Changes to the hydrostatic spectral-elements dynamical core for CESM3: SE-CSLAM

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Outline: From HOMME* to CAM-SE-CSLAM

- Dry-mass vertical coordinate
- Separate physics grid and tracer transport grid/scheme
- Condensates incl. in pressure; variable latent heats / coupling with MOM6
- Reference profiles for hyperviscosity

Changes energy equation!

- High top stability
- Computational speed-up

*High-Order Method Modeling Environment

From moist to dry-mass vertical coordinate system

Consider a 'moist' η-coordinate system: The pressure is given by

$$p(\eta) = A(\eta)p_0 + B(\eta)ps,$$

where ps is 'moist' surface pressure.

In a floating η-coordinate system, $\dot{\eta} = 0$, the continuity equation for p can be written as

$$\frac{\partial}{\partial t}\left[\left(\frac{\partial p}{\partial \eta}\right)\right] + \nabla \cdot \left[\left(\frac{\partial p}{\partial \eta}\right)\vec{v}\right] = S^p,$$

where $S^p(q_v)$ is the source/sink term for pressure ($q_v \equiv$ specific humidity).

See also ECMWF Technical Memoranda
https://www.ecmwf.int/en/elibrary/81081-dry-mass-versus-total-mass-conservation-ifs

If one uses a dry mass vertical coordinate

$$p(\eta_d) = A(\eta_d)p_0 + B(\eta_d)ps_d,$$

where ps_d is dry surface pressure, then the continuity equation for pressure does not have sources/sinks

$$\frac{\partial}{\partial t}\left[\left(\frac{\partial p_d}{\partial \eta_d}\right)\right] + \nabla \cdot \left[\left(\frac{\partial p_d}{\partial \eta_d}\right)\vec{v}\right] = 0.$$

Changes to other equations not shown!

Lauritzen et al. (2018);
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2017MS001257

Separate physics, transport and dynamics grid

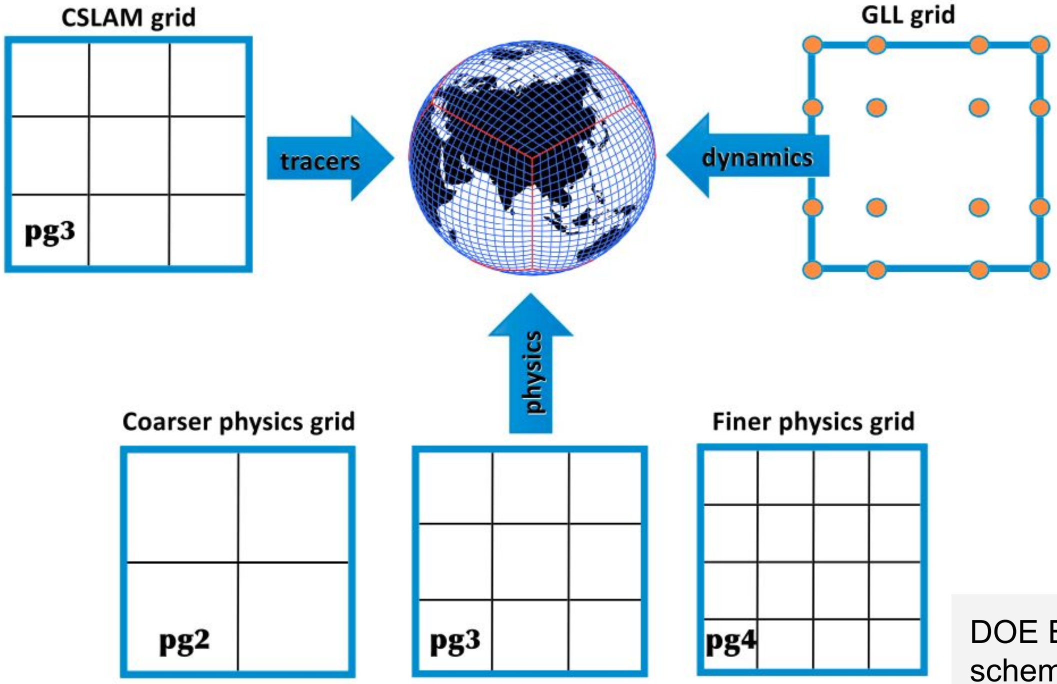

Figure 1. An overview of the different grids in CAM-SE-CSLAM.

For CESM3 we use pg3 grid for CAM physics!

Separating grids is not trivial - mapping between grids must be done carefully!
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019ms001684

Transport scheme:
Conservative Semi-LAgrangian Multi-tracer scheme
(consistent coupling with spectral-elements dycore described here https://journals.ametsoc.org/view/journals/mwre/145/3/mwr-d-16-0258.1.xml)

Note: Dry-mass vertical coordinate makes CSLAM-SE dycore coupling more consistent!

DOE E3SM is using similar approach (but transport scheme faster and supports variable resolution grids)

UK Met Office is exploring separation of grids as well

HOMME: Constant latent heats formulation of dynamical core

Large-scale models have traditionally assumed that dry air and water vapor constitutes moist air and the specific heat for water vapor is assumed that of dry air which leads to the following total energy equation for the atmosphere

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

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

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

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

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022MS003117

HOMME: Constant latent heats formulation of dynamical core

Large
vapor
assur
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Choosing the same heat capacity for all components of moist air -> constant latent heats:

Latent heat of sublimation (solid → water vapor):

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

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

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

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

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

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

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SE-CSLAM: Variable latent heats formulation of dynamical core

Switched to variable latent heat formulation and incl. all components of moist air in pressure:

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

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

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

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

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

Energy fixer in CAM physics reformulated to be consistent with SE dynamical core (and MPAS dynamical core based on a constant volume energy formula)

At end of physics energy increment in physics made consistent with the dynamical core (for SE heating added under the assumption of using variable latent heats)

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022MS003117

SE-CSLAM: Variable latent heats formulation of dynamical core

Assuming pressure is constant (94) is satisfied in CAM physics. At the end of physics pressure is updated (to reflect changes of water in the column). The energy change associated with that is corrected with global energy fixer (we do not explicitly incl. enthalpy flux terms)

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

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

Kinetic and potential energy of water leaving/entering atmosphere small compared to enthalpy flux terms

SE-CSLAM: Variable latent heats formulation of dynamical core

Most of the energy fixer (excl. dynamical core energy errors) fixes energy change due to entahlpy flux:

$$\approx \underline{\sum_{\ell \in \mathcal{L}_{H_2O}} F_{net}^{(\ell)} \left[c_p^{(\ell)} \left(\tilde{T}_s - T_{00} \right) + h_{00}^{(ice)} \right]} + F_{net}^{(wv)} L_{s,00} + F_{net}^{(liq)} L_{f,00},$$

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

Kinetic and potential energy of water leaving/entering atmosphere small compared to enthalpy flux terms

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Enthalpy flux terms and coupling with MOM6

MOM6 uses enthalpy flux in its boundary condition (using a liquid reference state) but since CAM currently can’t receive these fluxes, they are fixed with a global fixer through sensible heat flux to atmosphere:

$$F_{net}^{(h)} \approx F_{net}^{(H_2O)} \left[c_p^{(liq)} \left(\tilde{T}_s - T_{00}\right) + h_{00}^{(liq)}\right] + F_{net}^{(wv)} L_v \left(\cancel{\tilde{T}_s}\right) - F_{net}^{(ice)} L_f \left(\cancel{\tilde{T}_s}\right)$$

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

MOM6 assumes constant latent heats

Loosely speaking: each components does it’s own thing and fixes its own thing independently of each other …

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Enthalpy flux te

MOM6 uses er ing a liquid reference state these fluxes, they are fixed with a o atmosphere:

$$\approx \sum_{\ell\in\mathcal{L}_{H_2}} \quad - F_{net}^{(ice)} L_{f,00}$$

)

MOM6 assumes constant latent heats

Loosely speaki g and fixes its own thing inde

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022MS003117

Our proposal:

Both components use variable latent heats (and be very careful with different reference states) and enthalpy flux incl. in CAM energy equation, then the fluxes match and we can eliminate “sensible heat flux fixer” in coupler and atmospheric global energy fixer will fix less

$$\approx \sum_{\ell \in \mathcal{L}_{H_2O}} F_{net}^{(\ell)} \left[c_p^{(\ell)} \left(\tilde{T}_s - T_{00} \right) + h_{00}^{(liq)} \right] + F_{net}^{(wv)} L_{v,00} - F_{net}^{(ice)} L_{f,00}$$

MOM6

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

$$\approx \sum_{\ell \in \mathcal{L}_{H_2O}} F_{net}^{(\ell)} \left[c_p^{(\ell)} \left(\tilde{T}_s - T_{00} \right) + h_{00}^{(ice)} \right] + F_{net}^{(wv)} L_{s,00} + F_{net}^{(liq)} L_{f,00},$$

CAM7

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

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Our proposal:

Both compo reful with
different ref ergy
equation, th nsible heat
flux fixer” in l fix less

Status

Variable latent heat formulation of SE-CSLAM - done

Changing energy formulation in CAM physics - done

Since CAM physics does not use variable latent heats the temperature tendencies are scaled as if the heating had been added under variable latent heat assumptions before returning them to the dycore - done

Code to send enthalpy fluxes from/to CAM - in progress

(thanks to Jim Edwards for CMEPS support)

MOM6

CAM7

$$\sum_{\ell\in\mathcal{L}_{H_2O}} F_{net}\left[c_p(T_s - T_{00}) + h_{00}\right] + F_{net}L_{s,00} + F_{net}L_{f,00},$$

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

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- Dry-mass vertical coordinate
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- Reference profiles for hyperviscosity
- High top stability:
- Computational speed-up

Changes energy equation!

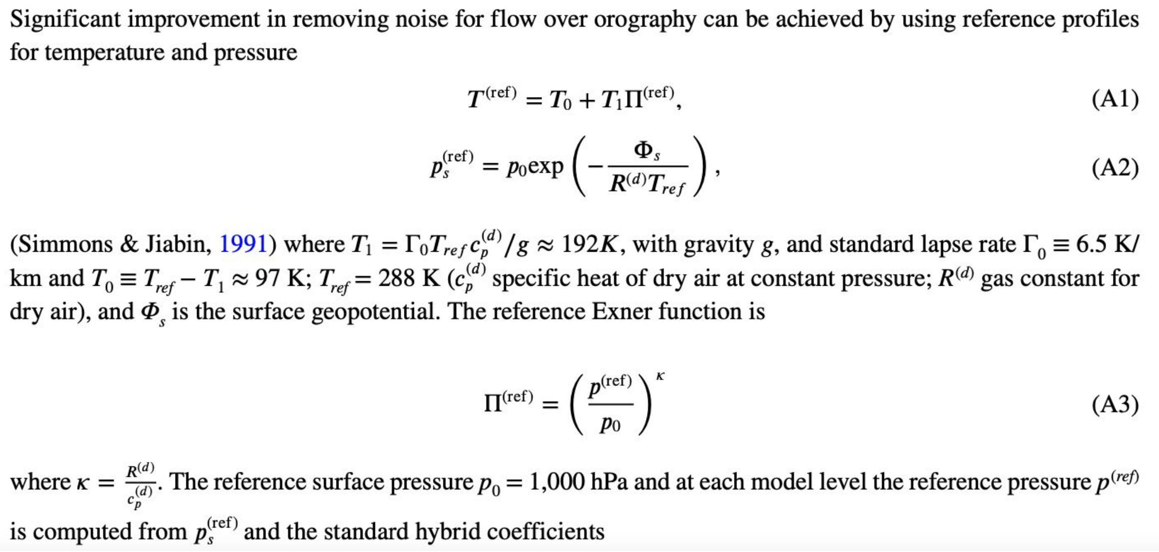
*High-Order Method Modeling Environment

Reference profiles for hyperviscosity and PGF

$$\nabla_\eta^4 T \quad \rightarrow \quad \nabla_\eta^4\left(T - T^{(\text{ref})}\right),$$

$$\nabla_\eta^4 \delta p^{(d)} \rightarrow \nabla_\eta^4\left(\delta p^{(d)} - \delta p^{(\text{ref})}\right).$$

where the reference profiles are given by



Significant improvement in removing noise for flow over orography can be achieved by using reference profiles for temperature and pressure

$$T^{(\text{ref})} = T_0 + T_1\Pi^{(\text{ref})}, \tag{A1}$$

$$p_s^{(\text{ref})} = p_0\exp\left(-\frac{\Phi_s}{R^{(d)}T_{ref}}\right), \tag{A2}$$

(Simmons & Jiabin, 1991) where $T_1 = \Gamma_0 T_{ref} c_p^{(d)}/g \approx 192K$, with gravity g, and standard lapse rate $\Gamma_0 \equiv 6.5$ K/km and $T_0 \equiv T_{ref} - T_1 \approx 97$ K; $T_{ref} = 288$ K ($c_p^{(d)}$ specific heat of dry air at constant pressure; $R^{(d)}$ gas constant for dry air), and Φ_s is the surface geopotential. The reference Exner function is

$$\Pi^{(\text{ref})} = \left(\frac{p^{(\text{ref})}}{p_0}\right)^{\kappa} \tag{A3}$$

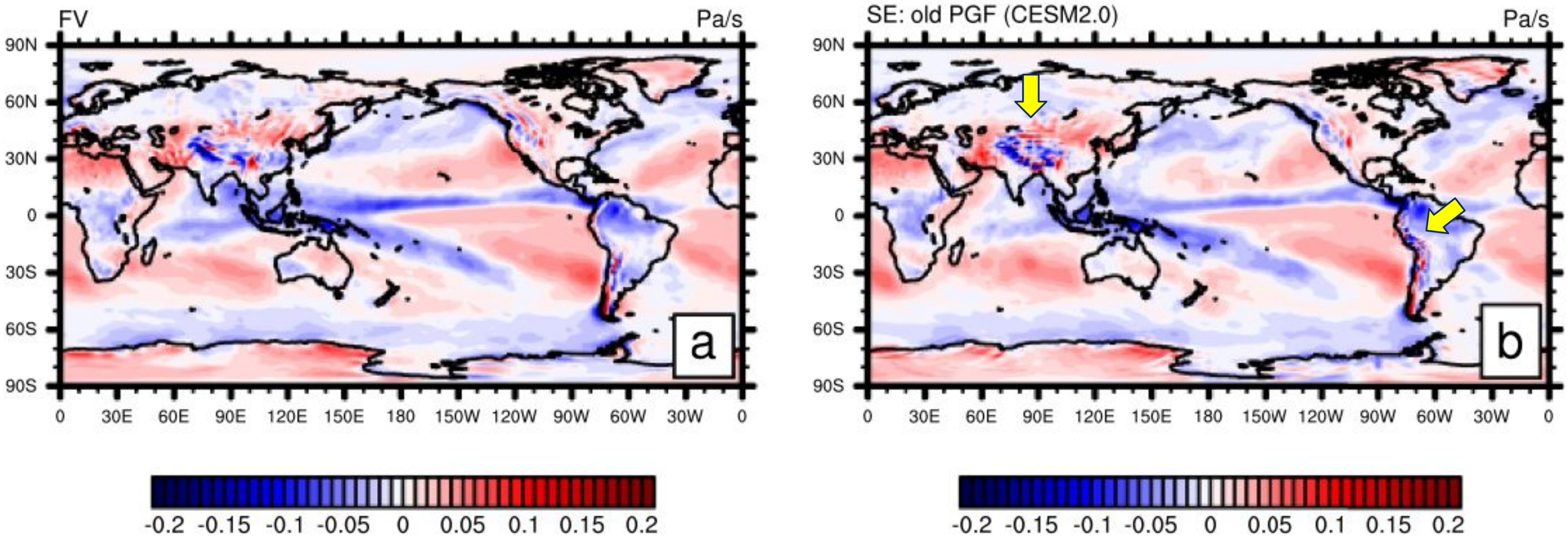
where $\kappa = \frac{R^{(d)}}{c_p^{(d)}}$. The reference surface pressure $p_0 = 1{,}000$ hPa and at each model level the reference pressure $p^{(ref)}$ is computed from $p_s^{(\text{ref})}$ and the standard hybrid coefficients

Similarly for the pressure-gradient force (PGF)

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022MS003192
(collaboration with M. Taylor DOE)

Reference profiles for hyperviscosity and PGF

One year averages of vertical pressure velocity at 500 hPa (OMEGA500): AMIP



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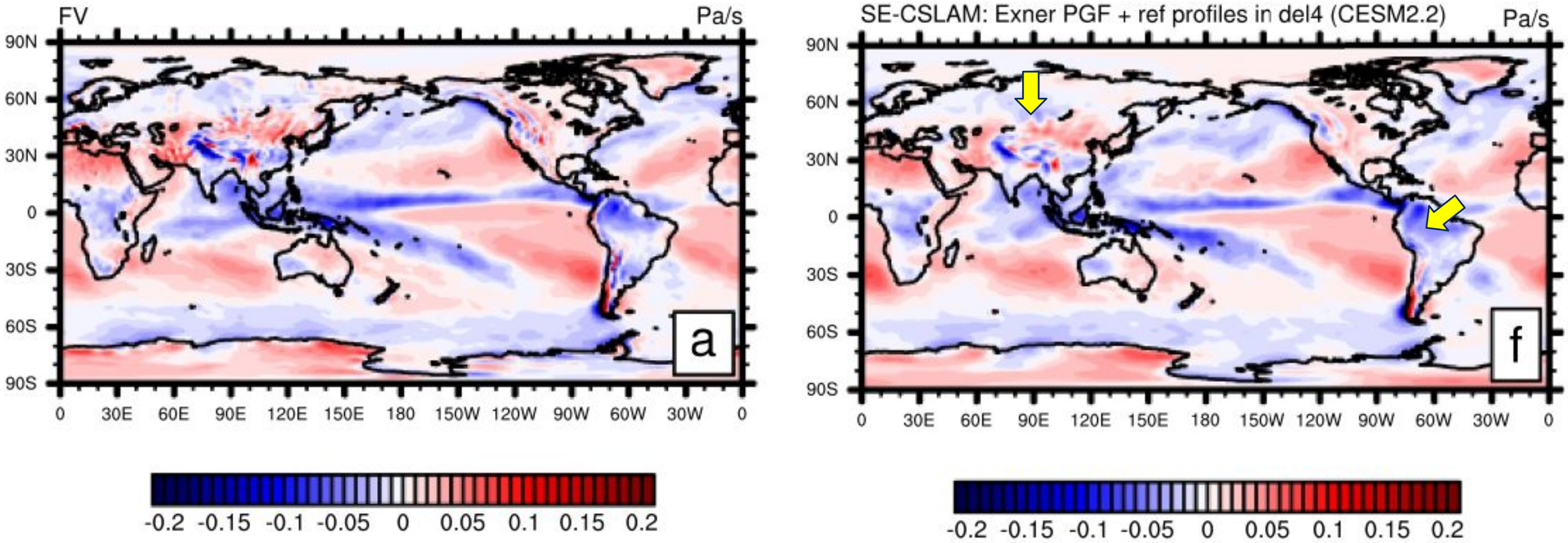

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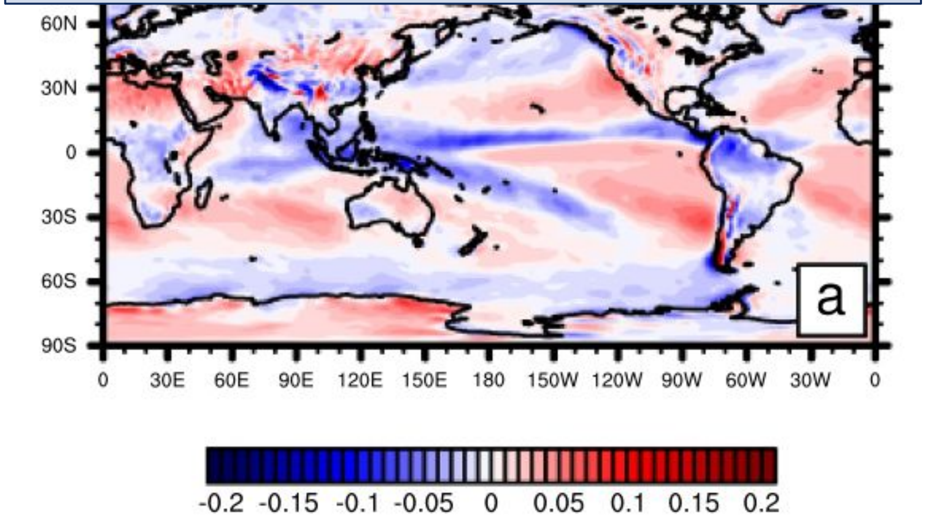
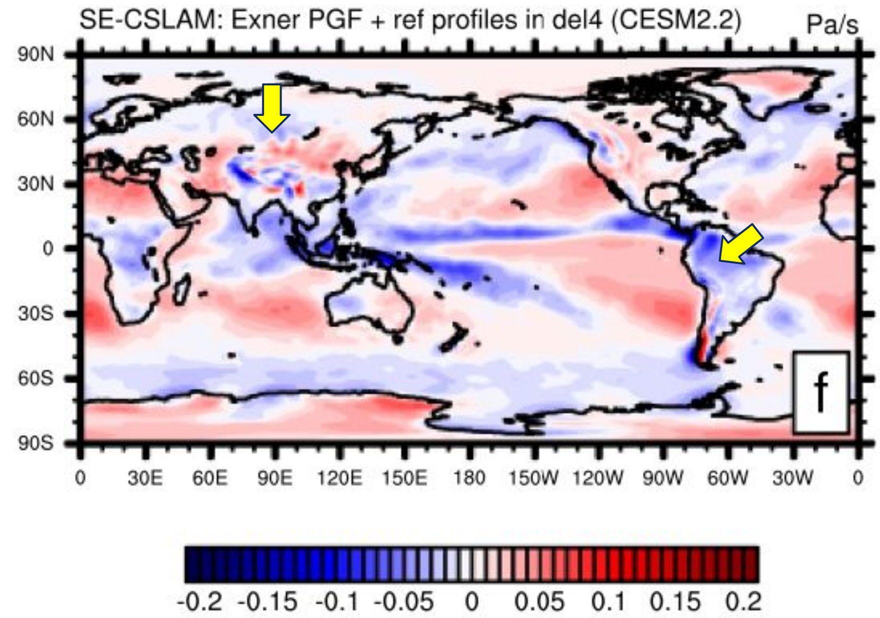
Reference profiles for hyperviscosity and PGF

=> We can now run with rougher topography similar to what is used in MPAS, that is, use half the smoothing scale compared to what we used in CESM2 (this is currently being explored)

velocity at 500 hPa (OMEGA500): AMIP





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- Computational speed-up

Changes energy equation!

*High-Order Method Modeling Environment

Computational speed-up

No double-advection of thermodynamic active tracers and other changes …

Timing for coupled simulation (old dycore):

```
Overall Metrics:
   Model Cost:            6436.15   pe-hrs/simulated_year
   Model Throughput:         8.11   simulated_years/day
```

Timing for coupled simulation (faster dycore + pe_layout1)

```
 Overall Metrics:
    Model Cost:            5135.40   pe-hrs/simulated_year
Model Throughput:        10.77   simulated_years/day
```

*High-Order Method Modeling Environment

https://github.com/ESCOMP/CAM/pull/968