Current status of the CAM dynamical cores and ~~vertical resolution~~

Peter Hjort Lauritzen, pel@ucar.edu

http://www.cgd.ucar.edu/cms/pel

Atmospheric Modeling and Prediction (AMP) Section
Climate and Global Dynamics (CGD) Laboratory
National Center for Atmospheric Research (NCAR)

CESM Atmosphere / Whole Atmosphere / Chemistry-Climate WINTER WORKING GROUP MEETING, February 7-10

National Center for Atmospheric Research is a major facility sponsored by the NSF under Cooperative Agreement No. 1852977.

Current status of the CAM dynamical cores and enthalpy flux plans

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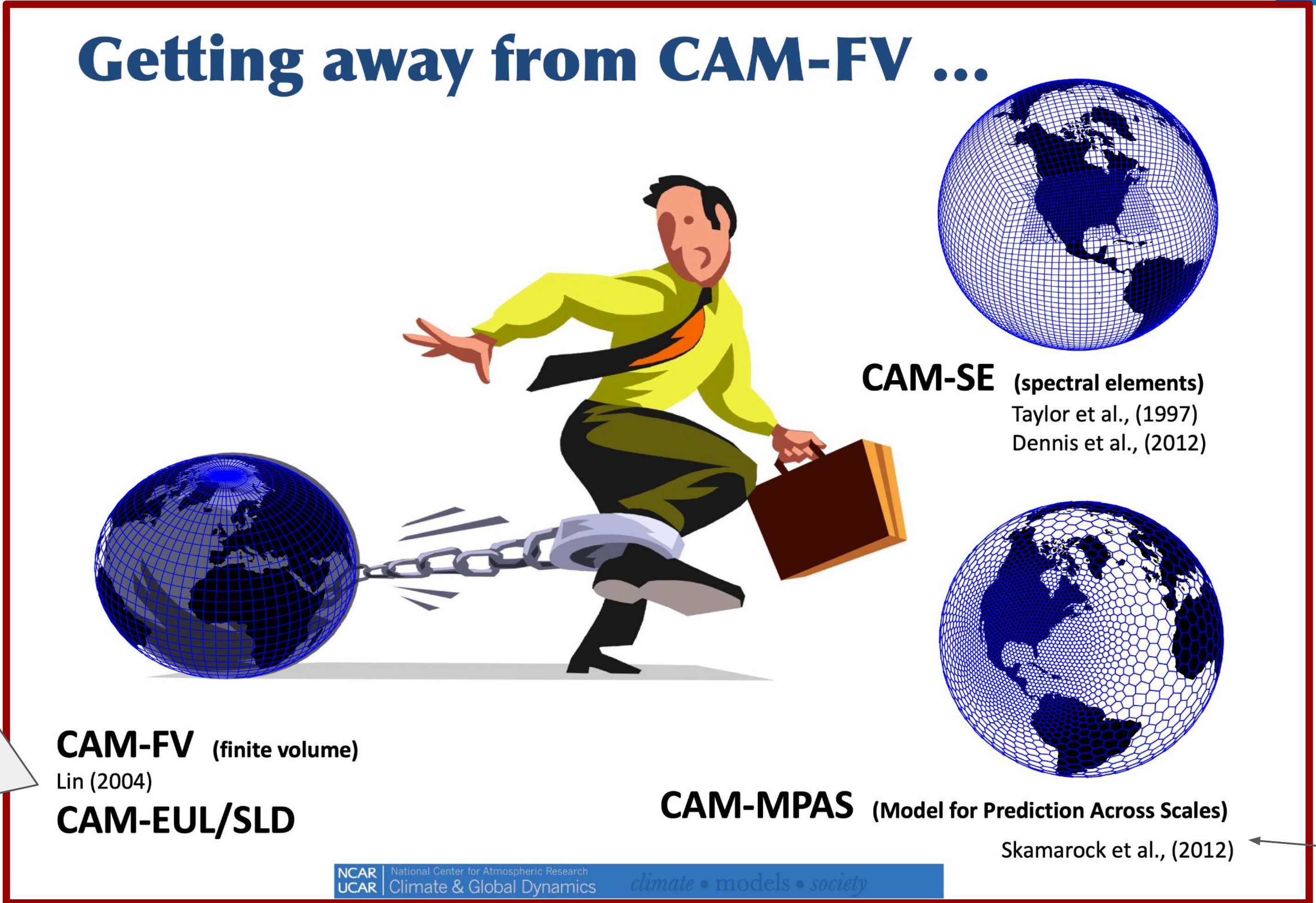

Getting away from CAM-FV …

CAM-SE (spectral elements)
Taylor et al., (1997)
Dennis et al., (2012)

CAM-FV (finite volume)
Lin (2004)

CAM-EUL/SLD

CAM-MPAS (Model for Prediction Across Scales)
Skamarock et al., (2012)

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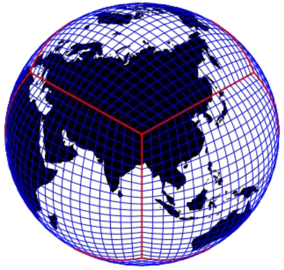
No active development in over a decade

Available in CAM since 2020:



CAM-FV3
(GFDL/NOAA global dynamical core)

Available in CAM since 2021

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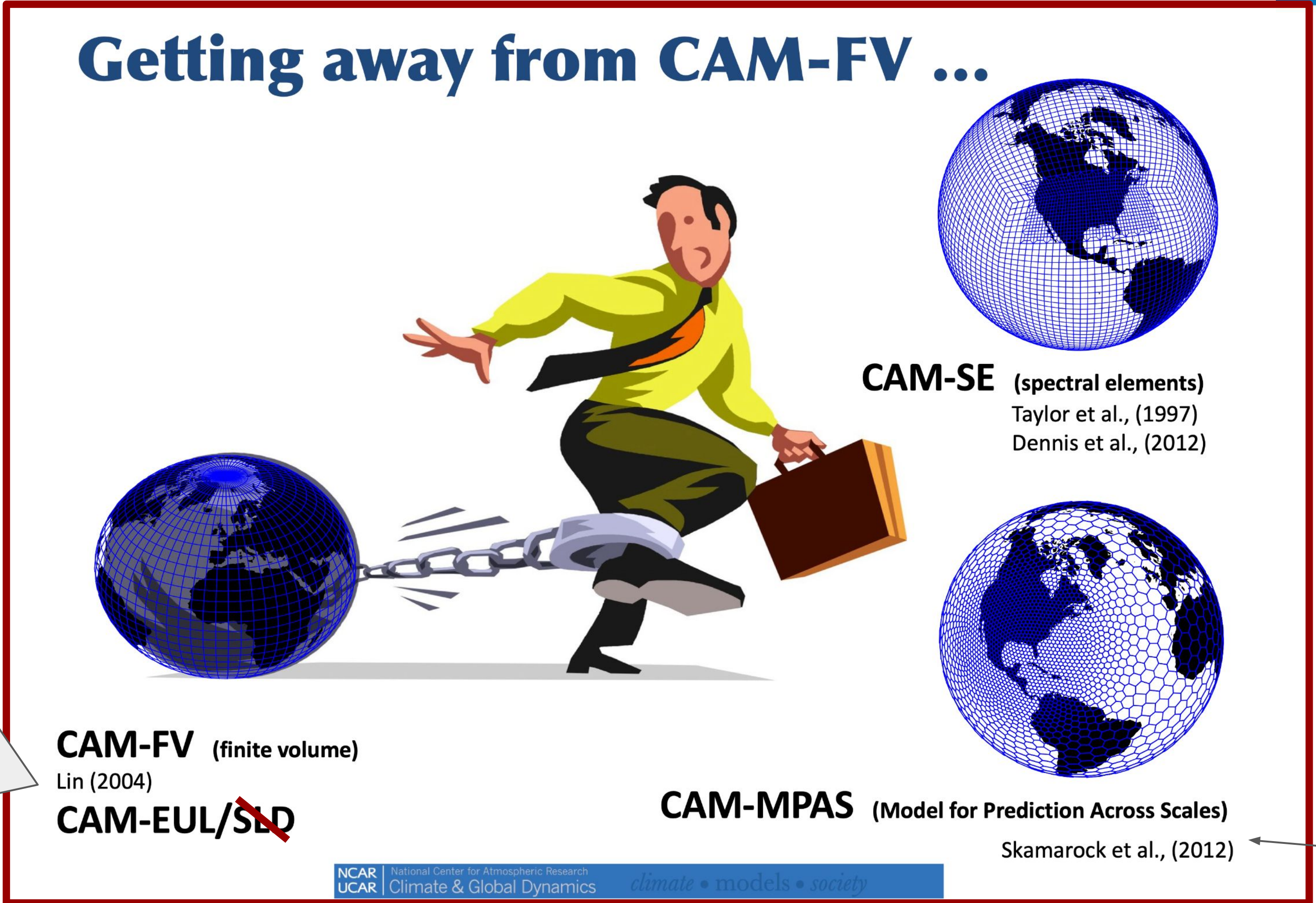

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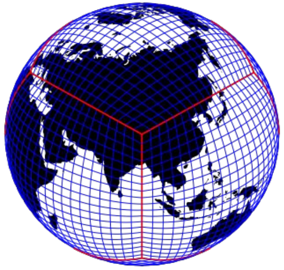

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(GFDL/NOAA global dynamical core)

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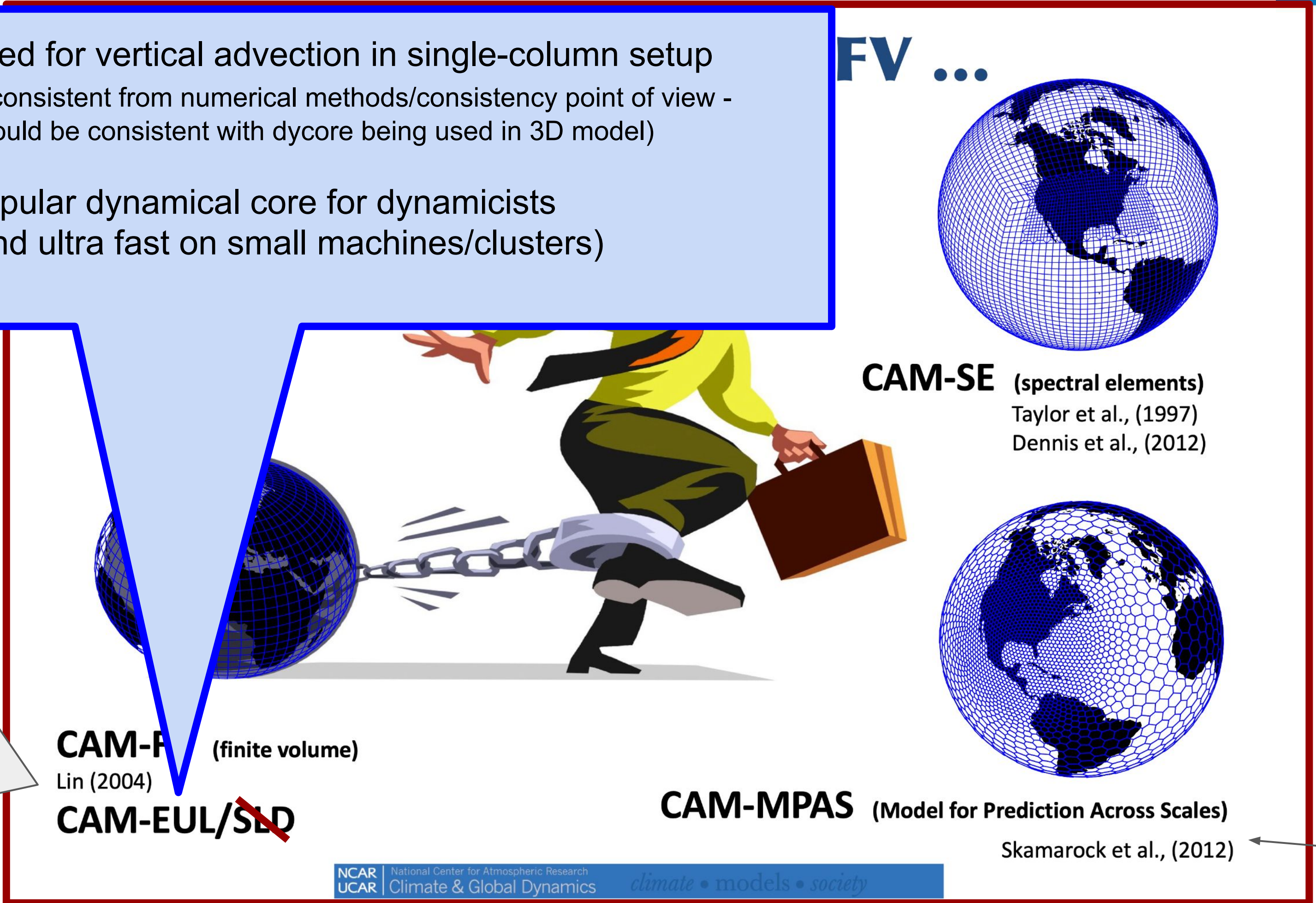
Red box: Slide from AMWG 2016

- used for vertical advection in single-column setup
  (inconsistent from numerical methods/consistency point of view - should be consistent with dycore being used in 3D model)
- popular dynamical core for dynamicists
  (and ultra fast on small machines/clusters)



FV …

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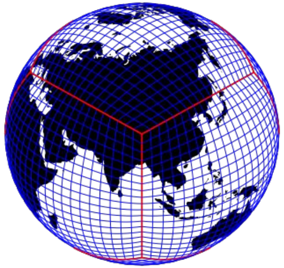

CAM-FV3
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Available in CAM since 2021

Red box: Slide from AMWG 2016

Getting aw

- Dycore was used for IPCC (CESM2) so likely will be needed as a reference for a while!
- Used for low resolution (e.g. paleo, low res WACCM) applications
  (could SE do that? Need “extreme” scalability at low res for fast throughput!)

CAM-SE **(spectral elements)**
Taylor et al., (1997)
Dennis et al., (2012)

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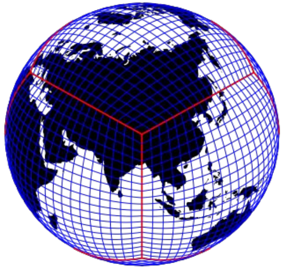


CAM-FV3
(GFDL/NOAA global dynamical core)

Available in CAM since 2021

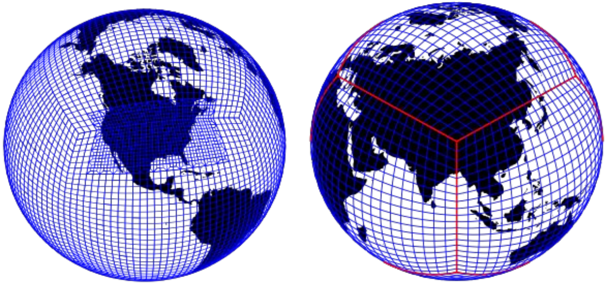
Next generation dycore implementation for climate
Current status with respect to CAM7 (new vertical resolution)

- **SE**: **Fully functional with new vertical resolution**
  (FYI: NOAA seed project for developing SE for Mars funded - *CESM Alternative Earths effort*)

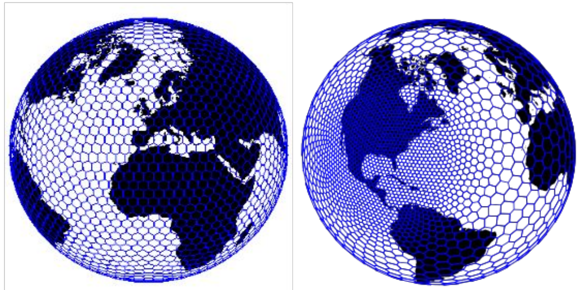
- **MPAS**: **Fixed some physics-dynamics coupling issues (at high horizontal resolution); implementing frontogenesis functions (needed for ~80km and higher top); setup new vertical resolution** (FYI: lots going on for high resolution and high top - see SIMA and EarthWorks presentations later today)

- **FV3**: **Upgrading to new GFDL code base; implementing frontogenesis functions; setup new vertical resolution**

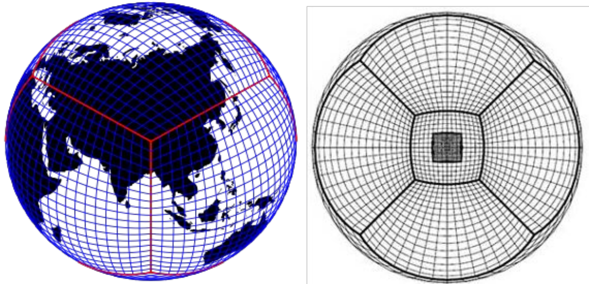
CAM-SE(CSLAM)



CAM-MPAS



CAM-FV3



“Enthalpy flux” plans

- Why? The upper boundary condition for MOM6 ocean model requires explicit specification of the heat fluxes associated with water leaving/entering the ocean (a.k.a. enthalpy fluxes)

- Why? Enthalpy fluxes neglected in CAM energy budgets; effectively in CAM’s global energy fixer
  - see AMWG talk 2021: https://www.cgd.ucar.edu/cms/pel/papers/L2021AMWG.pdf or Lauritzen et al. (2022, in prep)

Note: If one naively adds flux terms to CAM and does nothing else, one can easily introduce energetic and thermodynamic inconsistencies in the coupled system so we have to be very careful on how we proceed …

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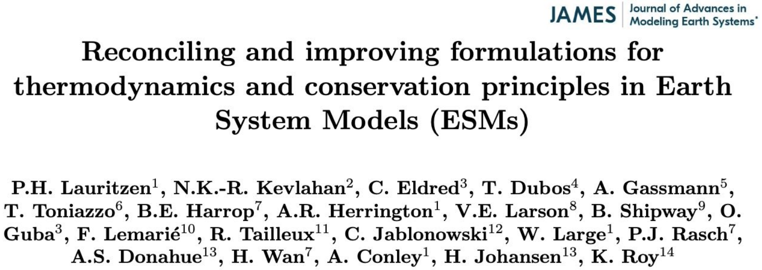


JAMES | Journal of Advances in Modeling Earth Systems

Reconciling and improving formulations for thermodynamics and conservation principles in Earth System Models (ESMs)

P.H. Lauritzen[1], N.K.-R. Kevlahan[2], C. Eldred[3], T. Dubos[4], A. Gassmann[5], T. Toniazzo[6], B.E. Harrop[7], A.R. Herrington[1], V.E. Larson[8], B. Shipway[9], O. Guba[3], F. Lemarié[10], R. Tailleux[11], C. Jablonowski[12], W. Large[1], P.J. Rasch[7], A.S. Donahue[13], H. Wan[7], A. Conley[1], H. Johansen[13], K. Roy[14]

Note: Discusses CLUBB-CAM thermodynamic consistency that A. Herrington mentioned in his talk!

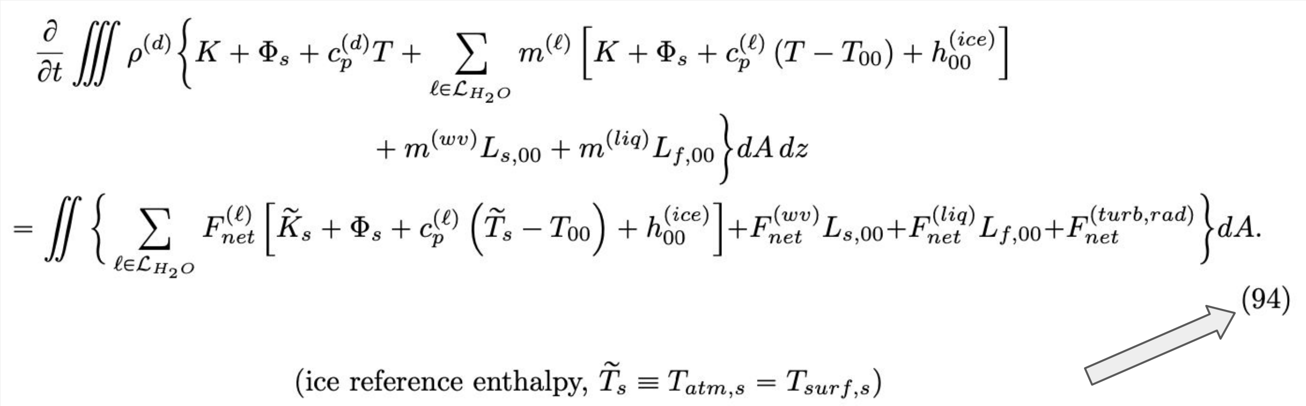
Total energy equation

Lauritzen et al. (2022, in prep)

Assume:

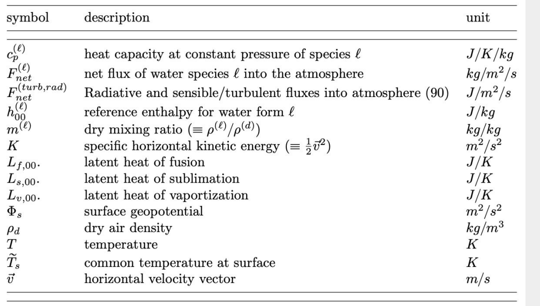
- Primitive equations (hydrostatic, shallow atmosphere, ideal gas)
- Assume model top pressure is constant
- All components of moist air have the **same temperature** and move with the **same horizontal velocity**
- Assume that water entering the atmosphere (evaporation, snow drift, sea spray) has **same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



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

(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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Then it can be shown that the following globally integrated to

Total water held fixed during physics parameterizations; updated at end of physics and the energy associated with water changes stays in the atmosphere (in the form of a global uniform temperature increment)

Lauritzen et al. (2022, in prep)

Many models make these assumptions:

$$\frac{\partial}{\partial t}\iiint \rho^{(d)}\left\{\overline{K}+\overline{\Phi}_s+c_p^{(d)}\overline{T}+\sum_{\ell\in\mathcal{L}_{H_2O}} m^{(\ell)}\left[\overline{K}+\overline{\Phi}_s+c_p^{(\ell)}\left(\overline{T}-T_{00}\right)+h_{00}^{(ice)}\right]\right.$$

$$\boxed{\mathcal{L}_{H_2O} =' wv'} \qquad \left.+\overline{m}^{(wv)}L_{s,00}+\overline{m}^{(liq)}L_{f,00}\right\}dA\,dz \qquad \boxed{c_p^{(\ell)} = c_p^{(d)}}$$

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

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

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“Enthalpy flux” plan

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ing globally integrated total energy equation holds:

incl. all forms of water in lhs. terms
(small energy budgets change - Lauritzen et. al (2022))

Many models make these assumptions:

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

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“Enthalpy flux” plan

Switch to variable latent heats (to be consistent /w MOM6)

(note: FV3 and SE already use variable latent heats)

- change CAM’s thermodynamic variable (%s) to use variable latent heats
- if parameterizations use constant latent heat assumption that needs to be changed

Lauritzen et al. (2022, in prep)

Assume:

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- Assume model top pressu
- All components of moist a **ntal velocity**
- Assume that water enterin **temperature** as water leaving the atmosphere (c **ACCURATE!**

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$$+\overline{m}^{(wv)}L_{s,00}+\overline{m}^{(liq)}L_{f,00}\Big\}dA\,dz$$

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

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

“Enthalpy flux” plan

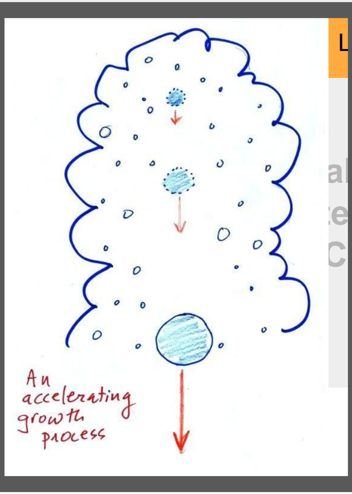
Explicit enthalpy flux term:

What temperature to use?

Evaporation : surface T (SST over ocean)
Precipitation : T where is was created? Neglects frictional heating

(note: “naturally” incorporated using barycentric velocity framework (Lauritzen et al., 2022))

T in lowest model level?



L uritzen et al. (2022, in prep)

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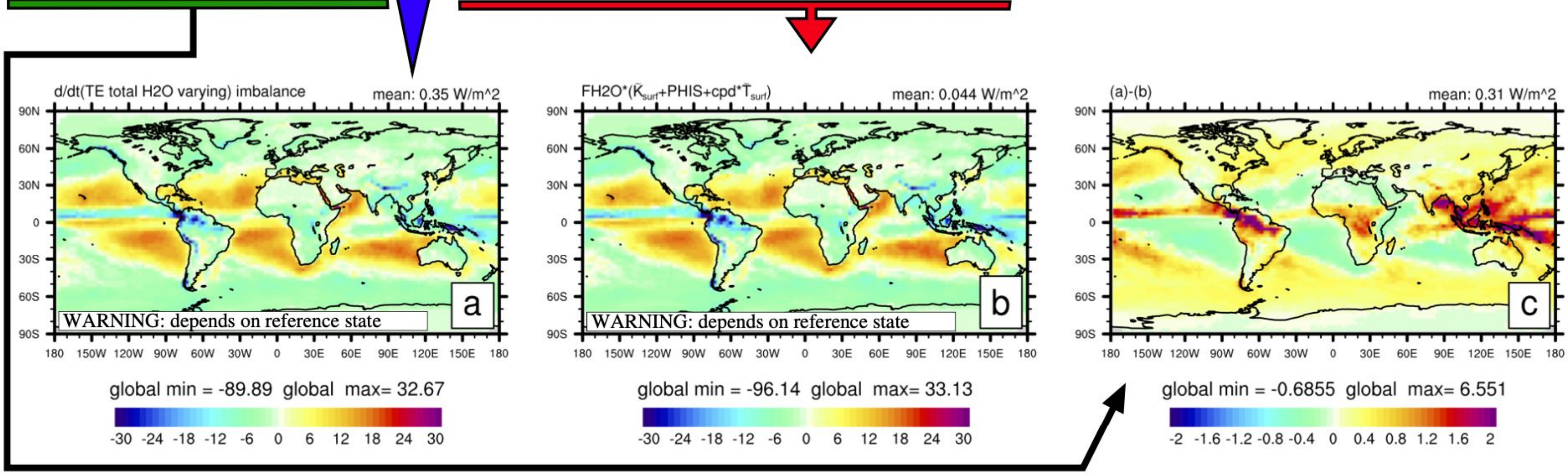
Now also assume that the energy equation is valid for grid mean values in the model (**QUESTIONABLE ASSUMPTION!**)

Modified CAM total energy equation incl. missing flux terms

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

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



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Why does CESM have multiple atmosphere dynamical cores?

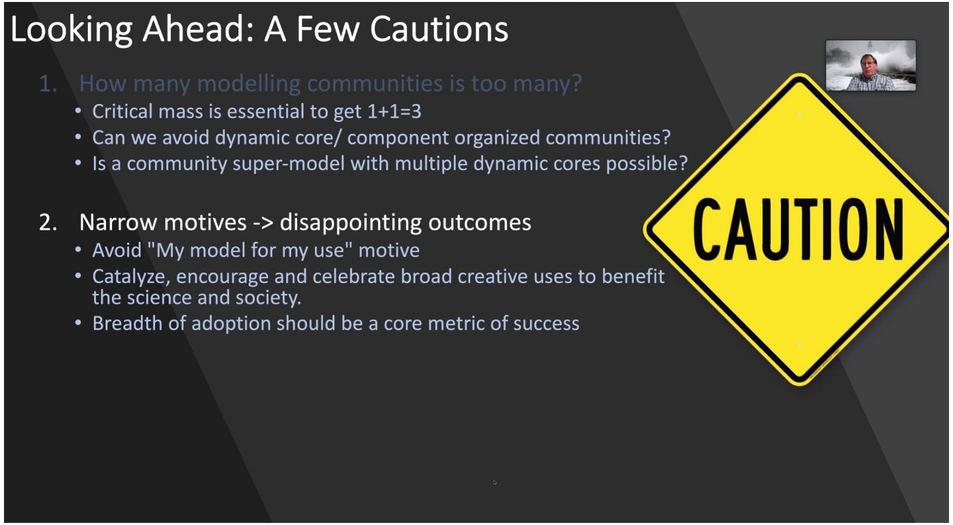
- To assess (structural) uncertainty due to dynamical core one needs more than 1 dynamical core

- Dynamical cores are strongly depending on compute platform and programming paradigm (MPI communication, vectorization,…); supercomputing environment is constantly changing!

- Dynamical core science is not settled though many strong opinions in the community

- CESM is unique in that it enables "advanced" dynamical core science in the sense of having idealized to full climate functionality with multiple dynamical cores in one system!

Slide from P. Neilley
(Director of Weather Forecasting Sciences, Technologies and Operations at IBM's Weather Company)
First Symposium on Earth Prediction Innovation and Community Modeling
at AMS, 2022



Looking Ahead: A Few Cautions

1. How many modelling communities is too many?
   - Critical mass is essential to get 1+1=3
   - Can we avoid dynamic core/ component organized communities?
   - Is a community super-model with multiple dynamic cores possible?
2. Narrow motives -> disappointing outcomes
   - Avoid "My model for my use" motive
   - Catalyze, encourage and celebrate broad creative uses to benefit the science and society.
   - Breadth of adoption should be a core metric of success

Total er

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- All components of moist air have the **s** … **elocity**
- Assume that water entering the atmos … **perature** as water leaving the atmosphere (dew, liquid ar … **RATE!**

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

$$+ \overline{m}$$

$$= \iint \left\{ \cancel{\sum_{\ell \in \mathcal{L}_{H_2O}} F_{net}^{(\ell)} \left[\overline{\widetilde{K}_s} + \overline{\Phi}_s + \right.} \right.$$

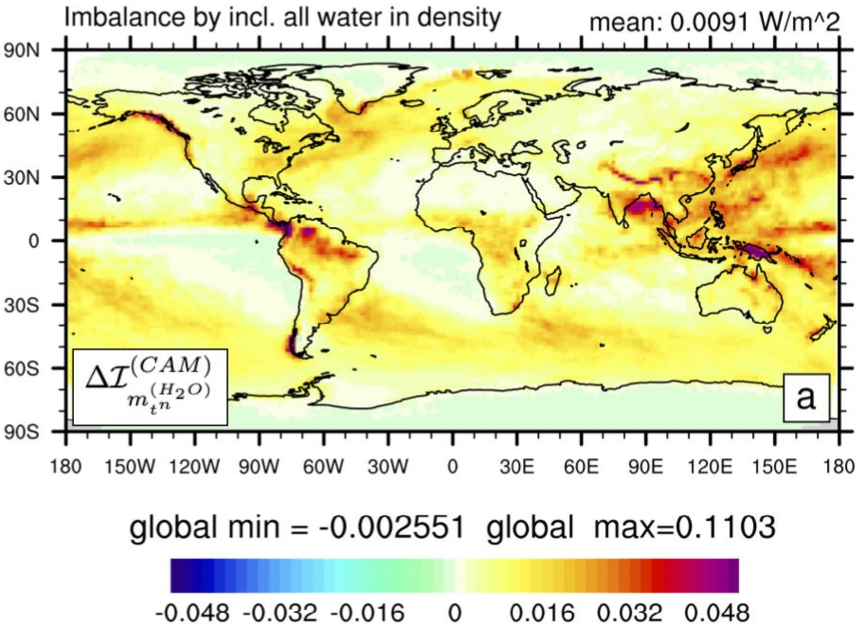
(ice refere

Now also assume that the energy equation is … **E**
ASSUMPTION!)

Imbalance of incl. all forms of water in CAM's parameterization total energy equation:

$$\Delta \mathcal{I}^{(CAM)}_{m_{tn}^{(H_2O)}} =$$

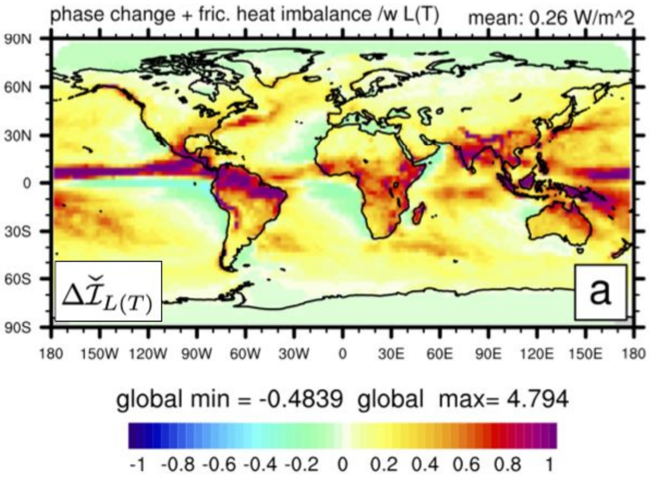
$$\int \left[\rho^{(d)} \left(\sum_{\ell \in \mathcal{L}_{cond}} \overline{m}_{tn}^{(\ell)} \right) \right] \frac{\partial}{\partial t} \left(\overline{K} + \overline{\Phi}_s + c_p^{(d)} \overline{T} \right) dz$$



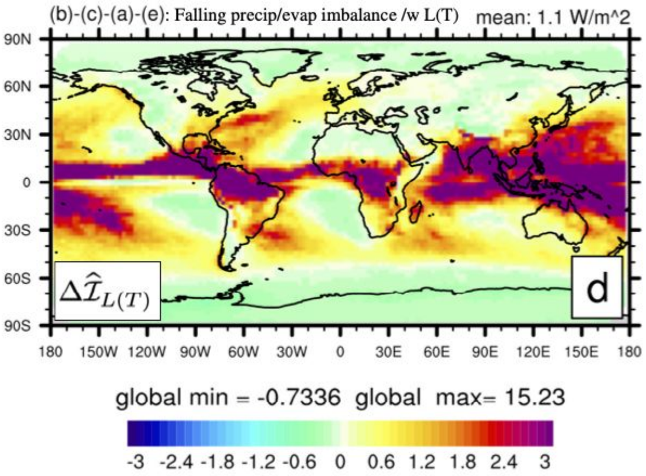
Modified (consistent) total energy equation assuming variable latent heats

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

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



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



(b) Imbalance for falling precip. & evap.