



Water vapor is included in the mass used for our energy expression. It has internal, potential, and kinetic energy, just like the dry air. The inconsistency appears when water vapor changes phase. Because we do not keep track of liquid or ice in the energy expression, we throw away the energy associated with any water vapor that has condensed during the physics timestep, creating the adjustment energy tendency.

The preceding interpretation sounds nice, but “sounds nice” isn’t science. Let’s verify it.

- If the adjustment energy tendency really represents untracked energy associated with water, we can verify it by calculating offline budgets of missing energy fluxes associated with water:
 - Full surface enthalpy flux
 - Change in thermal and potential energy of hydrometeors as they fall

$$F_{hw} = \underbrace{c_{pd}ET_{\text{sfc}} - c_{pd}PT_p}_{\text{Surface Missing Enthalpy flux (SMH)}} + \underbrace{L_sE - L_fP_{\text{rain}}}_{\text{Latent heat flux (accounted for in model)}}$$

Hydrometeors warm up as they fall



Rain starts up high and cold, i.e., with a large potential energy and small thermal energy



As they fall...
...potential energy goes into heating atmosphere.
...atmosphere loses energy to heat hydrometeors.

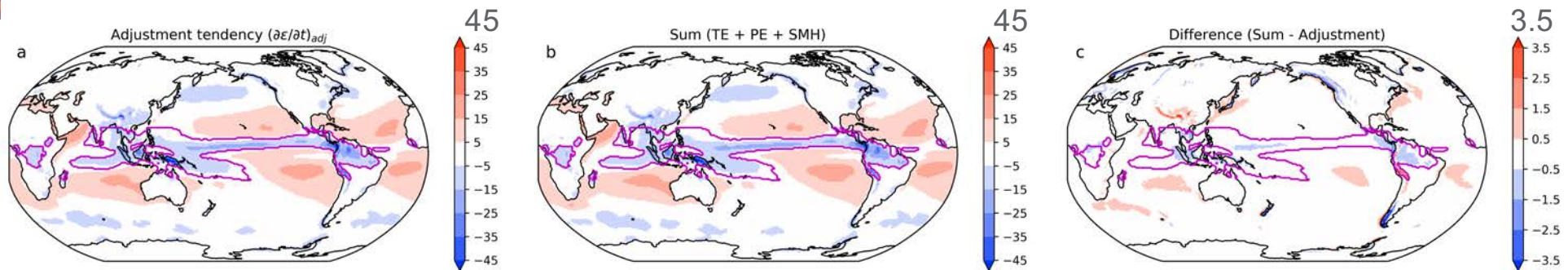


Rain ends up low and warm, i.e., with a small potential energy and large thermal energy



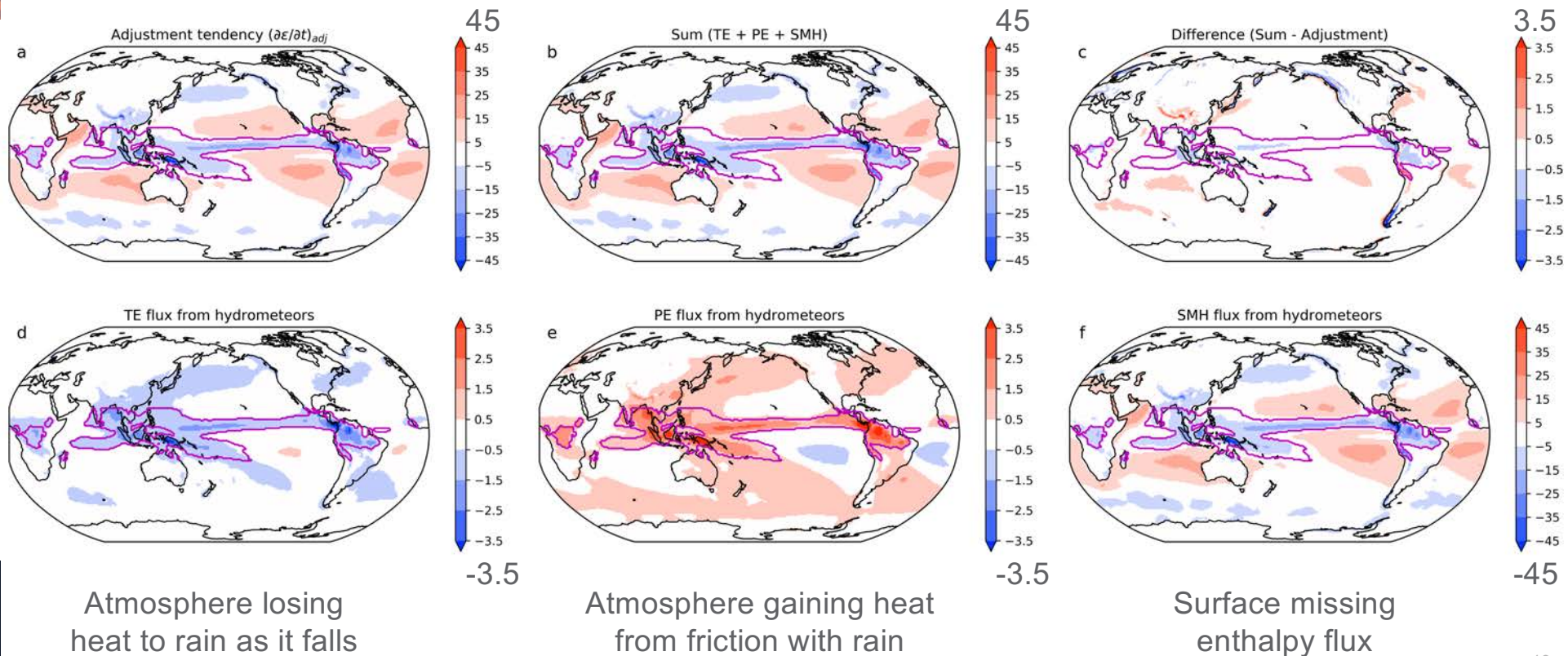
The missing terms sum up to be approximately equal to the adjustment energy tendency

Note that the colorbar limits aren't all the same.



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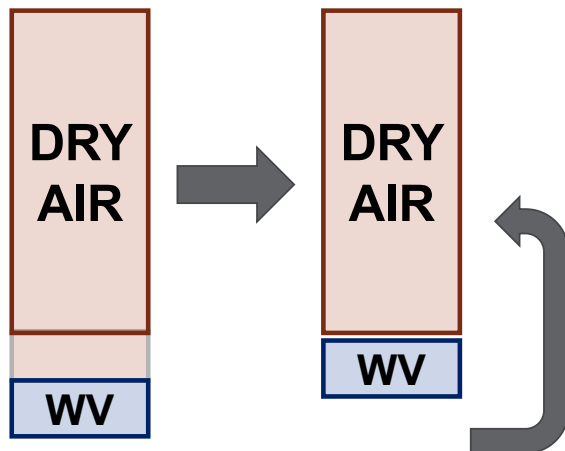
Dramatic changes to tropical rainfall variability

3. How can we make things better?

Fix the inconsistency with a more rigorous energy budget

An easy first test on whether any of this matters is to simply “give back” the energy lost

CAM/EAM level

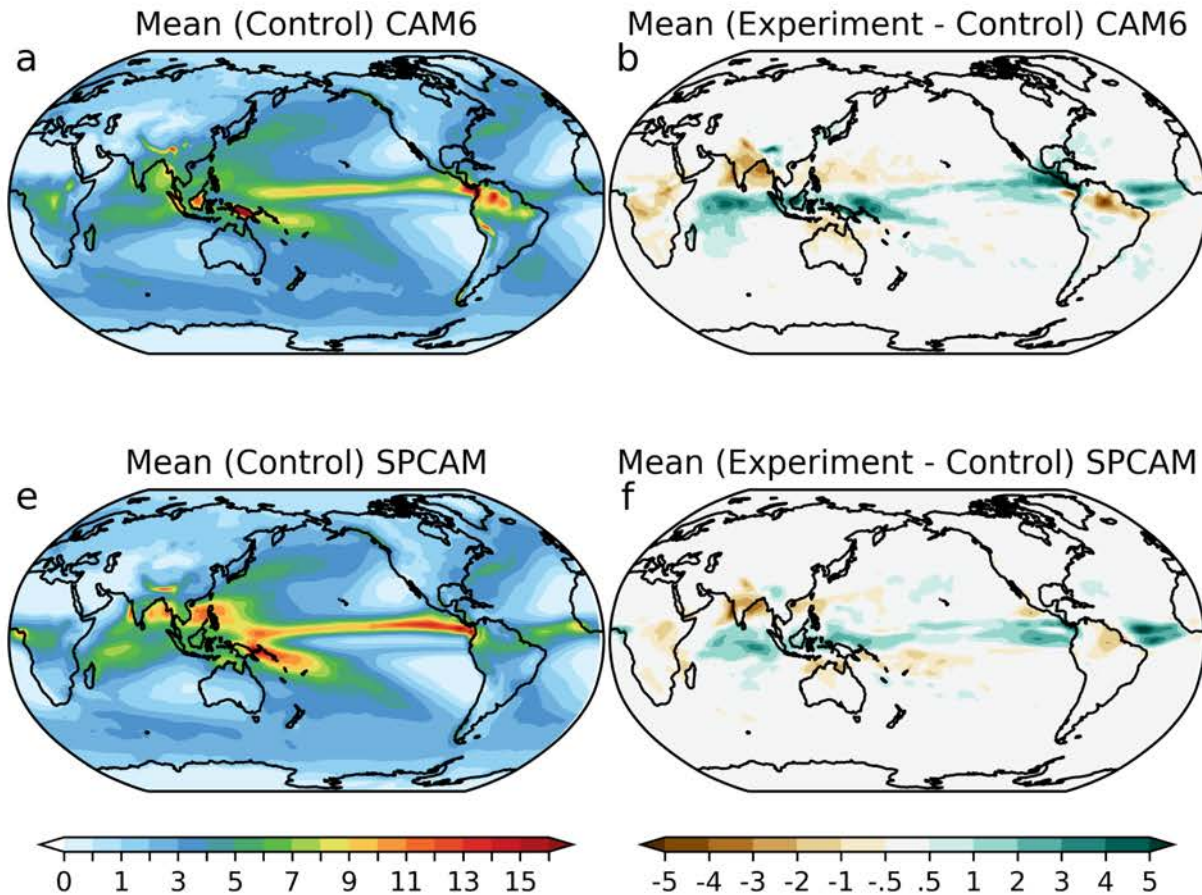


$$T_{n+1}^k = \frac{T_{n*}^k}{1 - q_{v,n}^k + q_{v,n*}^k}$$

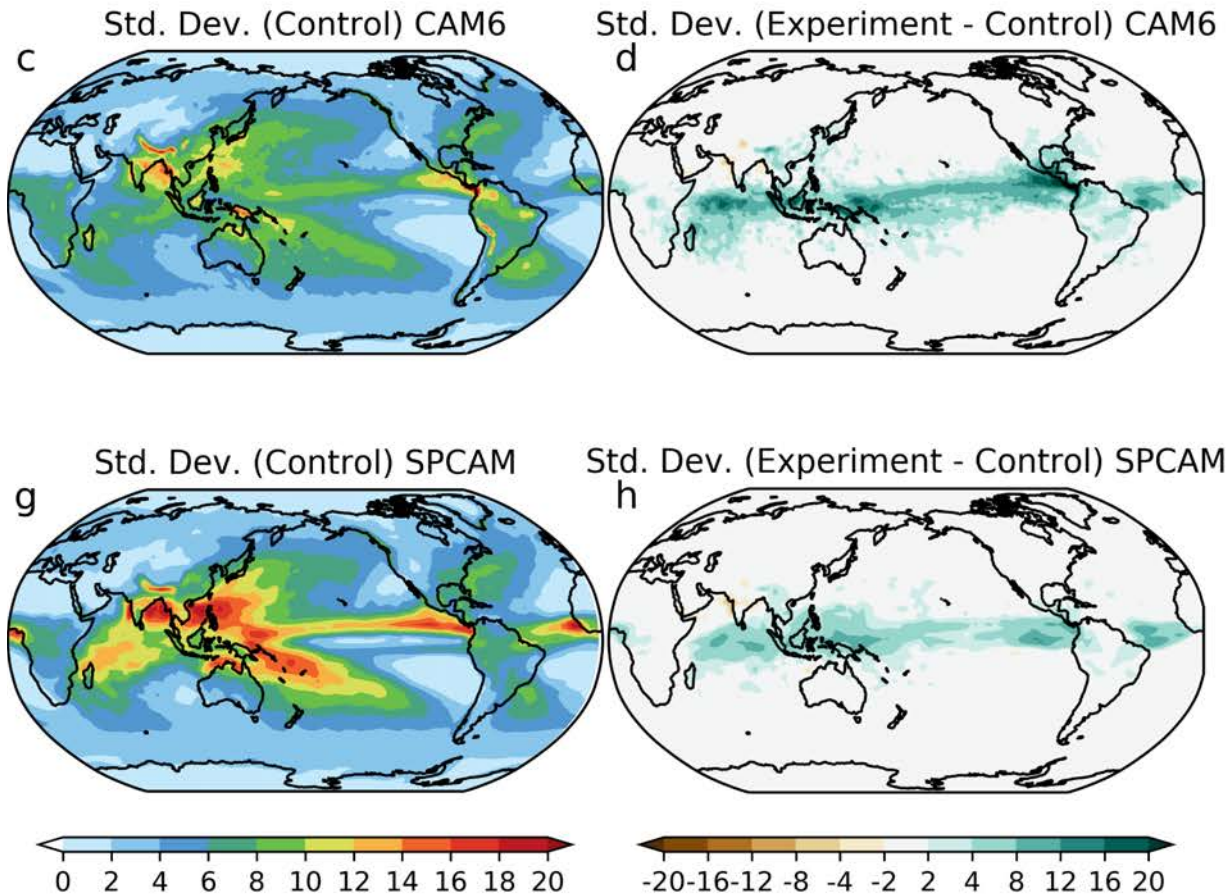
Energy associated
with the mass lost
during adjustment is
given back to the
atmosphere.

The experimental adjustment “gives back” the energy thrown away when water vapor condenses by retroactively assuming that heating and cooling is only applied to dry air plus uncondensed water vapor.

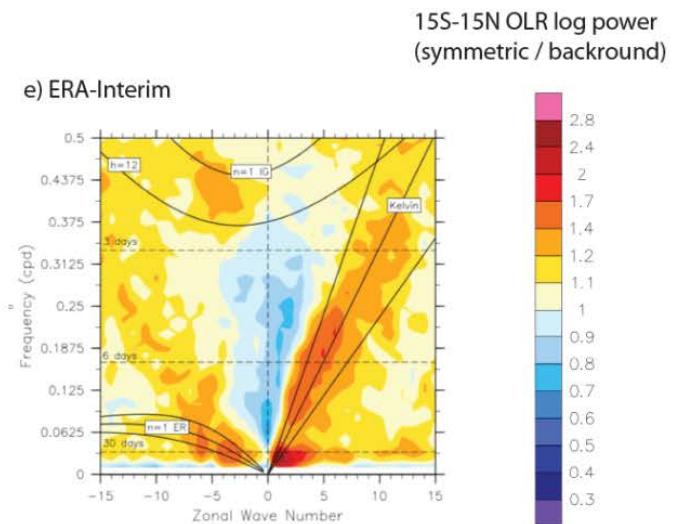
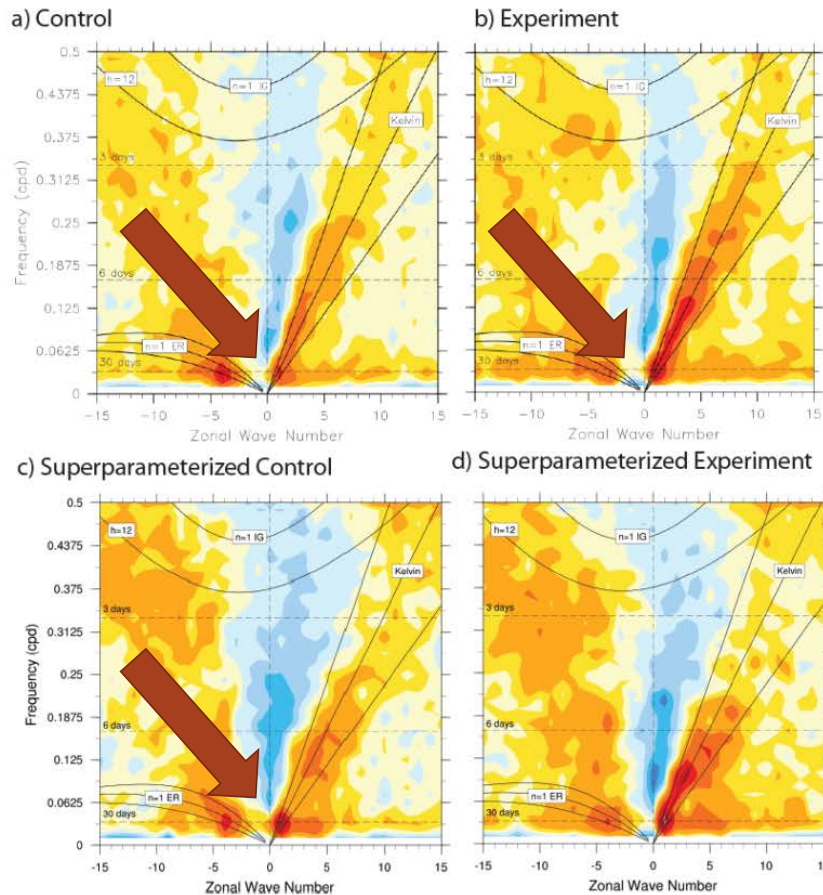
Tested in both parameterized-convection CAM6 and SPCAM. Responses are similar



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.



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Surface missing enthalpy flux is reminiscent of our old friend, the IEFLX fixer

$$F_{hw} = \underbrace{c_{pd}ET_{sfc} - c_{pd}PT_p}_{\text{Surface Missing Enthalpy flux (SMH)}} + L_sE - L_fP_{\text{rain}}$$

Surface Missing Enthalpy flux (SMH)

Surface missing enthalpy flux is reminiscent of our old friend, the IEFLX fixer

$$F_{hw} = \underbrace{c_{pd}ET_{sfc} - c_{pd}PT_p}_{\text{Surface Missing Enthalpy flux (SMH)}} + L_s E - L_f P_{\text{rain}}$$

Surface Missing Enthalpy flux (SMH)

$$\text{IEFLX} = c_{p,sw}ET_{sfc} - c_{p,sw}PT_{sfc}$$

IEFLX needed because EAM and MPAS-Ocean don't compute surface enthalpy flux the same way

We can compute a more rigorous version of surface enthalpy flux for water

$$F_{hw} = \underbrace{c_{pd}ET_{sfc} - c_{pd}PT_p}_{\text{Surface Missing Enthalpy flux (SMH)}} + L_s E - L_f P_{\text{rain}}$$

Surface Missing Enthalpy flux (SMH)

$$\text{IEFLX} = c_{p,sw}ET_{sfc} - c_{p,sw}PT_{sfc}$$

IEFLX needed because EAM and MPAS-Ocean don't compute surface enthalpy flux the same way

What should the surface enthalpy flux for water actually be?

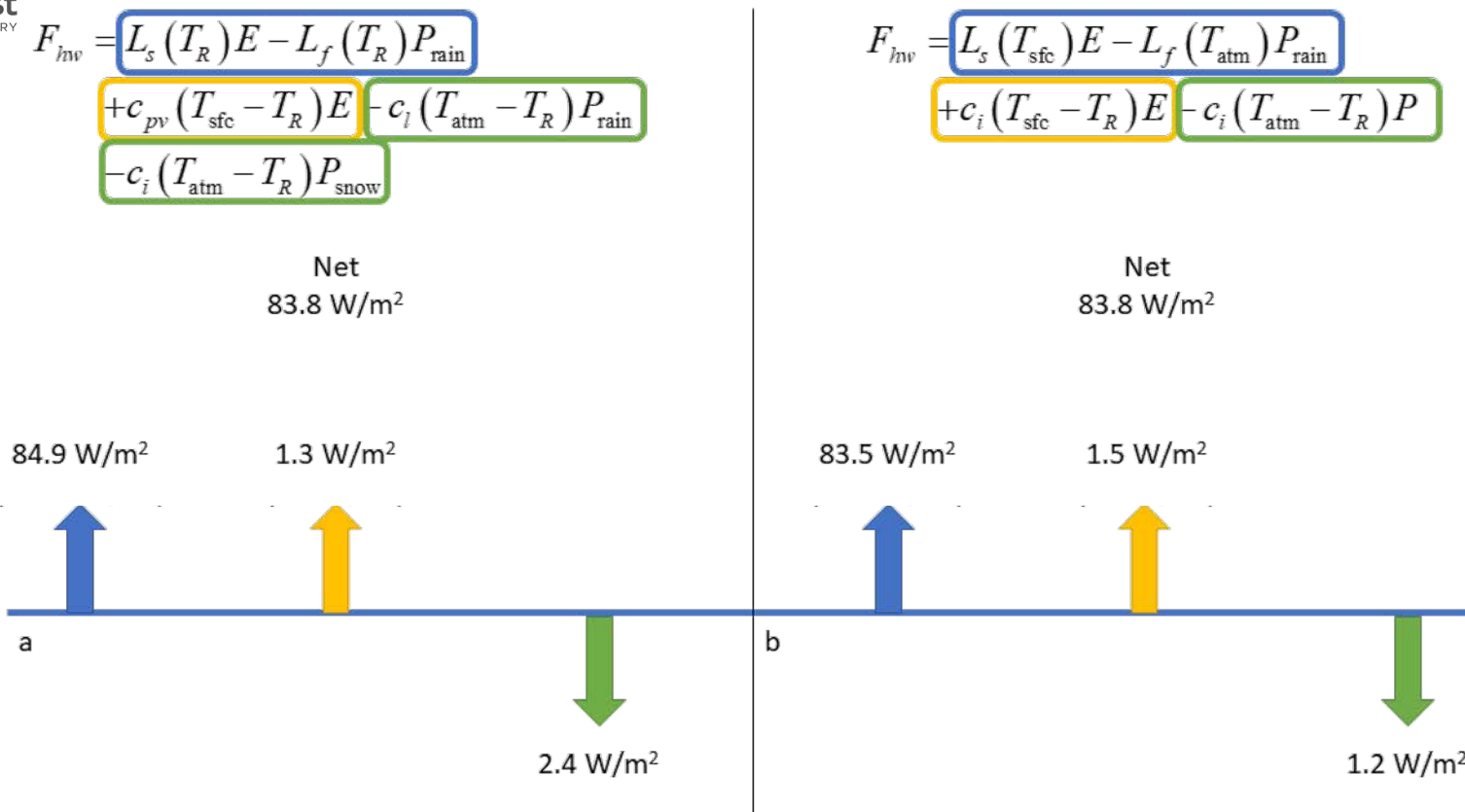
$$F_{hw} = \underbrace{c_{pv}(T_{sfc} - T_R)E - c_l(T_{\text{atm}} - T_R)P_{\text{rain}} - c_i(T_{\text{atm}} - T_R)P_{\text{snow}}}_{\text{Surface Missing Enthalpy flux (SMH)}} + \underline{L_s(T_R)E - L_f(T_R)P_{\text{rain}}}$$

Surface Missing Enthalpy flux (SMH)

$$F_{hw} = c_i(T_{sfc} - T_R)E - c_i(T_{\text{atm}} - T_R)P + L_s(T_{sfc})E - L_f(T_{\text{atm}})P_{\text{rain}}$$

Surface enthalpy flux for water can be expressed in other equivalent forms

Different surface enthalpy flux formulations show pitfalls of simplifying assumptions

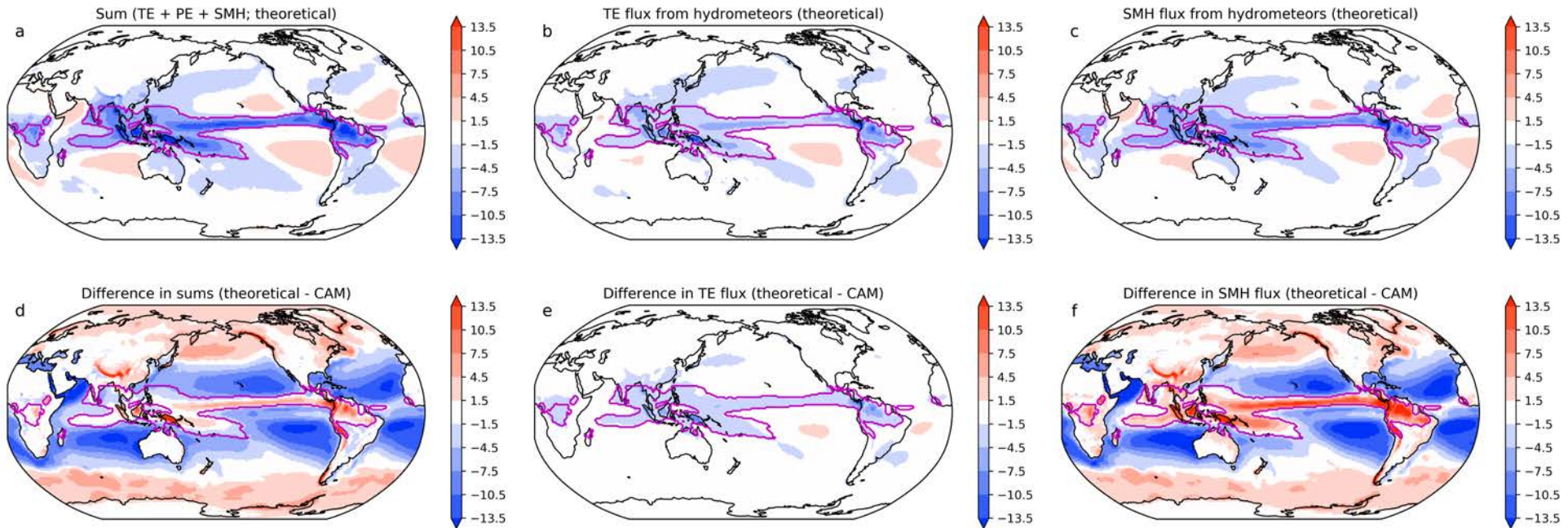


IEFLX takes a ~1 W/m² overestimate in surface enthalpy flux (from ocn → atm) and makes it 0.4 W/m² worse... oops

The “better” version is significantly different from the CAM version

Atmosphere losing
heat to rain as it falls

Surface missing
enthalpy flux



Top row uses the rigorous enthalpy treatment from the previous slides. Bottom row shows the difference between this rigorous treatment and what we computed before using expressions that were consistent with the CAM6 energy framework.

What do we takeaway from all of this?

- In CAM/EAM, **water vapor has energy, but liquid and ice do not**. This leads to spurious energy sinks when vapor changes phase
- 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
- We can **go in one of three directions**:
 - Remove water vapor from the mass in the energy equation and make it a **dry mass energy budget**
 - Live with the inconsistency but **pass the adjustment energy tendency to the surface** so that the coupled model is balanced
 - Include **all phases of water in the energy budget** and use the **correct surface enthalpy fluxes for all components**



Thank you

