Progress toward Adaptive Vertical Grid Enhancement in E3SM

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1. Project Overview

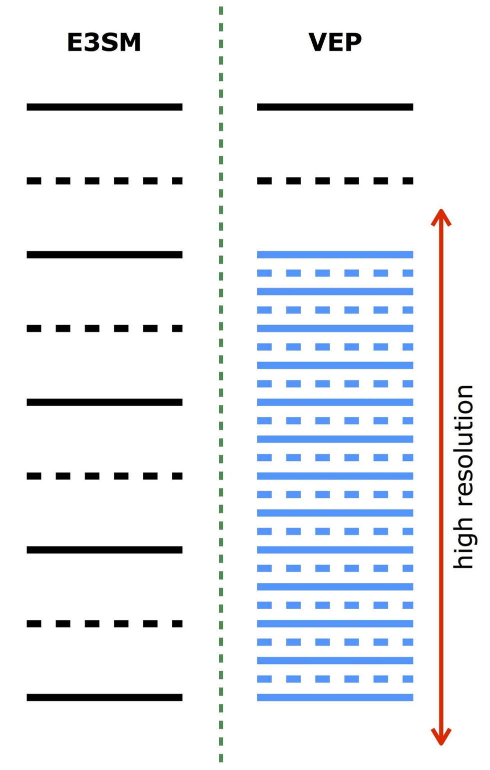
Thin clouds, i.e., stratocumulus and cirrus clouds, are poorly represented in state-of-the-art global models like E3SM. This SciDAC project aims to ***improve representation of boundary layer clouds, as well as cirrus clouds, by implementing a new computational framework, Framework for Improvement by Vertical Enhancement (FIVE; Yamaguchi et al. 2017), into E3SM***. FIVE is a novel method that contains elements of the nested grid method, the multigrid method, and the multiscale modeling framework, and is based on the fact that improvement of representation of these clouds can be gained by simulating them with high vertical resolution. Our goal is not only to implement FIVE into E3SM, but also to ***evolve FIVE into a computationally efficient version by adding a capability of dynamically adapting vertical resolution depending on the atmospheric state (Adaptive Vertical Grid; AVG)***.

This project consists of 4 tasks:

Task 1 implements FIVE into E3SM v1 and its single column model.
Task 2 refines the existing FIVE with SAM coupled with E3SM v4 physics (SHOC, P3, RRTMG).
Task 3 works on computational aspects of AVG.
Task 4 develops resolution criteria for AVG.

2. Framework for Improvement by Vertical Enhancement (FIVE)

FIVE is summarized in Figs. 1 and 2 below. In Yamaguchi et al. (2017), a prototype version of FIVE implemented into a regional model, the System for Atmospheric Modeling (SAM; Khairoutdinov and Randall 2003), shows dramatic improvement for drizzling stratocumulus clouds in, for instance, inversion height, cloud water path, rainwater path, and various vertical thermodynamic profiles. FIVE also has the potential to improve representation of cirrus clouds and mixed phase stratocumulus. One notable advantage of FIVE is its flexibility; FIVE can be used with any choice of combination of parameterizations.



← Fig. 1
In addition to the E3SM vertical grid, FIVE additionally constructs partially high resolution vertical level and separately allocates prognostic variables there. Selected processes are computed on this high resolution grid, termed the Vertically Enhanced Physics (VEP).

Variables are allocated on both levels.

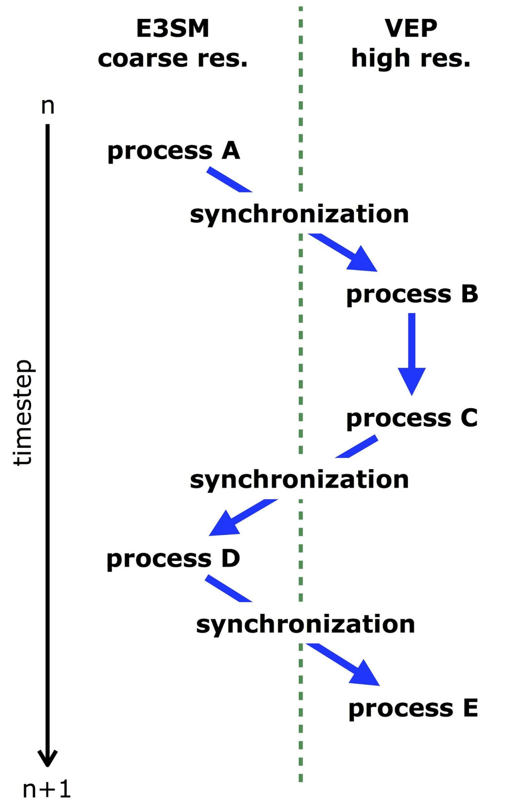


Fig. 2 →
Flowchart for process calculations over one time step for FIVE. In FIVE, selected processes, in this example process B, C, and E, are computed on VEP. Synchronization proceeds either E3SM or VEP to the appropriate partial timestep by adding tendency.

3. Adaptive Vertical Grid for VEP

The first version of E3SM-FIVE, presented here, uses a stationary VEP vertical level, which will be computationally expensive for the regions where the current parameterization can reasonably represent atmospheric state with E3SM's standard 72 levels. Stratocumulus columns will be better represented with higher resolution than shallow cumulus columns (Fig. 3). The project has been developing an AVG method for VEP level so that the resolution for the VEP level dynamically adjusts to the atmospheric state. For multi-core computations, however, AVG does not guarantee reduction of computational cost due to the load balancing problem. Possible methods to overcome this problem include performance tuning, work stealing, and GPUs.

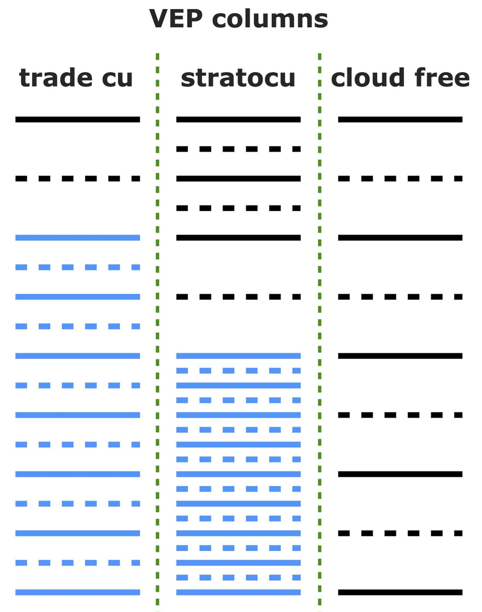


Fig. 3 →
Schematic for AVG for VEP

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4. Benchmark High Resolution Hindcast Simulations

Fig. 4 and 5 show bias in low cloud amount and shortwave radiative forcing for a 10-year simulation of E3SM v1 (72 levels; 1 degree mesh; Control) as well as doubled, quadrupled, and octupled vertical resolution below 700 hPa (Table 1). The low cloud amount for Control is too small: the stratocumulus regions are too dark and the trade cumulus regions are too bright. Increasing vertical resolution in the boundary layer generally results in increased low cloud amount, and more reflective marine stratocumulus and less reflective trade cumulus. Especially ***with octupled resolution, the biases are significantly reduced***. An equivalent set of simulations for high clouds at levels 400 hPa to 50 hPa is currently running.

The runs with doubled, quadrupled, and octupled cases required changes in the host (E3SM) and CLUBB timestep for stability (Table 1). A sensitivity test to timestep for the standard configuration (72 levels) was carried out in order to elucidate any potential differences that are coming from changing the time step (Table 2; Fig. 6). The test shows that ***decreasing timestep in the standard 72 level E3SM tends to reduce low clouds***.

Table 1: E3SM configuration (10 year duration).

Case	Levels	E3SM time step (s)	Micro. And CLUBB time step (s)	Deep convective time scale (s)	Simulated year per day (1024 cpus)
CNTL	72	1800	300	3600	4.6
DOUB	93	900	300	3600	2.5
QUAD	123	600	200	3600	0.83
OCT	194	300	100	600	0.125

Table 2: Configurations for timestep sensitivity test (72 level; 2 year duration).

Case	E3SM time step (s)	Micro. And CLUBB time step (s)	Deep convective time scale (s)
CNTL900	900	300	3600
CNTL600	600	200	3600
CNTL300	300	100	3600
CNTL300deep	300	100	600

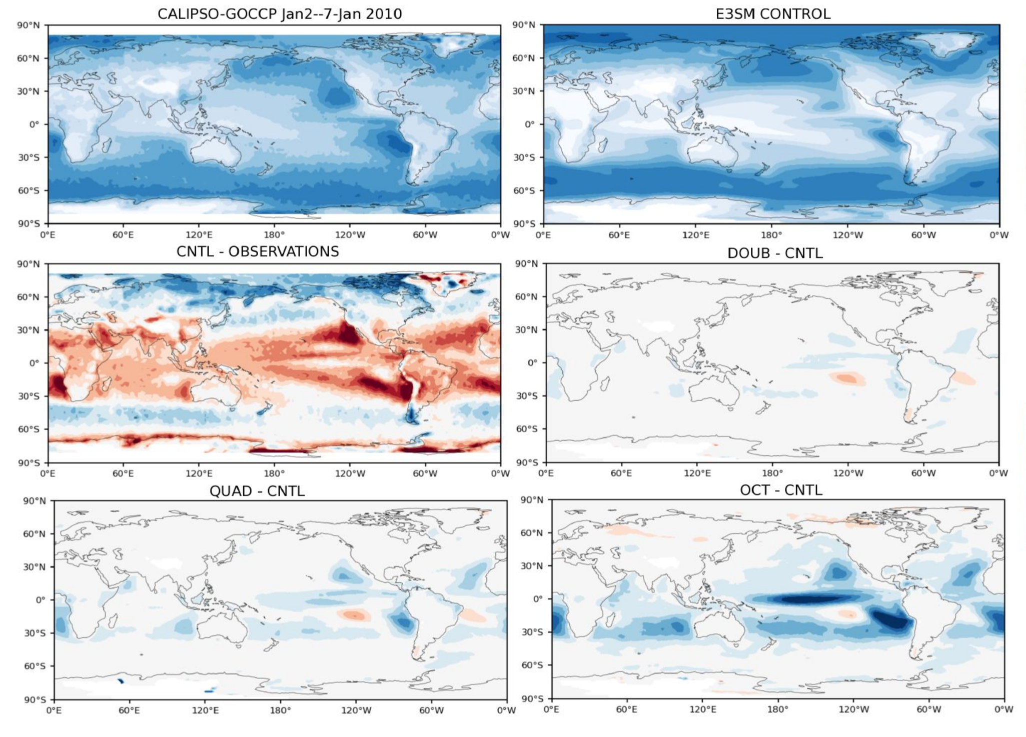

Fig. 4: Low cloud amount from CALIPSO observations and simulator. For difference plots between the high resolution simulations and Control, the low cloud amount is increased in the blue contour regions.

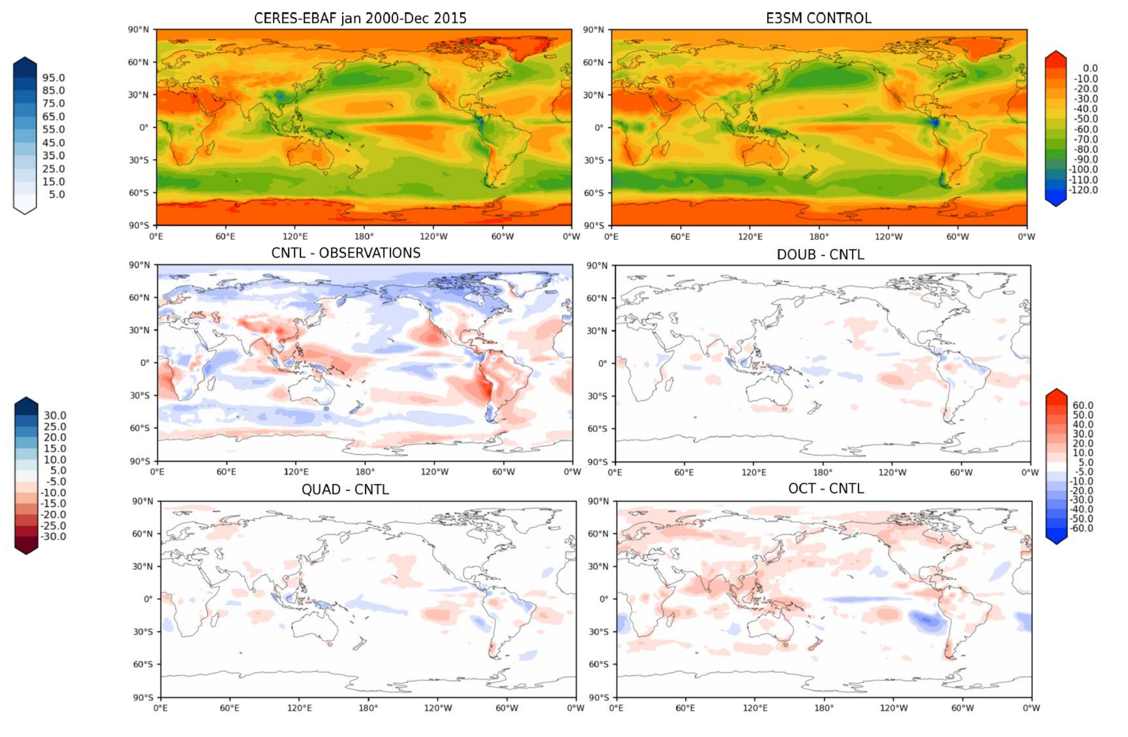

Fig. 5: Shortwave cloud forcing from CERES-EBAF and simulator. For difference plots between the high resolution simulations and Control, clouds become brighter than the Control in the blue contour areas, and darker in the red contour areas. Note the improvements in stratocumulus shortwave cloud forcing, particularly the Peruvian SCu.

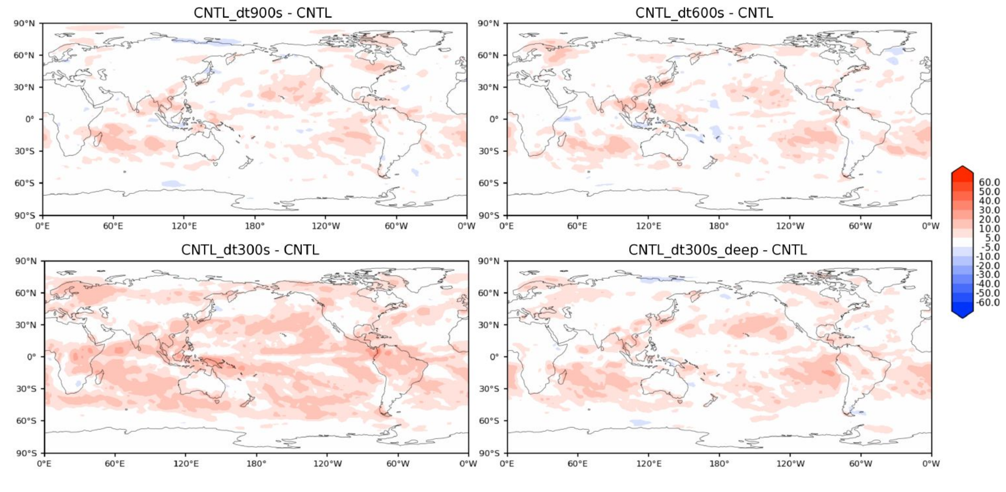

Fig. 6: Differences in shortwave cloud forcing from Control for timestep sensitivity test. With smaller timestep, low clouds are reduced in the red contour areas compared with Control.

5. Preliminary Results from Prototype E3SM-FIVE without Large-Scale Vertical Advection in VEP

Three physics parameterization schemes (turbulence, microphysics, and radiation) have been coupled to the prototype FIVE (stationary VEP grid). The large-scale vertical advection is necessary to balance entrainment via the turbulence scheme and is currently being implemented. For the results shown in Fig. 7 below, the tendency of large-scale vertical advection is interpolated to the VEP grid. The figure compares between prototype E3SM-FIVE without vertical advection and standard E3SM for simulations of 2 year duration. ***Improvements in both low cloud amount and shortwave cloud forcing follow benchmark simulations***, even without large-scale vertical advection. We found that ***no modification to any of E3SM's timesteps is necessary in order for E3SM-FIVE to stably run for 2 years, which reduces a large portion of computational cost compared with high vertical simulations without FIVE***.

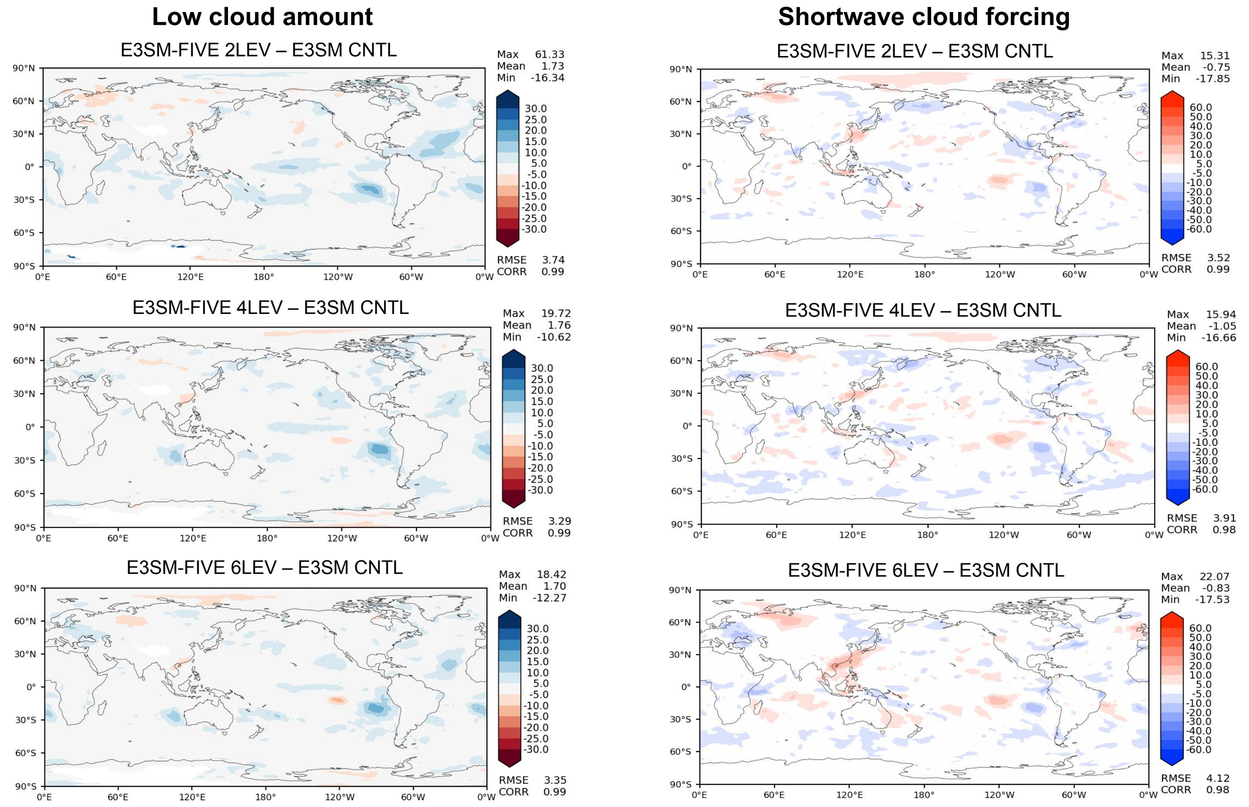

Fig. 7: Difference in low cloud amount and shortwave cloud forcing compared to Control. For E3SM-FIVE, 2LEV, 4LEV, and 6LEV correspond to 3, 5, and 7 times higher resolution below 700 hPa, respectively.

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6. AVG Development

Implementation of AVG is two-fold: algorithmic design and decision criteria for the VEP resolution. For algorithmic design, several options have been considered: a) block-structured AVG or column-structured AVG, b) nested refinement (i.e., multi-resolution VEP in one column) or not (Fig. 8). The column-structured AVG is straightforward but probably less efficient than the block-structured AVG while the block-structured AVG has disadvantages; e.g., all of process codes used in VEP will need to be adjusted so that they can predict variables and compute fluxes only within a high resolution block. Also, the block-structured AVG has to use the fluxes computed from low resolution for the top and bottom boundary conditions of a block.

AVG requires decision criteria to adjust VEP resolution based on the current and very near future atmospheric state. Development of the resolution criteria for AVG will explore a number of ideas ranging from lower tropospheric stability to machine learning with information that would be available when FIVE is used on the fly (i.e., E3SM as well as VEP information).

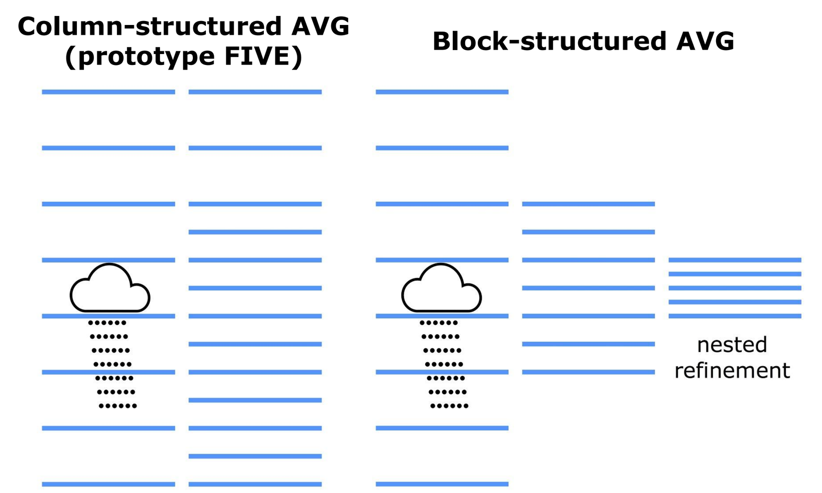


Fig. 8: A schematic for the two types of AVG currently considered.

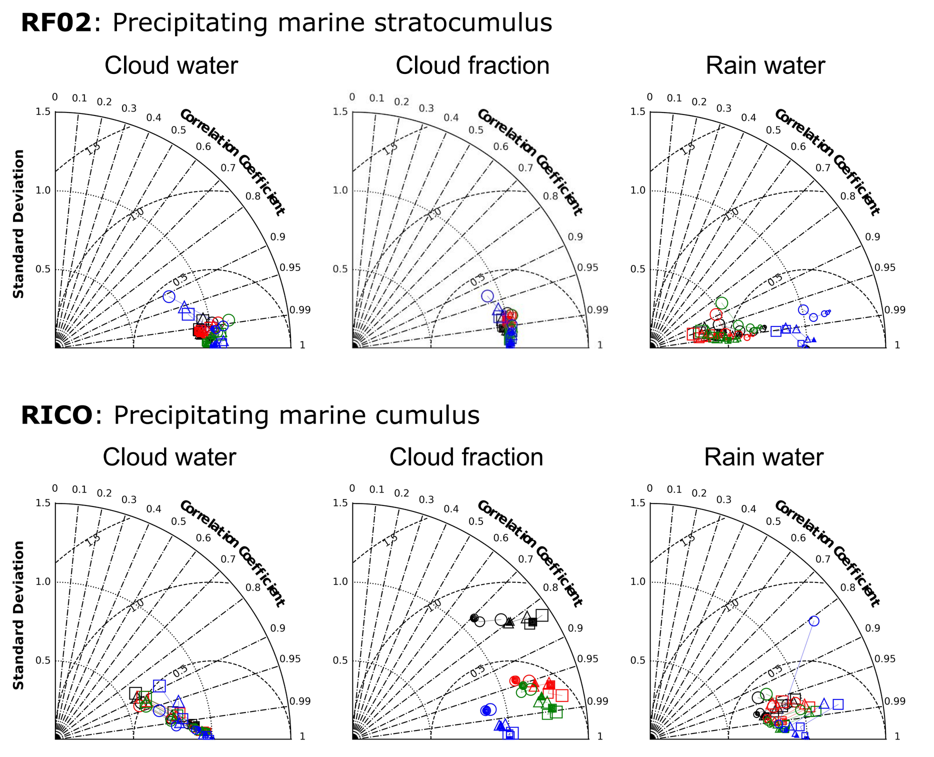
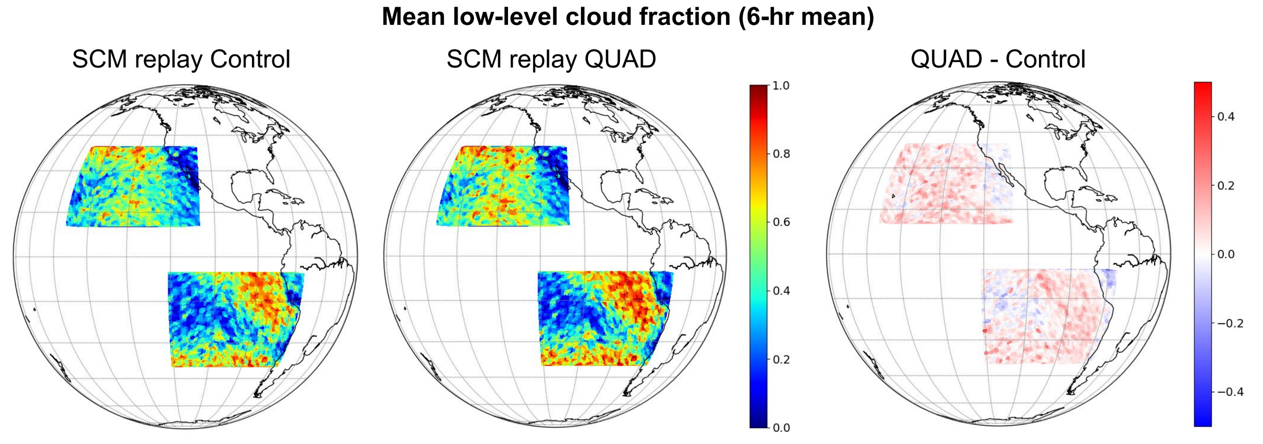


Fig. 9 →
E3SM SCM convergence test for vertical resolution and dynamical timesteps. The profiles from the finest vertical/temporal resolution are used as reference. Color/shape represents vertical resolution below 4 km (50-15 m). Size of symbol represents dynamical timestep (the smaller the shorter). A fixed ratio between dynamical timestep and physics timestep is used.



Prior to the development of decision criteria, we examined the sensitivity of the convergence of the E3SM single column model to vertical resolution, dynamical timestep, and physics timestep. The tests show that ***(a) With moderately refined vertical grid, SCM profiles converge for a dynamical timestep shorter than 300 s (Fig. 9) and (b) SCM profiles converge nicely for a physics sub-timestep threshold somewhere between 300 s and 100 s***.

We also examined if the improvements using high vertical resolution can be seen in very short term SCM simulations, e.g, 6 hours. The SCM replay mode, which forces the SCM with E3SM output, was used for 12,000 locations/times (Fig. 10). ***Differences between high and standard vertical resolution replay SCM runs share similar features to GCM simulations***.

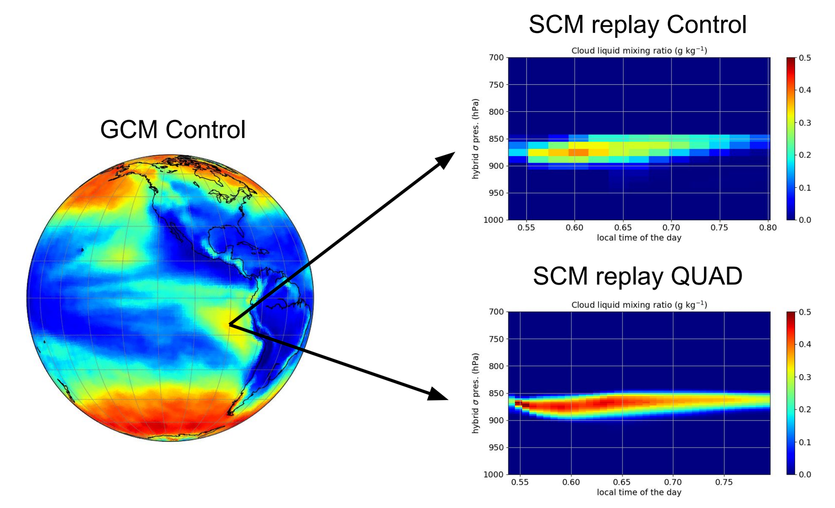
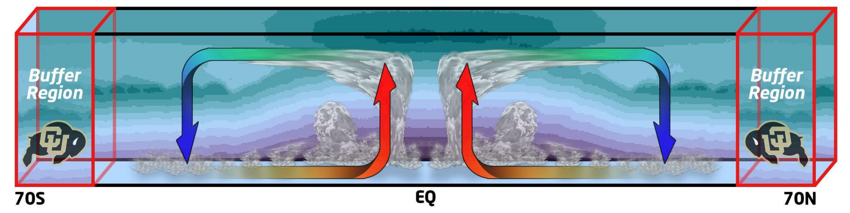


Fig. 10: Very short term SCM replay test. After 1-year spinup of E3SM, Jan/Apr/Jul/Oct output from the 2nd year was saved every timestep to drive the SCM at 12,000 locations/times. Each replay SCM runs for 6 hours. For the QUAD runs, all inputs are vertically interpolated.

7. 2D Hadley Circulation Modeling to Test FIVE for E3SM v4

E3SM v4 (aka. SCREAM) will run as a global cloud system resolving model (3 km horizontal mesh) with non-hydrostatic dynamical core and new physical parameterizations such as SHOC (Bogenschutz and Krueger, 2013) for turbulence and P3 (Morrison and Milbrandt, 2015) for microphysics. To assess the benefits and potential difficulties of using FIVE in GCSRM, we have used an upgraded version of SAM to model the Hadley circulation in a North-South, 2 dimensional computational domain.



Benefits of 2D modeling
- Simple – easy to prepare the simulation, easy to describe the phenomena
- Lightweight – computationally inexpensive, easy for file I/O and analysis

List of upgrades
- Implementation of E3SM v4 physics (SHOC and P3)
- North-South 2D mode (including removal of limitation of number of cores associated with pressure solver)
- Open lateral boundary condition
- Initialization with real data, e.g., ERA5

Remarkably small computational resources are required for a realistic Hadley circulation in the 2D framework.
- 50 days of time integration can be done with 4 days of CPU time with 512 cores
- The Hadley circulation appears by the 20th day for initial conditions at rest.

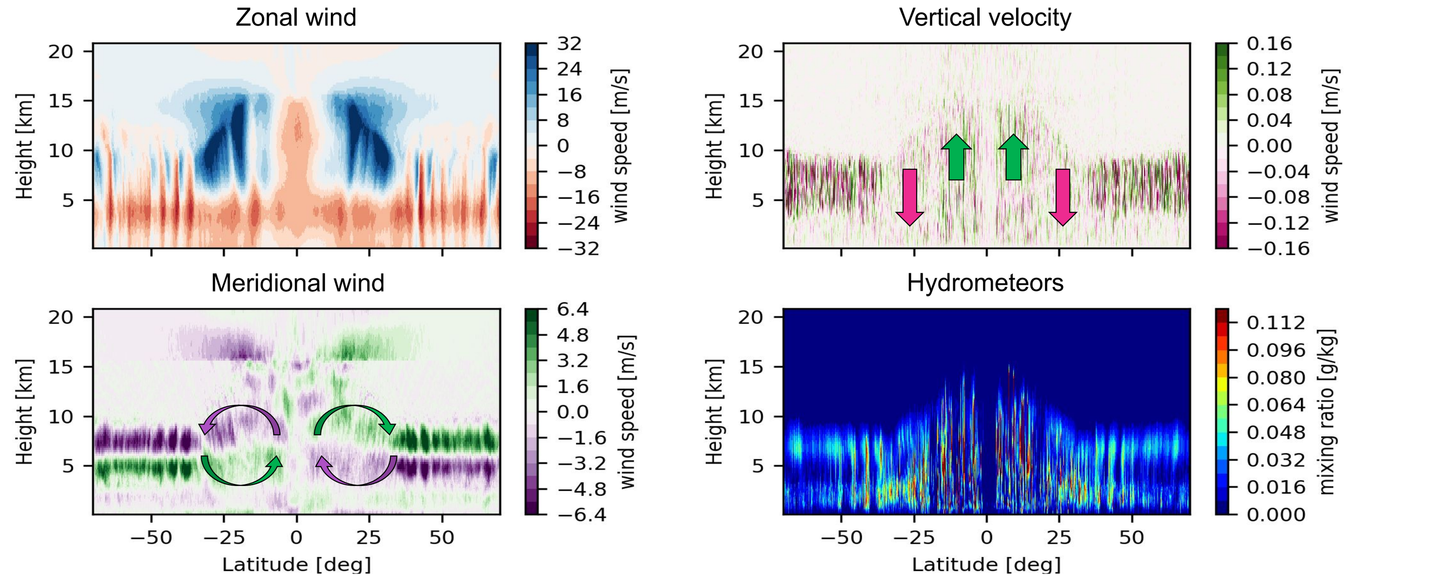


Fig. 11: A preliminary result of a pilot test (last 30 day mean; 50 day duration; dx=2 km and 128 levels).