Update on activities at the Atmospheric Modeling Program (AMP) related to the Water Cycle: 1) Background and recent development; 2) CESM2 and MPAS merge

Julio Bacmeister and Peter Lauritzen (CGD/NCAR)

Water System Retreat
NCAR, April 26-28, 2023

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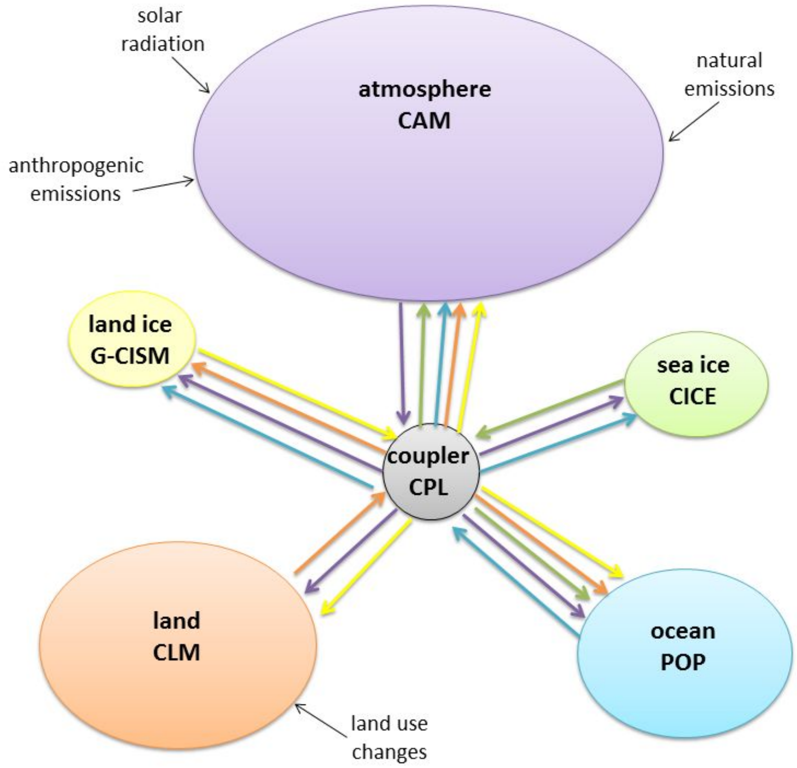
CESM (Community **Earth System Model**)



CESM==water cycle science

CESM incorporates every process that touches water in the Earth System, past, present and future (Carboniferous ~300MA ⇒??)

CESM (Community **Earth System Model**)

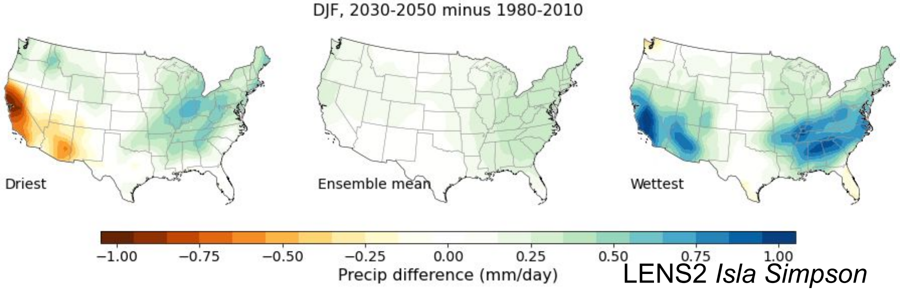
Why do we need a coarse (~100km) model for Water Cycle science? There aren't TC's, MCS's, squall lines, steep mountains … .

Reliable observational record ~100 years: Not long enough to characterize things like ENSO-QBO-SSW interactions …

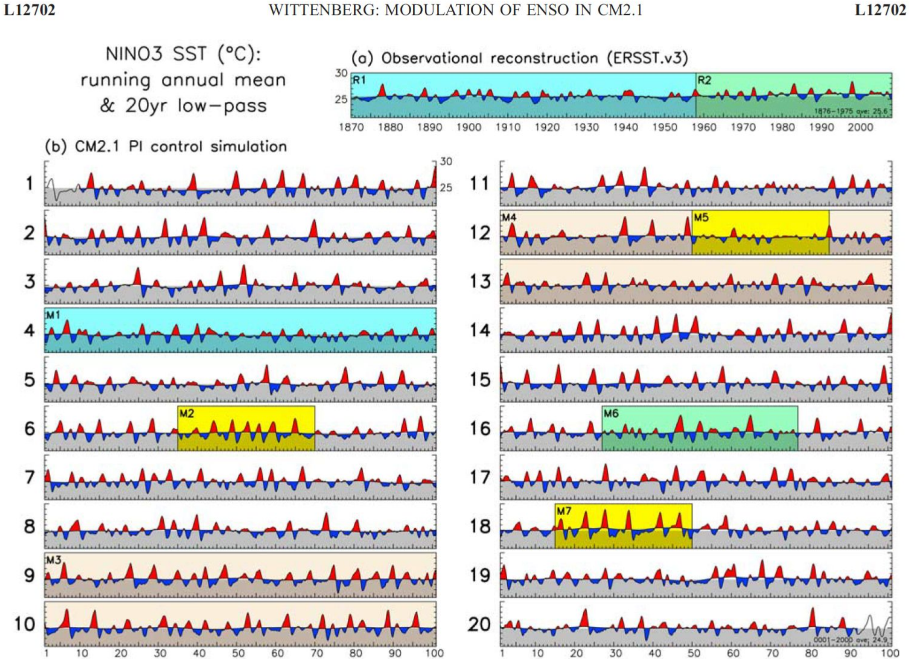
It takes *many* years simulation (~1,000's of SY) to characterize internal variability in the coupled system (***Caveat:*** *this is based on simulations using 1° resolution)*

Examples:

- Large ensembles (LENS) 50x100's SY
- ENSO variability
- S2S,S2I,S2D forecasts ~10,000SY

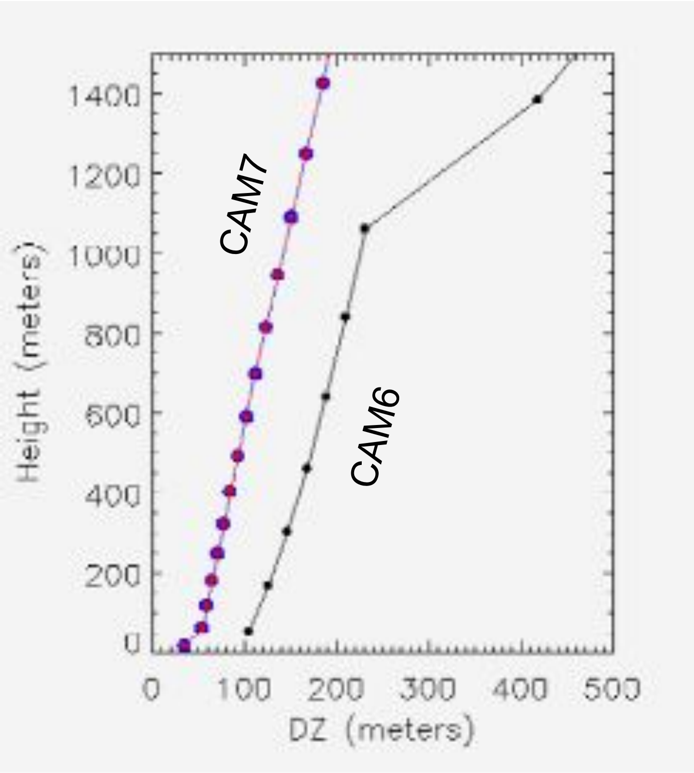


LENS2 *Isla Simpson*

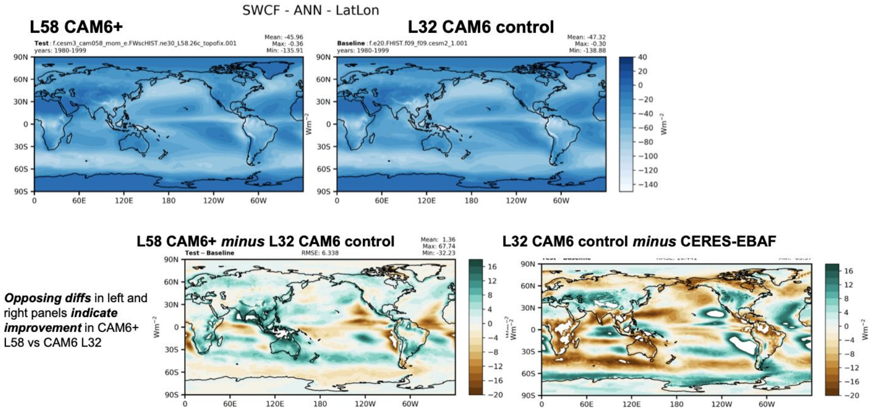


Recent CAM Development:

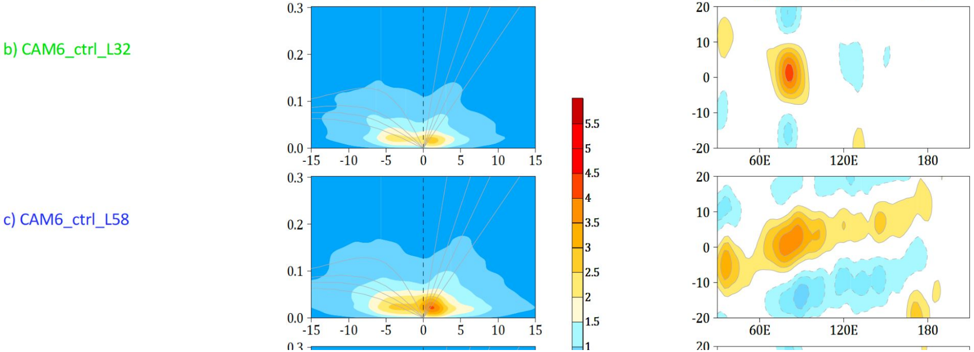
Increased vertical resolution:
Largest increase in 20+ years



Progress towards CAM7

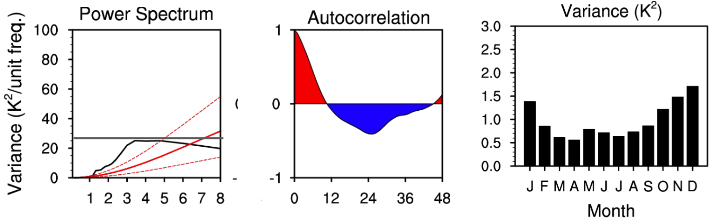


Better F-case MJO

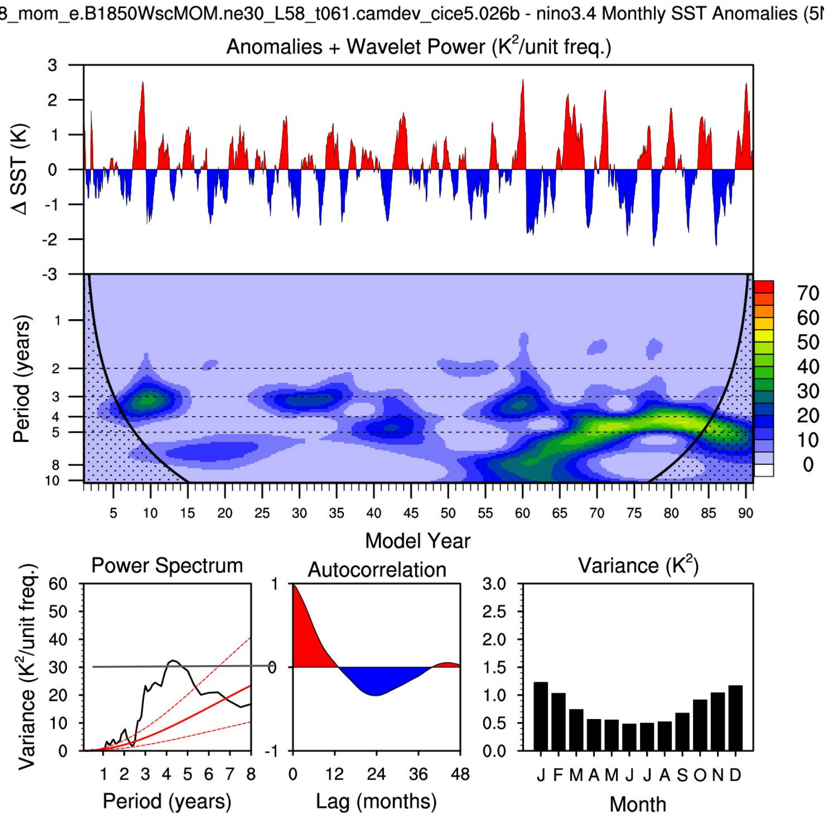


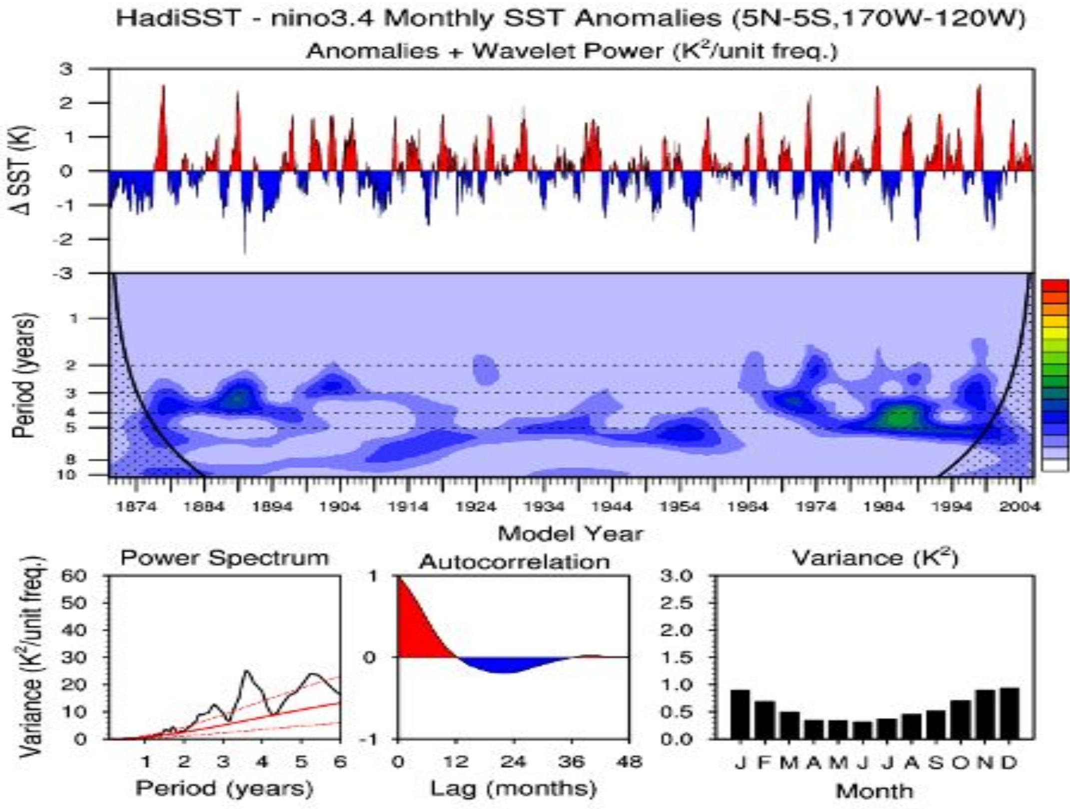
Nino3.4 SST anomalies

1982-2005



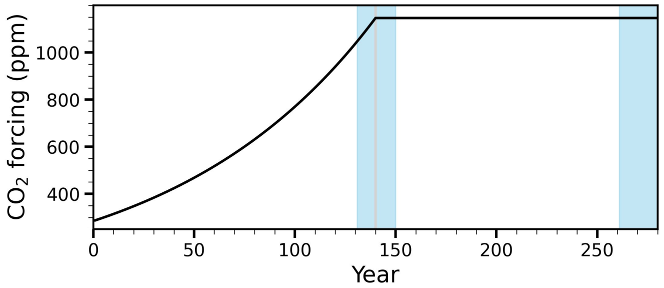
L58 CAM6+/CESM2+ *Rich Neale*





Idealized Warming Experiment

1%CO2/yr; hold fixed at 4XCO2 →



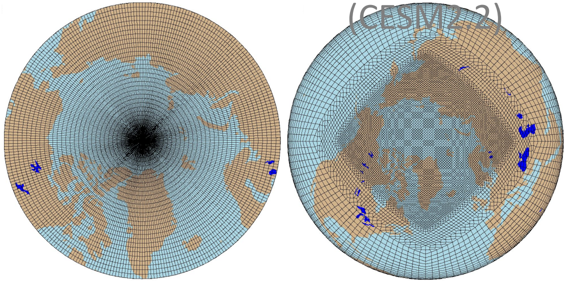
ARCTIC grid reduces excessive GrIS inland preicp. and costal melting in PD compared to f09 (Herrington et al 2022).

Here, we couple the ARCTIC grid to POP2, re-tune the model and test:

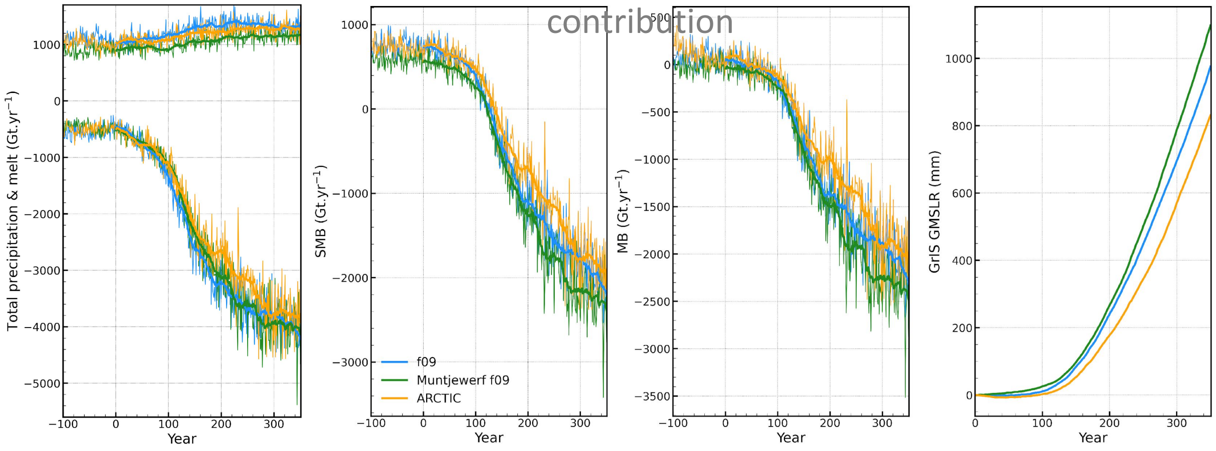
Is the GriS response also different?

- **f09** – CESM2.1-CMIP6; Muntjewerf et al. 2020
- **f09** – CEMS2.1-no hacks** – this study
- **ARCTIC** – CESM2.2 – this study

f09 (CESM2.1) **ARCTIC** (CESM2.2)



GrIS integrated mass balance components and sea level contribution



ARCTIC exhibits a smaller increase in melting, which primarily explains its lower mass loss and sea level rise:

- **f09 ~ 1100 mm sea level equiv.**
- **f09 ~ 975 mm sea level equiv.**
- **ARCTIC ~ 825 mm sea level equiv.**

** no hacks removes the hacks used in CMIP6 configuration to reduce GrIS precip biases in f09.

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Enabling “weather resolution” in CESM:
MPAS dynamical core coupled with the CAM physics suite

Current functionality:

- AMIP setup at 1 degree is supported (regression tested) and runs out-of-the-box pulling MPAS in as an external
- Earthworks is using this code base on their branch/fork
- Used in several SIMA applications/configurations

Challenges on the “CESM-side”:

- **Memory bottlenecks** when ingesting meshes from files (ESMF).

- **New entirely parallel surface dataset generation in land model (CLM)** was created that permitted very high resolution raw datasets to be read in parallel and mapped in parallel to the target model resolution grid. Without this new capability it would have been impossible to actually generate a 3.75 km CLM surface dataset with the older surface dataset generation utility. With the new utility, a 7.5 km surface dataset was generated in 10 minutes whereas previously it had taken 2 days.

- **Still I/O bottlenecks in CAM history** and restarts at 3.75km uniform resolution

- **Physics-dynamics coupling**: Coupling a pressure-based physics package with a height-based dynamical core while preserving energy and thermodynamic consistency

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Discretization issue

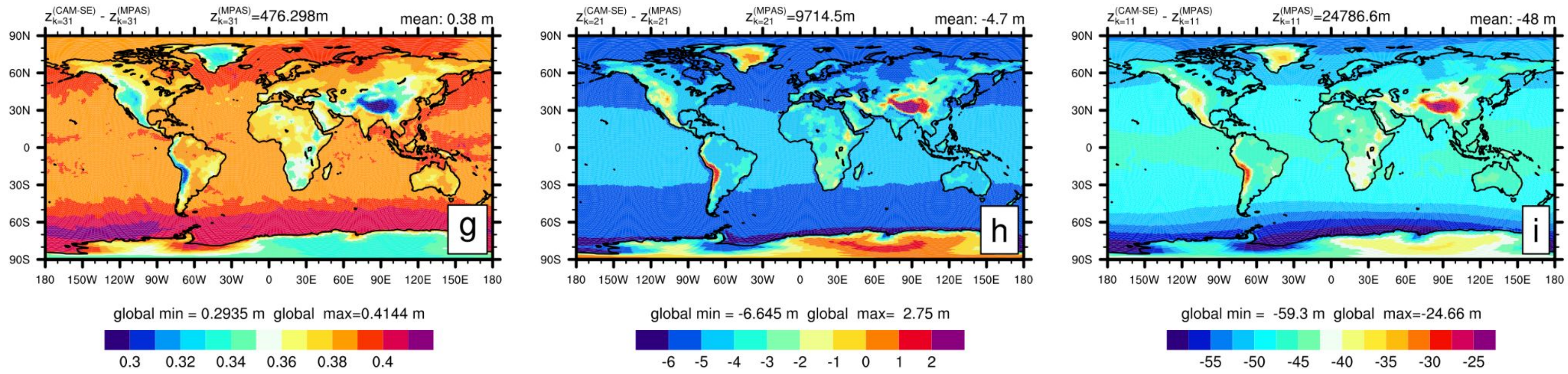
Prognostic and diagnostics variables

See Lauritzen, Skamarock, ... et al. (in prep) for details

Discrete representation of state in physics and dynamics may differ (both in terms of prognostic variables and staggering) which can lead to inconsistencies. Example:

$$\left(\theta_k^{(m)}, \vec{v}_k^{\perp}, \rho_k^{(d)}, z_{k+1/2}^{(MPAS)}, m_k^{(\ell)}\right) \qquad \left(T_k, \vec{v}_k, p_{k+1/2}, q_k^{(\ell)}, m_k^{(\ell)}\right)$$

Problem: z is fixed in MPAS whereas z is diagnosed (from hydrostatic balance) in CAM physics! If not careful in physics dynamics coupling -> z discrepancies. Example below:



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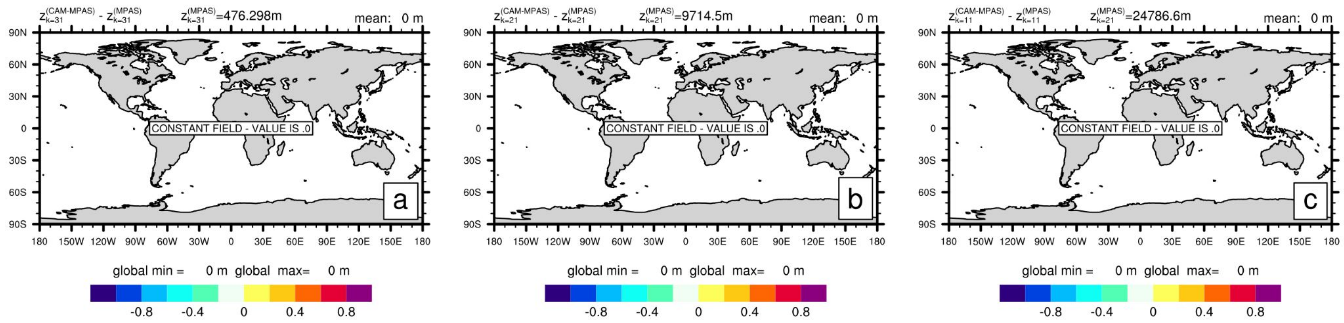
CAM-MPAS physics dynamics coupling

(addresses some consistency issues but not all)

See Lauritzen, Skamarock, … et al. (in prep) for details

- Preserving hydrostatic relations (heights diagnosed in physics consistent with MPAS dycore by cleverly choosing how the mid-level hydrostatic pressure is computed from MPAS state)



- Energy increments in physics (under constant pressure assumption) matching energy increment in hydrostatic MPAS (by scaling temperature increment and careful conversion from temperature tendency to modified potential temperature tendency used in MPAS)
- Making sure CAM physics energy fixer uses total energy formula consistent with hydrostatic MPAS
- Part of this is adding all condensates to hydrostatic pressure/density in CAM physics

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

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

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)

Please note that CCPP will not guarantee thermodynamic/energy consistency!

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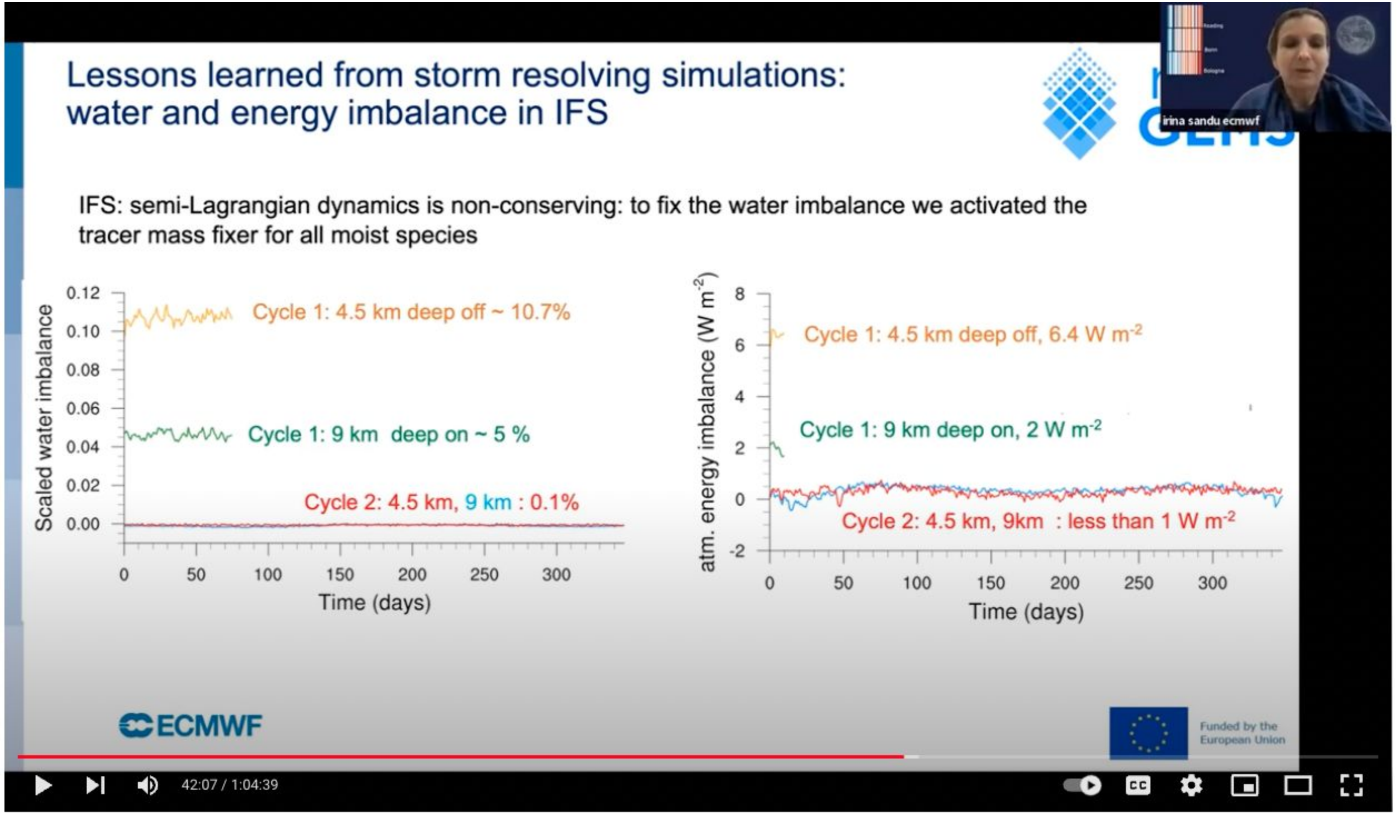

MMM Seminar - Irina Sandu

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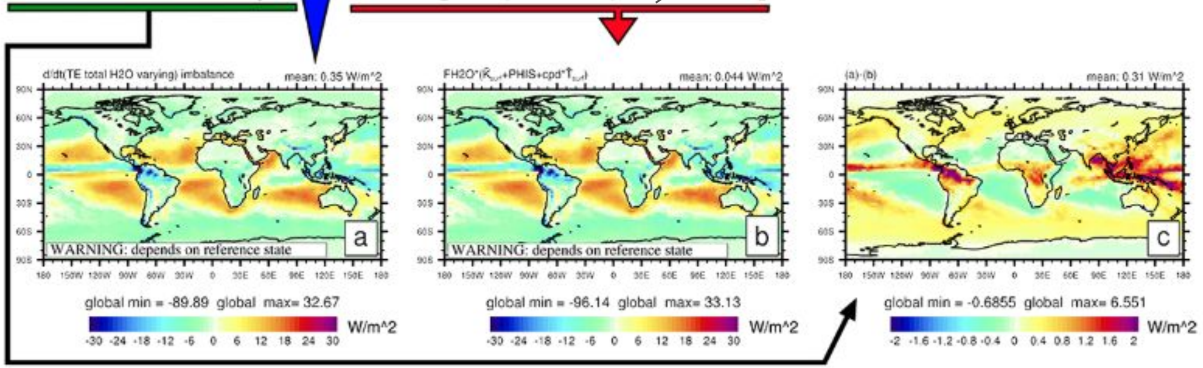
Missing enthalpy flux terms

Modified CAM total energy equation incl. missing flux terms

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

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



Panel a shows the discrepancy in the column-integrated energy budget of a typical Earth System Model that results from a common approximation: neglecting the energy loss associated with precipitation of frozen and liquid water. Panel b shows the discrepancy in the surface energy flux that results from another common approximation: neglecting the energy carried by precipitation reaching the surface. Both fields are large but are almost equal (panel c shows a minus b). A more consistent treatment of the energy budget would relax both approximations at the same time. Credit: Lauritzen et al. [2022], Figure 6

We are working towards incl. missing enthalpy flux term in CESM3:

- Change spectral-element dynamical core to effectively use variable latent heats - 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)

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