E3SM Water Cycle Group

Chris Golaz, Luke Van Roekel on behalf of the entire group

Water Cycle Group effort: 8-10 FTEs

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DOE Internal Review of E3SM Phase II – 9-10 November 2020

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E3SM Energy Exascale Earth System Model

U.S. DEPARTMENT OF ENERGY

Water Cycle Group – Phase II Goals

- v1 Simulation Campaign
- v1 Analysis
- v2 Model Development

Water Cycle - Science Drivers

How does the **hydrological cycle** interact with the rest of the human-Earth system on local to global scales to determine **water availability** and **water cycle extremes**?

Phase II Goals - v1 Simulation Campaign

Table 1. *Water cycle simulations for v1.*

Simulation	Duration	Resolution	Notes
Pre-industrial (1850) control	500 years	LR	DECK
Historical transient (1850-2014)	165 years per ensemble member	LR	DECK - minimum of 3, ideally 5 ensemble members.
Abrupt 4xCO2	150 years	LR	DECK
1%/yr CO2 increase	150 years	LR	DECK
AMIP (1970-2014)	45 years	LR	DECK - possibility of starting earlier (1870) and performing multiple ensemble members
1950 control	50 years	LR, HR	HighResMIP like
1950-2050 (all forcings)	100 years	LR, HR	HighResMIP like - 3 ensemble members
1950-2050 (GHG-only)	100 years	LR, HR	HighResMIP like - 3 ensemble members
AMIP (2000-2010)	10 years	⅛ degree, global	Atmosphere-only global high-resolution simulation
AMIP (2000-2010)	10 years	⅛ degree, RRM	Atmosphere-only high-resolution simulation over North America using RRM

✓
✓ 5 members
✓ Extended to 300 years
✓
✓ 3 members, 165 years each
✓
✓ LR complete
✓ HR near completion

Completed test simulations, but effort redirected.

Additional simulations

- AMIP simulations to compute ERF.
- LR simulations with HR tunings to explore impact of resolution.
- Continental RRM (1/4 deg) atmosphere simulations.

Phase II Goals – Publications (25 and counting)

Overviews

- Golaz, et al. (2019). The DOE E3SM coupled model version 1: Overview and evaluation at standard resolution. JAMES, 11, 2089–2129.
- Caldwell et al. (2019). The DOE E3SM coupled model version 1: Description and results at high resolution. JAMES, 11, 4095-4146.

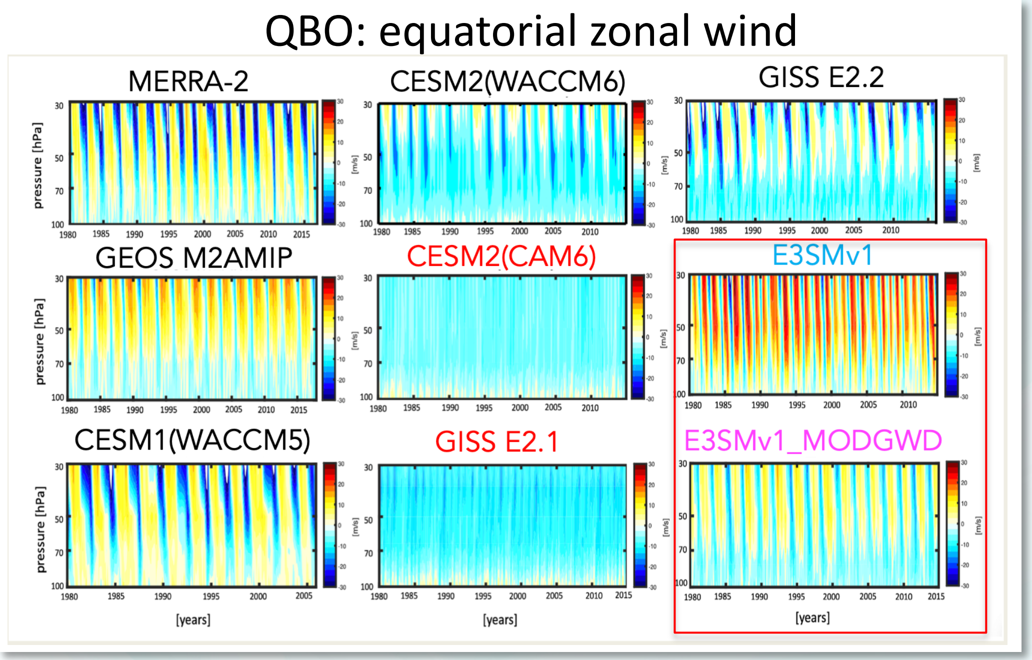
v1 Analysis

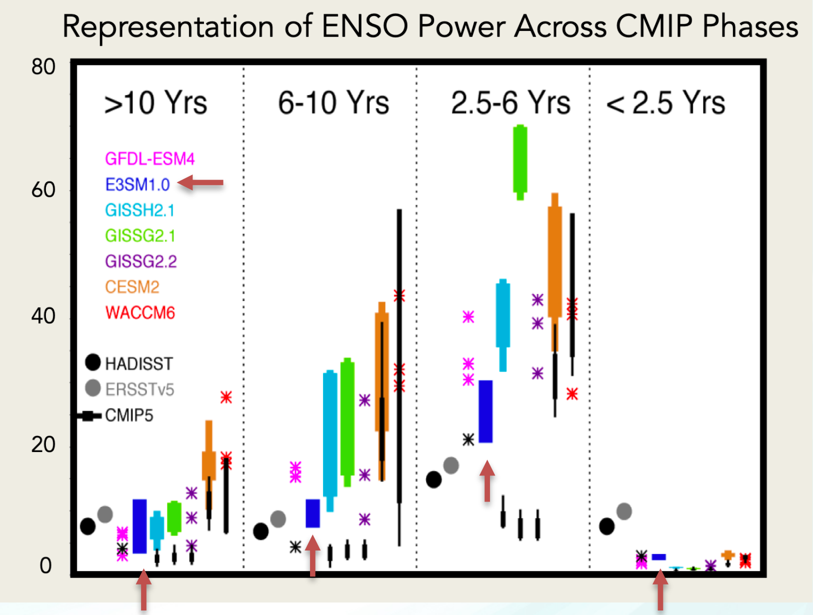
- Qian et al. (2018). Parametric sensitivity and uncertainty quantification in the version 1 of E3SM atmosphere model based on short perturbed parameter ensemble simulations. JGR, 123, 13,046–13,073
- Xie et al. (2018). Understanding cloud and convective characteristics in version 1 of the E3SM atmosphere model. JAMES, 10, 2618–2644.
- Jiang et al. (2019). Northern Hemisphere blocking in ~25-km-resolution E3SM v0.3 atmosphere-land simulations. JGR, 124, 2465–2482.
- Reeves Eyre, et al. (2019). Ocean barrier layers in the Energy Exascale Earth system model. GRL, 46, 8234–8243.
- Zhang et al. (2019). Evaluation of Clouds in Version 1 of the E3SM Atmosphere Model With Satellite Simulators. JAMES, 11, 1253-1268.
- Xie et al. (2019). Improved Diurnal Cycle of Precipitation in E3SM With a Revised Convective Triggering Function. JAMES, 11,
- Brunke et al (2019). Subtropical marine low stratiform cloud deck spatial errors in the E3SMv1 Atmosphere Model. GRL, 46, 15,598-12,607.
- Harrop et al. (2019). Understanding monsoonal water cycle changes in a warmer climate in E3SMv1 using a NGMS framework. JGR, 124
- Zheng et al (2019). The summertime precipitation bias in E3SM Atmosphere Model version 1 over the Central United States. JGR, 124,
- Orbe et al. (2020). Representation of Modes of Variability in Six U.S. Climate Models. J. Climate, 33 (17), 7591–7617.
- Hu et al. (2020). Role of AMOC in TCR to Greenhouse Gas Forcing in Two Coupled Models. J. Climate, 33 (14): 5845–5859.
- Balaguru et al. (2020). Characterizing tropical cyclones in the Energy Exascale Earth System Model version 1 JAMES, 12, e2019MS002024.
- Dunne et al. (2020). Comparison of equilibrium climate sensitivity estimates from slab ocean, 150-year, and longer simulations. GRL, 47,
- Balaguru et al. (2020). Enhanced predictability of eastern North Pacific tropical cyclone activity using the ENSO Longitude Index. GRL, 47,
- Wu et al. (2020). Understanding Processes that Control Dust Spatial Distributions with GCMs and Satellite Observations. ACP, accepted,

v1/v2 Model development

- Rasch et al. (2010). An Overview of the Atmospheric Component of the Energy Exascale Earth System Model. JAMES, 11, 2377-2411.
- Tang et al (2019) Regionally refined test bed in EAMv1) and applications for high-resolution modeling, GMD, 12,
- Sun et al (2019). Impact of Nudging Strategy on the Climate Representativeness and Hindcast Skill of Constrained EAMv1 Simulations, JAMES, 11, 3911–3933.
- Bisht & Riley (2019). Development and verification of a numerical library for solving global terrestrial multiphysics problems JAMES 11,
- Tesfa et al. (2020). Exploring topography-based methods for downscaling subgrid precipitation for use in Earth System Models. JGR, 125,
- Hoch et al (2020). MPAS-Ocean simulation quality for variable-resolution North American coastal meshes. JAMES, 12, e2019MS001848.
- Zhou et al. (2020). Global irrigation characteristics and effects simulated by fully coupled land surface, river, and water management models in E3SM. JAMES, 12,
- Wang et al. (2020). Aerosols in the E3SMv1: New developments and their impacts on radiative forcing. JAMES, 12, e2019MS001851

Orbe et al (2020, *J Climate*): Representation of Modes of Variability in Six U.S. Climate Models

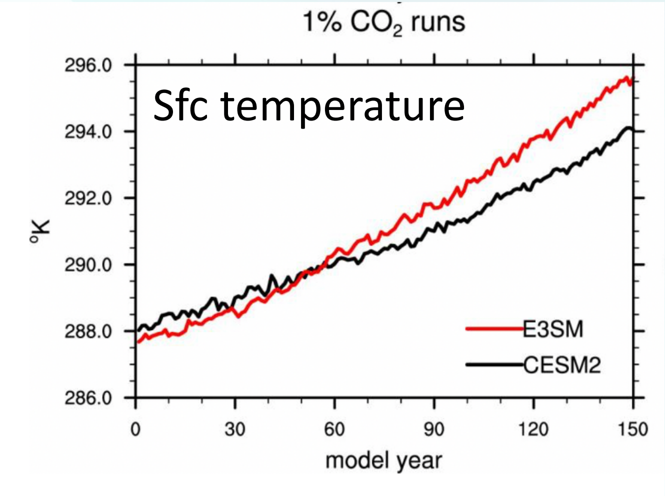


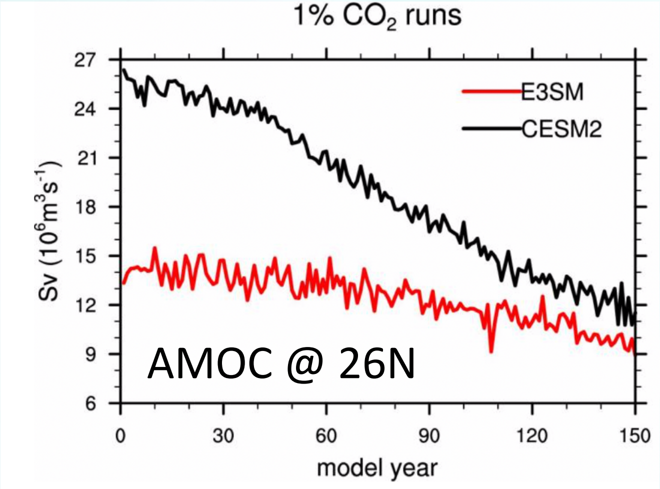


Improved QBO from NGD-Atmosphere work
See Richter et al. (2019, JAMES).

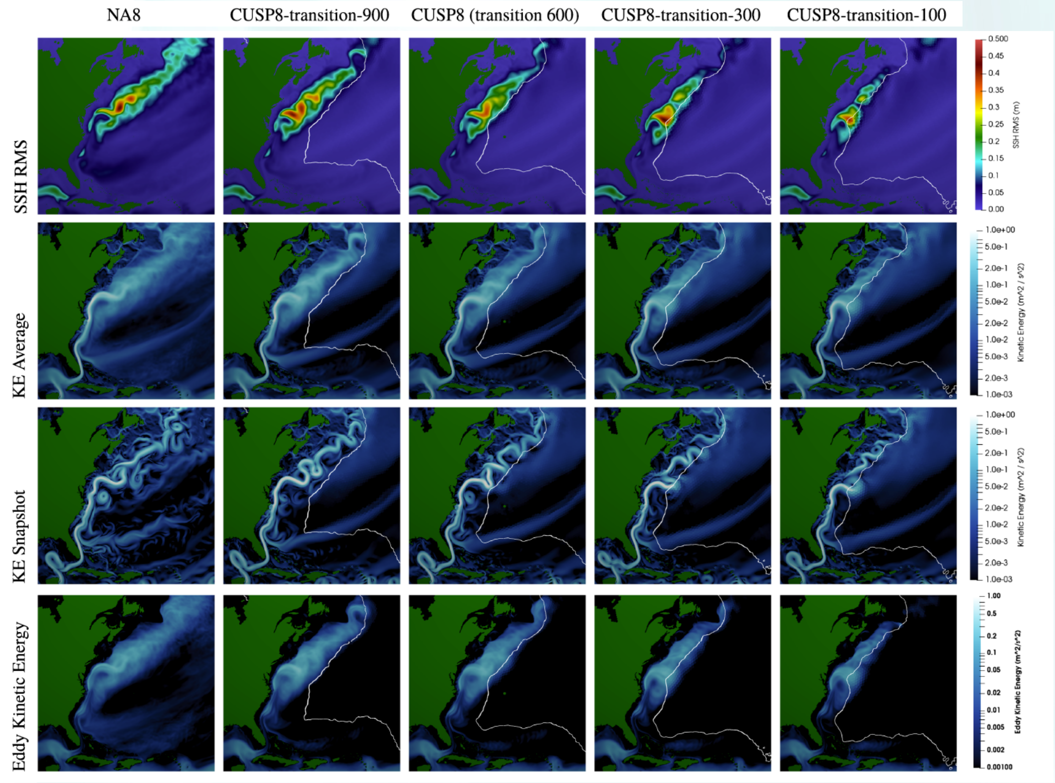
Hu et al (2020, *J Climate*): Role of AMOC in Transient Climate Response to Greenhouse Gas Forcing in Two Coupled Models

- E3SMv1 and CESM2 have nearly identical **equilibrium climate sensitivity** (ECS = 5.3 K, Gregory regression).
- E3SM **transient climate response** (TCR) much larger.
- Potentially due to weak AMOC in E3SM

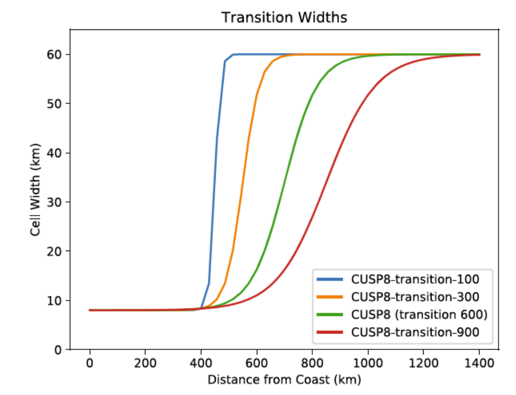




Hoch et al. (2020, *JAMES*): MPAS-Ocean Simulation Quality for Variable-Resolution North American Coastal Meshes



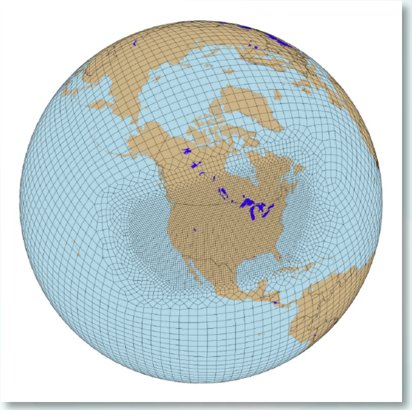
- MPAS-Ocean sensitive to **transition width**
- less sensitive to **mesh quality**
- Study informed final design of WC14 mesh for v2



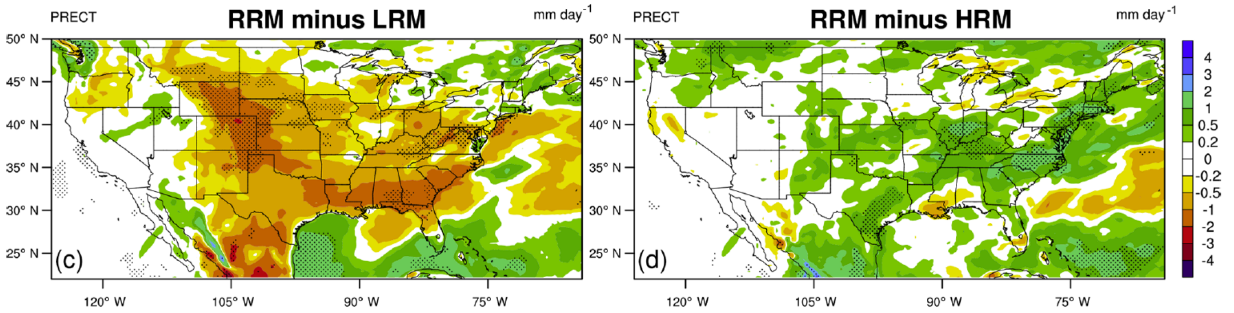
Decreasing Transition Width

Tang et al (2019, GMD): Regionally refined test bed in E3SM atmosphere model version 1 (EAMv1) and applications for high-resolution modeling

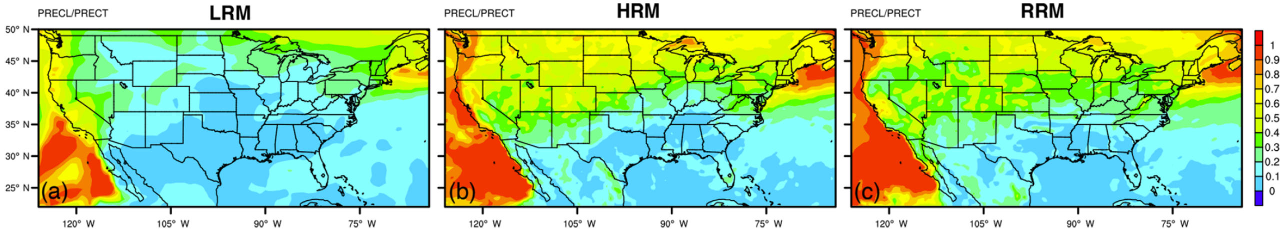
Continental US RRM (v1)



JJA Precipitation



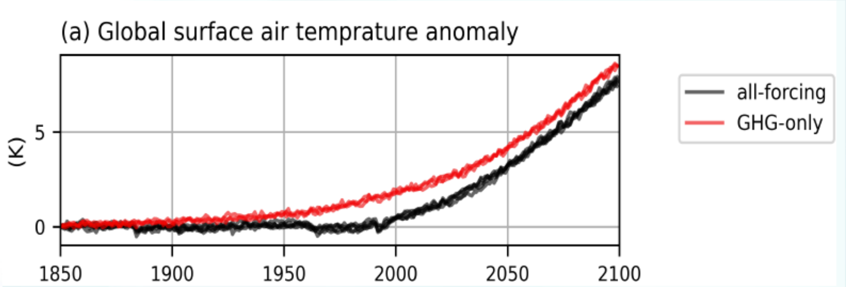
- RRM precipitation much closer to high-resolution than low-resolution (↑)
- RRM large-scale precipitation fraction similar to high-resolution (↓)

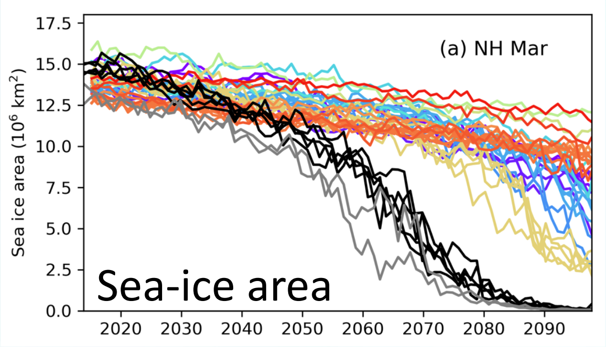


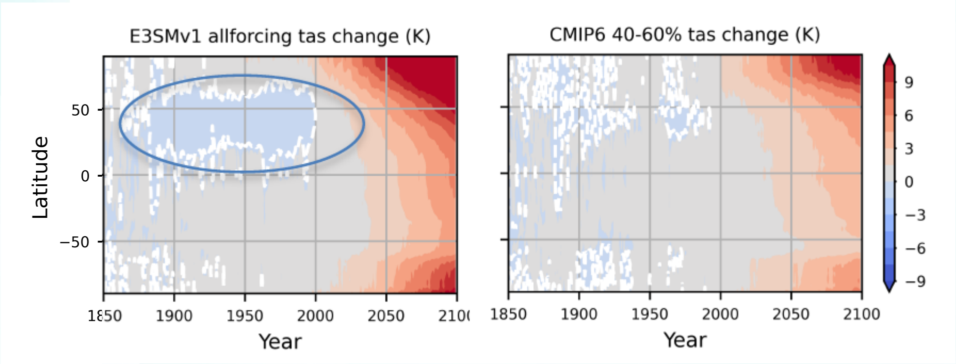
Analysis of future scenario runs (SSP5-8.5)

All-forcing and GHG-only forcing

Analysis led by Xue Zheng (LLNL)







Regional impacts of GHG vs other forcings

- **Patterns of the ocean** change in all-forcing simulations and GHG-only simulations are similar.
- However, for **runoffs**, the difference between all-forcing and GHG-only is notably larger in the future simulations.

Actionable metrics: moisture availability

Focus on USGS Hydrological Units Maps (HUC2)

Metrics led by Bryce Harrop (PNNL)

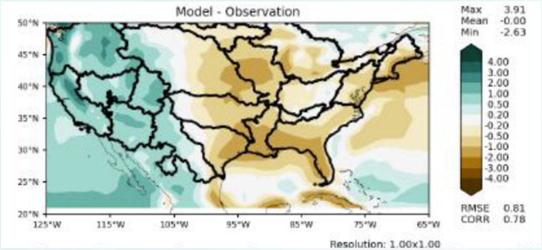
$$\Delta S = P - ET - Q - D$$

- ΔS: Change in storage
  - soil moisture
  - snowpack
  - groundwater
- P: precipitation
- ET: evapotranspiration
- $Q - D$: surface and sub-surface runoff

Spatial Distribution of Mean State	Seasonal Cycle	Variability Across Timescales	Intensity / Frequency Distributions	Extremes	Drought
RMS Error / MAE of mean state	Amplitude + phase of seasonal cycle	Standard deviation at different timescales	Simple Daily Intensity Index (SDII)	Rx1day	Frequency of SPI spells below a threshold
Pattern correlation	Monthly score (RMS error)	Diurnal cycle – phase and amplitude	Unevenness	Rx5day	Consecutive dry days
Monthly mean snow			Mean and variance of daily precip.	20y return values (from GEV)	
			Perkins score	Rx3h	
			Fraction of precipitating days	Seasonal breakdown	

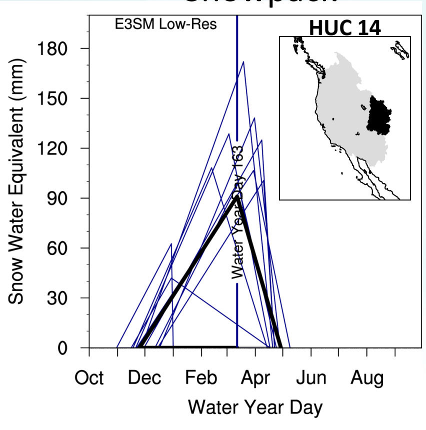
Evaluation Options	Spatial Extent	Climatological Period
	(regional, continental, global)	(annual, seasonal, monthly)

Precipitation bias

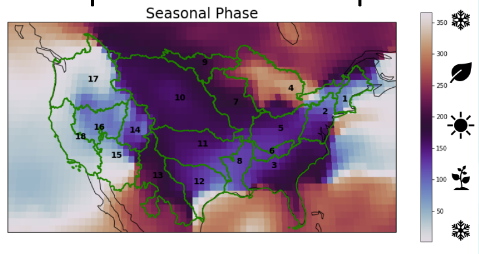


Streamflow

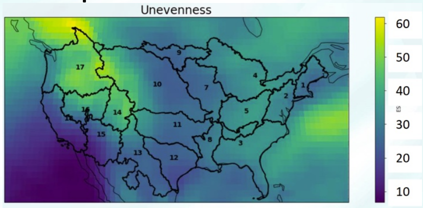
Snowpack



Precipitation seasonal phase



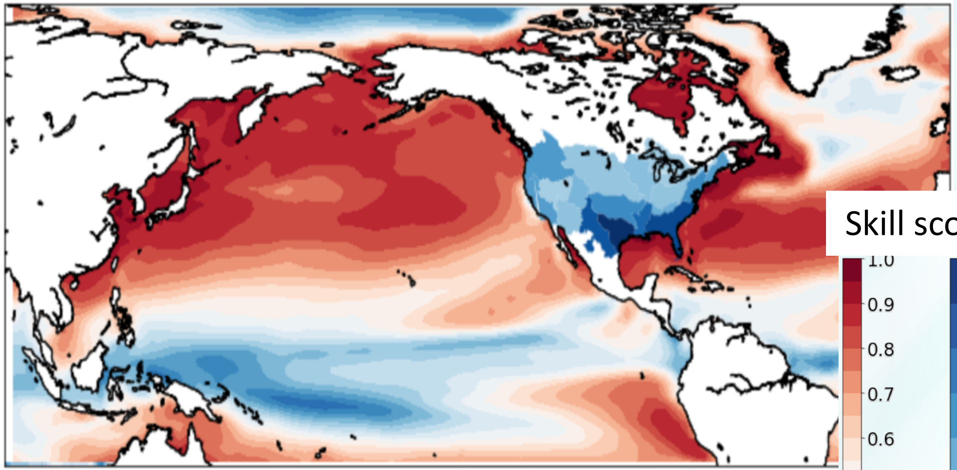
Precipitation unevenness



Actionable metrics
SST variability metric

- Led by LeAnn Conlon (LANL)
- Nearing finalization
- Metric assesses E3SM ability to reproduce observed SST variability and influence of SST variability on CONUS precipitation (HUC2 basins).

1950 Control run vs observation



Skill scores

Model **SST variability skill** (over oceans)
Model **skill in relationship between SST variability and precipitation** (HUC2 regions)

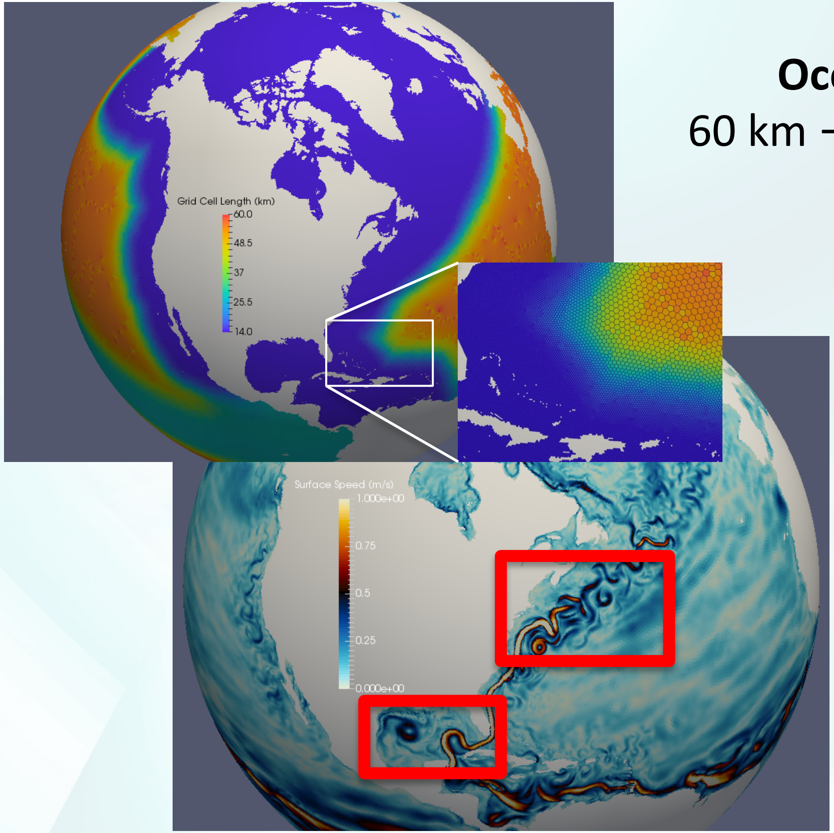
- Remaining work
  - Apply new metric to E3SMv1 LR and HR historical simulations
  - Incorporate to E3SM-diags
  - Submit paper describing relationship between SST variability and precipitation in E3SM

Phase II Goals - v2 Model Development

E3SMv2 Water Cycle in a nutshell

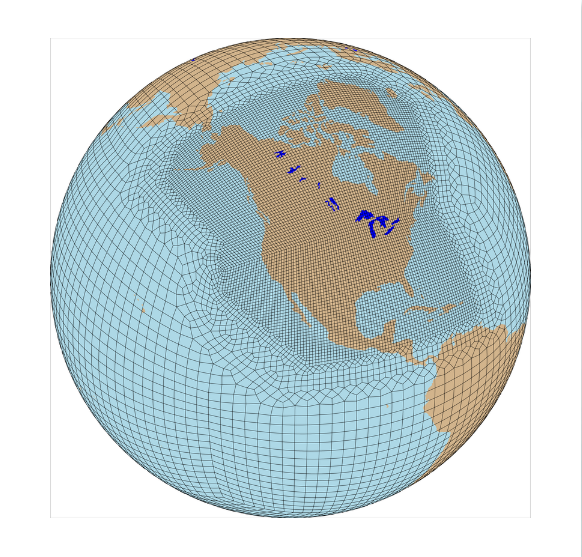
- Evolution from v1, but nevertheless many improvements.
- New **regionally refined** capabilities for **coupled simulations**.
- Getting close to finalize model and start simulation campaign.
- Compared to v1: "**faster and better**".

Regionally Refined Meshes



Ocean
60 km → 14 km

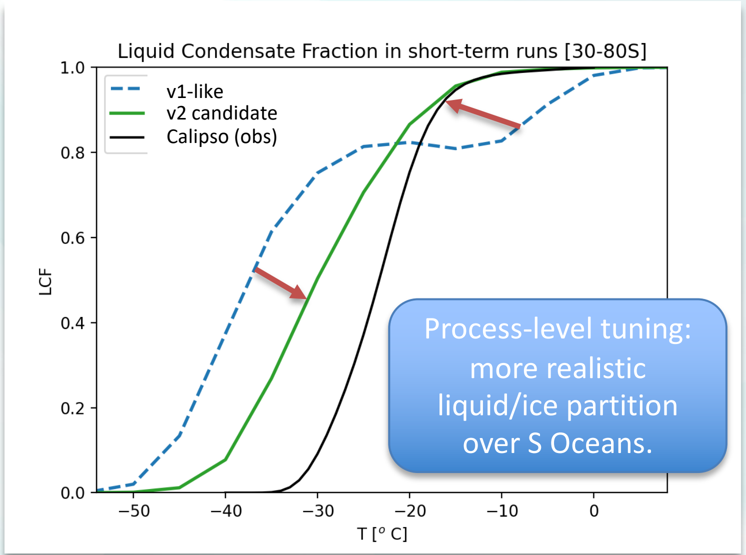
Atmosphere
100 km → 25 km



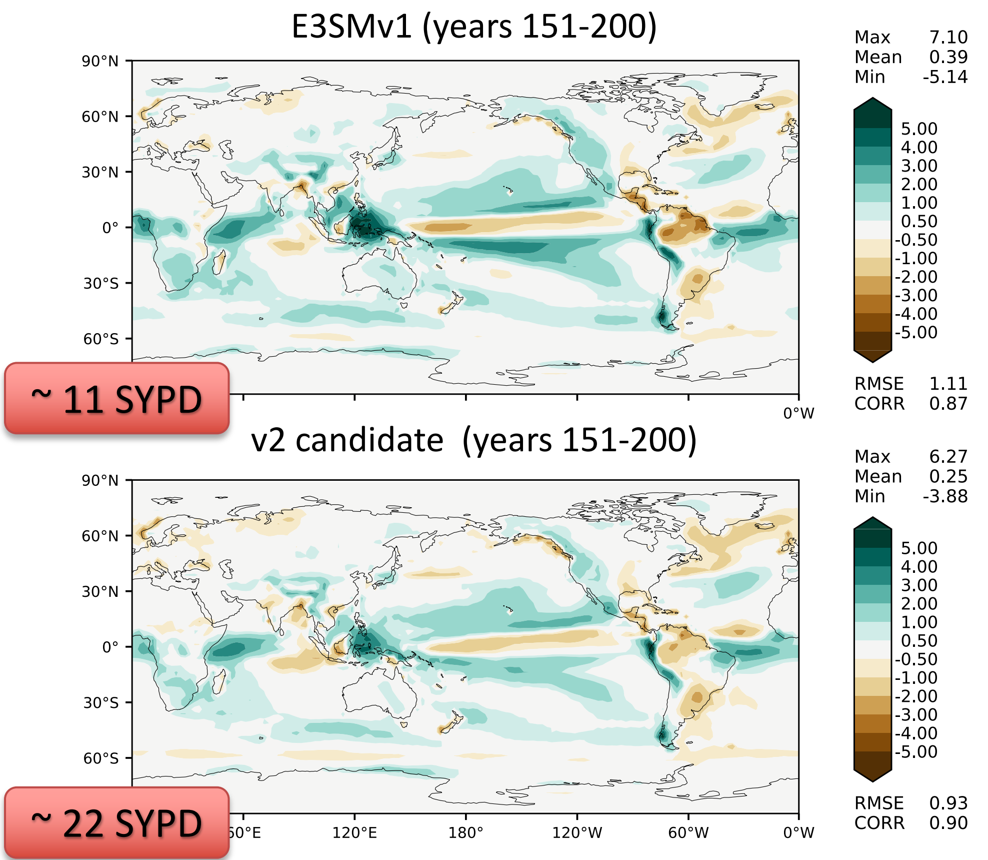
"Faster and better"

Performance on compy

Model	Nodes	SYPD
v1	92	~11
v2 candidate	90	~22



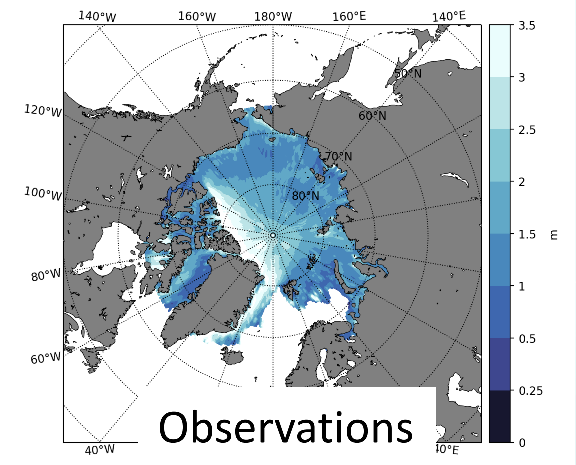
Coupled piControl simulations: precipitation bias

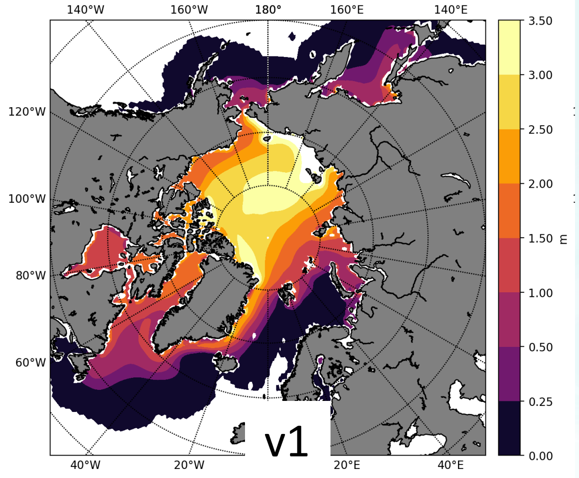


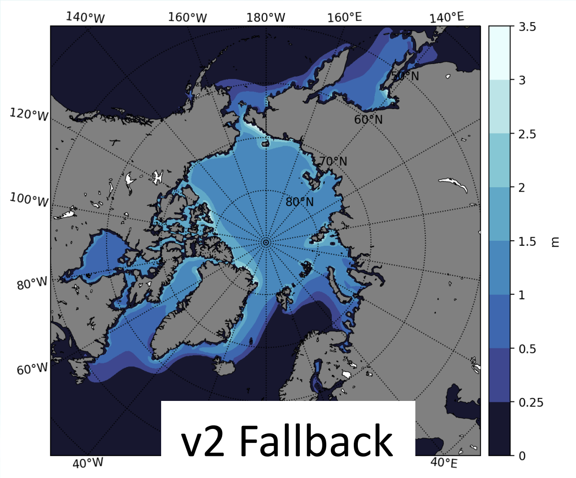
SYPD: simulated years per day

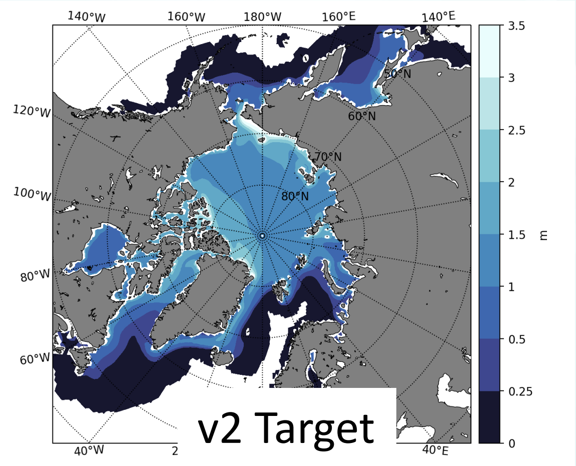
Ocean, sea ice improvements

- Climatological ice thickness
  - v1 (left) ice too thick in central Arctic and Labrador Sea
  - v2 “fallback ocean” improves central Arctic ice
  - v2 “target ocean” improves Labrador sea bias









Performance improvements

Collaboration with core groups, NGDs

Atmosphere

- New **dynamical core** (theta)
- **Semi-Lagrangian** (SL) tracer transport
- **Physics grid** (pg2)

✓ ~3-5x faster tracer transport

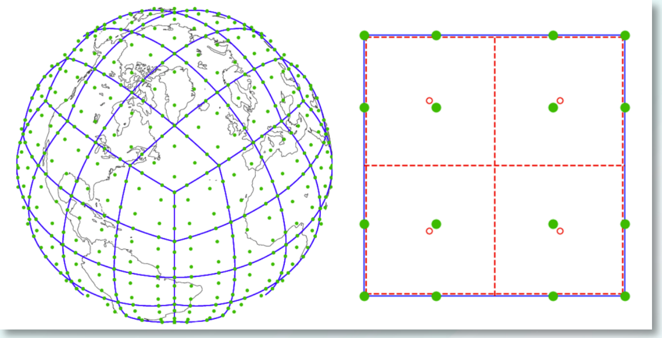
✓ ~2x faster atmosphere

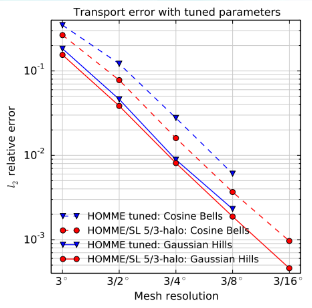
Ocean

- Improved time stepping

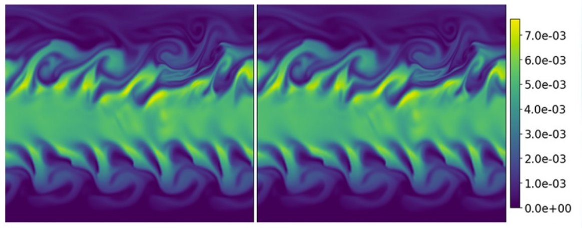
I/O

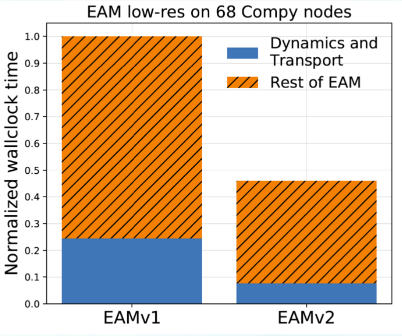
- New SCORPIO library

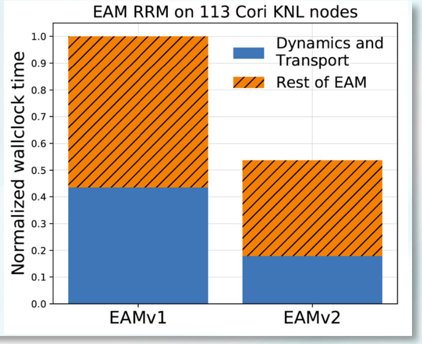




v2 tracer transport is faster than v1, with no loss of accuracy

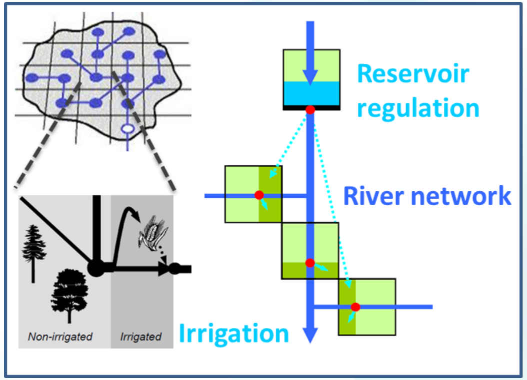




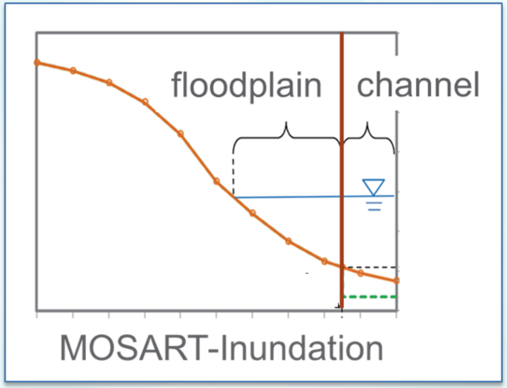


2x faster atmosphere: 1 deg and RRM

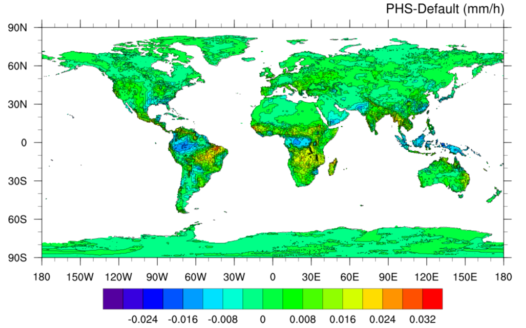
New land and river features



- **Land** and **river** models now on a **common grid** (1/2 or 1/8°), separate from atmosphere ("tri-grid").
- **Water management** and two-way coupled **irrigation** schemes.
- Flood **inundation** scheme.
- New **plant hydraulics** (PHS).
- **Sub-grid topographic units** with downscaling of atmospheric forcing.

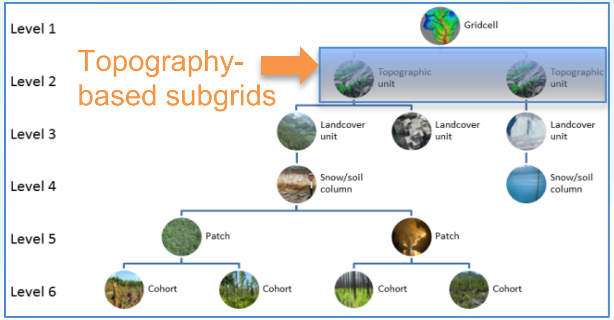


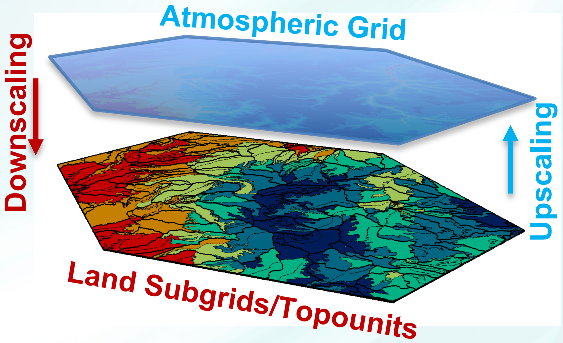
Annual average ΔET (mm/h)



ET increases in the deciduous forest of tropical regions with PHS

Hierarchical sub-grid structure in E3SM





Coordination with external DOE funded projects

- Modes of Pacific Variability (PI: di Lorenzo): Luke Van Roekel has been working with that project to setup the large ensemble and secure sufficient computer and storage resources. Will set the stage for future E3SM core efforts.
- Initialized Prediction (Kirtman + Meehl): Jon Wolfe and Luke Van Roekel assisted in the spin up of the low-res ocean for prediction experiments.
- University of Arizona – Delivered and tested new coupler surface flux routines.
- InterFACE: Andrew Roberts is the ESMD lead and is working to make sure developments smoothly feed between E3SM and InterFACE. Mat Maltrud and Luke Van Roekel are also key staff on InterFACE
- COMPOSE (SciDAC): Andrew Bradley. SL transport in the atmosphere, helped with bug fixes in the ocean.
- CICE Consortium: Andrew Roberts and Elizabeth Hunke have communicated critical developments and bug fixes from the CICE Consortium to E3SM.

Coordination (cont'd)

- ICoM: E. Hunke, A. Roberts, L. Conlon, T. Zhou, J. Wolfe, G. Bisht all coordinating with project to ensure developments will be E3SM ready.
- EAGLES: Kai Zhang and Hailong Wang. Aerosols and cloud interactions.
- PCMDI-SFA (RGMA): Steve Klein and Mark Zelinka have been sharing their cloud feedback diagnostics with Xue Zheng and Chris Golaz and helped interpreting them.
- ECP: E3SM-MMF (PI: Mark Taylor). Walter Hannah: key contributions to PG2 development. Jayesh Krishna and Danqing Wu: SCORPIO, E3SM's new I/O infrastructure.
- CMDV-RRM: Water Cycle v2 grid, improved convective trigger, v1 analysis.
- ESGF-LLNL: E3SM data publication and curation; CDAT (Community Data Analysis Tools) Python package.

Questions?