Missing Enthalpy Flux in CAM

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Reconciling and improving formulations for thermodynamics and conservation principles in Earth system models

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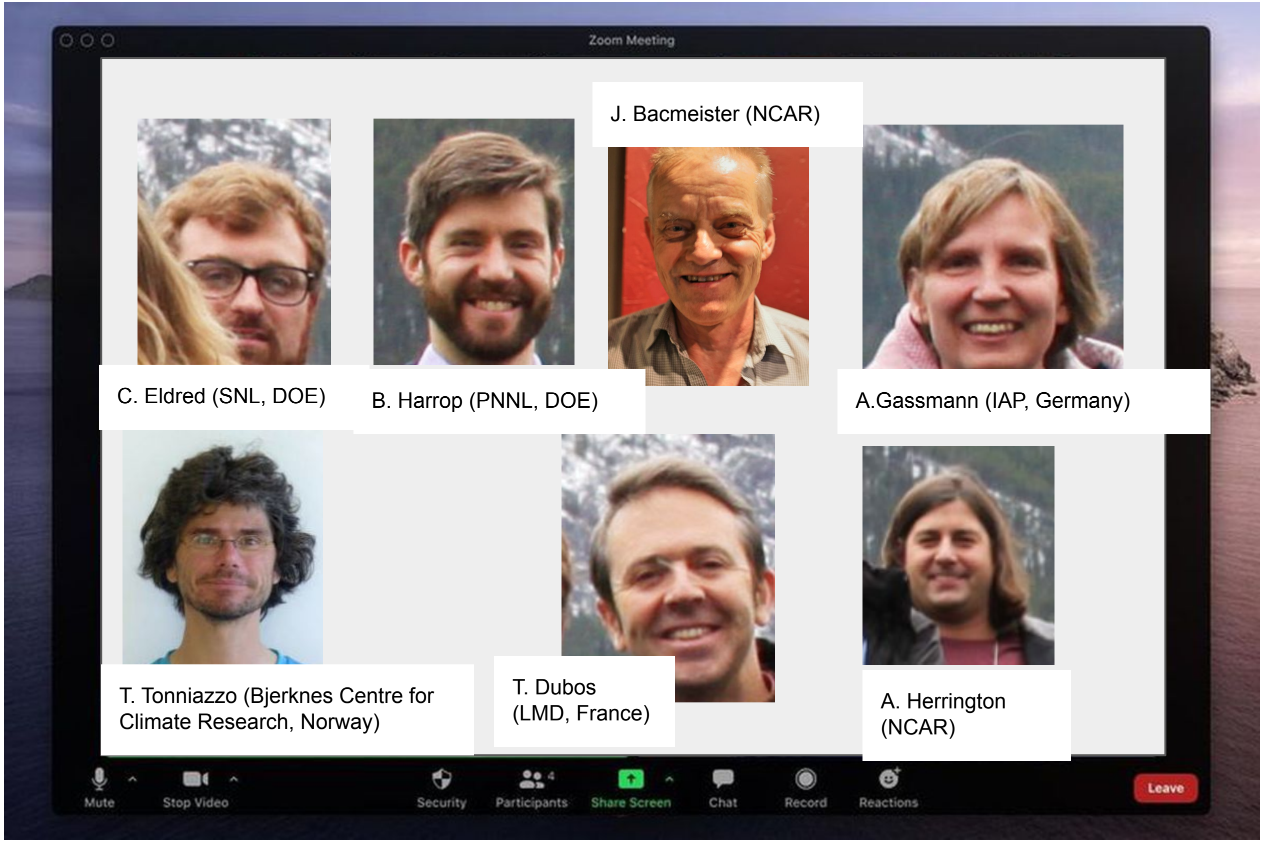
What is the total energy equation for the atmosphere?



Reconciling and improving formulations for thermodynamics and conservation principles in Earth system models

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Total energy equation

Assume:

- Primitive equations (hydrostatic, shallow atmosphere, ideal gas)
- Assume model top pressure is constant (equations could also be derived for constant volume models!)
- All components of moist air have the same temperature and move with the same barycentric 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 energy equation holds (assuming ice enthalpy reference state):

$$\frac{\partial}{\partial t}\iiint \rho^{(d)}\left\{\left(m^{(d)}+m^{(H_2O)}\right)(K+\Phi_s)+c_p^{(d)}T+m^{(H_2O)}c_p^{(ice)}T+m^{(wv)}L_s(T)+m^{(liq)}L_f(T)\right\}dA\,dz$$
$$=\iint\left\{c_p^{(ice)}\widetilde{T}_{surf}F_{net}^{(H_2O)}+F_{net}^{(H_2O)}(\widetilde{K}_{surf}+\Phi_s)+F_{net}^{(wv)}L_s(\widetilde{T}_{surf})+F_{net}^{(liq)}L_f(\widetilde{T}_{surf})+F_{net}^{(turb,rad)}\right\}dA,$$

[see Lauritzen et al., in prep., and CGD seminar from 3/16/2021 https://www.cgd.ucar.edu/cms/pel/papers/L2021CGD-SEMINAR.pdf]

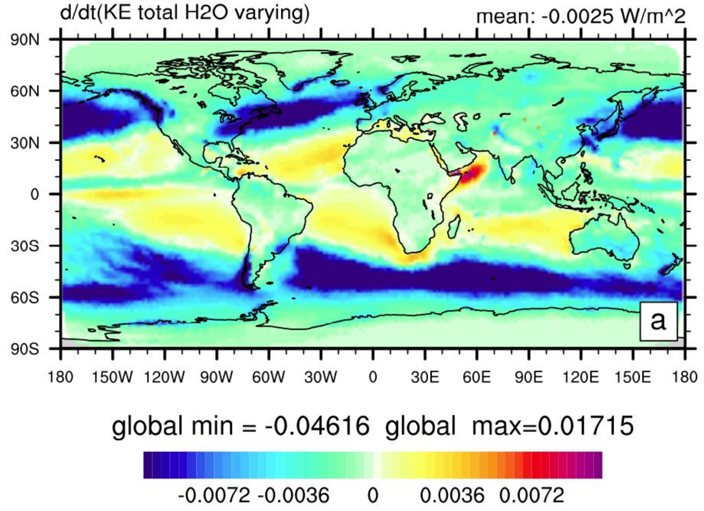
Now also assume that the energy equation is valid for grid mean values in the model.

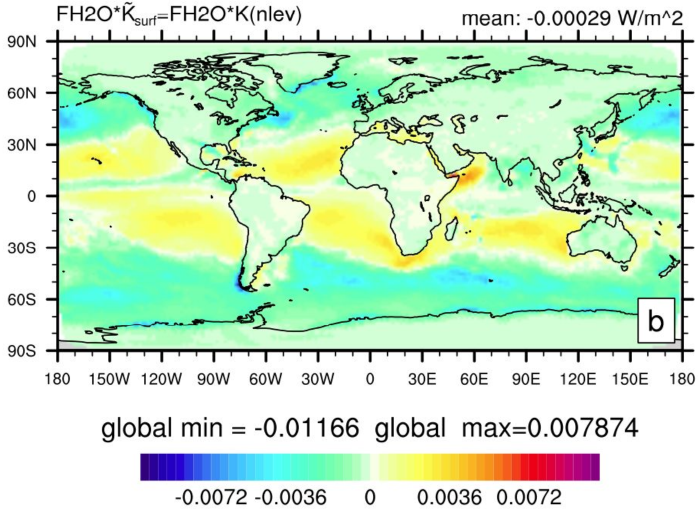
Total energy equation

$$\frac{\partial}{\partial t}\iiint \rho^{(d)}\left\{\left(m^{(d)}+m^{(H_2O)}\right)(K+\Phi_s)+c_p^{(d)}T+m^{(H_2O)}c_p^{(ice)}T+m^{(wv)}L_s(T)+m^{(liq)}L_f(T)\right\}dA\,dz$$

$$=\iint\left\{c_p^{(ice)}\widetilde{T}_{surf}F_{net}^{(H_2O)}+F_{net}^{(H_2O)}(\widetilde{K}_{surf}+\Phi_s)+F_{net}^{(wv)}L_s(\widetilde{T}_{surf})+F_{net}^{(liq)}L_f(\widetilde{T}_{surf})+F_{net}^{(turb,rad)}\right\}dA,$$

Kinetic energy terms





Plots (a) and (b) show estimate of 1 year average K terms associated with water flux in/out of the atmospheric column

$\widetilde{K}_{surf}$ = (lowest level atmosphere winds)^2

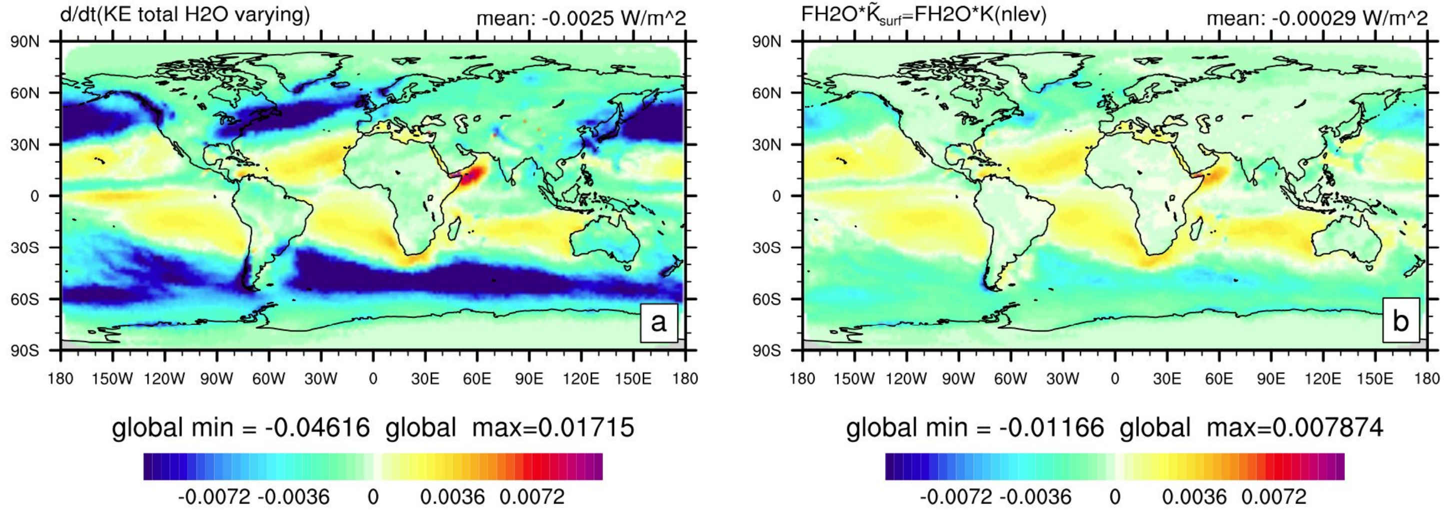
(CAM-SE-CSLAM, 1 degree horizontal resolution, 32 levels, diagnostics computed inline in code)

Total energy equation

$$\frac{\partial}{\partial t}\iiint \rho^{(d)}\Big\{\Big(m^{(d)}+m^{(H_2O)}\Big)(K+\Phi_s)+c_p^{(d)}T+m^{(H_2O)}c_p^{(ice)}T+m^{(wv)}L_s(T\cdots$$

$$=\iint\Big\{c_p^{(ice)}\widetilde{T}_{surf}F_{net}^{(H_2O)}+F_{net}^{(H_2O)}(\widetilde{K}_{surf}+\Phi_s)+F_{net}^{(wv)}L_s(\widetilde{T}_{surf})+F_{net}^{(liq)}L_f(\widetilde{T}_{s}\cdots$$

Kinetic energy terms



- Terms are small
- (a) and (b) do not balance very well.

  E.g. when precipitation is produced at a certain level it instantaneously leaves the atmosphere

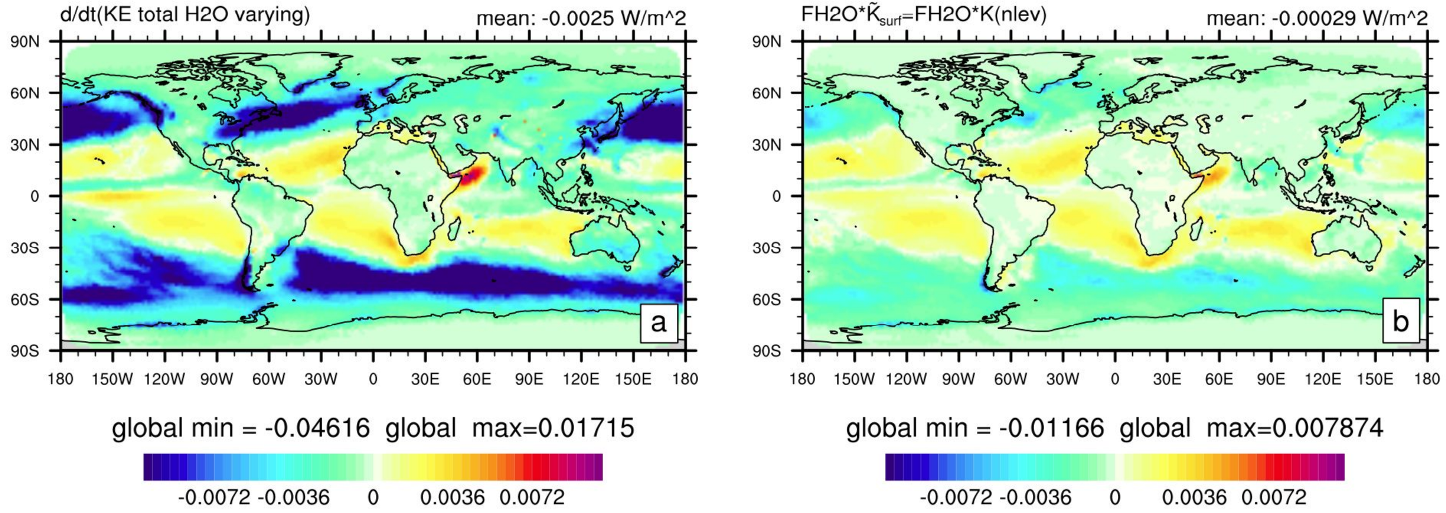
  => has different K than the surface K; we are not rigorously modeling falling precipitation (frictional heating, drag of falling precipitation,etc.)

Total energy equation

$$\frac{\partial}{\partial t}\iiint \rho^{(d)}\left\{\left(m^{(d)}+m^{(H_2O)}\right)(K+\Phi_s)+c_p^{(d)}T+m^{(H_2O)}c_p^{(ice)}T+m^{(wv)}L_s(T)+m^{(liq)}L_f(T)\right\}dA\,dz$$

$$=\iint\left\{c_p^{(ice)}\widetilde{T}_{surf}F_{net}^{(H_2O)}+F_{net}^{(H_2O)}(\cancel{\widetilde{K}_{surf}}+\Phi_s)+F_{net}^{(wv)}L_s(\widetilde{T}_{surf})+F_{net}^{(liq)}L_f(\widetilde{T}_{surf})+F_{net}^{(turb,rad)}\right\}dA,$$

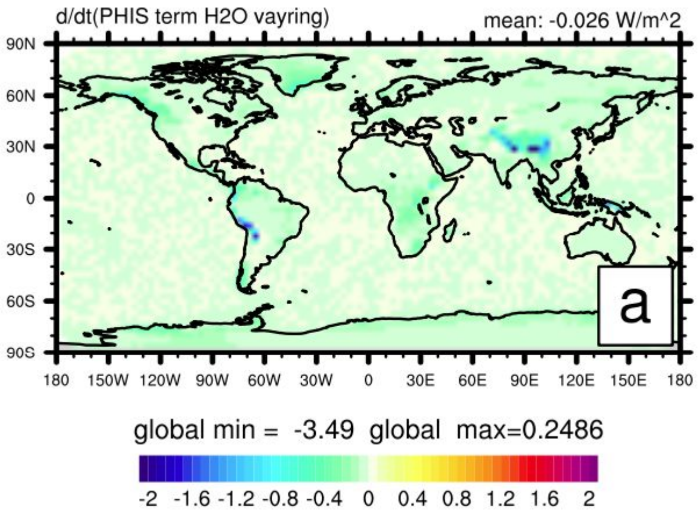
Kinetic energy terms

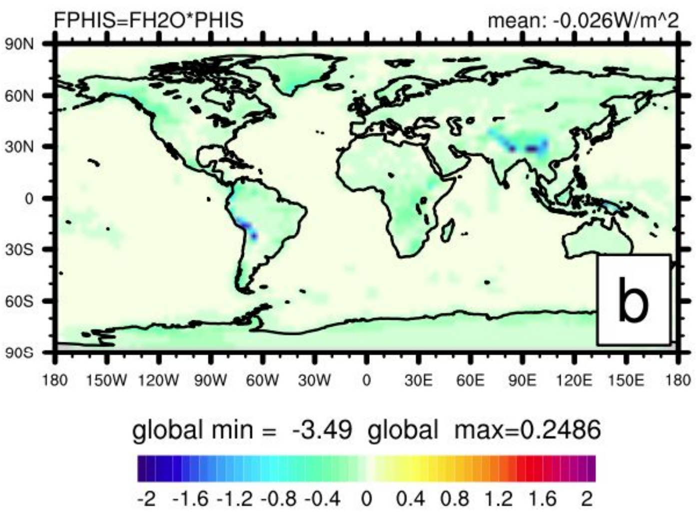


Total energy equation

$$\frac{\partial}{\partial t}\iiint \rho^{(d)}\left\{\left(m^{(d)}+\underline{m^{(H_2O)}}\right)(K+\underline{\Phi_s})+c_p^{(d)}T+m^{(H_2O)}c_p^{(ice)}T+m^{(wv)}L_s(T)+m^{(liq)}L_f(T)\right\}dA\,dz$$

$$=\iint\left\{c_p^{(ice)}\widetilde{T}_{surf}F_{net}^{(H_2O)}+\underline{F_{net}^{(H_2O)}}(\widetilde{K}_{surf}+\underline{\Phi_s})+F_{net}^{(wv)}L_s(\widetilde{T}_{surf})+F_{net}^{(liq)}L_f(\widetilde{T}_{surf})+F_{net}^{(turb,rad)}\right\}dA,$$





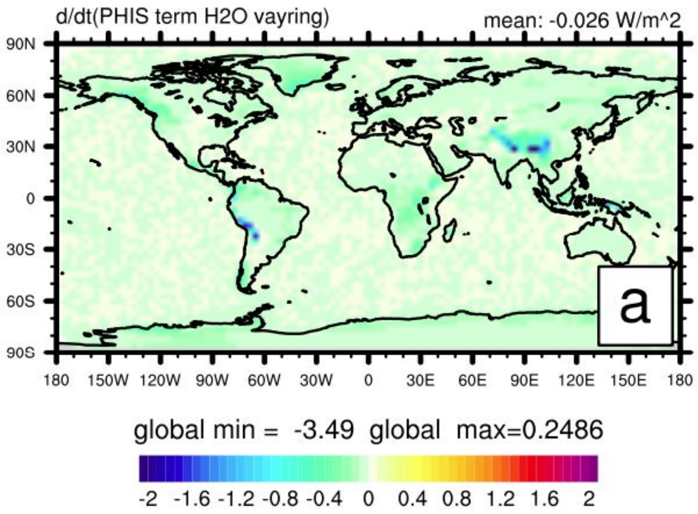
Plots (a) and (b) show estimate of 1 year average PHIS terms associated with water flux in/out of the atmospheric column (.ne. potential energy but related!)

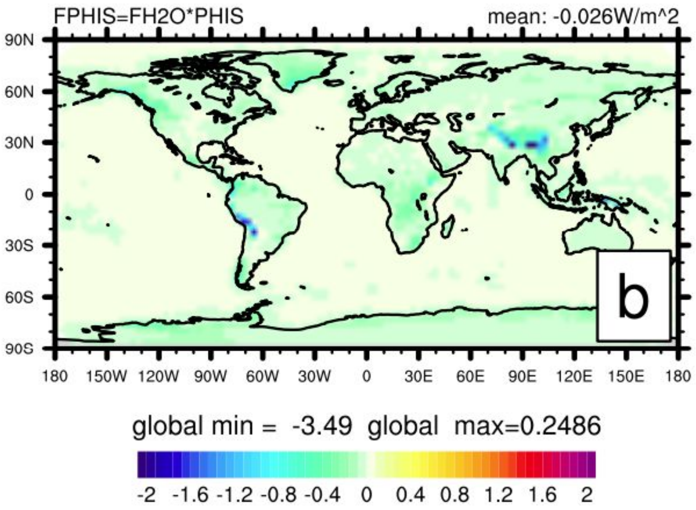
- Exactly match
- Small term!

Total energy equation

$$\frac{\partial}{\partial t}\iiint \rho^{(d)}\left\{\left(m^{(d)}+m^{(H_2O)}\right)(K+\Phi_s)+c_p^{(d)}T+m^{(H_2O)}c_p^{(ice)}T+m^{(wv)}L_s(T)+m^{(liq)}L_f(T)\right\}dA\,dz$$

$$=\iint\left\{{\color{red}c_p^{(ice)}}\widetilde{T}_{surf}F_{net}^{(H_2O)}+F_{net}^{(H_2O)}(\cancel{\widetilde{K}_{surf}}+\cancel{\Phi_s})+F_{net}^{(wv)}L_s(\widetilde{T}_{surf})+F_{net}^{(liq)}L_f(\widetilde{T}_{surf})+F_{net}^{(turb,rad)}\right\}dA,$$





Total energy equation

$$\frac{\partial}{\partial t}\iiint \rho^{(d)}\left\{\left(m^{(d)}+m^{(H_2O)}\right)(K+\Phi_s)+c_p^{(d)}T+m^{(H_2O)}c_p^{(ice)}T+m^{(wv)}\underline{L_s(T)}+m^{(liq)}\underline{L_f(T)}\right\}dA\,dz$$

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Assume constant latent heats <=> heat capacity for all forms of water is the same:

The latent heat formulas for sublimation (solid → water vapor):

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

The latent heat formulas for fusion (solid → liquid):

$$L_f(T)=L_{f,00}+\left(c_p^{(liq)}-c_p^{(ice)}\right)(T-T_{00})\,,\ \text{where } L_{f,00}\equiv h_{00}^{(liq)}-h_{00}^{(ice)}$$

In CAM we use: $c_p^{(\ell)}=c_p^{(d)}$ for $\ell\in\mathcal{L}_{H_2O}$.

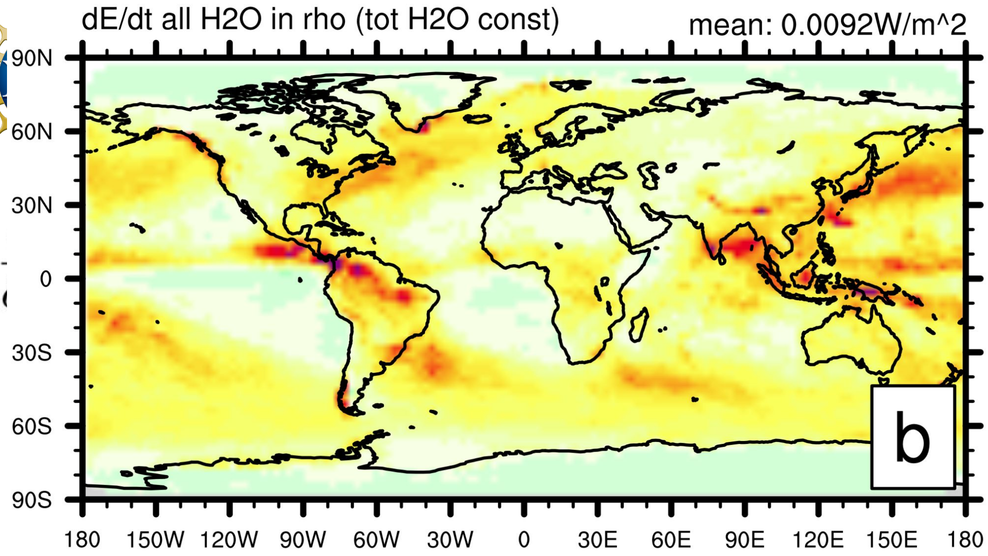
CAM energy equation

$$\frac{\partial}{\partial t}\iiint \rho^{(d)}\left\{\left[m^{(d)}+\underline{m_{t=t^n}^{(H_2O)}}\right](K+\Phi_s)+c_p^{(d)}T+\underline{m_{t=t^n}^{(H_2O)}}\,\underline{c_p^{(d)}}T+m^{(wv)}L_{s,00}+m^{(liq)}L_{f,00}\right\}dA\,dz$$

$$\approx \iint \left\{L_{s,00}F_{net}^{(wv)}+L_{f,00}F_{net}^{(liq)}+F^{(turb,rad)}\right\}dA. \quad (98)$$

Further simplifications in CAM:

1. Assume $m^{(H_2O)} = m^{(wv)}$
   i.e. condensates do not contribute to kinetic, internal or geopotential energy (they are mass-less!)
2. Assume that $\underline{m^{(H_2O)}}$ during physics updates: $m^{(H_2O)} = m_{t=t^n}^{(H_2O)}$
3. Discard enthalpy flux at the surface $c_p^{(d)}\widetilde{T}_{surf}F_{net}^{(H_2O)}$
4. Use heat capacity of dry air for all forms of water



Plot (b) shows energy imbalance by including all forms of water in pressure/density of air.

=> Assumption 1. is justifiable at 1 degree horizontal resolution!

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Consider a physics column (no interaction between columns so equation holds in column!):

- Each parameterization (in theory) satisfies this equation in CAM (see Figure no next slide)

This system is energetically consistent - **and cleverly chosen to keep energetics simple and let the CAM energy fixer restore global energy conservation for processes that we are not accounting for (e.g. enthalpy of hydrometeors leaving/entering the column, kinetic and geopotential energy associated with hydrometeors leaving/entering the column)**

CAM energy equation

$$\frac{\partial}{\partial t}\iiint \rho^{(d)}\left\{\left[m^{(d)}+m^{(H_2O)}_{t=t^n}\right](K+\Phi_s)+c_p^{(d)}T+m^{(H_2O)}_{t=t^n}c_p^{(d)}T+m^{(wv)}L_{s,00}+m^{(liq)}L_{f,00}\right\}dA\,dz$$

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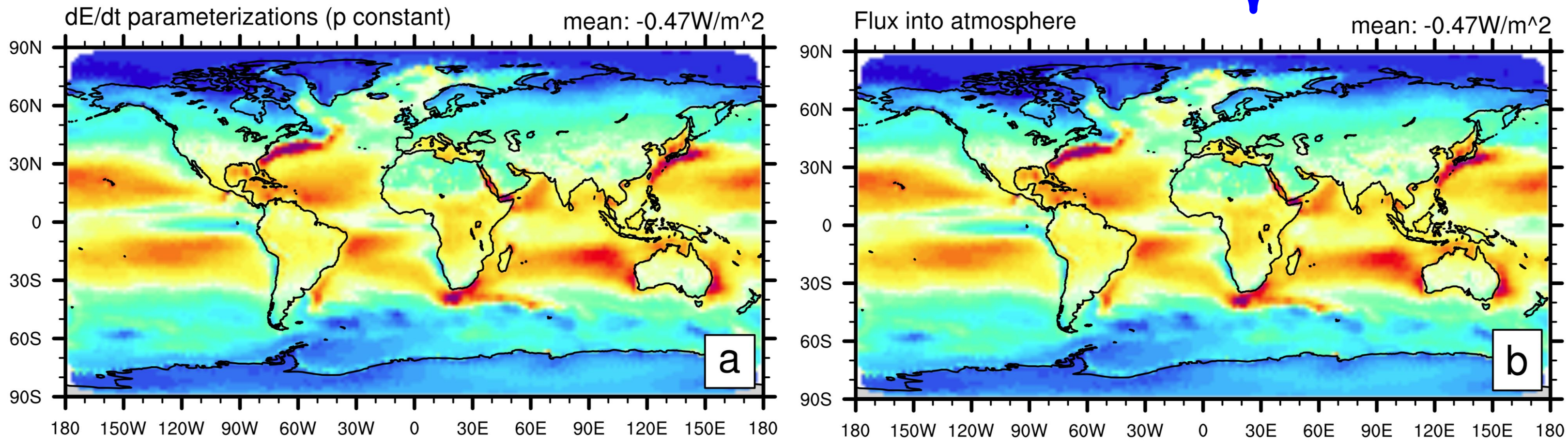
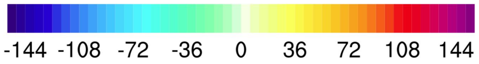


1 year ave, F2000climo, ne30pg3, CAM6



Diagnostics coded inline in CAM!

CAM energy equation

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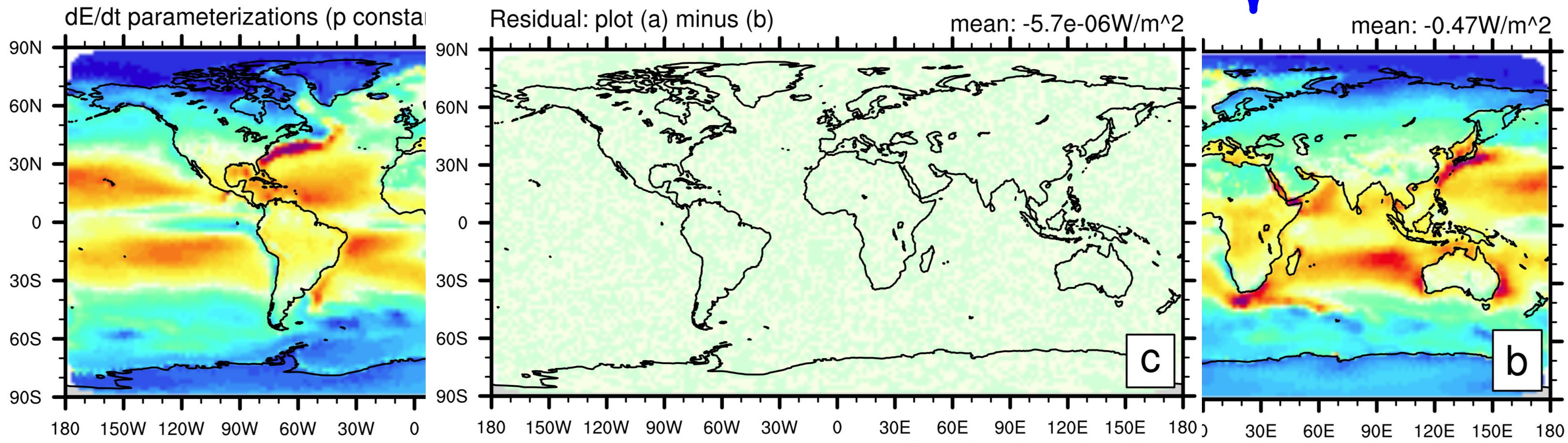

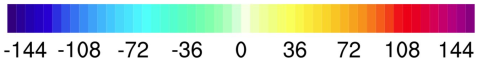

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CAM energy equation

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$$\approx\iint\left\{L_{s,00}F_{net}^{(wv)}+L_{f,00}F_{net}^{(liq)}+F^{(turb,rad)}\right\}dA. \quad (98)$$

Further simplifications in CAM:

- Assume $m^{(H_2O)}=m^{(wv)}$
  i.e. condensates do not contribute to kinetic, internal or geopotential energy (they are mass-less!)
- Assume that $m^{(H_2O)}$ during physics updates: $m^{(H_2O)}=m^{(H_2O)}_{t=t^n}$
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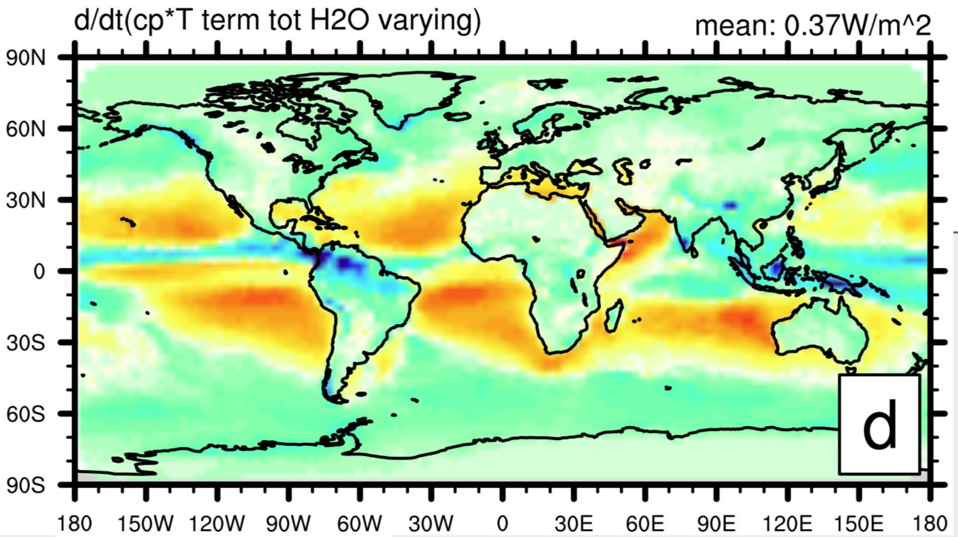
CAM energy equation

$$\frac{\partial}{\partial t}\iiint \rho^{(d)}\left\{\left[m^{(d)}+m^{(H_2O)}_{t=t^n}\right](K+\Phi_s)+c_p^{(d)}T+m^{(H_2O)}_{t=t^n}c_p^{(d)}T+m^{(wv)}L_{s,00}+m^{(liq)}L_{f,00}\right\}dA\,dz$$

$$\approx \iint \{L_{s,0}$$



Further simplifications in CAM:

- Assume $m^{(H_2O)} = m^{(wv)}$
  i.e. condensates do not contribute to kinetic, i
- Assume that $m^{(H_2O)}$ during physics updates
- Discard enthalpy flux at the surface $c_p^{(d)}\widetilde{T}_{surf}F_{net}^{(H_2O)}$
- Use heat capacity of dry air for all forms of water

Missing enthalpy flux at surface

using T at the surface, TS

$$\frac{\partial}{\partial t}\iiint \rho^{(d)}\left\{\left[m^{(d)}+\underline{m^{(H_2O)}_{t=t^n}}\right](K+\Phi_s)+c_p^{(d)}T+\underline{m^{(H_2O)}_{t=t^n}}\,\underline{c_p^{(d)}}T+m^{(wv)}L_{s,00}+m^{(liq)}L_{f,00}\right\}dA\,dz$$

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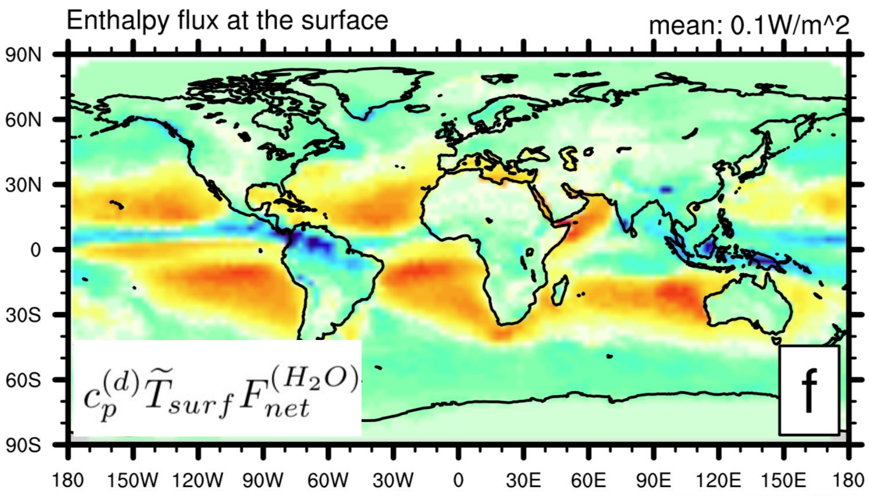
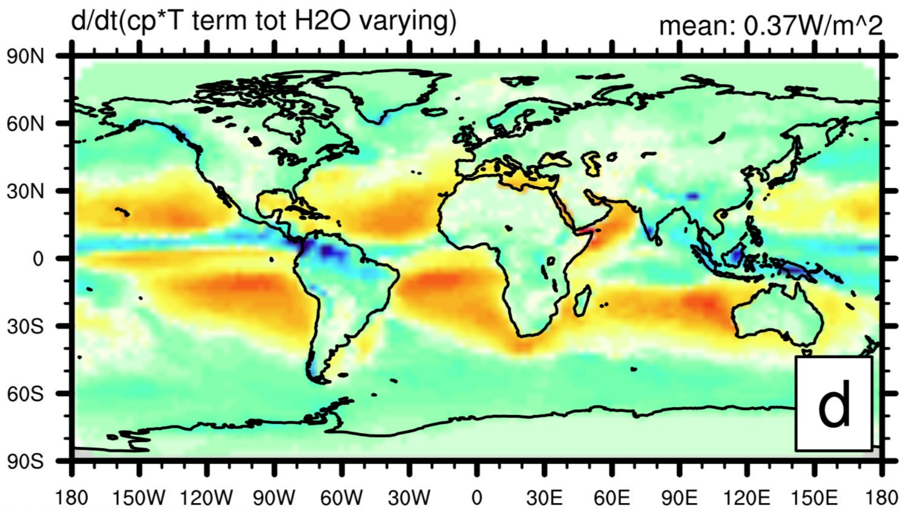
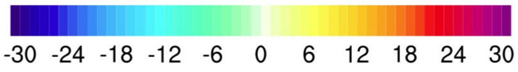


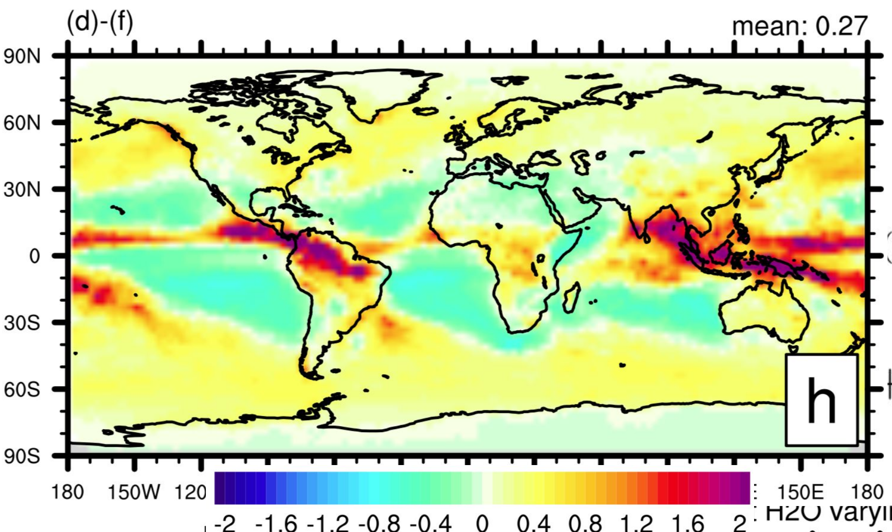


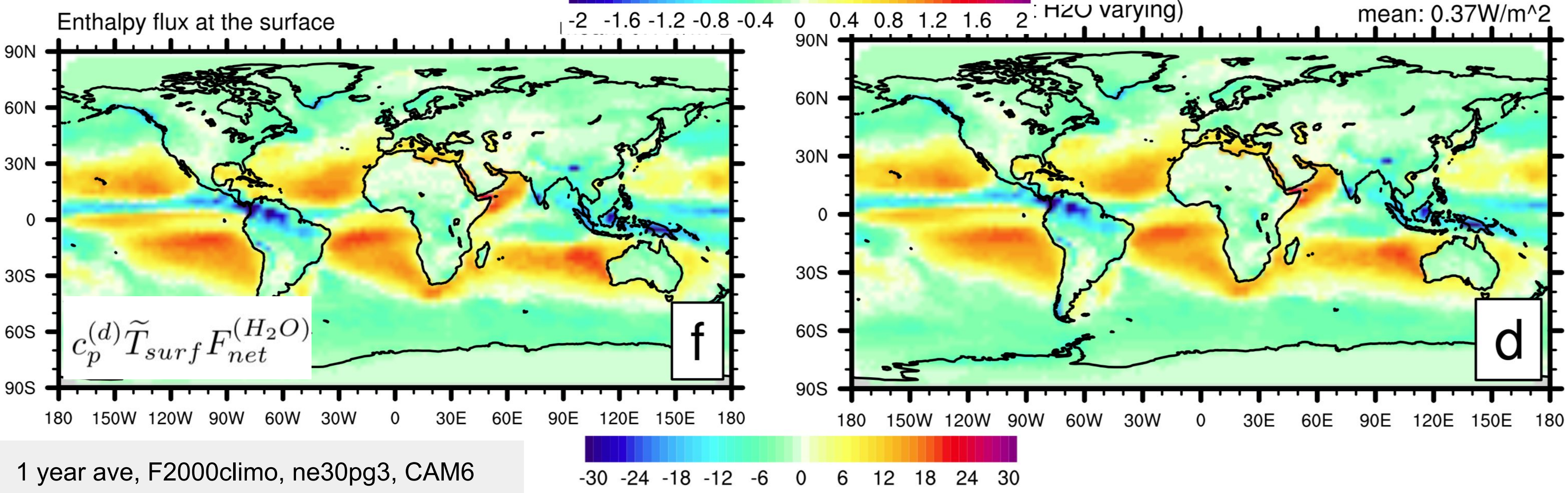


1 year ave, F2000climo, ne30pg3, CAM6

$$\frac{\partial}{\partial t}\iiint \rho^{(d)}\left\{\left[m^{(d)} + \ldots \right.\right. \quad \ldots {}^{(wv)} L_{s,00} + m^{(liq)} L_{f,00}\Big\} dA\, dz$$

$$\ldots + F^{(turb,rad)}\Big\} dA. \quad (98)$$





1 year ave, F2000climo, ne30pg3, CAM6

Concluding remarks

- The current framework will still need an energy fixer but local imbalances can be reduced significantly by including enthalpy flux term! Danger: if “surface” temperature is larger than the “true” T of water entering/leaving the column the energy that should have stayed in the atmosphere goes to surface component - vice versa for lower “surface” temperature! Use LES simulations to assess?

- Being rigorous in terms of monitoring energy conservation forces modelers to consider consistency between parameterizations and dynamical core!

- CESM3 ocean model (MOM6) requires enthalpy fluxes from atmosphere:

  M. Vertenstein, G. Marques, and F. Bryan have implemented infrastructure in CESM coupler to enable the exchange of enthalpy fluxes between atmosphere and ocean so we can start exploring the effect in coupled climate simulation ...

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