Dynamical Cores in the Community Earth System Model (CESM)

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Overview

The CESM community is discussing how to move forward with dynamical cores (in particular, what dynamical core to use as "workhorse" for the development of CESM3):

- What configurations must dynamical core(s) support in CESM?
- What dynamical core choices do we have?
- Evaluation of "intrinsic" dynamical core properties of interest to climate and climate-chemistry modeling at ~1 degree resolution ("IPCC class workhorse model"):

  - computational performance
  - tracer transport characteristics (mixing properties, conservation of pre-existing relations, etc.)
  - axial angular momentum conservation
  - flow over real-world topography
  - total energy conservation

At WCRP meeting ("The Earth's Energy Imbalance and its implications", Toulouse, 2018) I presented energy budget errors from physics and dynamics -> the working group strongly recommended CMIP diagnostics and further research in this area

"Workhorse" CESM2 configurations
(CAM=Community Atmosphere Model)

- **"Standard" CAM** (1°, 32 levels, top ~42km, 33 tracers):
  Need ~20 SYPD (century long simulations)
- **CAM-Chem**: Same as CAM but with extensive chemistry (~100+ tracers)
- **CAM paleo** applications (1° and 2°, 32 levels, top ~42km, 33 tracers):
  Very high throughput requirements
- **WACCM** (1°, 70 levels, top ~144km, ~60-135 tracers):
  Need ~4 SYPD (century long simulations)
- **WACCM-x** (1°, 130 levels, top ~600km, 70+ tracers):
  Coupled to ionosphere model, species dependent thermodynamics (cp, R, …)
  "No" SYPD requirements (model run for days to a couple of years)

> With CESM2.2 we have released infrastructure to facilitate species dependent thermodynamics in physics and dynamical core

Note: WACCM, WACCM-x and CAM-Chem have historically always used the dynamical core chosen by CAM!

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New CESM configurations

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System for Integrated Modeling of the Atmosphere (SIMA)

Frontier	*Science Question*	*Target Configuration*
Weather	Tropical Cyclones	4km refined mesh, coupled ocean, initialized
Climate	Hydrologic Extremes	4-6km refined mesh, initialized and climate simulations
Polar	Arctic Prediction, Ice Sheet	12km refined mesh, coupled ocean, land, sea ice, land ice. Initialized and climate simulations
Geospace	Space Weather Prediction	25km global atmosphere to the ionosphere, initialized
Chemistry	Biomass burning	14km refined global mesh initialized

- **CAM-Chem**: Same as CAM but with extens
- **WACCM-x** (1°, 130 levels, top ~600km, 70-

  Coupled to ionosphere model, species depe
  "No" SYPD requirements (model run for day
- **CAM paleo** applications (2°, 32 levels, top

  Very high throughput requirements

Note: WACCM, WACCM-x and CAM-Chem have historically always used the dynamical core

Additional/new configurations moving forward:

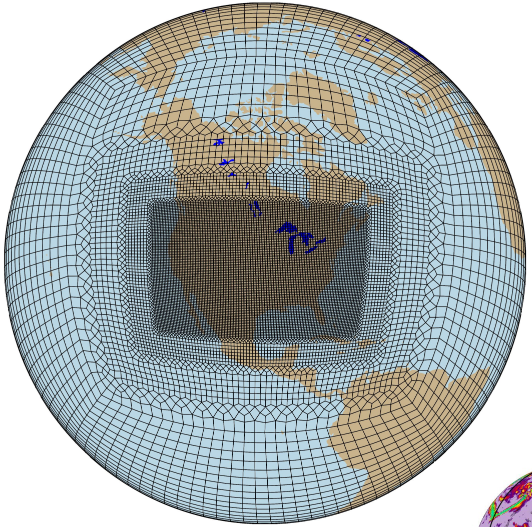
- Increasing interest in variable resolution modeling from community
- Likely a need for ½ and ¼ configurations for, e.g., sub-seasonal to seasonal (S2S) prediction applications and other applications that are run on shorter time-scales
- Interest in community for very high resolution coupled modeling with CESM:

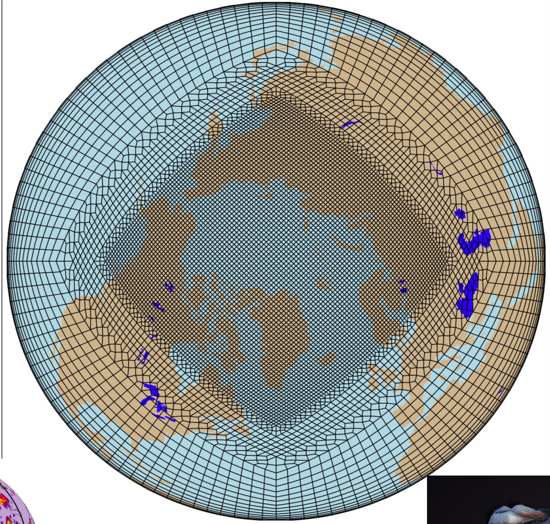
  - iHESP project: ¼ degree atmosphere fully coupled configuration for climate
  - iHESP: currently setting up ~6km atmosphere fully coupled configuration for climate
  - Recently funded project : EarthWorks (~4km atmosphere fully coupled CESM)

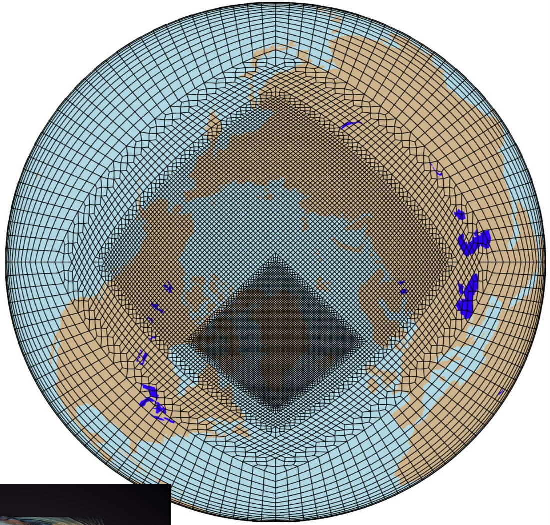
Variable resolution modeling with CAM

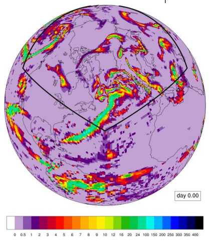
- Recent release of CESM2.2 has support for 3 variable resolution meshes:

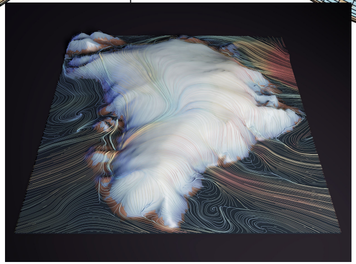
Figures courtesy of Adam Herrington











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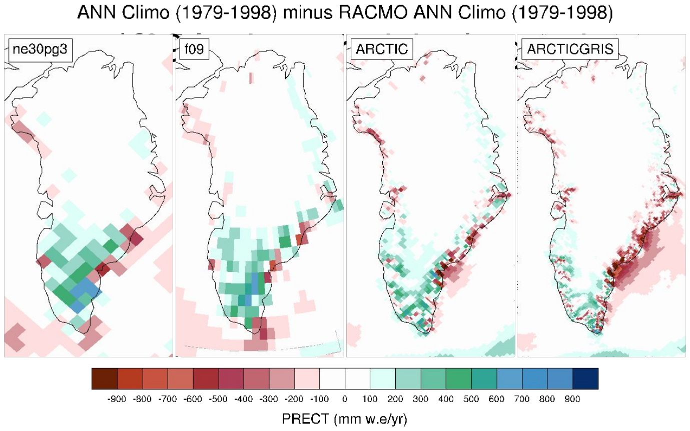
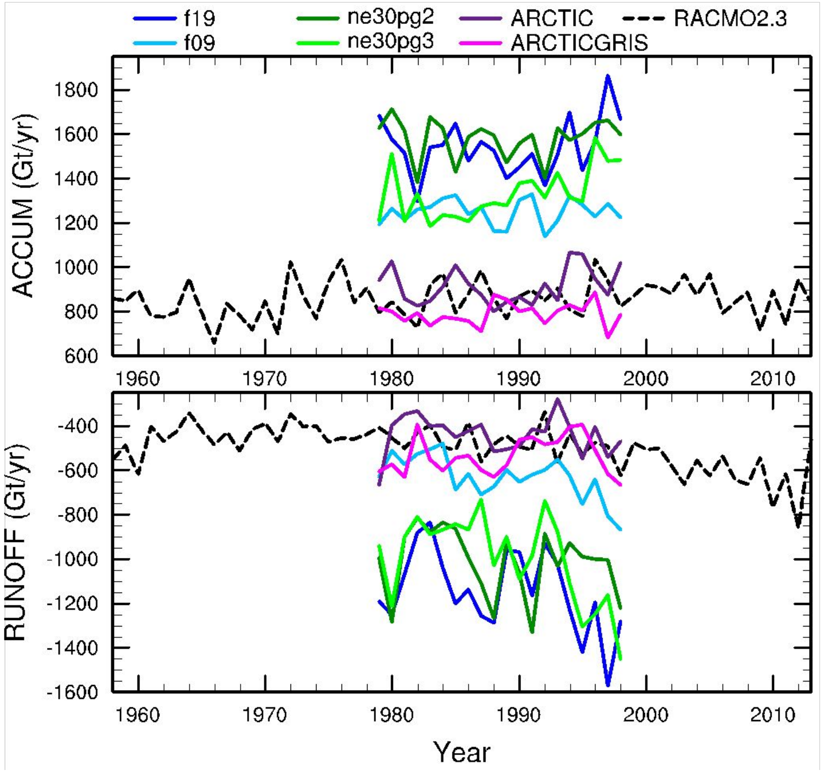
Surface Mass Balance (SMB) Temporal Evolution

SMB = ACCUM* + RUNOFF

*includes meltwater storage/refreezing

- Too much ACCUM at low res
- Too much RUNOFF at low res*





Slide courtesy of Adam Herrington

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New(er) dynamical cores in CESM

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

Released with CESM2.2 (bug fix in preparation))

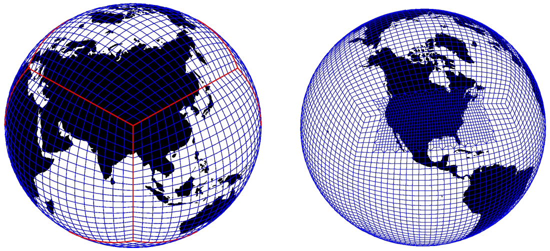
- Spectral-Element (**SE**) dynamical core with option for accelerated transport scheme (**CSLAM**)
  - highly scalable hydrostatic dynamical core with flexible mesh-refinement options
  - capability of running physics on a separate (coarser/finer) grid for uniform grid applications
  (see "Physics-dynamics coupling with element-based high-order Galerkin methods: quasi equal-area physics grid", MWR, 2018)

Released with CESM2.2 (bug fix in preparation))

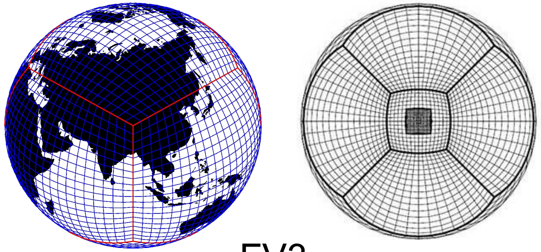
- **FV3**: GFDL's dynamical core used by NCEP for global weather forecasting
  - scalable finite-volume dynamical core (currently using hydrostatic version)
  - mesh-refinement/nesting and non-hydrostatic version not currently supported in CESM

Integration in progress

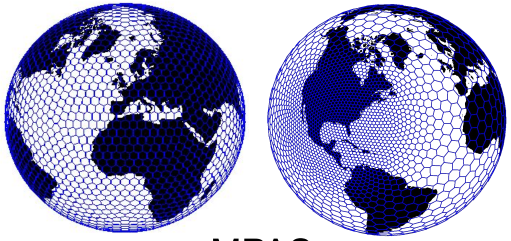
- **MPAS**: NCAR's global weather forecast model
  - non-hydrostatic finite-volume dynamical core that allows for flexible mesh-refinement



SE and SE-CSLAM



FV3



MPAS

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Aside: Dynamical cores and high top configurations

- Our experience with the spectral-element dynamical core has been that higher top configurations with tops at ~140km and ~600km have required significant efforts to stabilize
(numerical method less diffusive compared to FV)

- We are seeing significant differences between FV and SE-CSLAM at higher elevations that we are trying to understand (likely due to more resolved gravity waves)

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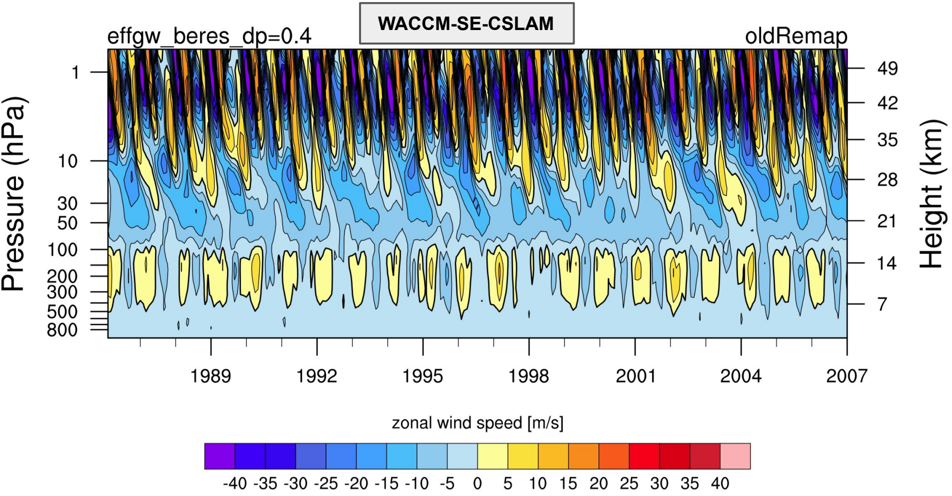
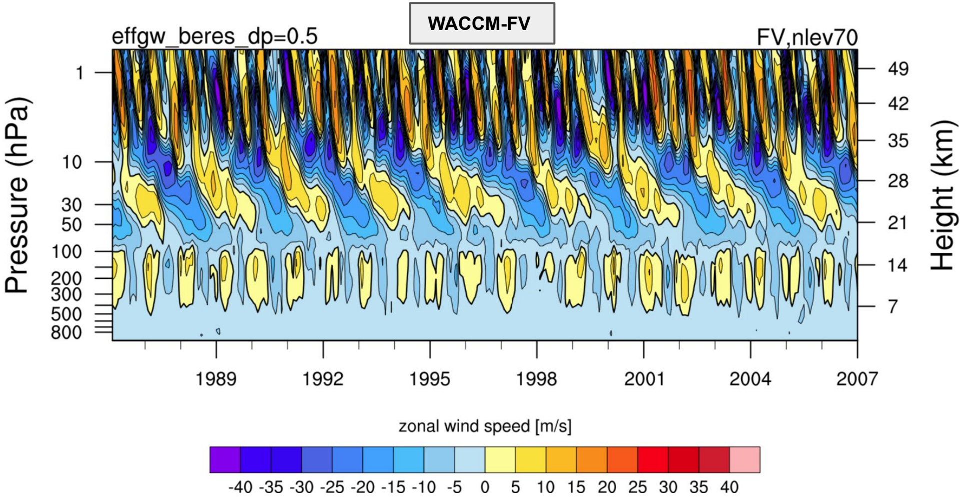
Aside: QBO with WACCM-SE-CSLAM

Initial simulations with WACCM-SE-CSLAM showed almost no QBO signal compared to WACCM-FV

- It did not appear to be “tunable” with gravity wave tuning parameters





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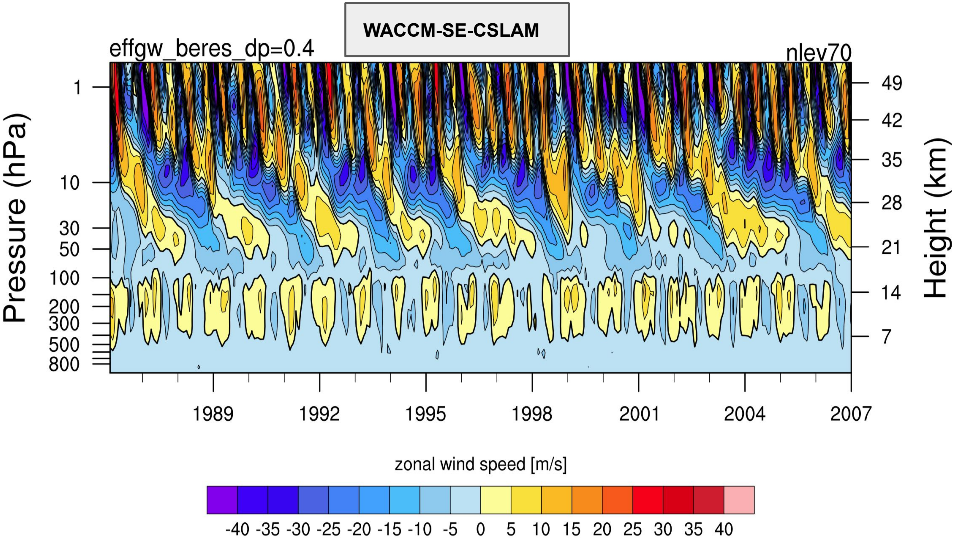
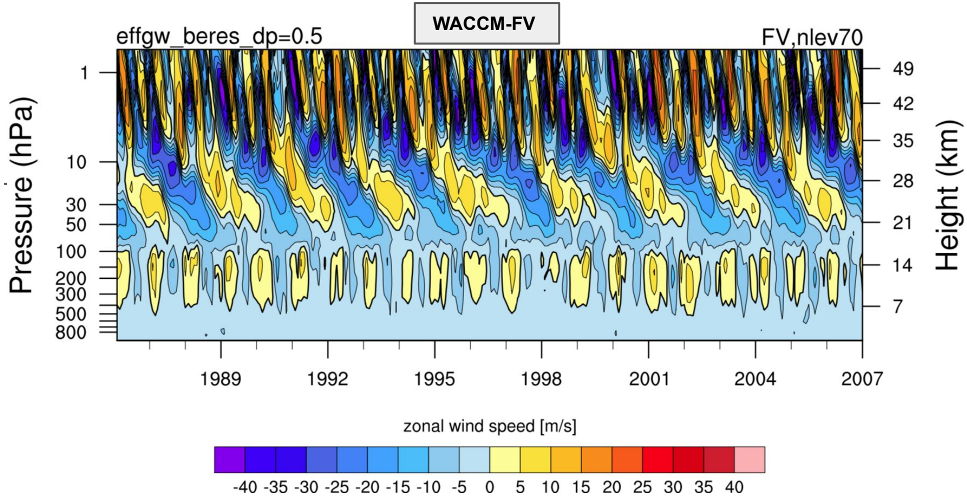
Aside: QBO with WACCM-SE-CSLAM

Changing to FV3 vertical remapping for u,v,T,and water species improved QBO simulation significantly!





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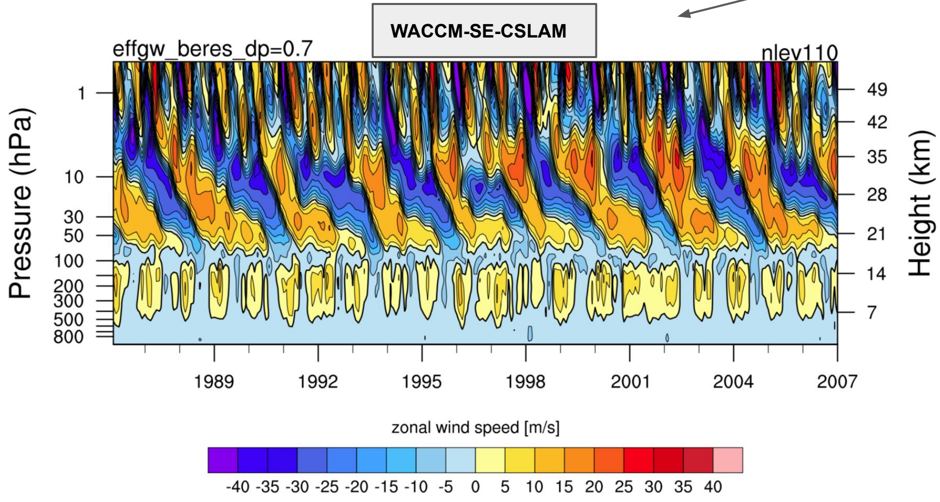
Aside: QBO with WACCM-SE-CSLAM

Still, we need higher vertical resolution for a good simulation of the QBO (e.g., 110 levels)



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CESM: Dynamical core science "paradise"

I would like to highlight that we are extremely close to a major achievement:

Changing between 5 state-of-the-art dynamical cores is a one line change in run-script:

```
se-cslam: /create_newcase -res ne30pg3_ne30pg3_mg17 ...
se      : /create_newcase -res ne30_ne30_mg17 ...
fv3     : /create_newcase -res C96_C96_mg17 ...
fv      : /create_newcase -res f09_f09_mg17 ...
mpas    : /create_newcase -res mpasa120_mpasa120 ...
```

Works already for CESM simpler models

That means diagnostics coded in physics can seamlessly be used with all dynamical cores

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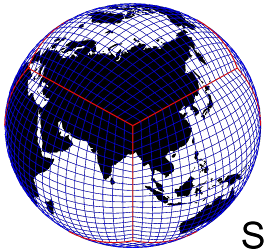
Preliminary performance data

- We are, at this point, interested in the performance for standard CMIP-like configurations!

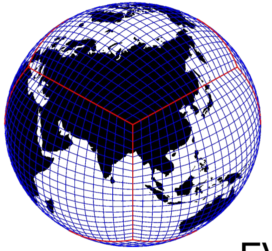
- All cores run at approximately 1 degree resolution (setup provided by developers).
  Note that the grids differ in number of degrees of freedom:

  FV (55296), FV3 (55296), SE (48600), MPAS (40962); for comparison:
  Note: FV3 has 35% more columns than MPAS and 13% more columns than SE

- We are not considering threading or GPU performance in this initial study



SE &
SE-CSLAM



FV3

MPAS

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Preliminary performance data

FKESSLER, 33 tracers, 1 month (no I/O)

Setup 1: Effectively dynamical core performance

- Baroclinic wave with simple physics (physics is "free")
- No I/O
- 33 tracers (=CAM6 #tracers)

QPC6, 1 month (incl. I/O)

Setup 2: "Full" model performance

- CAM6 physics (Aqua-planet)
- Timings include history I/O, writing restart file, etc.
- 33 tracers (=CAM6 #tracers)

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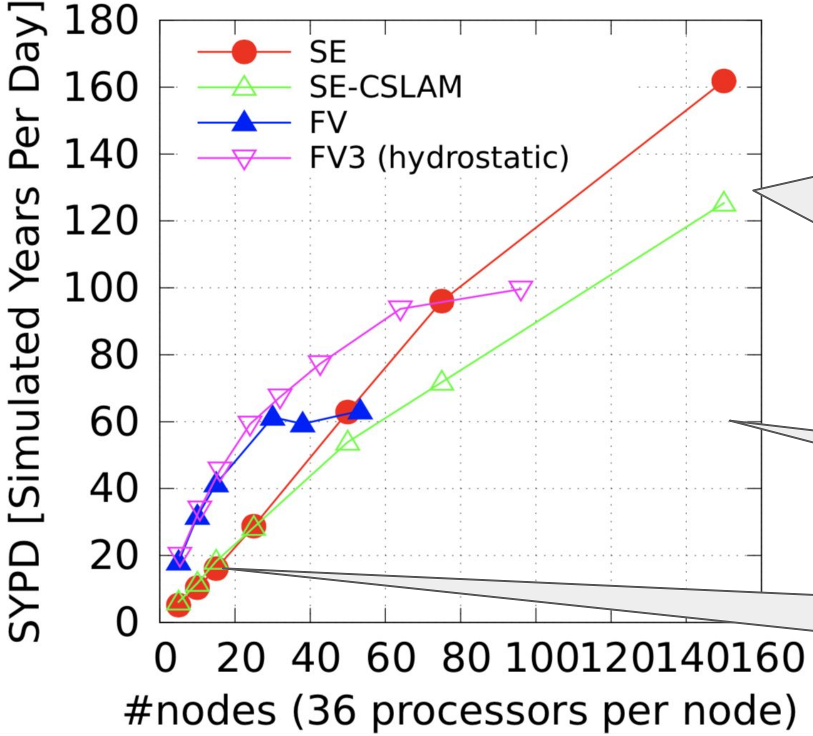
Preliminary perform

FKESSLER, 33 tracers, 1 month (no I/O)



S

Why is SE-CSLAM slower than SE?

- Double advection of water species (maybe not necessary)
- Mapping to-from dynamics and physics grid (not optimized)
- Overhead in computing dry air mass fluxes for CSLAM
- CSLAM has been coded so that sides of CSLAM control volumes on the edges of elements are duplicated on each element (reduces communication cost but is more work per degree of freedom - hurts performance at lower core counts)

At high core counts MPI communication becomes large for FV3 and FV

At low core counts FV and FV3 are clearly faster (methods are likely cheaper per degree of freedom compared to SE)

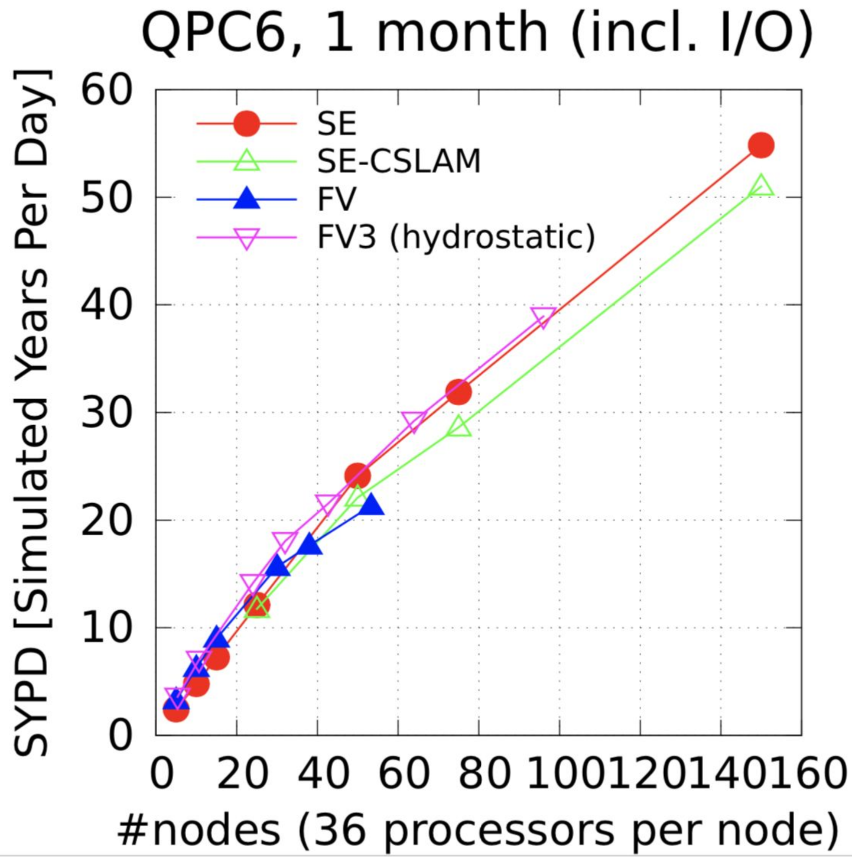
Preliminary performance data

Since physics is embarrassingly parallel and 50% of runtime, all dycores have better scaling characteristics

With 1800 processors (typical core count for development runs) all cores are within 4 SYPD of each other!

For maximum throughput (e.g. for paleo climate applications or meeting IPCC deadlines) SE and SE-CSLAM can get 50-55 SYPD with 5400 cores

FV3 reaches scaling limit 3456 processor with ~40 SYPD



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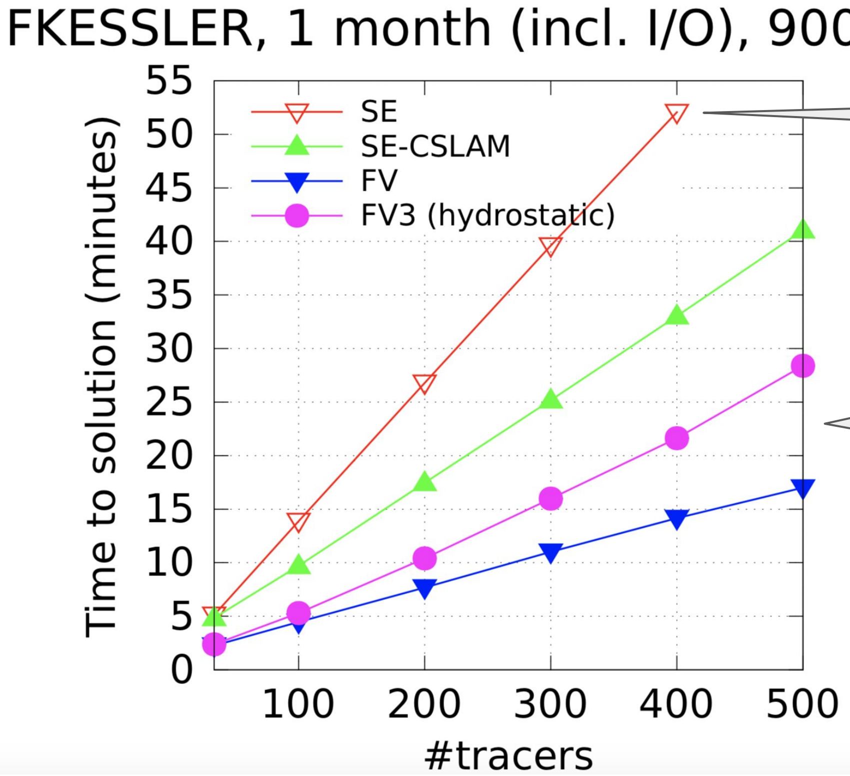
Preliminary performance data



Spectral-element advection is the slowest in terms of cost per additional tracer

FV and FV3 use dimensionally split advection schemes (computationally cheaper than fully 2D schemes such as CSLAM)

FV lat-lon advection algorithm cheaper than cubed-sphere version

Note: This plot would look different at large core counts ("just" 900 cores used here) ...

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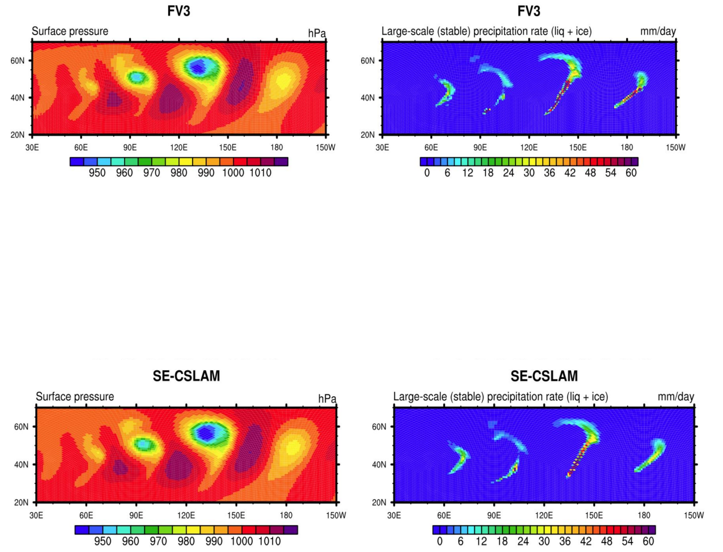
Tracer transport characteristics

Test case setup: moist baroclinic wave with a bunch of inert tracers and two reactive chlorine species

All diagnostics computed in physics!
No reference solution needed

- Mass-conservation
- Shape-preservation (overshooting, undershooting)
- Mixing for a single tracer: entropy measure
  (should be invariant in time)
- Mixing diagnostics for two non-linearly correlated tracers:
  3 mixing error norms
- Three or more tracers adding to a constant
  (practical example: total reactive Chlorine in stratosphere, aerosols)
- Linear correlation with idealized terminator chemistry
  (practical example: photolysis driven chemistry)



All tests at ~1 degree
(would be interesting to test variable resolution …)

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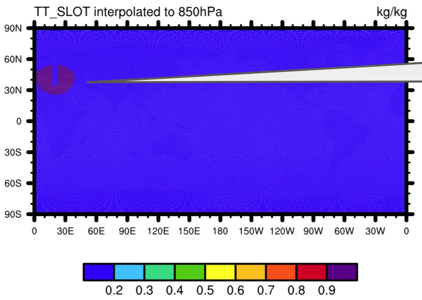
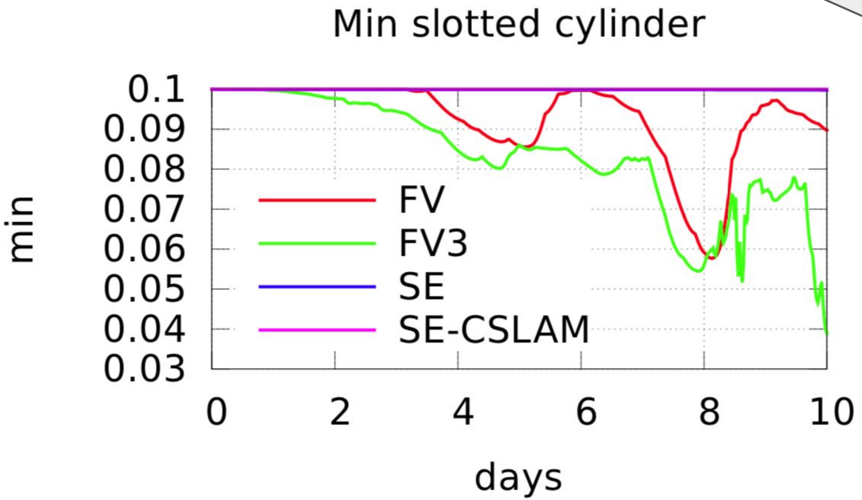
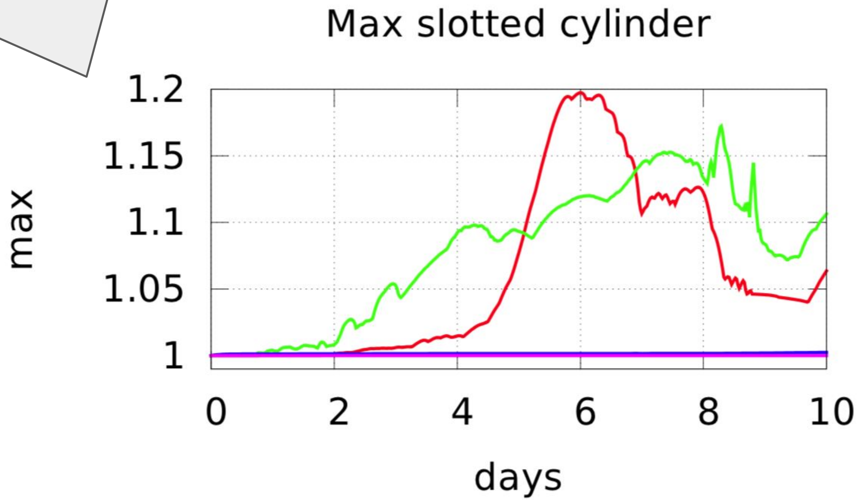
Shape-preservation



Min (=0.1) and max (=1.0) should be preserved and, in particular, range should not be expanded

FV and FV3 produce large errors!
Could be remedied with more restrictive limiters, however, not entirely due to dimensionally split scheme (limiters **limit only** in coordinate directions!)





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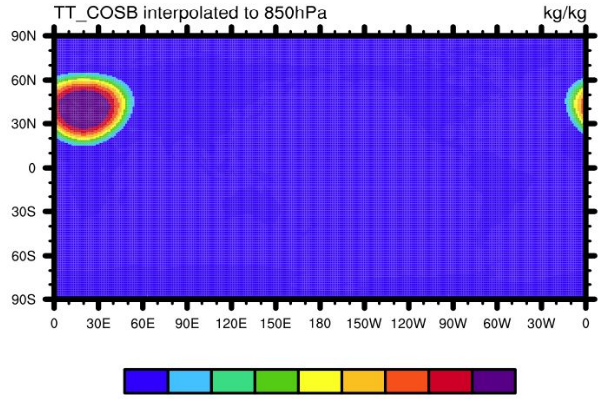
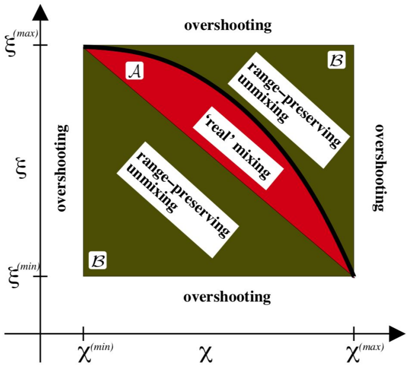
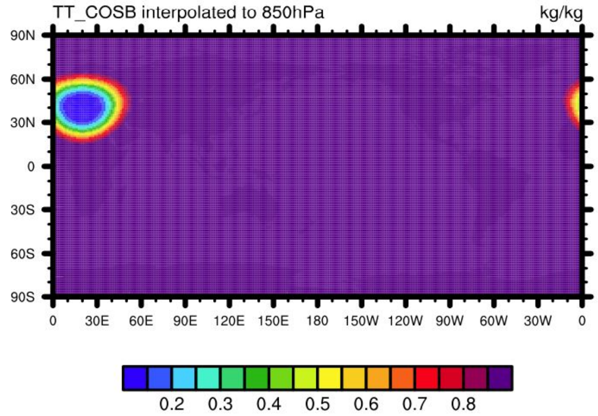
Non-linear correlation diags: scatter plots

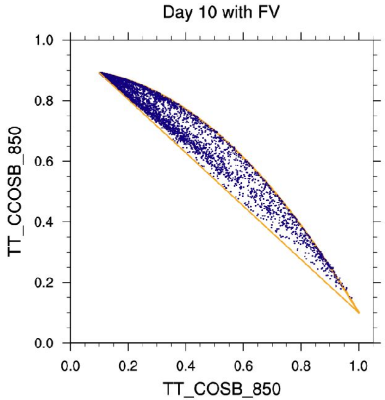


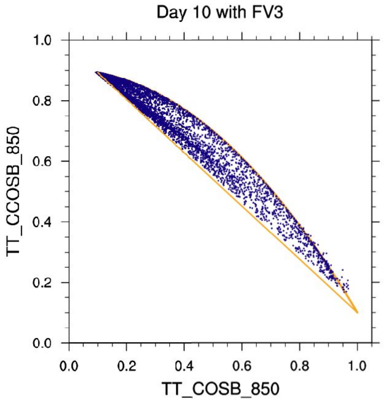


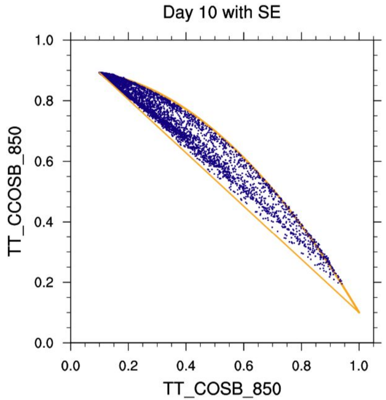


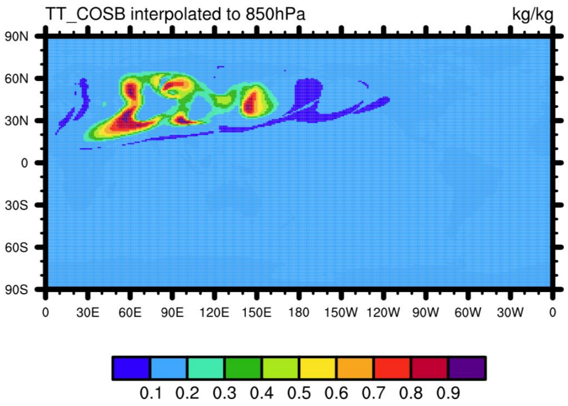
Non-linear correlation diags: scatter plots

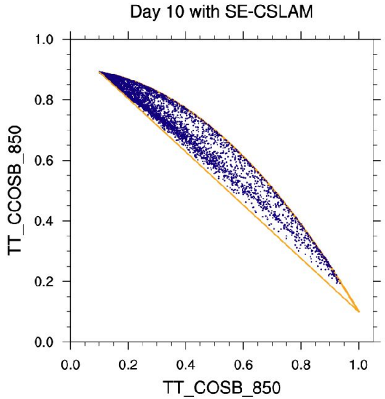
Lauritzen and Thuburn (2012)

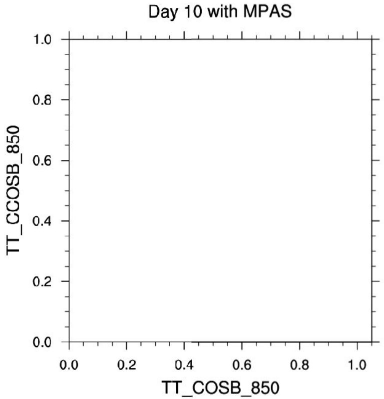


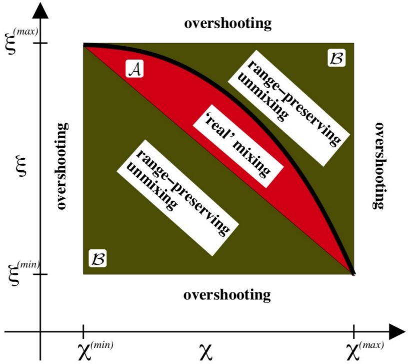


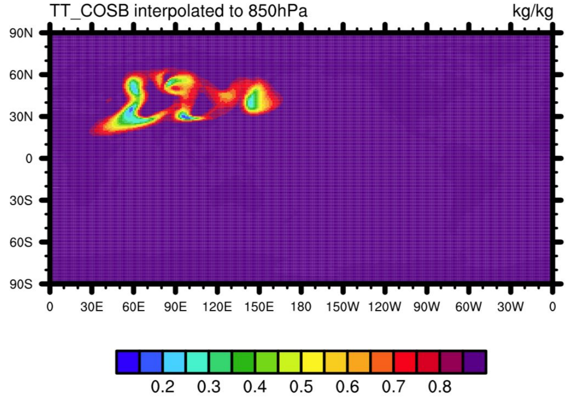












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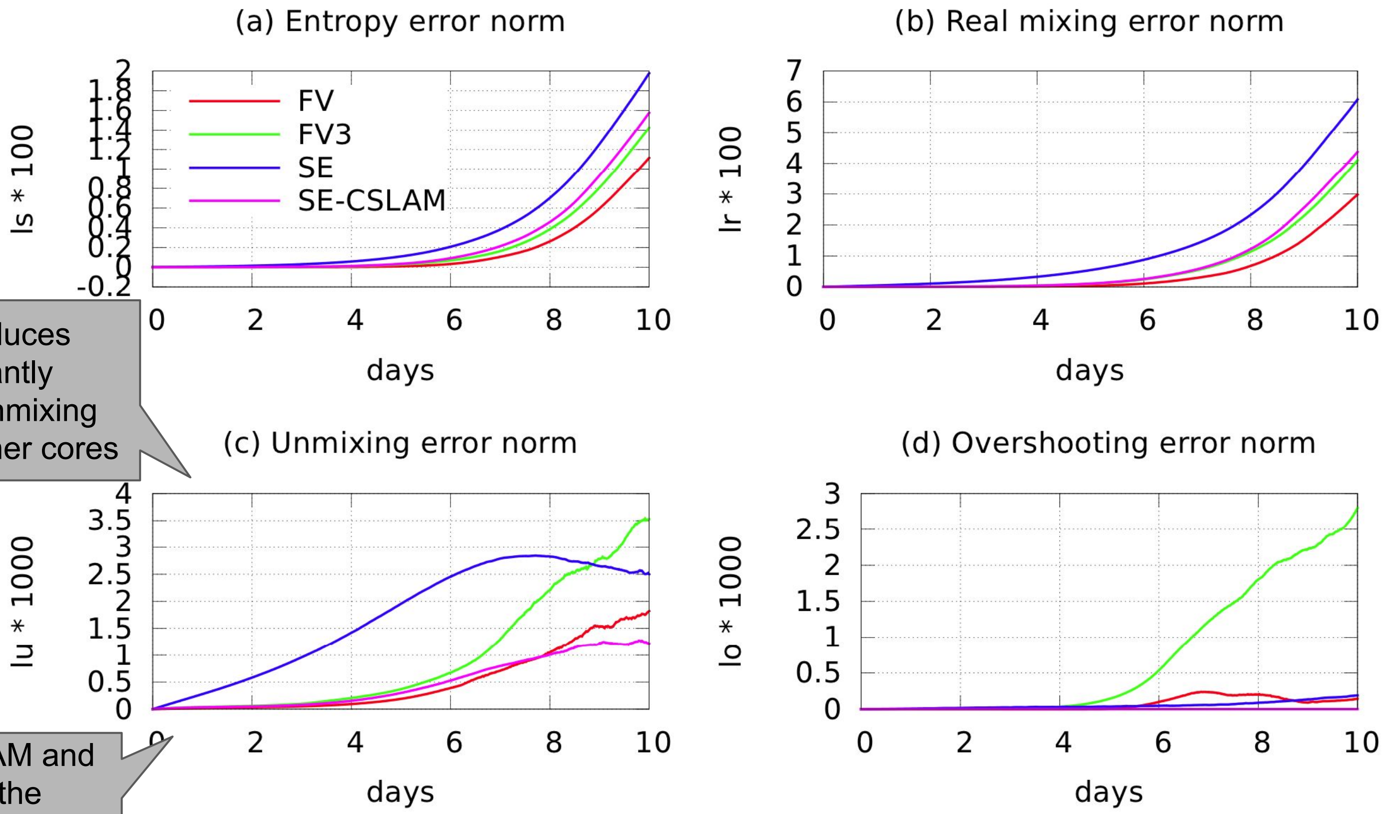
Entropy and non-linear correlation diags

Lauritzen and Thuburn (2012)



SE-CSLAM and FV3 produce similar amounts of real mixing

FV best due to higher resolution at 40N compared to other grids

SE produces significantly more unmixing than other cores

FV3 produces larger amounts of overshooting

SE and FV produce a little overshooting

SE-CSLAM produce none!

SE-CSLAM and FV have the least amount of unmixing

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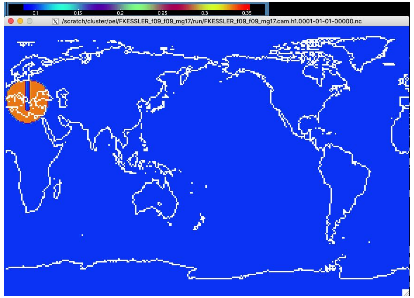
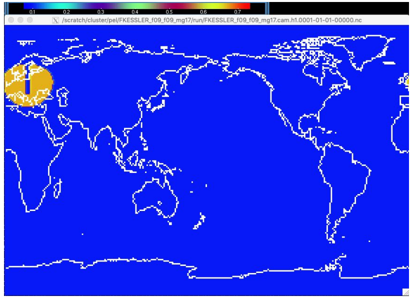
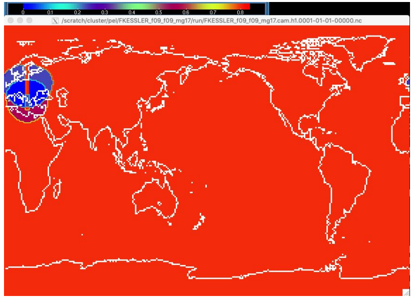
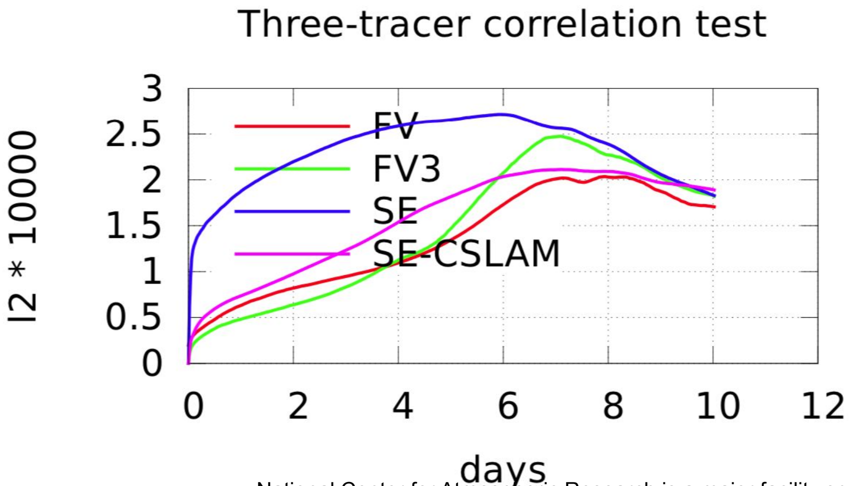
Three tracers adding to a constant

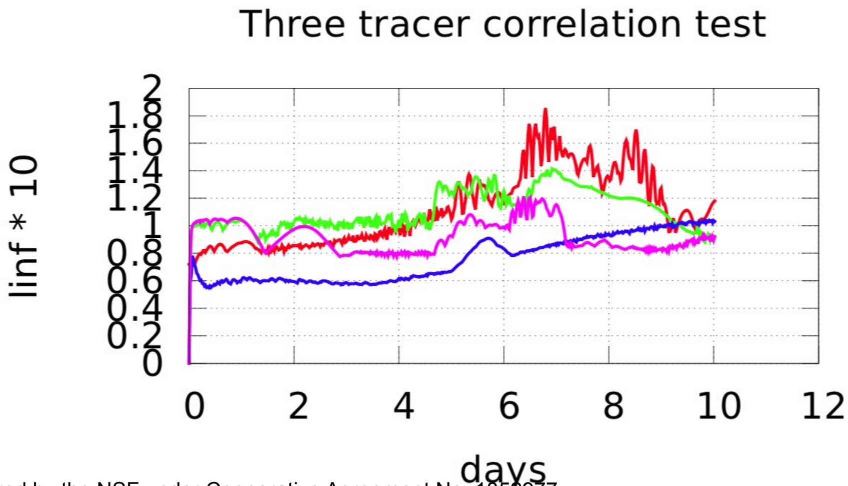
Lauritzen and Thuburn (2012)











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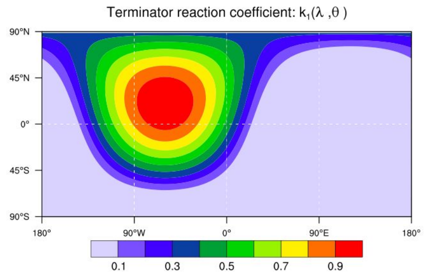
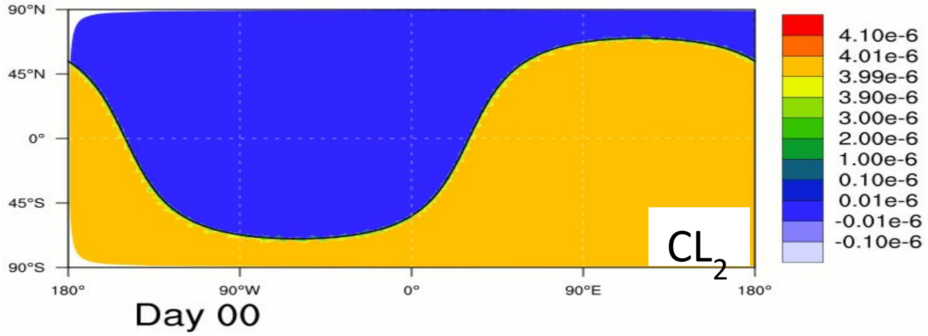
Terminator chemistry test

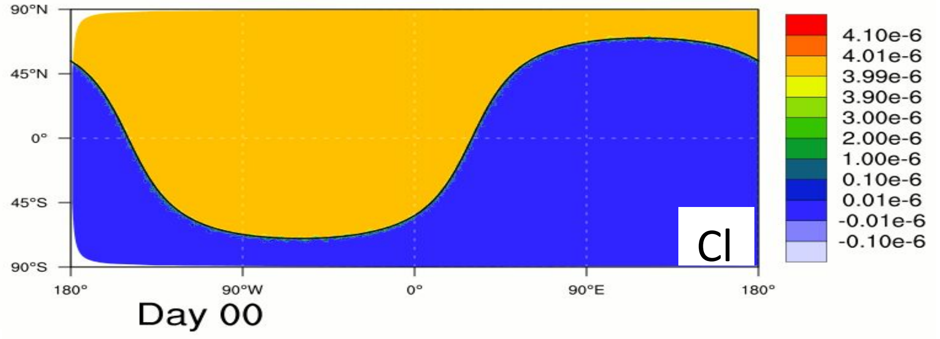
(Lauritzen et al., 2015)

Consider 2 reactive chemical species, Cl and Cl_2 :

$$Cl_2 \rightarrow Cl + Cl : k_1$$
$$Cl + Cl \rightarrow Cl_2 : k_2$$







- In any flow-field Cl_y=Cl+2*Cl_2 should be constant at all times (linear correlation preservation for reactive species).

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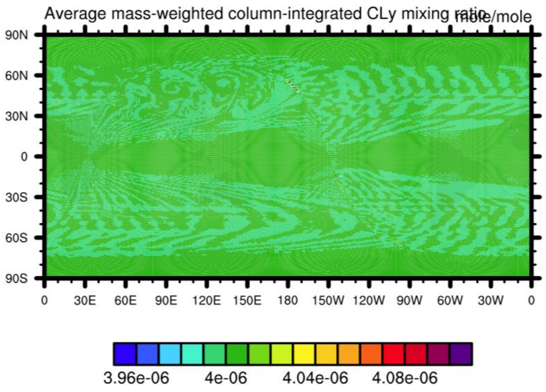
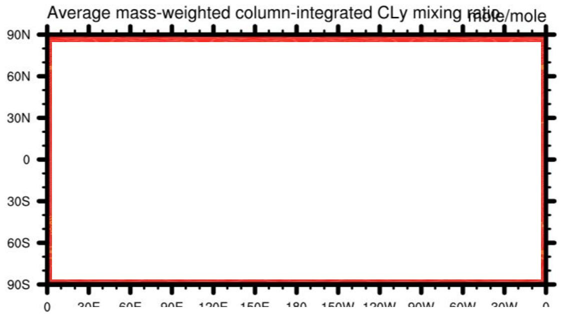
Terminator chemistry diagnostic

Lauritzen and Thuburn (2012)

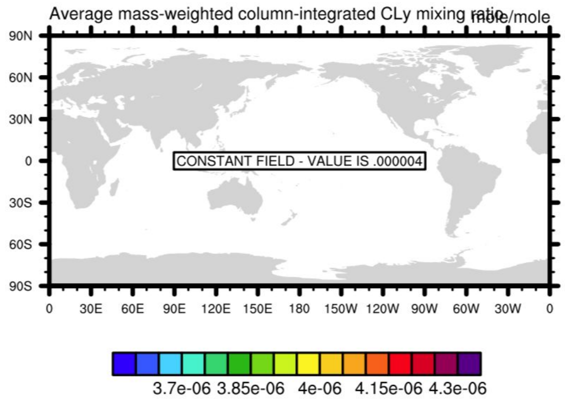
FV3



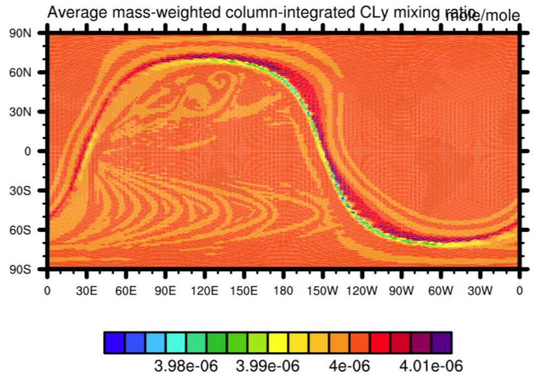
MPAS



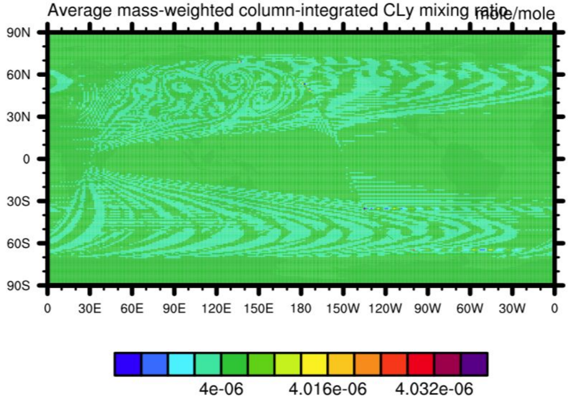
SE-CSLAM



SE



FV



Note: contour range/intervals different on each plot!

FV, FV3 and SE-CSLAM perform significantly better than SE

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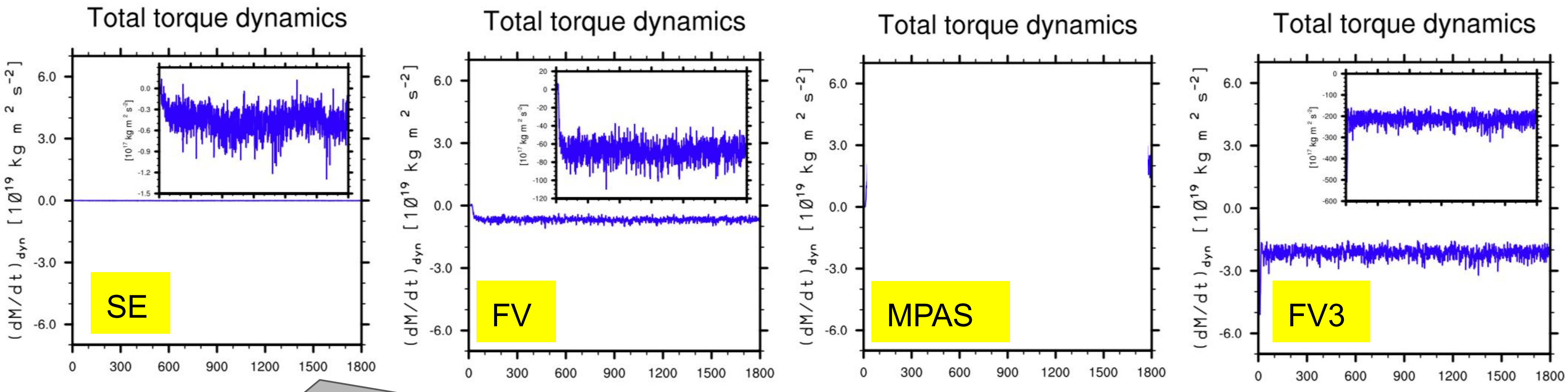
Axial angular momentum diagnostics

Setup: Held-Suarez forcing with flat Earth. Dynamical core should not be a source/sink of AAM
Plots show torque due to dynamical core as a function of time (days)



Only SE (and SE-CSLAM) do well on this test. FV and FV3 dynamical cores have spurious torques on the same order of magnitude as the physics torques

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The challenge of energy budget closure in Earth system models: dynamical core errors, physics errors, physics-dynamics coupling errors, …

- Energy budgets are complicated and require inline diagnostics in model code to assess errors (in particular, there can easily be compensating errors in the system):

$$-\partial \widehat{E}^{(efix)}_{phys} = \partial \widehat{E}^{(pwork)}_{phys} + \partial \widehat{E}^{(adiab)}_{dyn} + \partial \widehat{E}^{(pdc)} + \partial \widehat{E}^{(discr)}$$

Energy fixer

Pressure work (physics assumes constant pressure during physics updates)

Dynamical core

Physics-dynamics coupling

Continuous total energy formula discrepancy between physics and dynamics (e.g. internal energy, hydrostatic-nonhydrosttic, …)

(Lauritzen and Williamson., 2019)

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The challenge of energy budget closure in Earth system models: dynamical core errors, physics errors, physics-dynamics coupling errors

- Energy budgets are complicated ... d ... s (be compensating errors in the sy

0.3 W/m2

SE-CSLAM: -0.2 W/m2

FV and FV3 : -1.1 W/m2

0.05 W/m2

SE-CSLAM: 0.6 W/m2

$$-\partial \widehat{E}_{phys}^{(efix)} = \partial \widehat{E}_{phys}^{(pwork)} + \partial \widehat{E}_{dyn}^{(adiab)} + \partial \widehat{E}^{(pdc)} + \partial \widehat{E}^{(discr)}$$

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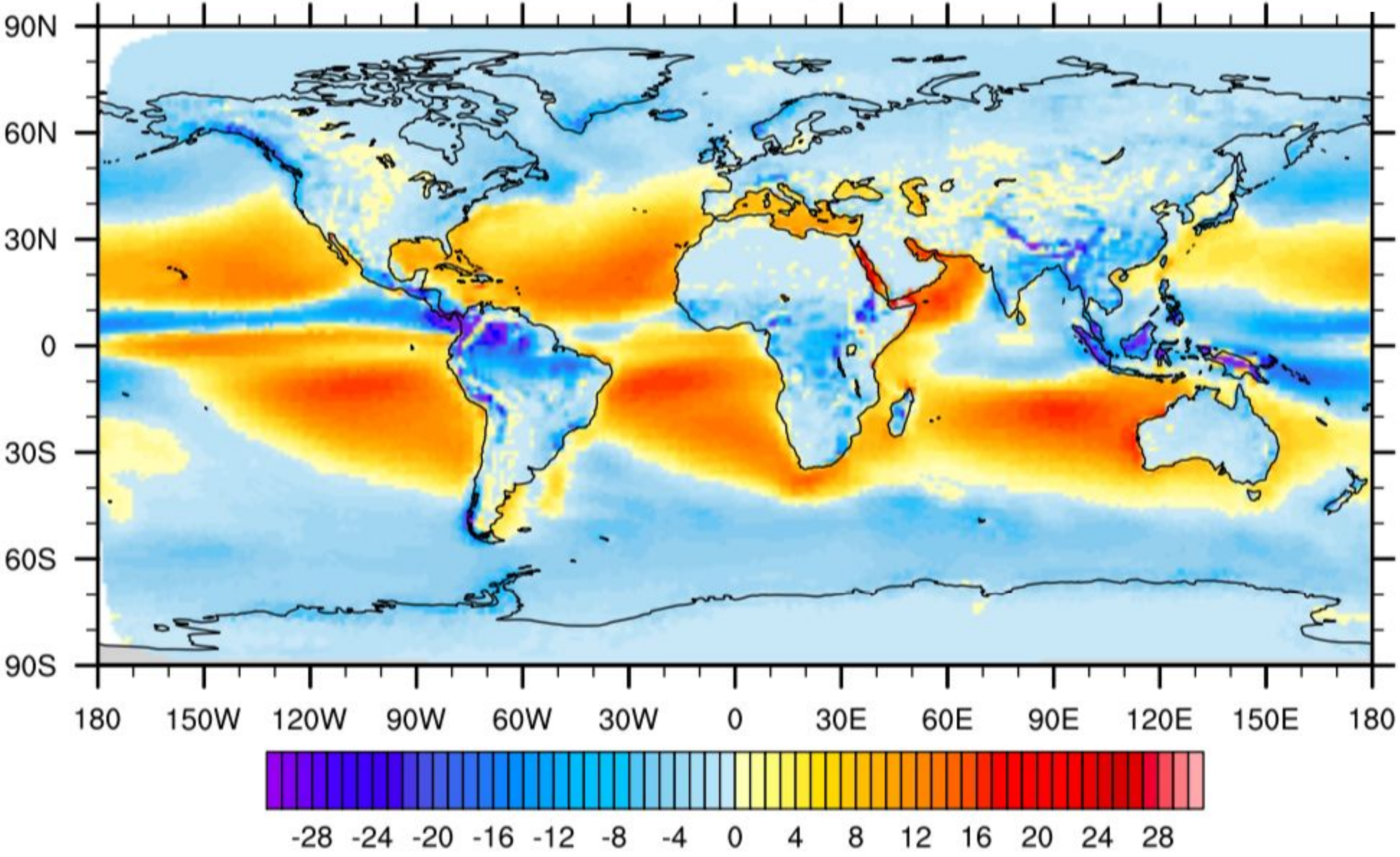
Pressure work tendency, 1 year average, W/m^2



SPURIOUS in each column

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Summary

- Unfortunately there is no one dynamical core / numerical method that is overall superior

- More testing in the pipeline:

  - idealized tests with real-world topography
  - moist physics (Aqua-planet, “real-world” AMIP and coupled)

- CESM/SIMA deliverables and progress:

  - CAM-Chem version with mesh-refinement (SE) is being used for science now
  - WACCM with SE-CSLAM is being evaluated
  - Close to having a SE and SE-CSLAM WACCM-x configuration ready for testing
  - Working on CAM-MPAS

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NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

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

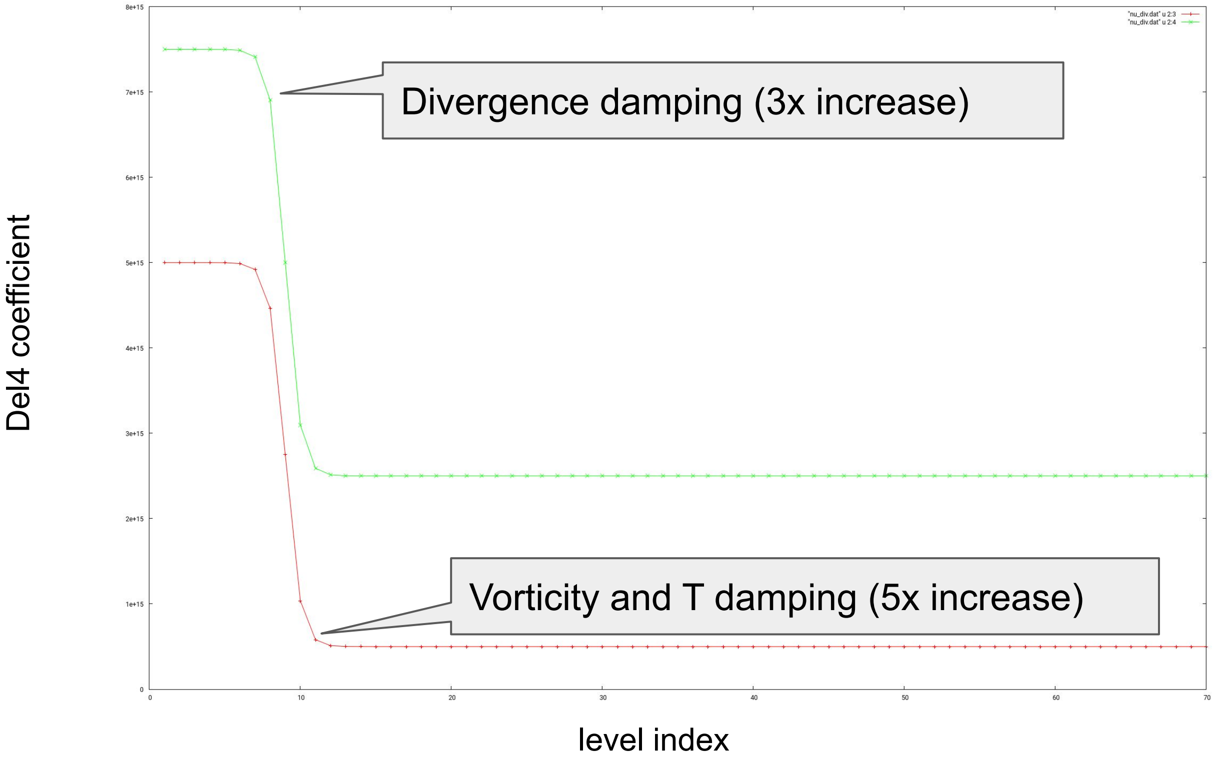
OVERVIEW

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

Aside: Stabilizing WACCM SE-CSLAM

Increased hyperviscosity (4th order) on divergence, vorticity and T in sponge
Was not possible to stabilize model with 2nd-order damping only!



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