Coupled simulations with FV, SE-CSLAM and FV3

Peter Hjort Lauritzen, John Truesdale, Adam Herrington, Julio Bacmeister, Brian Eaton, Cecile Hannay, Rich Neale, ...

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NCAR

AMWG, March 9-11, 2020

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

Historically CAM has been designed so that it can accommodate more than one dynamical core:

- One can easily assess simulation sensitivity to dynamical core
- A particular dynamical core may be better suited for certain applications compared to other cores
- One can use this functionality to better understand dynamical cores and their interplay with physics (the latter is poorly understood) -> this could accelerate progress in climate research
- One can do clean comparisons of computational performance
- In a sense one is better prepared for future architectures since different algorithms will “map” differently on different architectures

Downside: it requires resources and ...

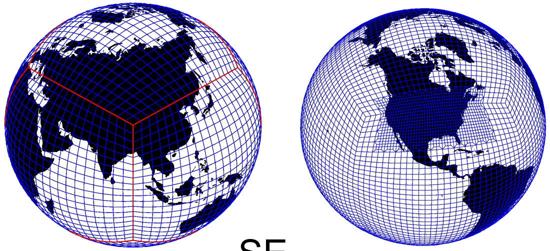
New dynamical cores in CESM

The following dynamical cores have been or are being integrated into the CESM:

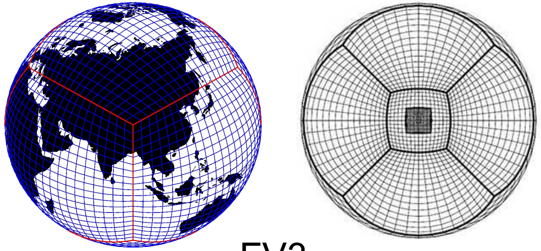
- Spectral-Element (**SE**) dynamical core with option for accelerated transport scheme (**CSLAM**)
  - highly scalable hydrostatic dynamical core with flexible mesh-refinement options
  - capability of running physics on a separate (coarser) grid for uniform grid applications

- **FV3**: GFDL's dynamical core used by NCEP for global weather forecasting
  - scalable finite-volume dynamical core (currently using hydrostatic version; non-hydrostatic available)

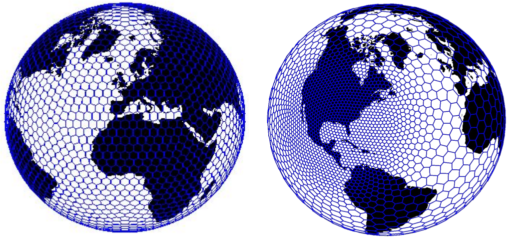
- **MPAS**: NCAR's global weather forecast model
  - non-hydrostatic finite-volume dynamical core that also allows for flexible mesh-refinement



SE



FV3



MPAS

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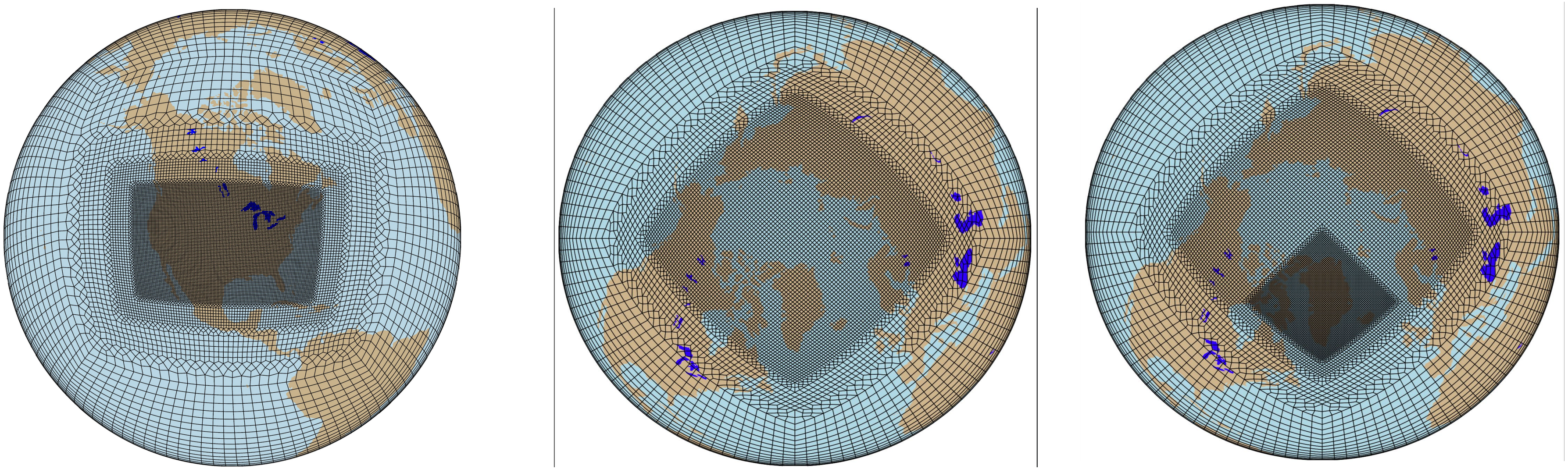
Status of spectral-element dynamical core in CESM

- To be released with CESM2.2 with support for uniform and 3 variable resolution meshes:



Figures courtesy of Adam Herrington

- Being evaluating in coupled simulations, WACCM and we are almost ready with a WACCM-x version
- SE is being extensively used for chemistry applications in ACOM (with or without mesh-refinement)

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Status of FV3 dynamical core in CESM

- To be released in CAM (part of collaboration with NOAA) (funding ended 2/28/2020)

- Being evaluating in coupled simulations

Status of MPAS dynamical core in CESM

- Implementation in CAM is in progress (close to being able to perform idealized simulations)

- Why is this taking so long?

  * MPAS dynamical core was not developed as an independent dynamical core but rather as part of a forecasting system (called MPAS) whereas CAM has been engineered/designed to accommodate different dynamical cores.

  It is taking time to “pull out” the MPAS dynamical and implement it in CAM (doing things the” CAM way”) … and a lot of back and forth with the MPAS group to reach compromises; initialization, I/O, grid definition, namelists, etc.

We have been working on getting experience with AMIP and coupled simulations with the new dynamical cores alongside more idealized testing

- We have worked through many details of physics-dynamics coupling and verified that the new dynamical cores have been coupled to CAM physics correctly (thermodynamic consistency, mass conservation, etc.)

  The new dynamical cores are not imported as black boxes; implementing various diagnostics in the dynamical cores has increased our understanding of the details of the algorithms used in FV3 and SE-CSLAM.

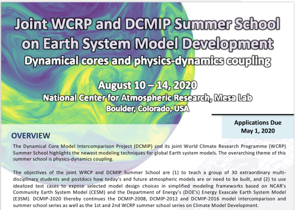
Thermodynamic and energy consistency between dynamical core and physics

Modern dynamical cores are “ahead” of physics packages in terms of more accurate total energy formulations ...

Enforcing better thermodynamic and energy consistency is a tedious/technical task and it involves physics, dynamical core and coupling layer!
(will almost certainly have large impacts on simulation!)

As a community we are starting to pay attention to these problems:

- Physics-Dynamics Coupling (PDC) workshop series (next at GFDL in June)
- 2019 BIRS workshop on physics-dynamics coupling in Earth system models
- WCRP-DCMIP summer school at NCAR in August 2020 on physics coupling in Earth system models
  (sponsored by NSF, DOE, WCRP, NCAR labs)



Joint WCRP and DCMIP Summer School
on Earth System Model Development
Dynamical cores and physics-dynamics coupling

August 10 – 14, 2020
National Center for Atmospheric Research, Mesa Lab
Boulder, Colorado, USA

Applications Due
May 1, 2020

OVERVIEW

The Dynamical Core Model Intercomparison Project (DCMIP) and its joint World Climate Research Programme (WCRP) Summer School highlights the newest modeling techniques for global Earth system models. The overarching theme of this summer school is physics-dynamics coupling.

The objectives of the joint WRCP and DCMIP Summer School are (1) to teach a group of 30 extraordinary multi-disciplinary students and postdocs how today’s and future atmospheric models are or need to be built, and (2) to use idealized test cases to expose selected model design choices in simplified modeling frameworks based on NCAR’s Community Earth System Model (CESM) and the Department of Energy’s (DOE’s) Energy Exascale Earth System Model (E3SM). DCMIP-2020 thereby continues the DCMIP-2008, DCMIP-2012 and DCMIP-2016 model intercomparison and summer school series as well as the 1st and 2nd WCRP summer school series on Climate Model Development.

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We have been working on getting experience with AMIP and coupled simulations with the new dynamical cores alongside more idealized testing

- We have worked through many details of physics-dynamics coupling and verified that the new dynamical cores have been coupled to CAM physics correctly (thermodynamic consistency, mass conservation, etc.)

- We have improved several aspects of the spectral-element dynamical core for better representation of flow over orography, comprehensive treatment of energy and condensates, stability in WACCM, bug fixes, …

- We have made variable resolution spectral-elements more user-friendly e.g. automatic scaling of viscosity coefficients and a better workflow for creating new resolutions (grid generation, variable resolution topography for CAM6 using NCAR topography software, etc. - see Patrick Callaghan’s presentation today!)

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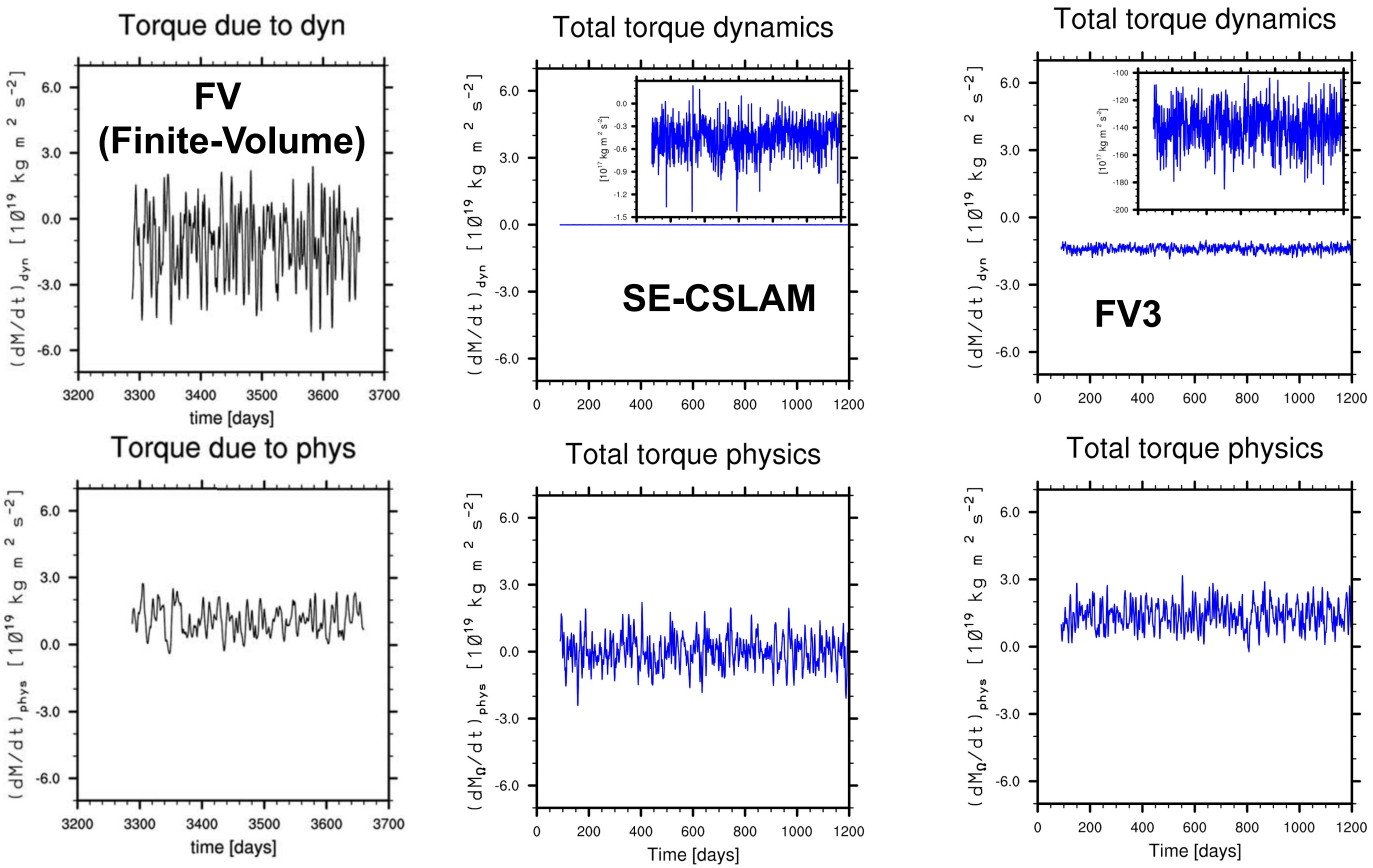
Idealized testing 1: Axial angular momentum conservation (using CESM simpler models: Held-Suarez physics forcing)

Approximately 1 degree horizontal resolution and 32 vertical levels

Spurious
Should be zero!

"Physical"



$$0 \sim \left(\frac{dM}{dt}\right)_{dyn} \ll \left(\frac{dM}{dt}\right)_{phys}.$$

Lauritzen et al. (2014)

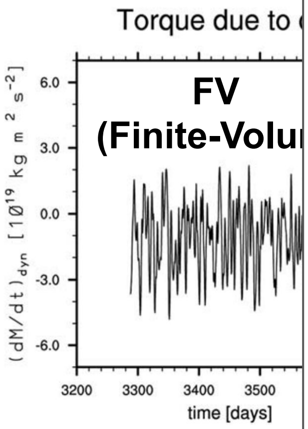
Idealized testin onservation (using CESM si sics forcing)

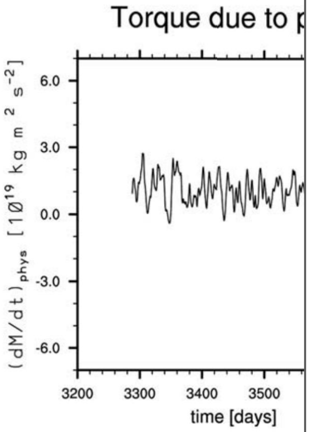
Approximately 1 degree horizontal resolution and 32 vertical levels

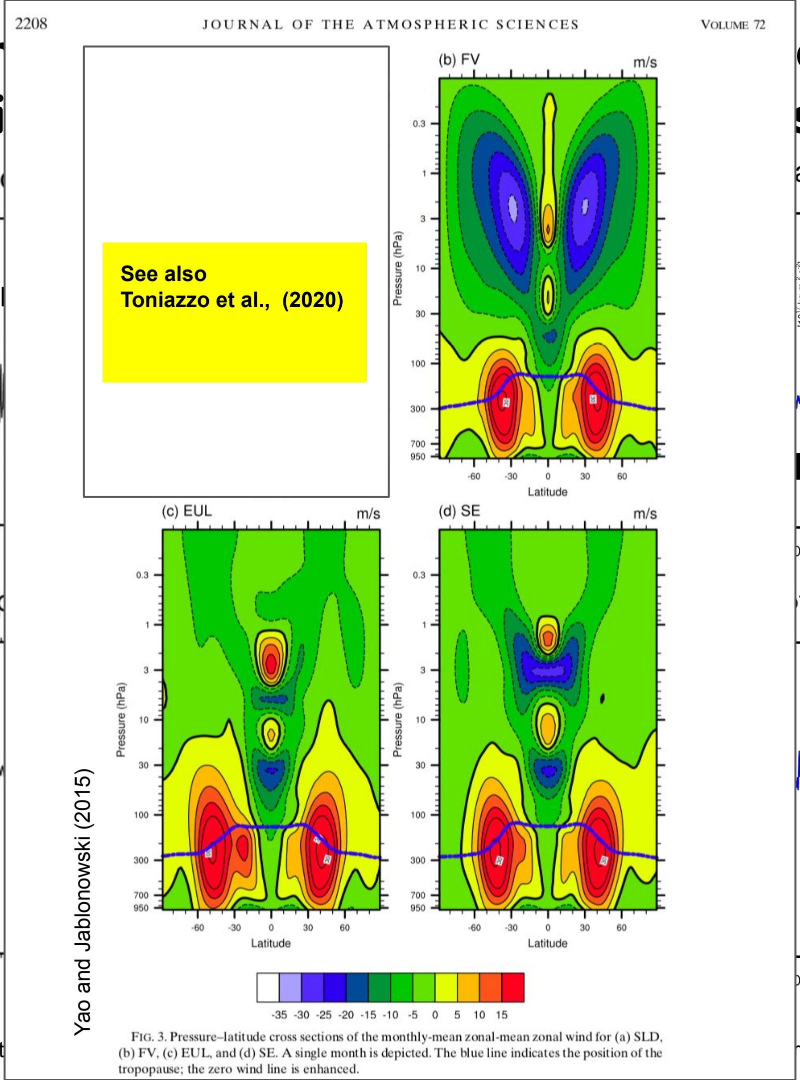
Spurious

Should be zero!

“Physical”



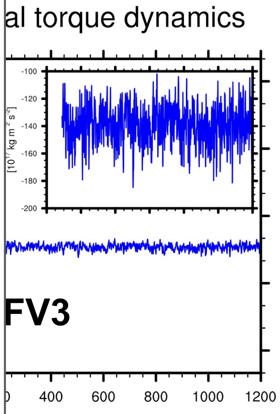


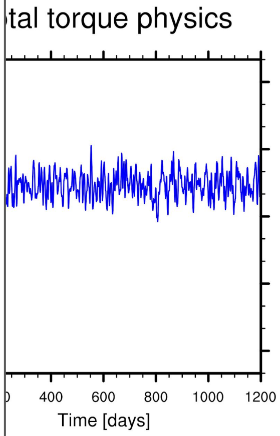


See also Toniazzo et al., (2020)

FIG. 3. Pressure–latitude cross sections of the monthly-mean zonal-mean zonal wind for (a) SLD, (b) FV, (c) EUL, and (d) SE. A single month is depicted. The blue line indicates the position of the tropopause; the zero wind line is enhanced.

Yao and Jablonowski (2015)





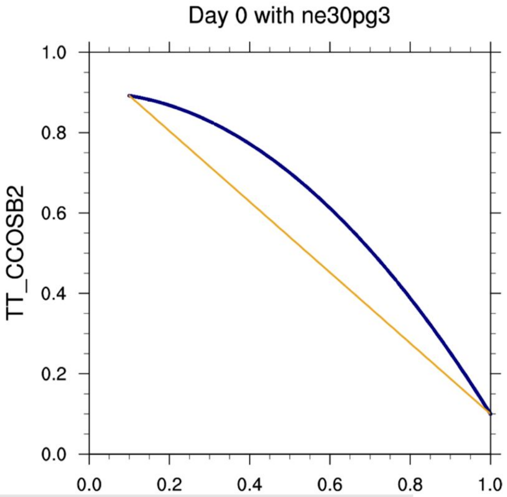
$$0 \sim \left(\frac{dM}{dt}\right)_{dyn} \ll \left(\frac{dM}{dt}\right)_{phys}.$$

Lauritzen et al. (2014)

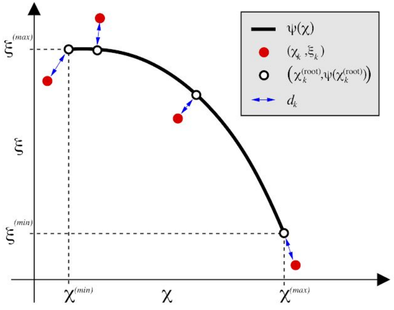
Idealized testing 2: Accuracy of tracer transport (using CESM simpler models: baroclinic wave)

Approximately 1 degree horizontal resolution and 32 vertical levels

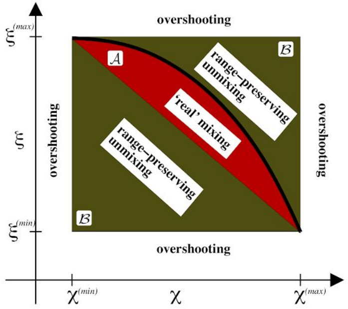
Correlation diagnostics



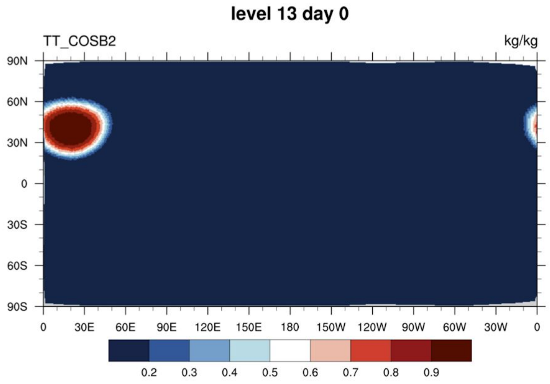
There is an analytical solution:
If there were no truncation errors points would remain on analytical curve throughout simulation regardless of flow

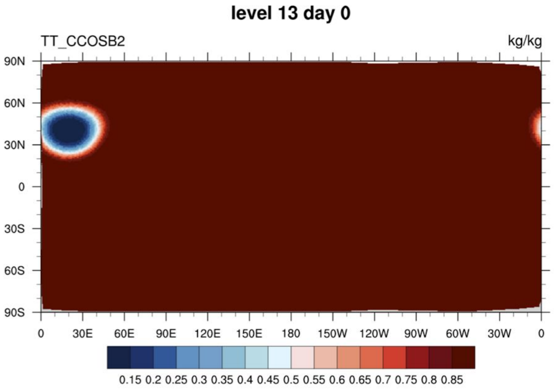


Quantification of mixing



Categorization of mixing



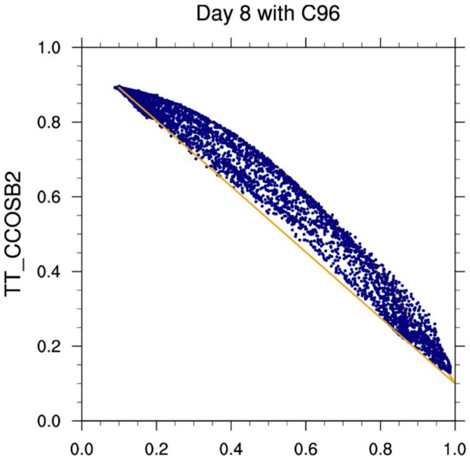


Lauritzen and Thuburn (2012)

Idealized testing 2: Accuracy of tracer transport (using CESM simpler models: baroclinic wave)

Approximately 1 degree horizontal resolution and 32 vertical levels

Correlation diagnostics



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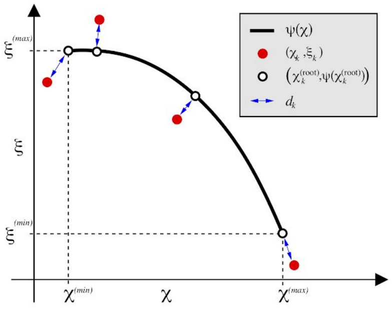
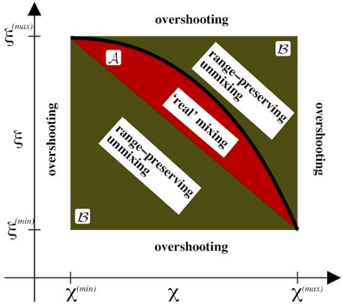
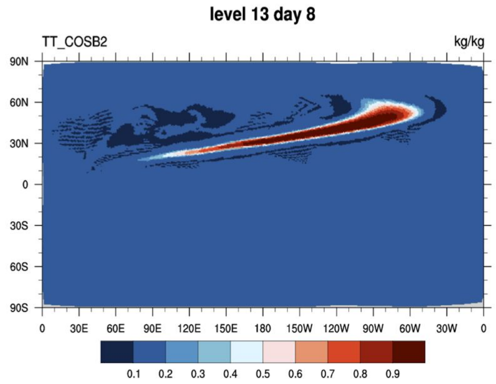
Lauritzen and Thuburn (2012)

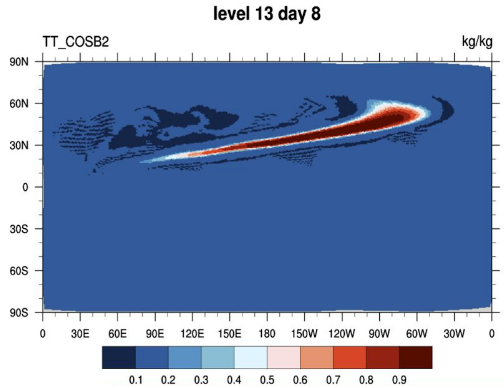


Quantification of mixing



Categorization of mixing

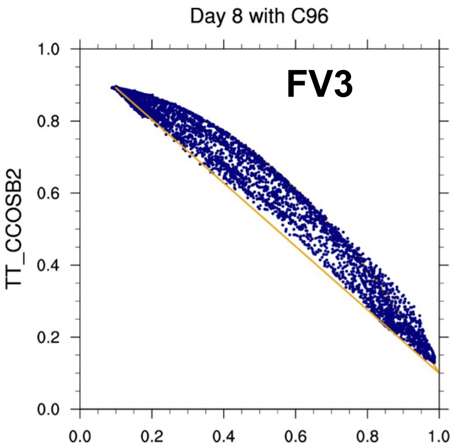


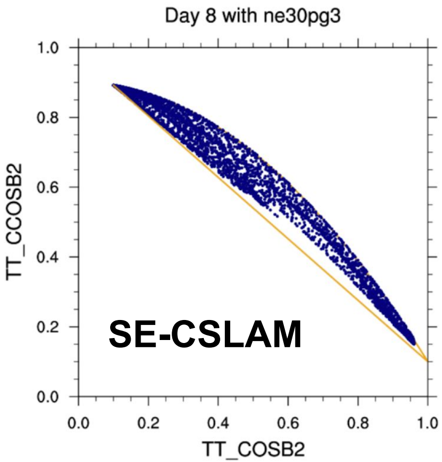


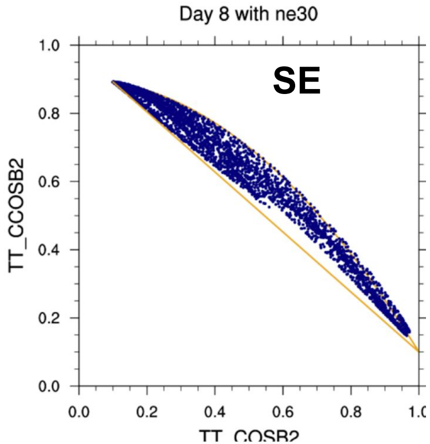
Idealized testing 2: Accuracy of tracer transport (using CESM simpler models: baroclinic wave)

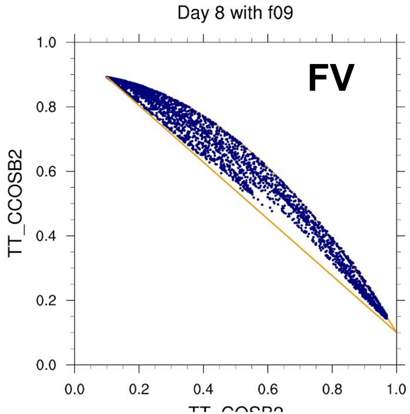
Approximately 1 degree horizontal resolution and 32 vertical levels

Correlation diagnostics


Day 8 with C96


Day 8 with ne30pg3


Day 8 with ne30


Day 8 with f09

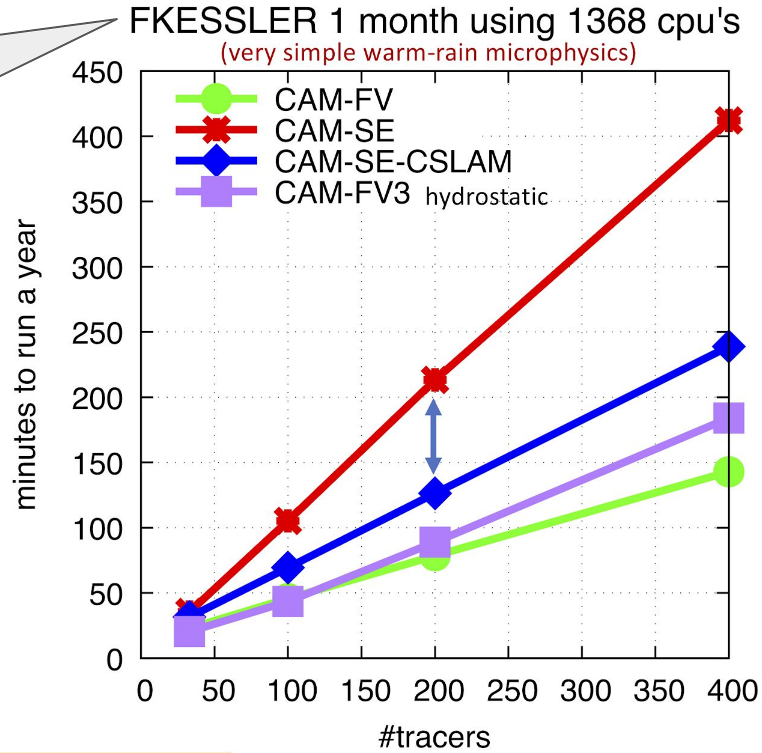
Questions we can answer:
- How diffusive is the numerical mixing?
- How realistic is the numerical mixing?

Lauritzen and Thuburn (2012)

Idealized testing 3: Speed of tracer transport (using CESM simpler models: Baroclinic wave)

1 THREAD; MPI SCALING ONLY!

Approximately 1 degree horizontal resolution and 32 vertical levels



We expect much larger throughput differences in WACCM and CAM-Chem than in standard CAM applications due to the large tracer counts (~200) and stability challenges in a high-top model

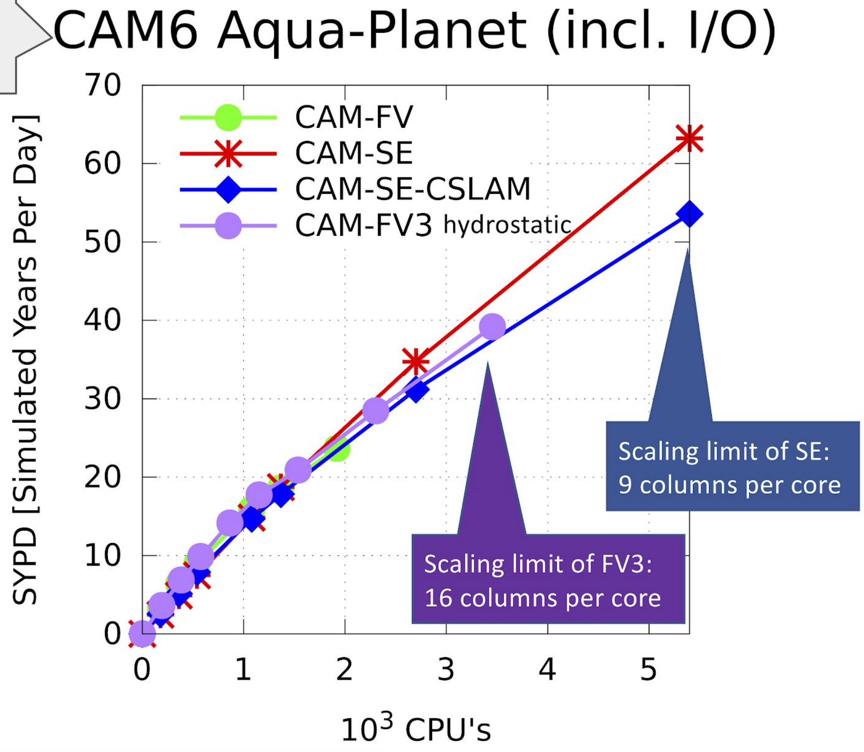
THROUGHPUT MUST BE EVALUATED IN WACCM-like setups!

WARNING: PRELIMINARY RESULTS

Idealized testing 4: Scalability (using CESM simpler models: Aqua-planet)

Approximately 1 degree horizontal resolution and 32 vertical levels

1 THREAD; MPI SCALING ONLY!



Scaling limit of FV3: 16 columns per core

Scaling limit of SE: 9 columns per core

At ~2000 cores all dycores give comparable throughput (within ~20%) in a standard CAM setup)

Please note:

- physics is ~50% of runtime
- There are “only” 33 tracers

WARNING: PRELIMINARY RESULTS

Total energy (TE) diagnostics: 1 degree CAM6

FV

Dycore TE dissipation:

-1.1 W/m2

SE-CSLAM

Dycore TE dissipation:

-0.3 W/m2
(2D dynamics : -0.1W/m2
 Vertical remap: -0.2W/m2)

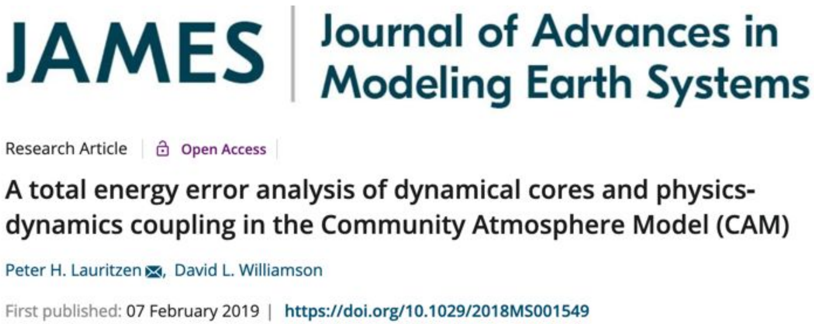
FV3

Dycore TE dissipation:

-1.1 W/m2
(2D dynamics: -2.1W/m2
 Vertical remap: 1.1W/m2)

Total energy formulas in SE-CSLAM and FV3 are more comprehensive & accurate than CAM physics

Leads to ~0.5W/m2 TE errors in physics-dynamics coupling!



JAMES | Journal of Advances in Modeling Earth Systems

Research Article | Open Access |

A total energy error analysis of dynamical cores and physics-dynamics coupling in the Community Atmosphere Model (CAM)

Peter H. Lauritzen, David L. Williamson

First published: 07 February 2019 | https://doi.org/10.1029/2018MS001549

SSC recommendation (June 2019)

We were advised to perform coupled simulations sooner rather than later to assess if there were major issues with the new dynamical cores!

Setup:
- we use spun-up ocean initial condition from the CESM2 pre-industrial control run (297)
- minimum RESTOM (= top of model residual energy balance) tuning using `clubb_gamma` (=skewness of vertical velocity profile) and some other tuning using well-known CLUBB parameters
- all dycores see exactly the same topography (same amount of smoothing)

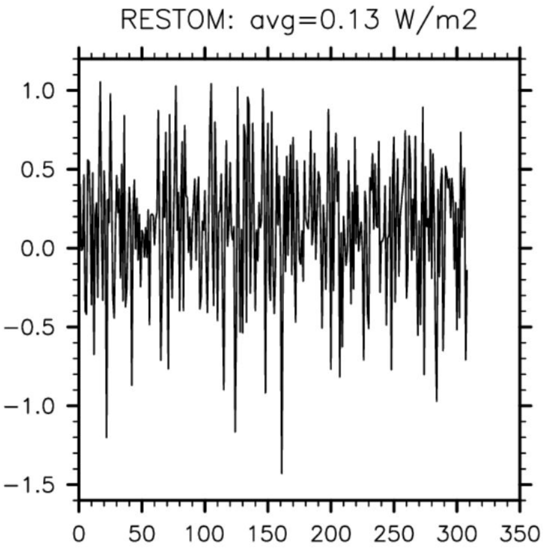
Note that CAM4,5,6 physics have been developed and tuned using the finite-volume dynamical core so there is "hysteresis" in the system in that CAM6 physics will likely favor dynamical cores with numerics similar to the FV dynamical core …

Coupled simulations: RESTOM

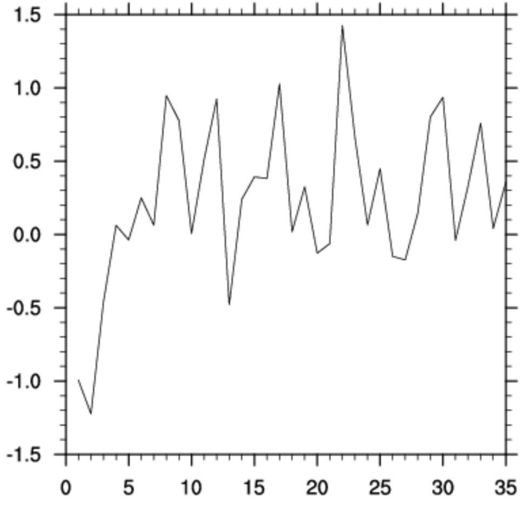
(=top of model residual energy balance)

CESM2

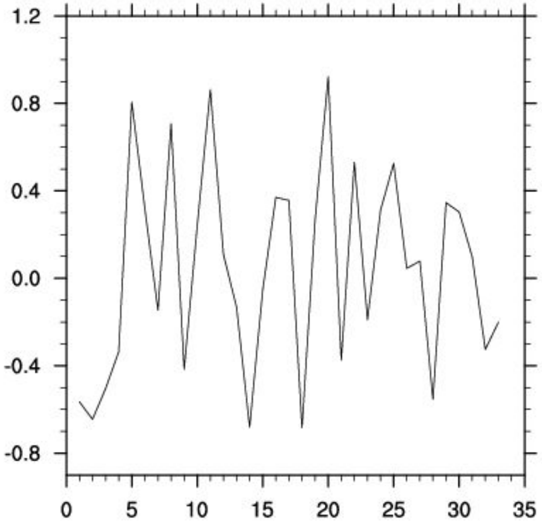
FV (finite-volume)



SE-CSLAM



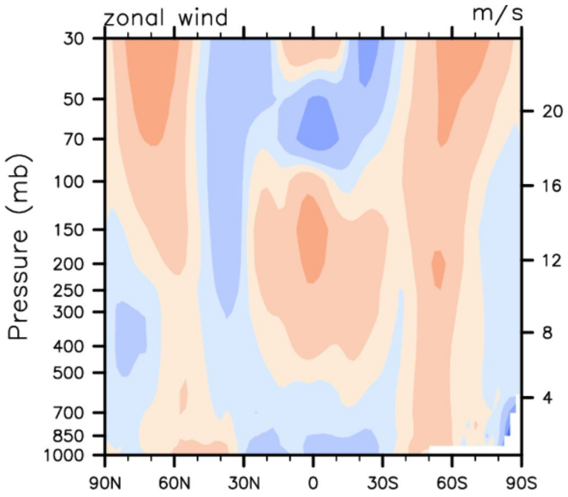
FV3



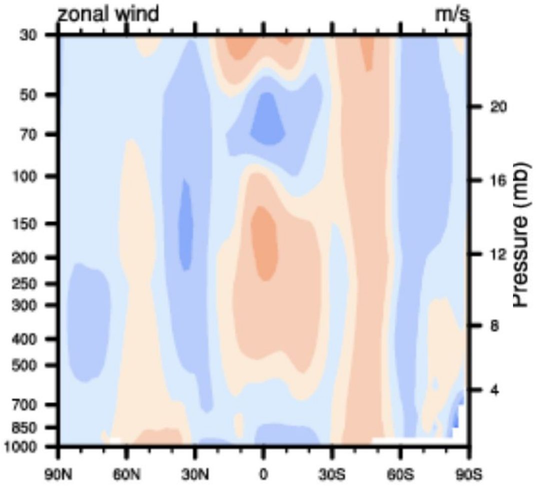
Note that simulation length varies and Y-axis are different!

Coupled simulations: Mean annual zonal wind bias (with respect to ERA40)

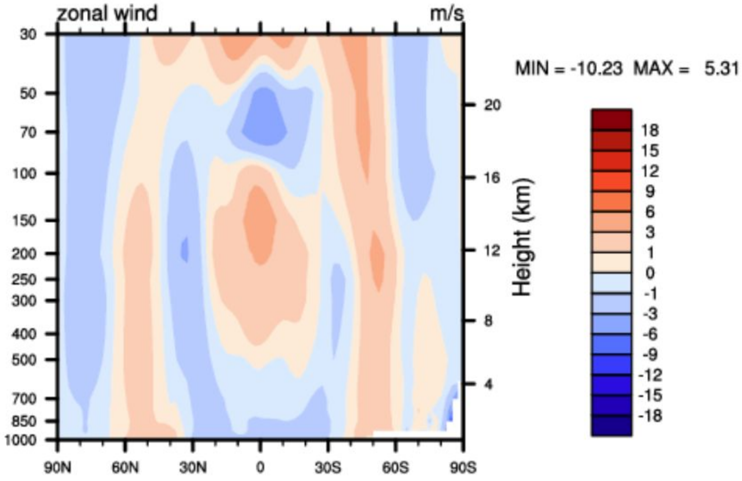
FV (finite-volume)



SE-CSLAM



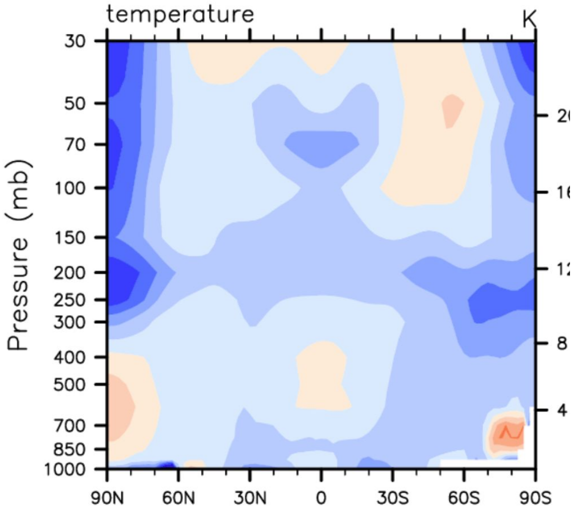
FV3



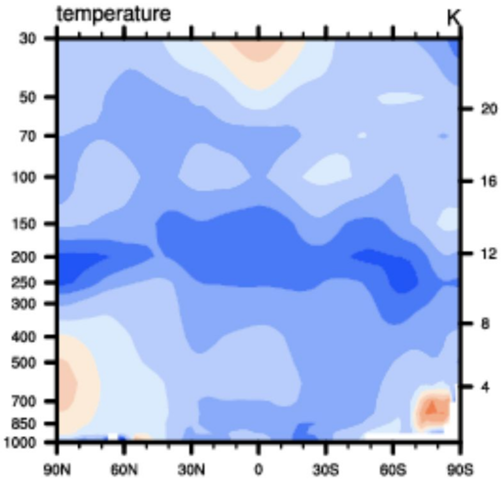
Significant reduction in polar stratospheric wind biases!

Coupled simulations: Mean annual zonal T bias (with respect to ERA40)

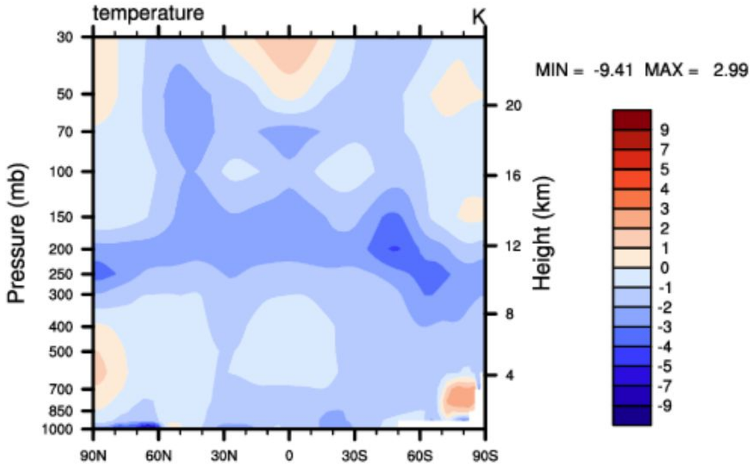
FV (finite-volume)



SE-CSLAM



FV3



Significant reduction in polar stratospheric temperature biases!

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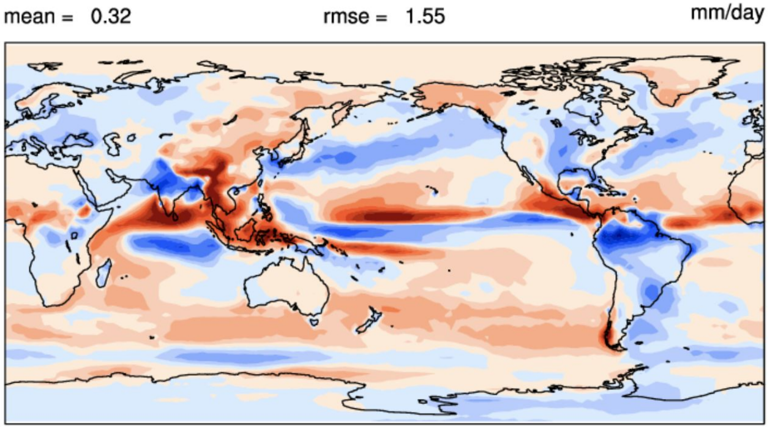
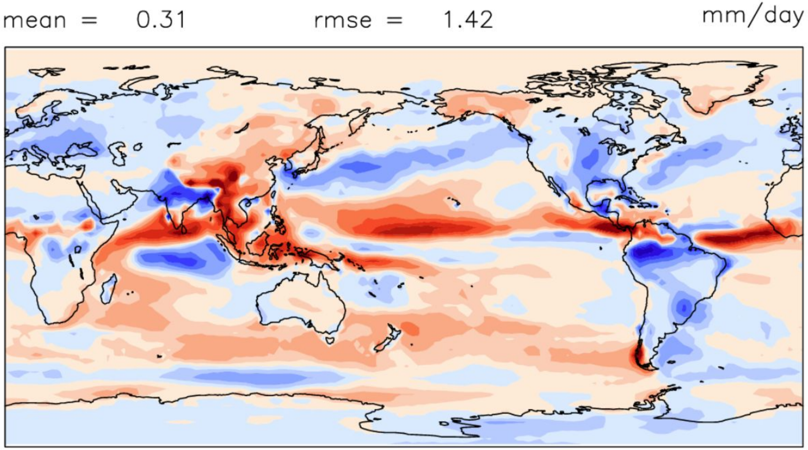
JJA PRECT bias with respect to GPCP

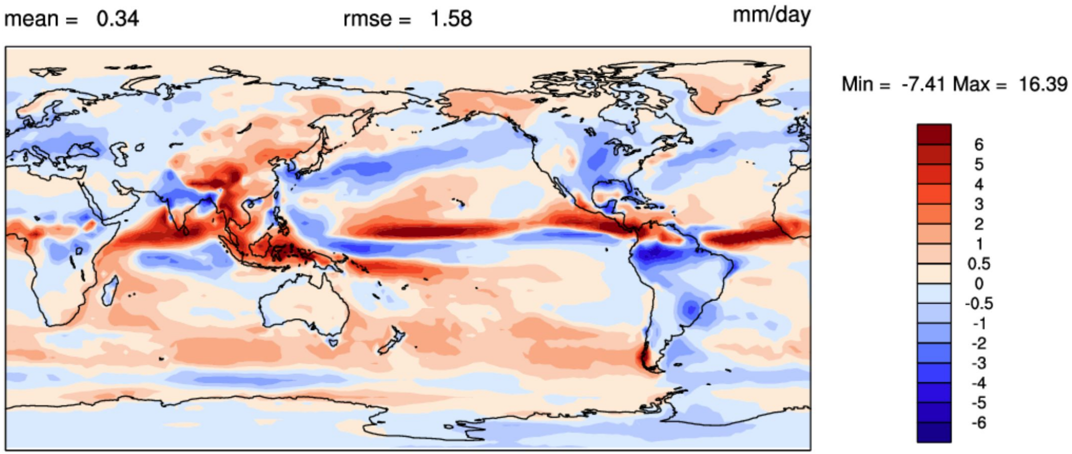
SE-CSLAM



FV



FV3



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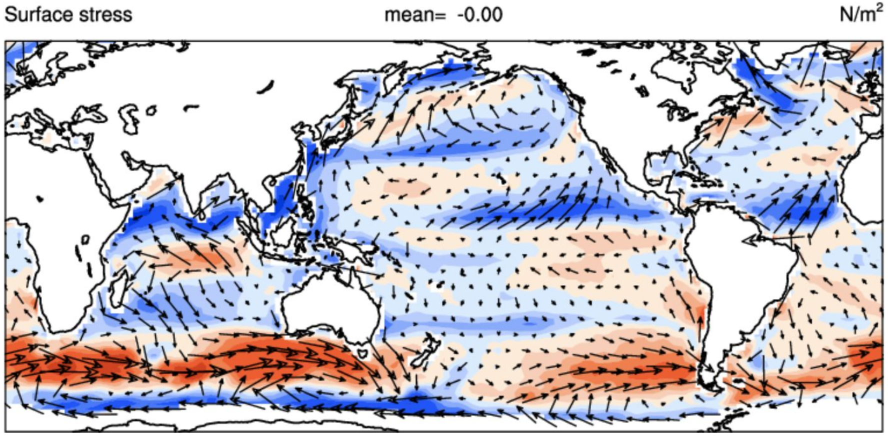
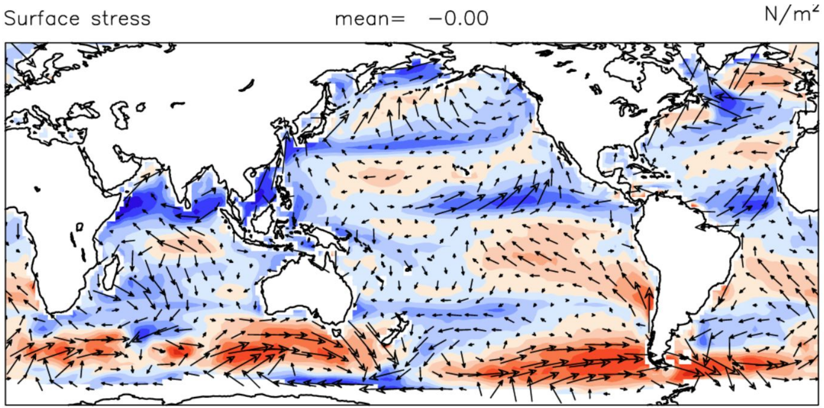
Wind stress bias with respect to Large-Yeager dataset

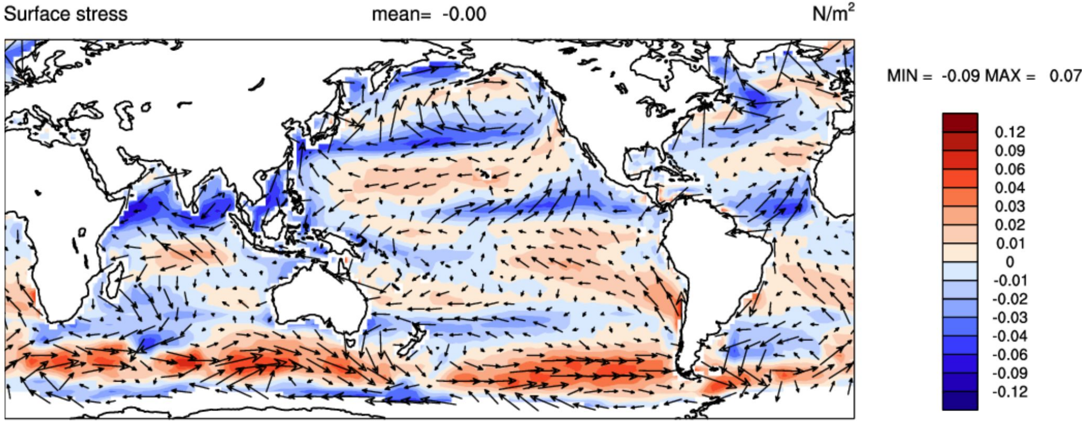
SE-CSLAM



FV



FV3



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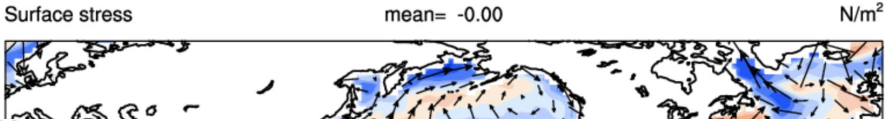
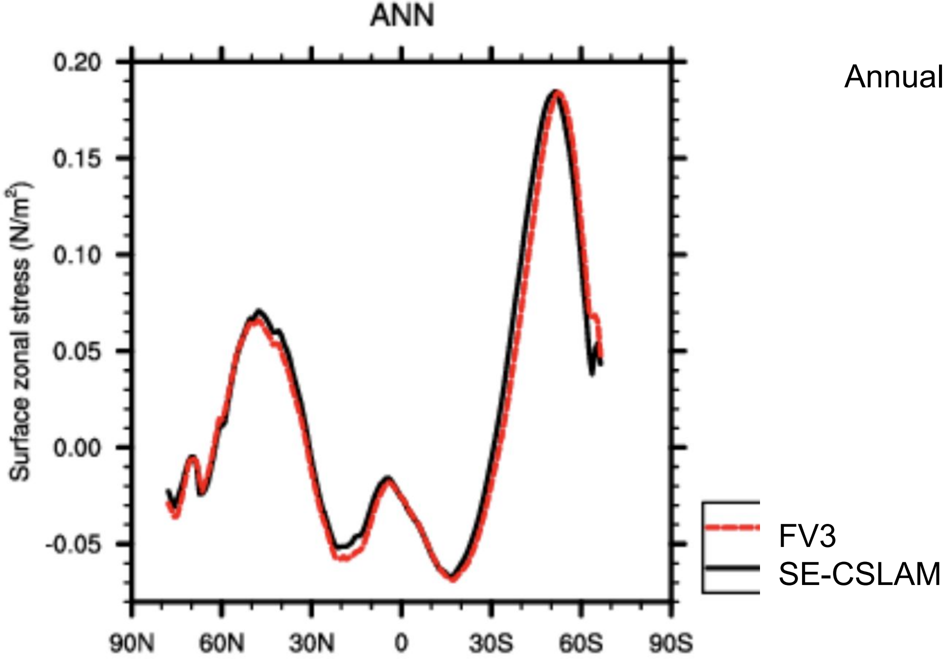
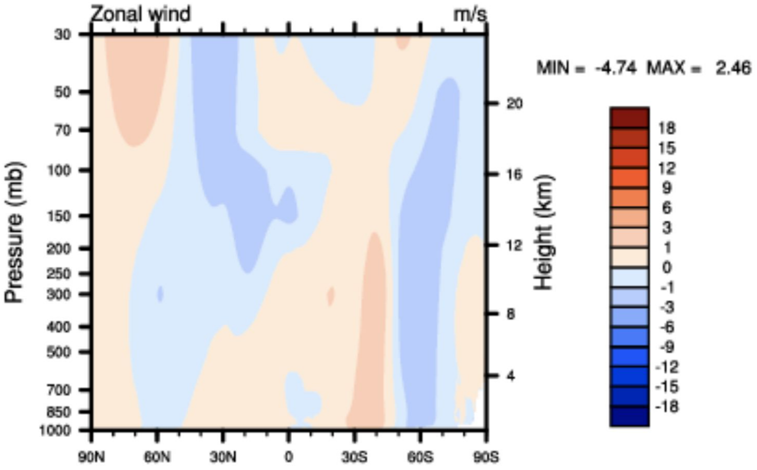
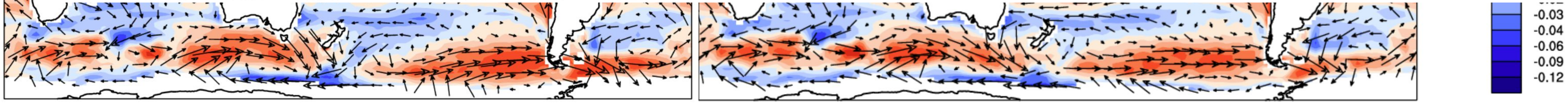
SE-CSLAM





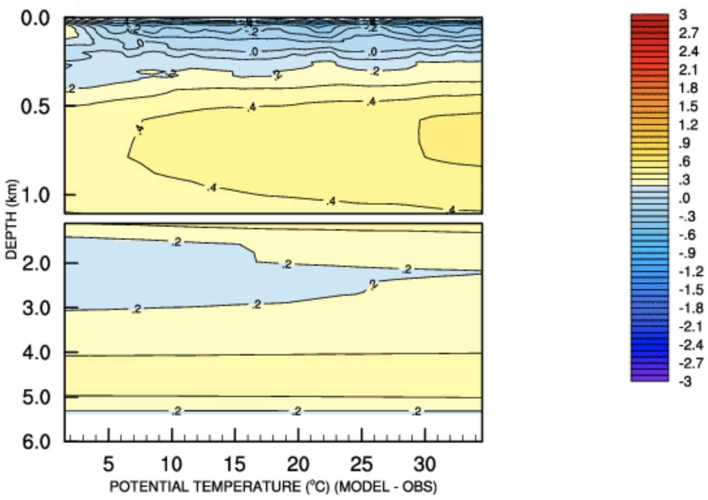
Annual mean zonal wind: SE-CSLAM minus FV3





OCEAN T time series bias with respect to PHC2

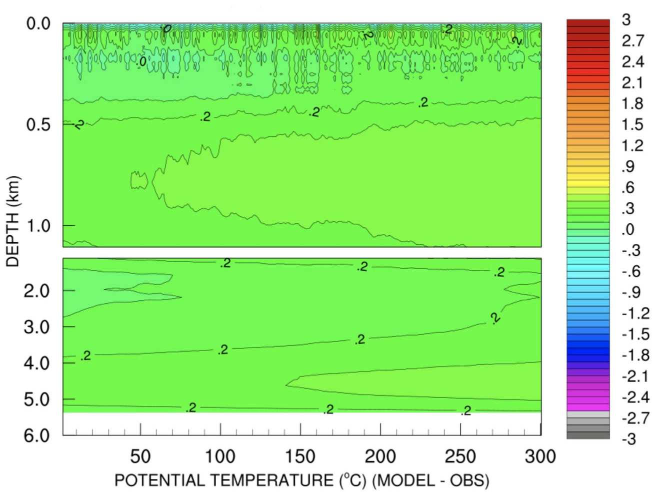
(= a blending of Levitus World Ocean Atlas data w/ better Arctic data)



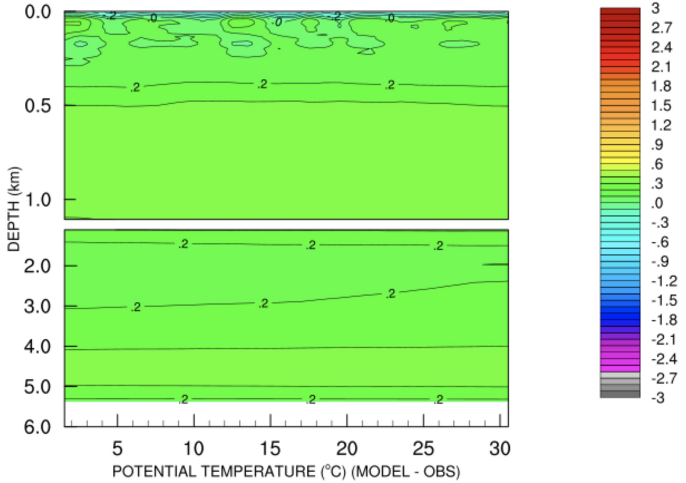
SE-CSLAM

Recall that RESTOM is ~0.26W/m2 in SE-CSLAM (still needs some tuning!)

FV



FV3



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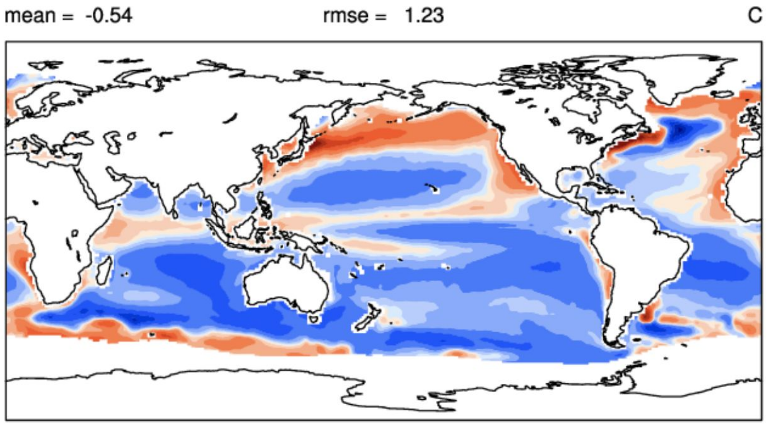
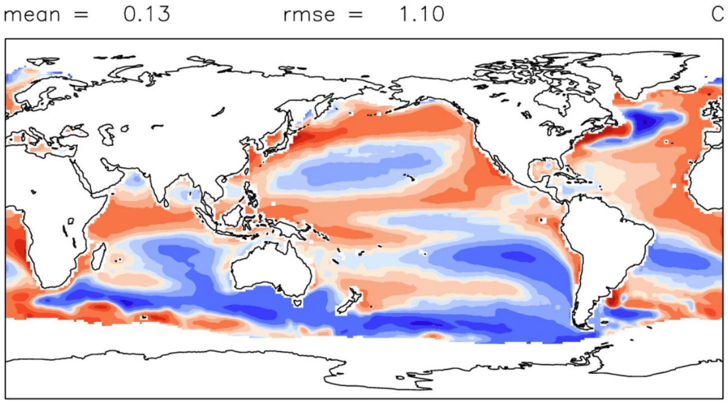
SST bias with respect to HadISST/OI.v2 (Pre-Indust) 1870-1900

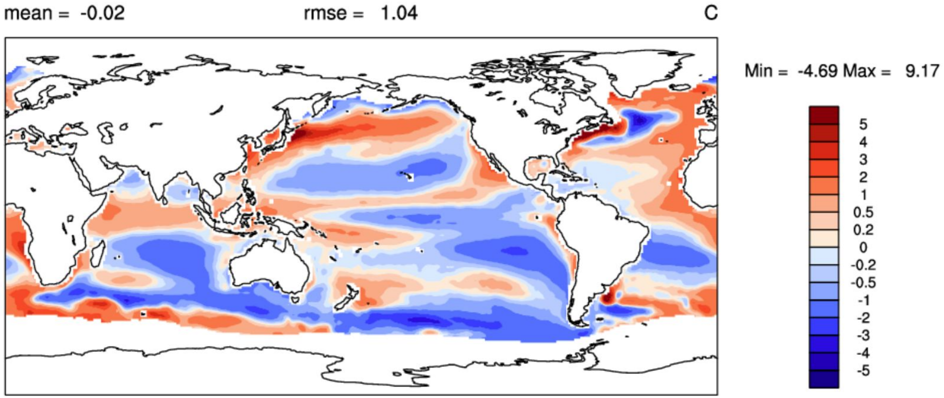
SE-CSLAM



FV



FV3



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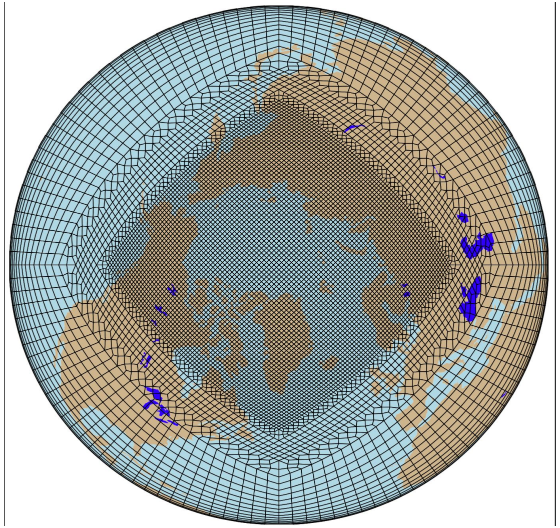
Summary

- Both FV3 and SE-CSLAM are viable alternatives for FV for “mainstream” CESM science
- When MPAS will be available in CAM we plan to go through the same exercise as with FV3 and SE-CSLAM



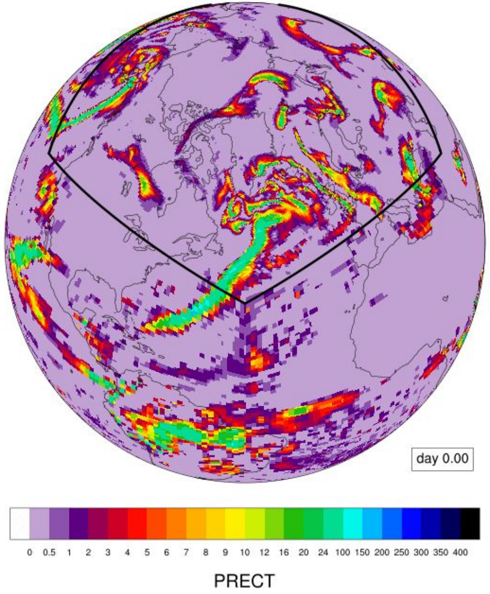


Figure courtesy of Adam Herrington

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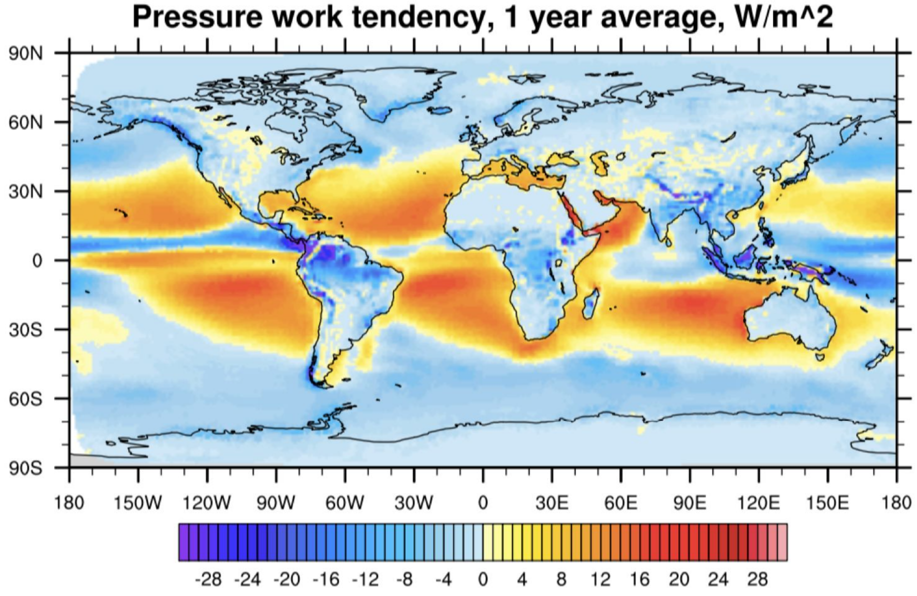
Extra slides

Thermodynamic and energy consistency between dynamical core and physics

- CAM’s parameterization are designed to have a closed total energy budget in each physics column under that assumption that pressure stays constant during physics updates

- Constant pressure assumptions leads to total energy errors: ~0.3W/m2

Lauritzen and Williamson (2019)



SPURIOUS in each column

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- There is no numerical method and/or grid that outperforms everything in the same way that the spectral transform method ”took over” global modeling over 40 years ago!

- At this point we do not know if there will be dynamical core meeting the needs of all CESM applications:

- weather resolutions of ~3km to “traditional” climate applications of ~100km
- temporal resolution of days to millennia
- throughput thresholds are different for weather climate (e.g., weak and strong scaling)
- throughput on “traditional” and future architectures
- accuracy (non-hydrostatic for high resolution, conservation for long time-scales, …)

- (IT’S COMPLICATED!) There are many details related to accuracy and conservation in dynamical cores that matter for different applications!

- **CESM is a <u>community modeling system</u> that enables research in dynamical cores and physics-dynamics coupling; for example, one can use CESM to assess sensitivity to dynamical core and compare dynamical cores in simple to complex physics settings.**

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