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

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Boulder, Colorado*

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

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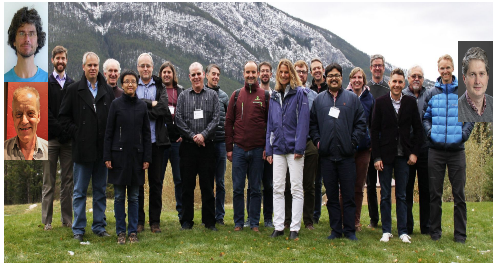
Physics-dynamics coupling is often overlooked; this paper is an attempt to draw more attention to this “complex” topic!

Featured as Editor’s Highlight in Eos:
https://eos.org/editor-highlights/consistently-closing-the-energy-budget-in-earth-system-models

Paper link: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2022MS003117
(warning: 83 pages)



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Total energy equation

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) **DEFINITELY NOT ALWAYS ACCURATE!**

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

$$\frac{\partial}{\partial t}\iiint \rho^{(d)}\left\{K+\Phi_s+c_p^{(d)}T+\sum_{\ell\in\mathcal{L}_{H_2O}} m^{(\ell)}\left[K+\Phi_s+c_p^{(\ell)}\left(T-T_{00}\right)+h_{00}^{(ice)}\right]\right.$$
$$\left.+\,m^{(wv)}L_{s,00}+m^{(liq)}L_{f,00}\right\}dA\,dz$$
$$=\iint\left\{\sum_{\ell\in\mathcal{L}_{H_2O}} F_{net}^{(\ell)}\left[\widetilde{K}_s+\Phi_s+c_p^{(\ell)}\left(\widetilde{T}_s-T_{00}\right)+h_{00}^{(ice)}\right]+F_{net}^{(wv)}L_{s,00}+F_{net}^{(liq)}L_{f,00}+F_{net}^{(turb,rad)}\right\}dA. \qquad (94)$$

(ice reference enthalpy, $\widetilde{T}_s \equiv T_{atm,s} = T_{surf,s}$)

symbol	description	unit
$c_p^{(\ell)}$	heat capacity at constant pressure of species ℓ	$J/K/kg$
$F_{net}^{(\ell)}$	net flux of water species ℓ into the atmosphere	$kg/m^2/s$
$F_{net}^{(turb,rad)}$	Radiative and sensible/turbulent fluxes into atmosphere (90)	$J/m^2/s$
$h_{00}^{(\ell)}$	reference enthalpy for water form ℓ	J/kg
$m^{(\ell)}$	dry mixing ratio ($\equiv \rho^{(\ell)}/\rho^{(d)}$)	kg/kg
K	specific horizontal kinetic energy ($\equiv \frac{1}{2}\vec{v}^2$)	m^2/s^2
$L_{f,00}$.	latent heat of fusion	J/K
$L_{s,00}$.	latent heat of sublimation	J/K
$L_{v,00}$.	latent heat of vaportization	J/K
Φ_s	surface geopotential	m^2/s^2
ρ_d	dry air density	kg/m^3
T	temperature	K
$\widetilde{T}_s$	common temperature at surface	K
$\vec{v}$	horizontal velocity vector	m/s

Now also assume that the energy equation is valid for grid mean values in the model (**QUESTIONABLE ASSUMPTION!**)

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$$=\iint\left\{\sum_{\ell\in\mathcal{L}_{H_2O}} F_{net}^{(\ell)}\left[\widetilde{\overline{K}}_s+\overline{\Phi}_s+c_p^{(\ell)}\left(\widetilde{\overline{T}}_s-T_{00}\right)+h_{00}^{(ice)}\right]+\overline{F}_{net}^{(wv)}L_{s,00}+\overline{F}_{net}^{(liq)}L_{f,00}+\overline{F}_{net}^{(turb,rad)}\right\}dA. \quad (94)$$

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Many models make these assumptions:

$\mathcal{L}_{H_2O} = ' wv'$

$c_p^{(\ell)} = c_p^{(d)}$

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In NCAR's Community Atmosphere Model (CAM): If assuming that total water (or pressure) is **constant** then the total energy budget is closed in each physics column during physics parameterization updates!

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$$= \iint\Big\{\sum_{\ell\in\mathcal{L}_{H_2O}} \overline{F}_{net}^{(\ell)}\left[\widetilde{K}_s+\overline{\Phi}_s+c_p^{(\ell)}\left(\widetilde{T}_s-T_{00}\right)+h_{00}^{(ice)}\right] + \overline{F}_{net}^{(wv)}L_{s,00}+\overline{F}_{net}^{(liq)}L_{f,00}+\overline{F}_{net}^{(turb,rad)}\Big\}dA. \qquad (94)$$

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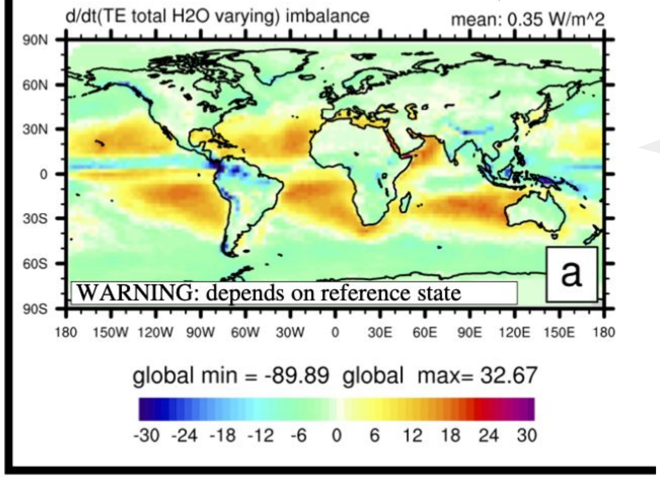
Now also assume that the energy equation is valid for grid mean values in the model (**QUESTIONABLE ASSUMPTION!**)

Modified CAM total energy equation incl. missing flux terms

$$\frac{\partial}{\partial t}\int \overline{\rho}^{(d)}\left\{\left(1+\overline{m}^{(H_2O)}\right)\left[\overline{K}+\overline{\Phi}_s+c_p^{(d)}\left(\overline{T}-T_{00}\right)\right]+\overline{m}^{(wv)}L_{s,00}+\overline{m}^{(liq)}L_{f,00}\right\}dz$$

$$-\Delta\widehat{\mathcal{I}}_{\partial m^{(H_2O)}/\partial t}-\Delta\mathcal{I}_{m_{tn}^{(H_2O)}} = \overline{F}_{net}^{(wv)}L_{s,00}+\overline{F}_{net}^{(liq)}L_{f,00}+\overline{F}_{net}^{(turb,rad)}$$



Energy error fixed with global energy fixer (uniform T increment); similarly the dynamical core and physics-dynamics coupling errors are fixed with a global energy fixer

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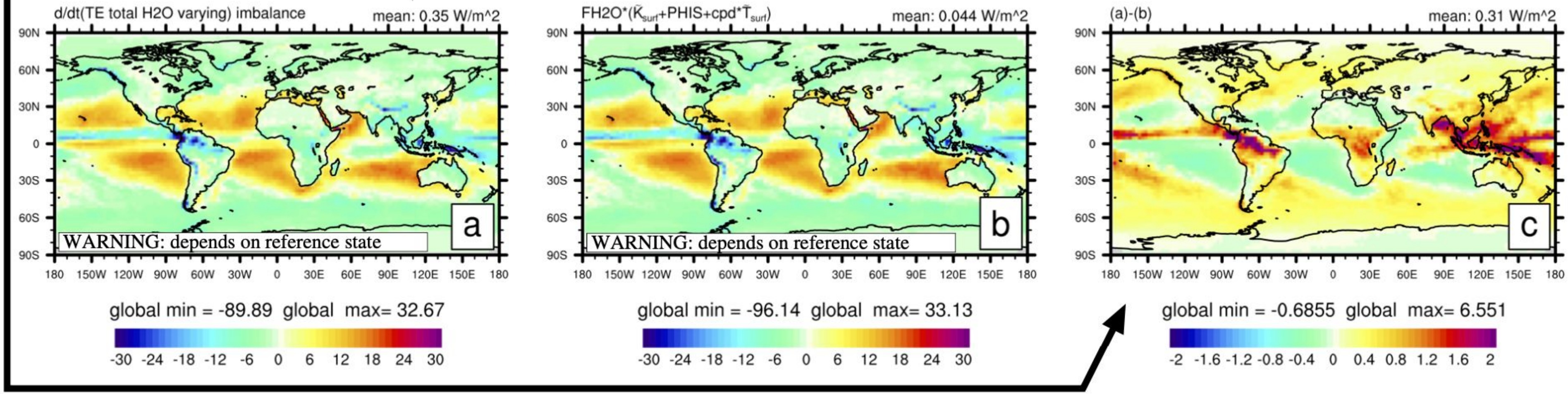
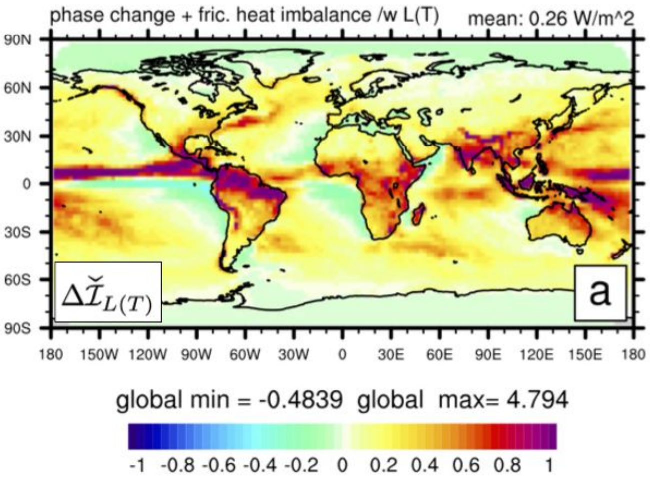
$$-\Delta\widehat{\mathcal{I}}_{\partial m^{(H_2O)}/\partial t}-\Delta\mathcal{I}_{m_{tn}^{(H_2O)}}=\overline{F}_{net}^{(H_2O)}\left[c_p^{(d)}\left(\widetilde{\overline{T}}_s-T_{00}\right)+\widetilde{\overline{K}}_s+\overline{\Phi}_s\right]+\overline{F}_{net}^{(wv)}L_{s,00}+\overline{F}_{net}^{(liq)}L_{f,00}+\overline{F}_{net}^{(turb,rad)}$$



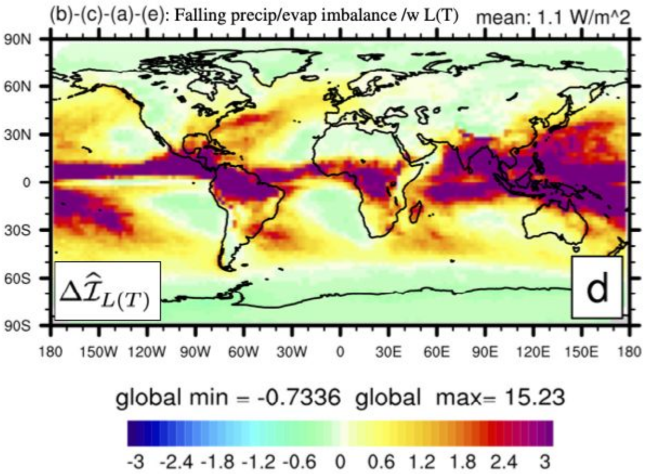
Modified (consistent) total energy equation assuming variable latent heats

$$\frac{\partial}{\partial t}\int \overline{\rho}^{(d)}\left\{\underline{\left(1+\overline{m}^{(H_2O)}\right)\left(\overline{K}+\overline{\Phi}_s\right)+c_p^{(d)}T+\sum_{\ell\in\mathcal{L}_{H_2O}}\overline{m}^{(\ell)}c_p^{(\ell)}\left(\overline{T}-T_{00}\right)}+\overline{m}^{(wv)}L_{s,00}+\overline{m}^{(liq)}L_{f,00}\right\}dz$$

$$-\Delta\check{\mathcal{I}}_{L(T)}-\Delta\widehat{\mathcal{I}}_{L(T)}=-\sum_{\ell\in\mathcal{L}_{H_2O}}\underline{\overline{F}_{net}^{(\ell)}\left[c_p^{(\ell)}\left(\widetilde{\overline{T}}_s-T_{00}\right)+\widetilde{\overline{K}}_s\right]}+\overline{F}_{net}^{(wv)}L_{s,00}+\overline{F}_{net}^{(liq)}L_{f,00}+\overline{F}_{net}^{(turb,rad)}$$



(a) Imbalance for processes not involving falling precip. & evap.



(b) Imbalance for falling precip. & evap.

Concluding remarks

- **Most global models do NOT rigorously account for processes associated with falling precipitation and evaporation in terms of kinetic, potential and internal energy**
  -> incl. boundary fluxes (in particular, enthalpy flux) improves energy budget massively!
  (other processes: frictional heating of falling precipitation, horizontal drag of precipitation, …)
- **Being rigorous in terms of monitoring energy conservation forces modelers to consider thermodynamic consistency between different parameterizations as well as dynamical core!**
  (inconsistency between CAM and CLUBB discussed in Lauritzen et al. (2022))
- **Note: For the enthalpy fluxes to be consistent with modern ocean models (e.g. GFDL's MOM6), atmosphere models must use variable latent heats**

Concluding remarks

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  -> incl. bou[...]get massively!
  (other proce[...]recipitation, …)

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  (inconsiste[...]l. (2022))

We are working towards incl. missing enthalpy flux term in NCARs' Community Earth System Model (CESM) version 3:

- Change spectral-element dynamical core to effectively use variable latent heats (see Lauritzen et al., 2018) - DONE
- Change CAM physics to incl. all condensates in pressure - DONE
- Change CAM physics to use variable latent heats (step 1 of 2 DONE)
- Pass enthalpy flux to other components (MOM6 straight forward, land and ice less obvious)

- Note: For the enthalpy fluxes to be consistent with modern ocean models (e.g. GFDL's MOM6), atmosphere models must use variable latent heats

Effort under WGNE/WCRP

How do we engage the global modeling community in assessing energy errors in their systems?

Questionnaire/survey sent to CMIP7 modeling groups and beyond trough WGNE/WCRP:

https://docs.google.com/document/d/1cztvWzraYX4oD_Vv8tJpUo3Af_kyG21hr1PDc9knu_4/edit

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