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RESEARCH ARTICLE
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Key Points:

- Closing total energy budgets in Earth System Models without *ad hoc* fixers is a monumental task
- Largest errors are from missing

Reconciling and Improving Formulations for Thermodynamics and Conservation Principles in Earth System Models (ESMs)

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and many discussion with M. Taylor and R. Roehrig

On the implementation of explicit enthalpy fluxes in CESM3

(CESM=NCAR's Community Earth System Model)

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Motivation:

- CESM version 3 is using a new ocean model component (GFDL's MOM6; = Modular Ocean Model version 6)

- MOM6 explicitly accounts for energy changes associated with the heat content of water fluxes, or in other words, does not neglect temperature dependent term in the latent heat terms, e.g.:

Latent heat of sublimation (solid → water vapor):

$$L_s(T) = L_{s,00} + \left(c_p^{(wv)} - c_p^{(ice)}\right)(T - T_{00}), \text{ where } L_{s,00} \equiv h_{00}^{(wv)} - h_{00}^{(ice)}.$$

I will be referring to the missing terms as "enthalpy flux terms"

Motivation:

Please note that I am trying to do this while we are developing our CMIP7 model … changes that are theoretically simple and easy to implement in toy models are much much harder to implement in full modeling systems!

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Many global atmosphere models assume constant latent heats …

My goal is to reformulate the atmospheric component of CESM to use variable latent heats … as you will see that is much easier said than done!

1st we need to derive/introduce the total energy formula for the atmosphere …

Latent heat of sublimation (solid → water vapo

$$L_s(T) = L_{s,00} + \left(c_p^{(wv)} - c_p^{(ice)}\right)(T - T_{00}), \text{ where } L_{s,00} \equiv h_{00}^{(wv)} - h_{00}^{(ice)}.$$

I will be referring to the missing terms as “enthalpy flux terms”

Assume:

- Primitive equations (hydrostatic, shallow atmosphere, ideal gas)
- Assume model top pressure is constant
- All components of moist air have the **same temperature** and move with the **same horizontal velocity**
- Assume that water entering the atmosphere (evaporation, snow drift, sea spray) has **same temperature** as water leaving the atmosphere (dew, liquid and frozen precipitation)

Then it can be shown that the following globally integrated total energy equation holds:

$$
\begin{aligned}
\frac{\partial}{\partial t} \iiint \rho^{(d)} \Bigg\{ \sum_{\ell \in \mathcal{L}_{all}} m^{(\ell)} \left(K + \Phi_s\right) + c_p^{(d)} T + m^{\left(H_2O\right)} \left[c_p^{(ice)} \left(T - T_{00}\right) + h_{00}^{(ice)}\right] \\
+ m^{(wv)} L_s(T) + m^{(liq)} L_f(T) \Bigg\}\, dA\, dz \\
= \iint \Big\{ F_{net}^{\left(H_2O\right)} \left(\tilde{K}_s + \Phi_s\right) + F_{net}^{\left(H_2O\right)} \left[c_p^{(ice)} \left(\tilde{T}_s - T_{00}\right) + h_{00}^{(ice)}\right], \\
+ F_{net}^{(wv)} L_s\left(\tilde{T}_s\right) + F_{net}^{(liq)} L_f\left(\tilde{T}_s\right) + F_{net}^{(turb,rad)} \Big\}\, dA \qquad (77)
\end{aligned}
$$

$$\left(\text{ice reference enthalpy}, \tilde{T}_s \equiv T_{atm,s} = T_{surf,s}\right)$$

Additional assumptions made in CAM (Community Atmosphere Model; atmosphere component of CESM):

- Constant latent heats and **cp=cpdry**:

Latent heat of sublimation (solid → water vapor):

$$L_s(T) = L_{s,00} + \cancel{\left(c_p^{(wv)} - c_p^{(ice)}\right)(T - T_{00})}, \text{ where } L_{s,00} \equiv h_{00}^{(wv)} - h_{00}^{(ice)}.$$

- Mass = dry air and water vapor (no condensates)

$$\mathcal{L}_{H_2O} \equiv \{wv, \cancel{cl, ci, rn, sw, gr}\}$$

- Assume total mass constant during physics updates => **no enthalpy and K/PHIS flux terms!**

$$\frac{\partial}{\partial t}\iiint \rho^{(d)} \left\{ \sum_{\ell \in \mathcal{L}_{all}} m^{(\ell)} (K + \Phi_s) + c_p^{(d)} T + m^{(H_2O)} \left[c_p^{(ice)} (T - T_{00}) + h_{00}^{(ice)}\right] + m^{(wv)} L_s(\cancel{T}) + m^{(liq)} L_f(\cancel{T}) \right\} dA\, dz$$

$$= \iint \left\{ \cancel{F_{net}^{(H_2O)} (\tilde{K}_s + \Phi_s) + F_{net}^{(H_2O)} \left[c_p^{(ice)} (\tilde{T}_s - T_{00}) + h_{00}^{(ice)}\right]}, + F_{net}^{(wv)} L_s(\cancel{\tilde{T}_s}) + F_{net}^{(liq)} L_f(\cancel{\tilde{T}_s}) + F_{net}^{(turb,rad)} \right\} dA \qquad (77)$$

$$\left(\text{ice reference enthalpy, } \tilde{T}_s \equiv T_{atm,s} = T_{surf,s}\right)$$

Goal: undo assumptions in CAM (dycore, physics, coupling to surface)

Spectral-element dycore: DONE (https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2017MS001257)

- changed to a variable latent heats formulation

$$c_p = \frac{\sum_{\ell \in \mathcal{L}_{\text{all}}} c_p^{(\ell)} m^{(\ell)}}{\sum_{\ell \in \mathcal{L}_{\text{all}}} m^{(\ell)}}$$

- added condensates to the mass of air

$$\rho = \rho^{(d)} \left(\sum_{\ell \in \mathcal{L}_{\text{all}}} m^{(\ell)} \right)$$

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

Goal: undo assumptions in CAM (dycore, physics, coupling to surface)

Change **global energy fixer** to use dynamical core total energy formula
(fixes dynamical core total energy dissipation, physics dynamics coupling errors, “dry-mass” adjustment)

- CAM accommodates several dynamical cores (spectral-elements, MPAS, FV3, FV) and each core uses a different total energy formula; implemented using a dycore specific variable that is passed to energy subroutine:

$$\texttt{cp\_or\_cv\_dycore} = \begin{cases} c_p^{(d)} & \text{, FV} \\ \frac{\sum_{\ell \in \mathcal{L}_{all}} m^{(\ell)} c_p^{(\ell)}}{\sum_{\mathcal{L}_{all}} m^{(\ell)}} & \text{, SE} \\ \frac{R^*}{R^{(d)}} c_v^{(d)} & \text{, MPAS} \end{cases}$$

-> dynamical core energy dissipation will be fixed with hydrostatic total energy formula consistent with dynamical core

See also Eldred et al., (2022)
https://doi.org/10.1002/qj.4353

Goal: undo assumptions in CAM (dycore, physics, coupling to surface)

- scale physics temperature tendencies for energy consistency with the dynamical core:

  Heating in CAM physics added under constant pressure assumption using cpdry:

$$\underbrace{\texttt{ptend\%s}}_{\text{CAM physics code}} = \frac{d}{dt}\left(c_p^{(d)} T\right)$$

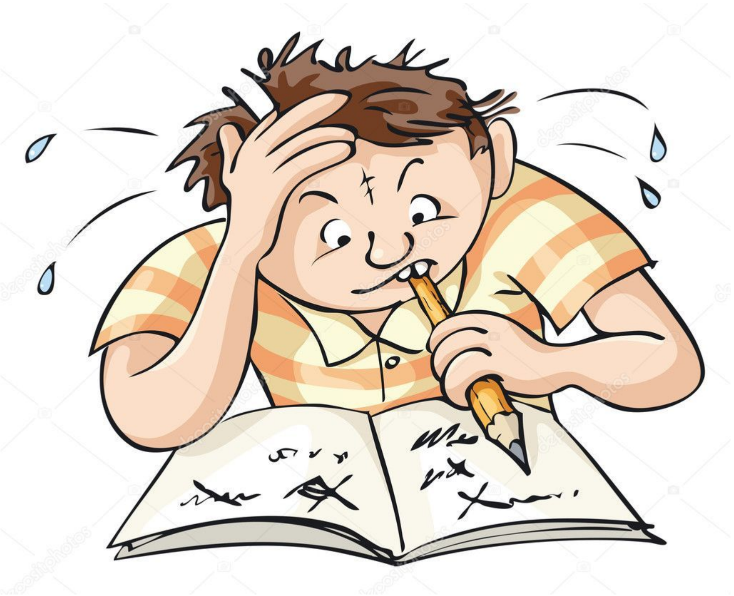
-> add accumulated heating under assumptions used in dynamical core (constant volume for MPAS, constant pressure but different cp for SE, etc.)

Dycore and physis "see" the same heating rates and temperature is updated accordingly!

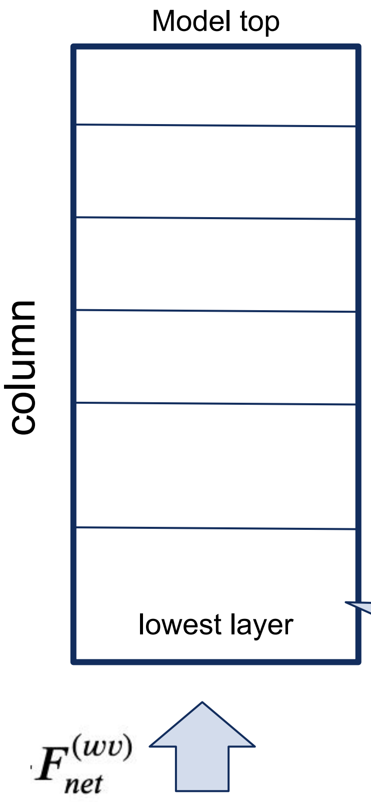
aside: using temperature or temperature tendency as a prognostic variable for updating state due to parameterizations is dangerous - you don't know under what assumptions that temperature tendency was computed!

Goal: undo assumptions in CAM (dycore, physics, coupling to surface)

Now to CAM physics …



Surface evaporation process only



CAM physics column energy equation:

2. Assumed constant during physics updates

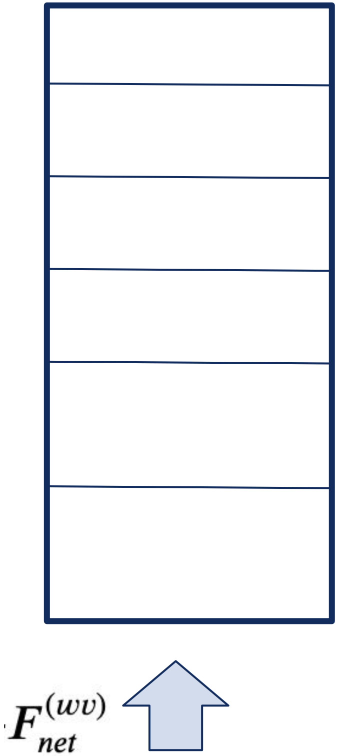
$$\frac{\partial}{\partial t}\int \overline{\rho}^{(d)}\left\{\underline{\left(1+\overline{m}^{(wv)}\right)\left[\overline{K}+\overline{\Phi}_s+c_p^{(d)}\left(\overline{T}-T_{00}\right)\right]}+\overline{m}^{(wv)}L_{s,00}+\overline{m}^{(liq)}L_{f,00}\right\}dz$$

$$= -c_p^{(d)}\overline{F}^{(wv)}_{net}T_{00}+\left\{\overline{F}^{(wv)}_{net}L_{s,00}+\overline{F}^{(liq)}_{net}L_{f,00}+\overline{F}^{(turb,rad)}_{net}\right\}$$

1. For now assume that the water vapor entering atmosphere has the temperature of the atmosphere lowest level

3. Since we are only considering surface evaporation several terms are zero … let's get rid of those frist for clarity

Surface evaporation process only



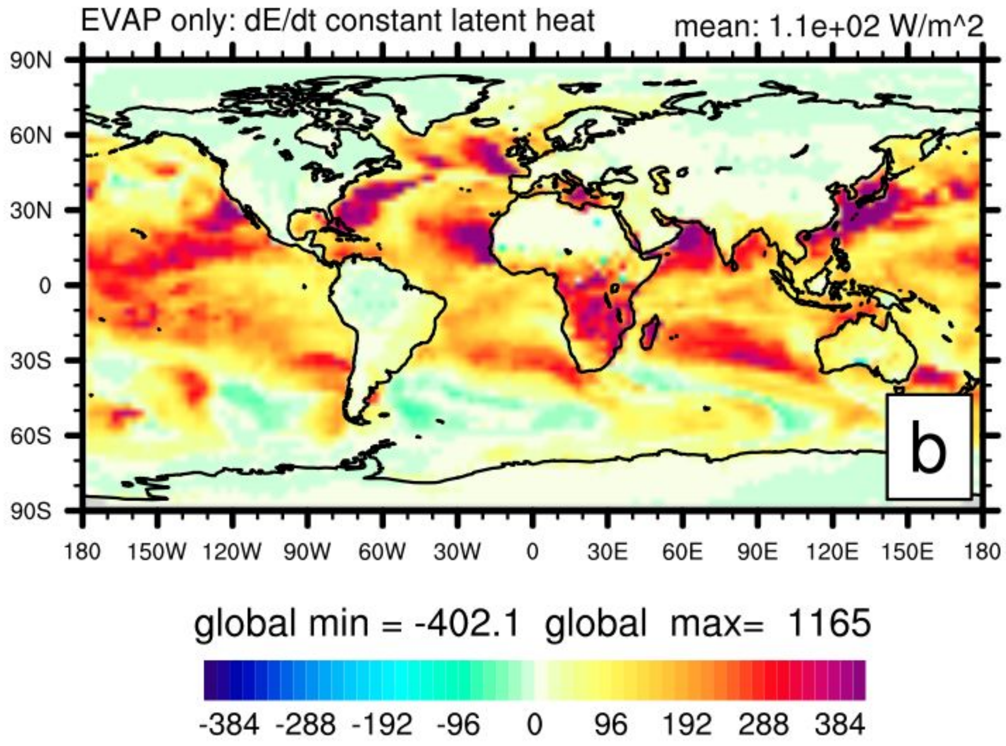
CAM physics column energy equation:

Assumed constant during physics updates

$$\frac{\partial}{\partial t}\int \overline{\rho}^{(d)}\left\{\underline{\left(1+\overline{m}^{(wv)}\right)\left[\overline{K}+\overline{\Phi}_s+c_p^{(d)}\left(\overline{T}\right.\right.}\right]+\overline{m}^{(wv)}L_{s,00}\right\}dz$$
$$=\qquad +\left\{\overline{F}^{(wv)}_{net}L_{s,00}\right\}$$

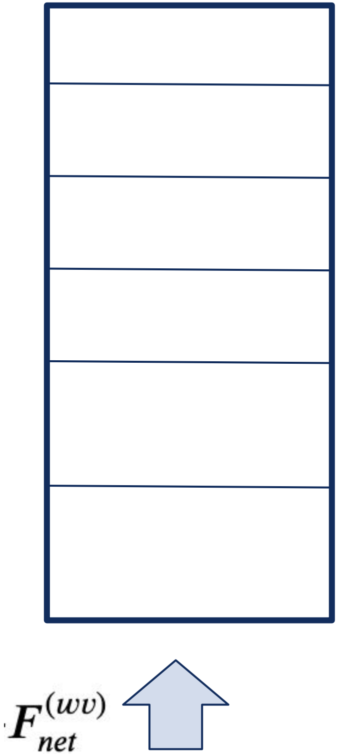
Constant latent heat change in the column exactly balances surface latent heat flux (pass to surface components) and energy budget is closed

Surface evaporation process only: constant latent heat term (which is exactly balanced by surface term)



Setup: instantaneous output from standard AMIP-like simulation

Surface evaporation process only



CAM physics column energy equation:

Assumed constant during physics updates

$$\frac{\partial}{\partial t}\int \overline{\rho}^{(d)}\left\{\underline{\left(1+\overline{m}^{(wv)}\right)\left[\overline{K}+\overline{\Phi}_s+c_p^{(d)}\left(\overline{T}\right.\right.}\right]+\overline{m}^{(wv)}L_{s,00}\left.\right\}dz$$

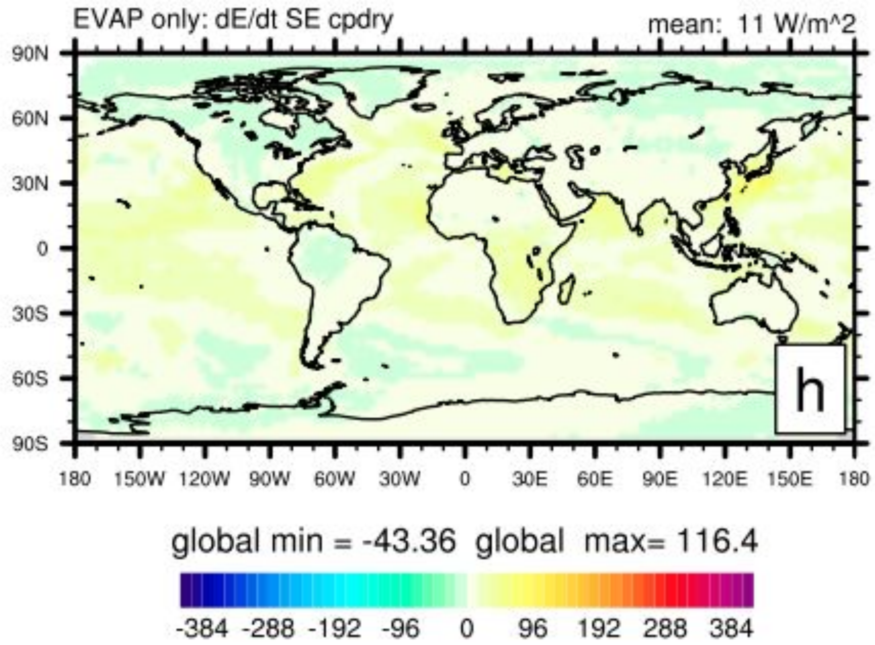
$$-\underline{\Delta\mathcal{I}^{(CAM)}_{\partial m^{(wv)}/\partial t}} = +\left\{\overline{F}^{(wv)}_{net}L_{s,00}\right\}$$

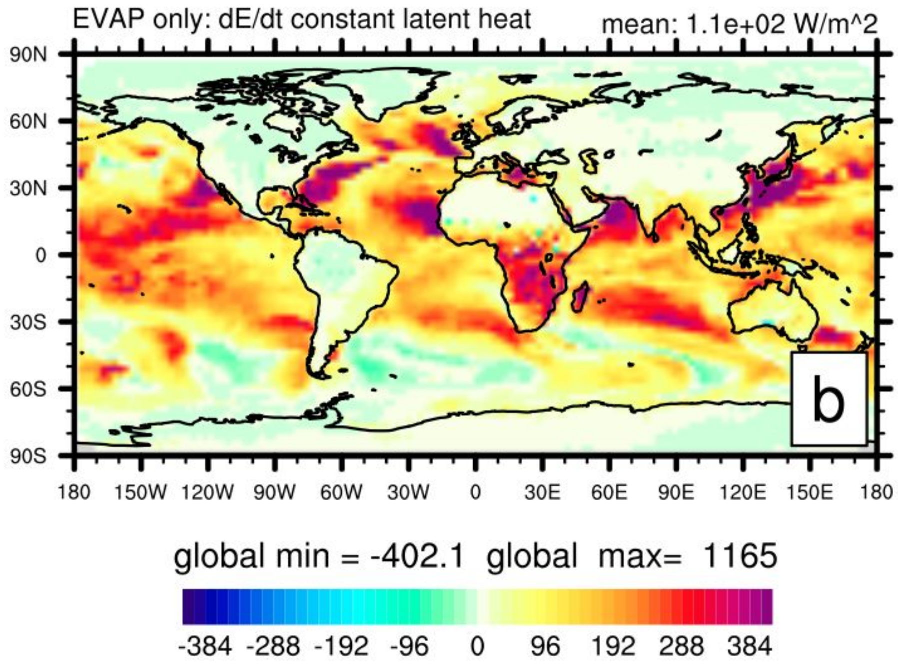
Constant latent heat change in the column exactly balances surface latent heat flux (pass to surface components) and energy budget is closed

At the end of CAM physics the total pressure/mass is updated to reflect total water change in column (kinetic, PHIS, enthalpy term change!)

Energy tendency associated with that (referred to as “dry-mass adjustment”) is fixed with global energy fixer

Surface evaporation process only: “dry-mass adjustment”

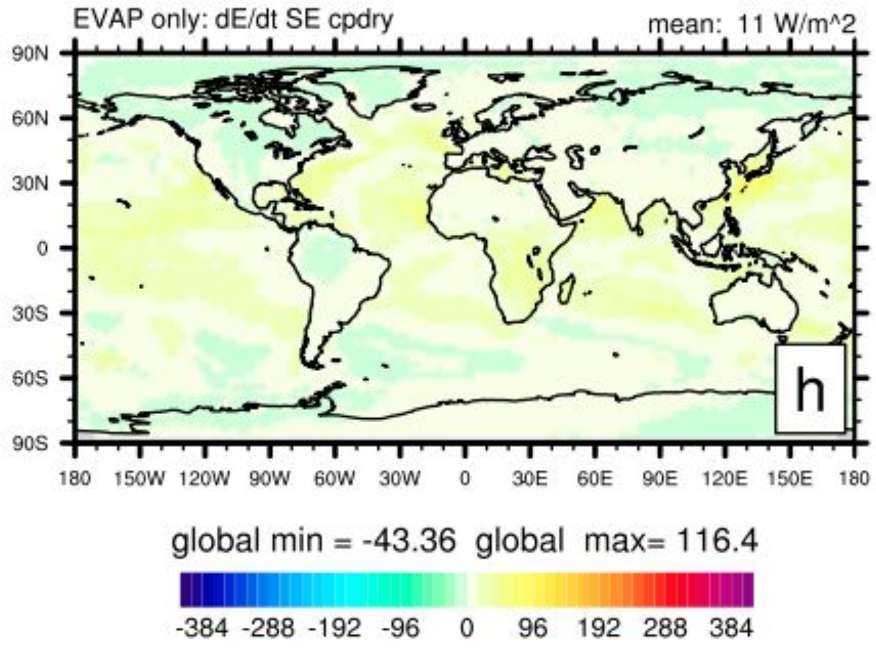


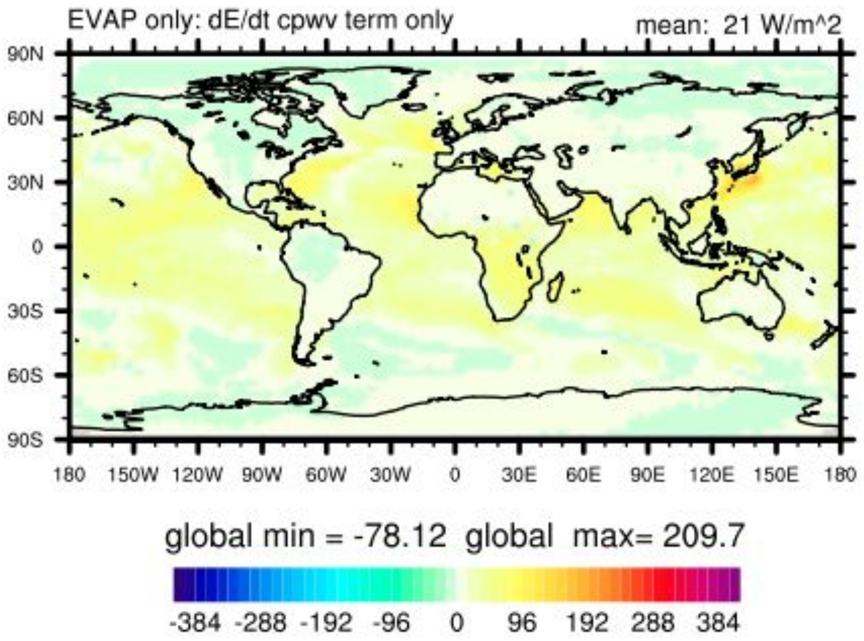


$$\frac{\partial}{\partial t}\int \overline{\rho}^{(d)}\left\{\underline{\left(1+\overline{m}^{(wv)}\right)\left[\overline{K}+\overline{\Phi}_s+c_p^{(d)}\left(\overline{T}\right.\right]}+\overline{m}^{(wv)}L_{s,00}\right\}dz$$

$$-\underline{\Delta\mathcal{I}^{(CAM)}_{\partial m^{(wv)}/\partial t}} = +\left\{\overline{F}^{(wv)}_{net}L_{s,00}\right\}$$

Surface evaporation process only: “dry-mass adjustment”

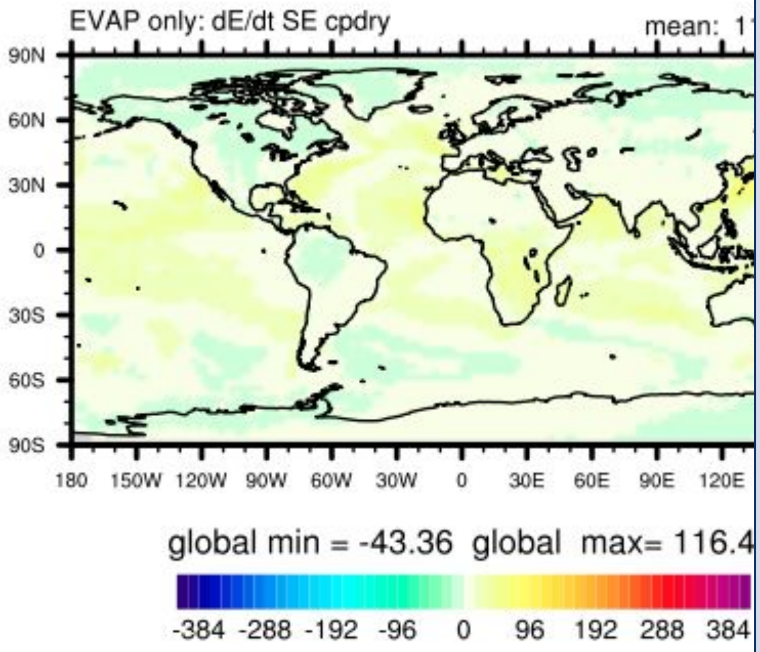




CAM energy change fixed with global fixer in atmosphere (using cpdry)

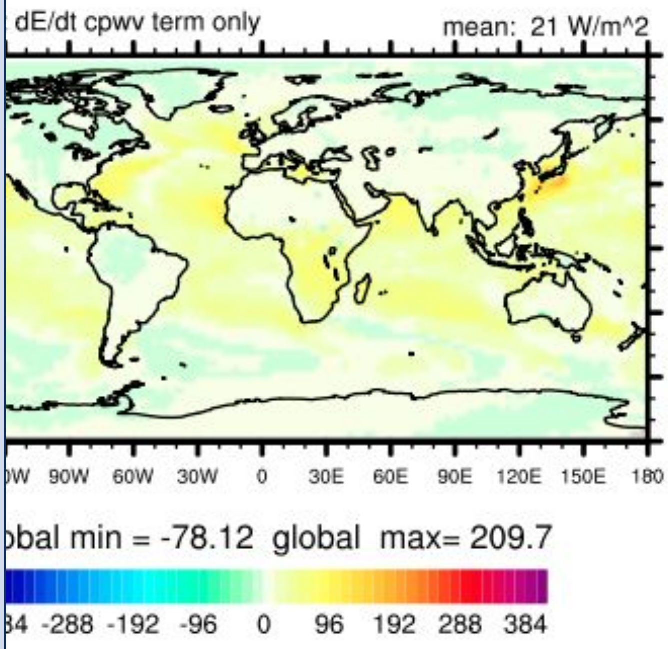
MOM6 enthalpy flux fixed through global fixer in coupler and passed to atmosphere via sensible heat flux (same as E3SM)

Surface evaporation process only: “dry-mass adjustment”



Note that both components locally “feel” the energy change due to water vapor leaving ocean and entering atmosphere *[pointed out to me by Mark Taylor]*

Part of what I am trying to do is to get rid of the fixer over ocean (and ultimately over land, ice, etc.)



CAM energy change fixed with global fixer in atmosphere (using cpdry)

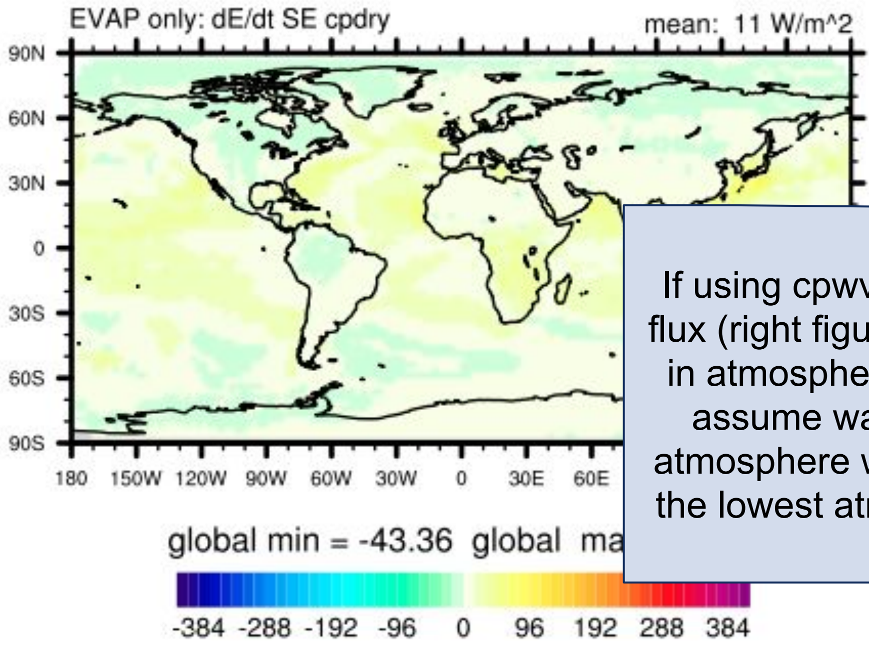
enthalpy flux fixed through global fixer in coupler and passed to atmosphere via sensible heat flux (same as E3SM)

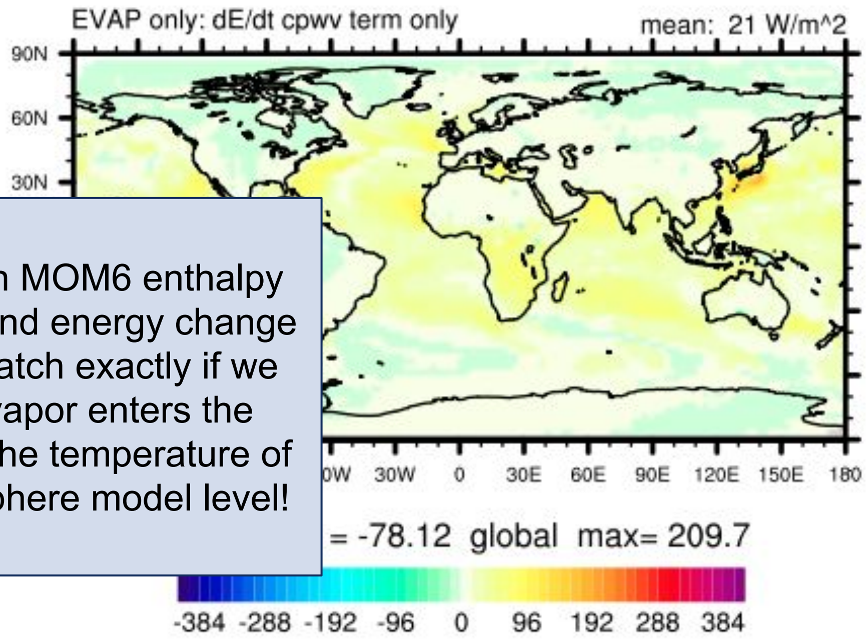
In order to be locally consistent with MOM6 the atmosphere should use the more rigorous total energy formula so that enthalpy fluxes match at the surface:

$$\frac{\partial}{\partial t}\iiint \rho^{(d)}\left\{K+\Phi_s+c_p^{(d)}T+\sum_{\ell\in\mathcal{L}_{H_2O}} m^{(\ell)}\left[K+\Phi_s+c_p^{(\ell)}\left(T-T_{00}\right)+h_{00}^{(ice)}\right]\right.$$
$$\left.+m^{(wv)}L_{s,00}+m^{(liq)}L_{f,00}\right\}dA\,dz$$
$$=\iint\left\{\sum_{\ell\in\mathcal{L}_{H_2O}} F_{net}^{(\ell)}\left[\cancel{\tilde{K}_s+\Phi_s}+c_p^{(\ell)}\left(\tilde{T}_s-T_{00}\right)+h_{00}^{(ice)}\right]\right.$$
$$\left.+F_{net}^{(wv)}L_{s,00}+F_{net}^{(liq)}L_{f,00}+F_{net}^{(turb,rad)}\right\}dA. \qquad (78)$$

$$\left(\text{ice reference enthalpy, } \tilde{T}_s\equiv T_{atm,s}=T_{surf,s}\right)$$

Surface evaporation process only: “dry-mass adjustment”



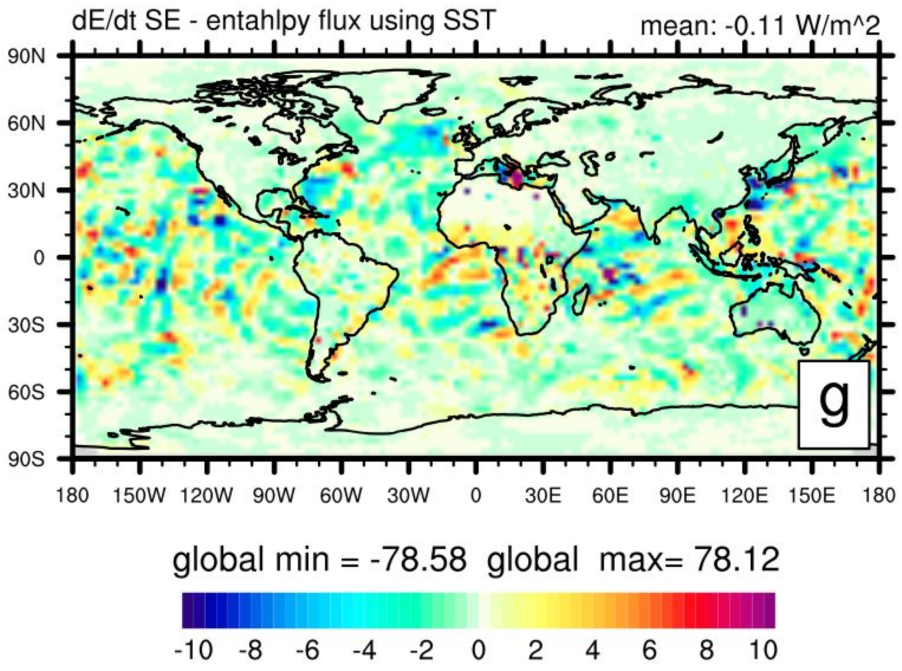


If using cpwv then MOM6 enthalpy flux (right figure) and energy change in atmosphere match exactly if we assume water vapor enters the atmosphere with the temperature of the lowest atmosphere model level!

CAM energy change fixed with global fixer in atmosphere (using cpdry)

MOM6 enthalpy flux fixed through global fixer in coupler and passed to atmosphere via sensible heat flux (same as E3SM)

Surface evaporation process only: “dry-mass adjustment”



Energy tendency due to “dry-mass adjustment” (cpwv term only; i.e. not incl. PHIS an K term) minus enthalpy flux using SST (sea surface temperature) instead of temperature of lowest model level

This would lead to a heating/cooling of the lowest atmosphere model layer:

- **note: it is a small term compared to the dry mass adjustment!**

This term can quite easily be added (0.1W/m2 compared to 21 W/m2)!

- The evaporation only process is somewhat straightforward to handle by changing to variable latent heats (enthalpy flux associated with evaporation will be balanced by atmosphere energy change if switching to variable cp)

  Incl. the effect of water vapor having a different temperature that the atmosphere is “straightforward”; e.g. in the evaporation zones in the tropics the water vapor will typically be warmer that atmosphere so there will be a heating term increasing temperature in the atmosphere lowest level.

- Heating in the atmosphere not associated with phase changes can be added under variable latent heating assumptions and energy budget should be closed

- The big challenge is phase changes and falling precipitation: we only know the flux at surface but we don’t know what fraction of phase changes turn into falling precipitation - working on ”ad hoc” method to close energy budget in column …

  Guba et al. (2024) https://doi.org/10.5194/gmd-17-1429-2024

- The evaporation only process is somewhat straightforward to handle by changing to variable latent he… …ed by atmosphere ene…

  Incl. the effect of … …ere is "straightforward" … …will typically be warm… …g temperature in th…

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- The big challenge is phase changes and falling precipitation: we only know the flux at surface but we don't know what fraction of phase changes turn into falling precipitation - working on "ad hoc" method to close energy budget in column …

  Guba et al. (2024) https://doi.org/10.5194/gmd-17-1429-2024

Longer term goal: Deep and shallow convection schemes need to provide information of where falling precipitation was formed and at what temperature (similarly for re-evaporation) - only then will I stand a chance to do things more right

(still neglecting other processes associated with falling precipitation -> potential energy turning into kinetic, frictional heating; drag of falling precipitation … see Lauritzen et al. (2019) for more details)