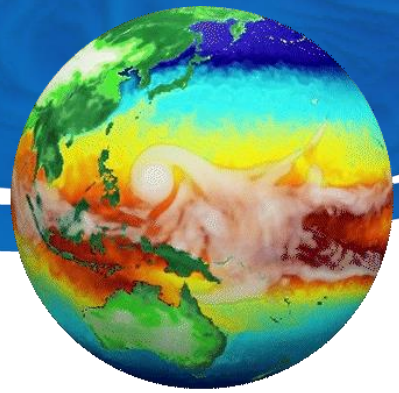
E3SM Groups Updates

Steve Price, Ben Bond-Lamberty, Bryce Harrop, Rob Jacob, Chris Golaz, Shaocheng Xie, Peter Caldwell, Luke van Roekel, Darin Comeau, Peter Thornton



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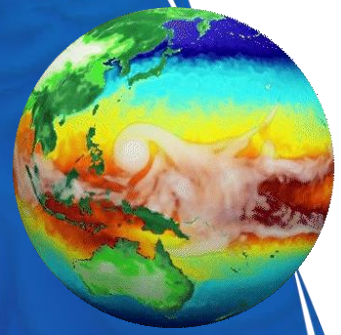
EESM PI Meeting
August 2024

E3SM
Energy Exascale Earth System Model



Polar Processes, Sea-level Rise and Coastal Impacts Group

Steve Price, Group Lead (GL)

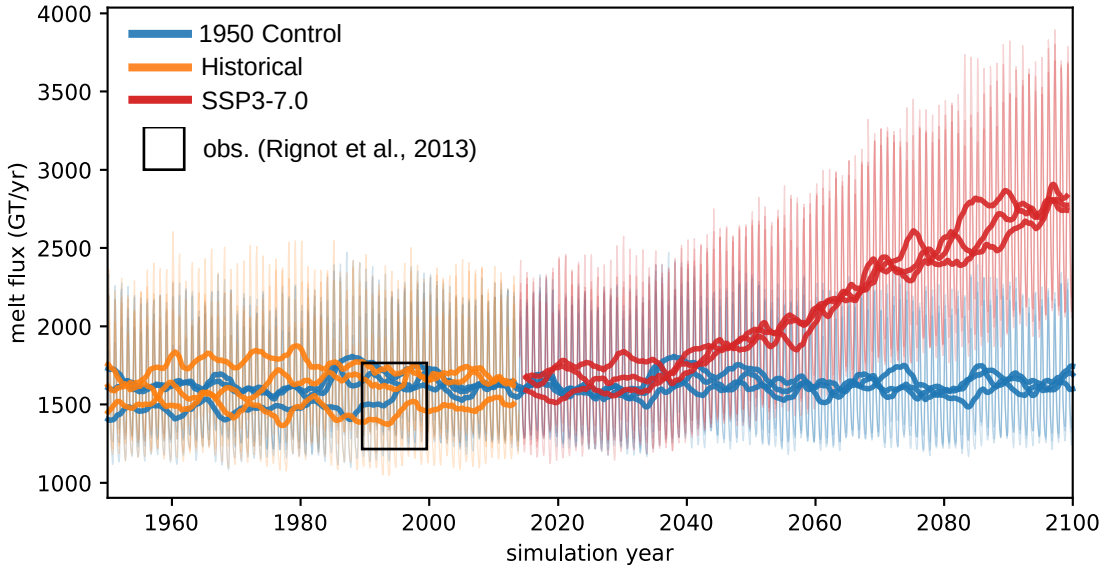
Andrew Roberts, Deputy GL

Ice Shelf & Ocean Interactions

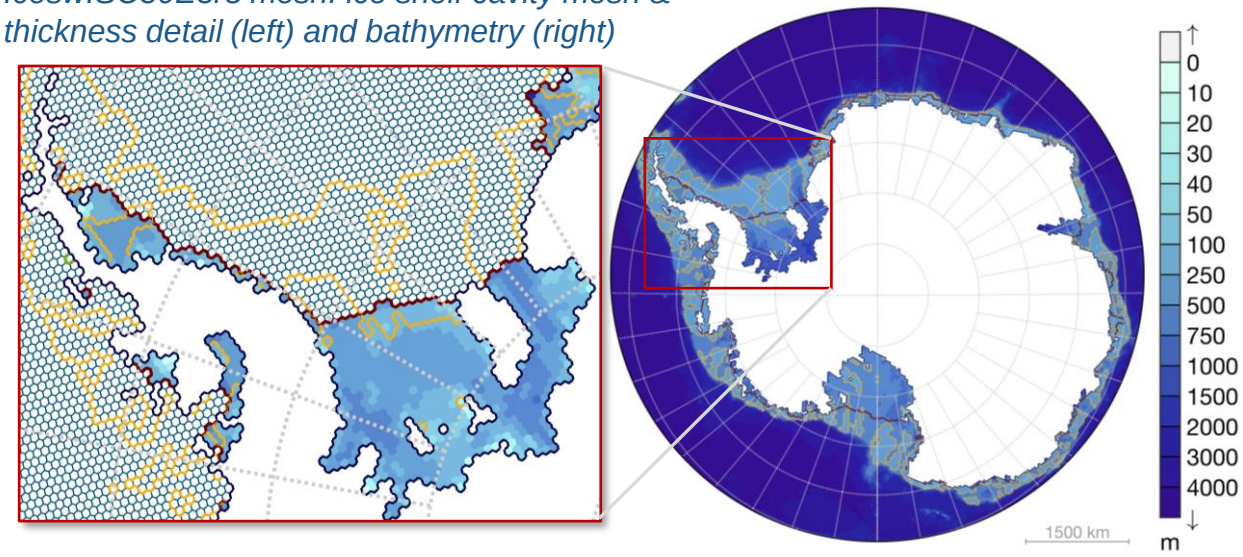
Posters:
D. Comeau
M. Hoffman
I. Vankova

- **Achievement:**
  - realistic, stable, Antarctic sub-ice shelf melt flux in global, coupled configuration
  - high-resolution (12km) near ice shelves via Southern Ocean Regionally Refined Mesh (SORRM v2.1)
  - 1000 yr spinup (repeat 1950); 3 historical & 3 SSP3-7.0 ensemble members through 2100
  - Antarctic ice shelf cavities in all v3 ocean meshes
- **Current work:**
  - publication on v2.1 simulation results (upper-right fig)
  - more physically realistic treatment of steady-state, Antarctic freshwater fluxes (improved “snowcapping”)
  - Analysis of regional and global impacts of explicit ice shelf melt-water fluxes
- **Future work:**
  - SORRM v3 simulations (improved climate & mesh)
  - validated data and prognostic melt fluxes

Total Antarctic sub-ice shelf melt flux from SORRM v2.1

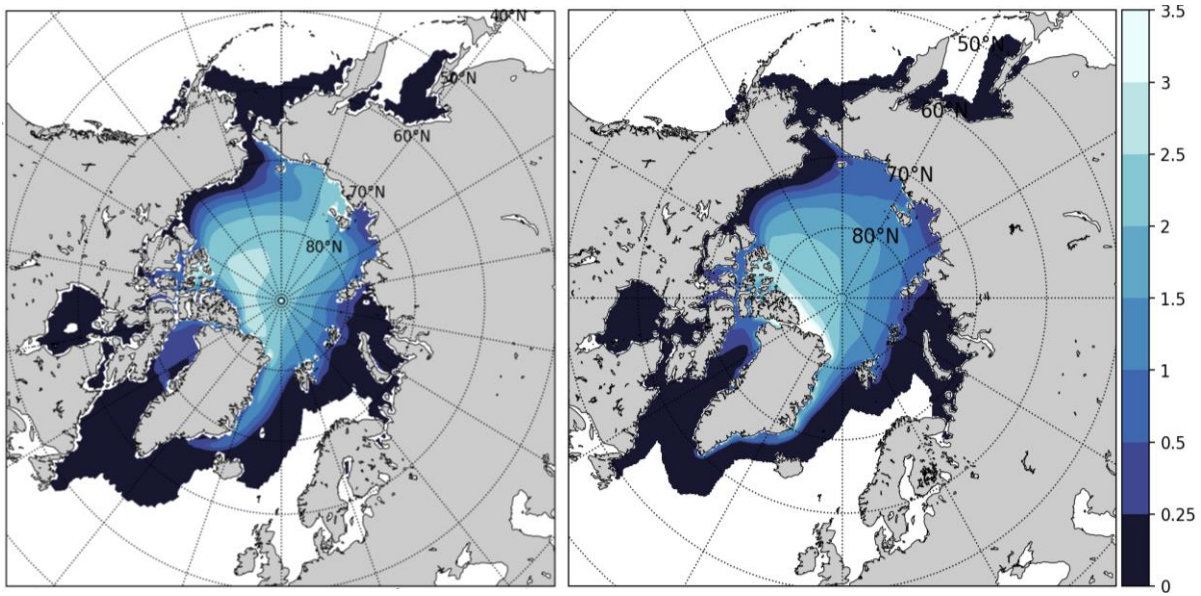


IcoswISC30E3r5 mesh: ice shelf cavity mesh & thickness detail (left) and bathymetry (right)

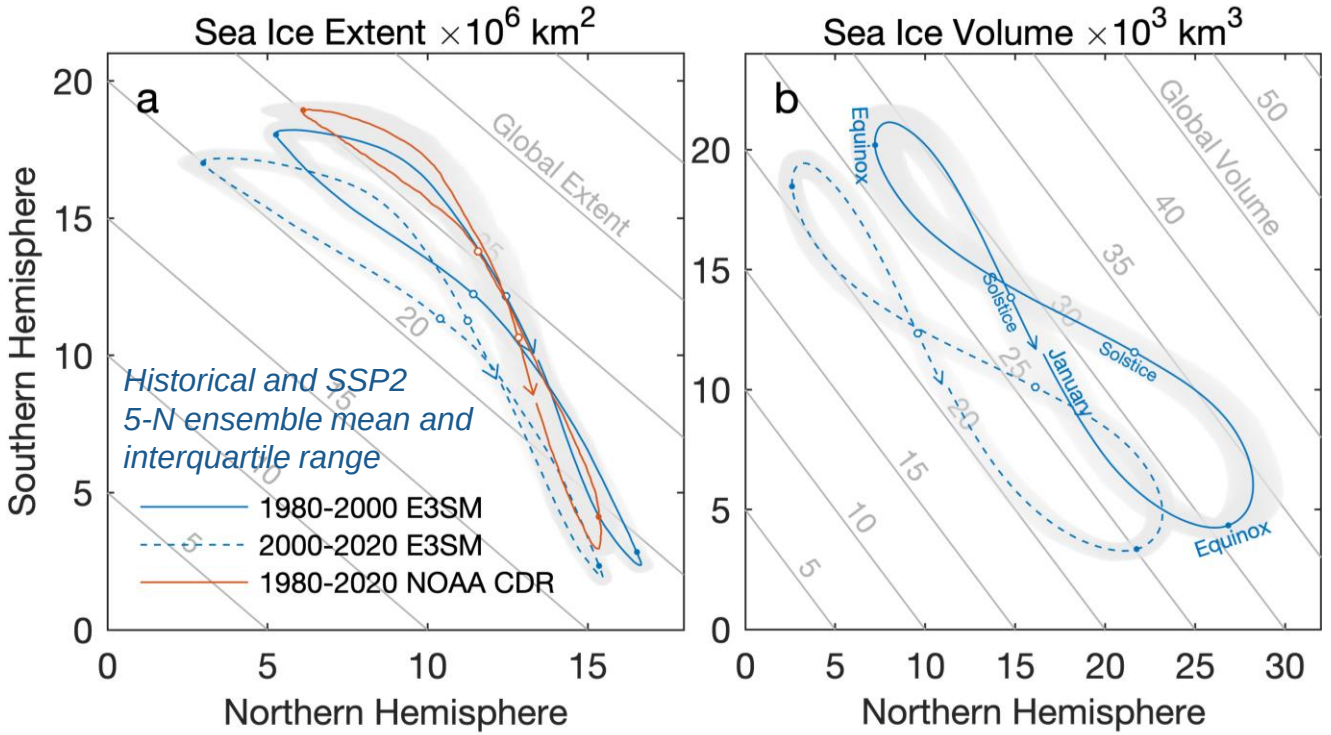


Sea Ice in E3SM V3 leading to V4

E3SM Version 2 *E3SM Version 3*



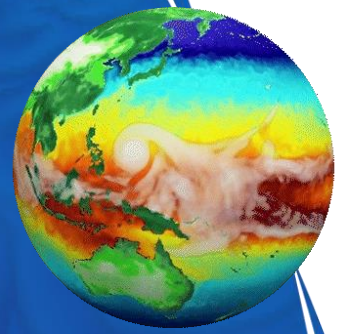
50-year exemplary pre-industrial means of Arctic sea ice thickness



- Vastly improved sea ice coastal dynamics in E3SM Version 3 as compared to Versions 1 and 2
- Resolution improved at the poles to 20-30km at standard resolution with EVP on an unstructured mesh
- E3SM now uses Icepack from the CICE Consortium including SNICAR-AD radiation with snow aging
- Equinox asymmetry in bias and skill amplifies with increasing atmospheric concentrations of CO_2
- Next step is to incorporate a trainable variational state space including sea ice macroporosity

E3SM
Energy Exascale
Earth System Model

Human Earth Systems (HES)



Ben Bond-Lamberty, Group Lead (GL)
Jennifer Holm, Nicole Jeffery,
and Qing Zhu, Deputy GL

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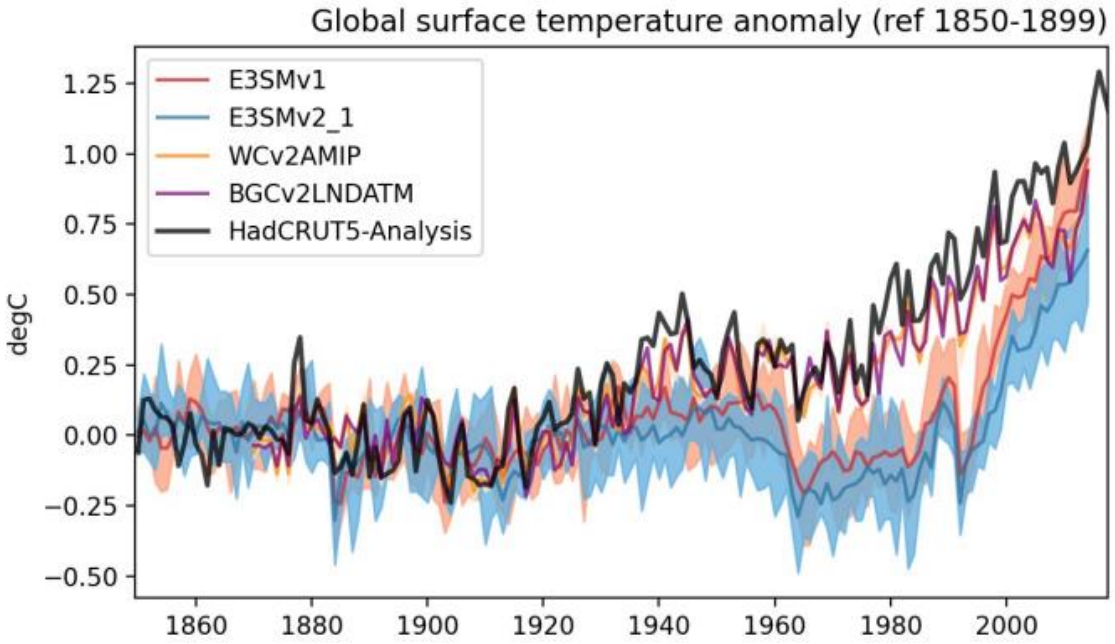
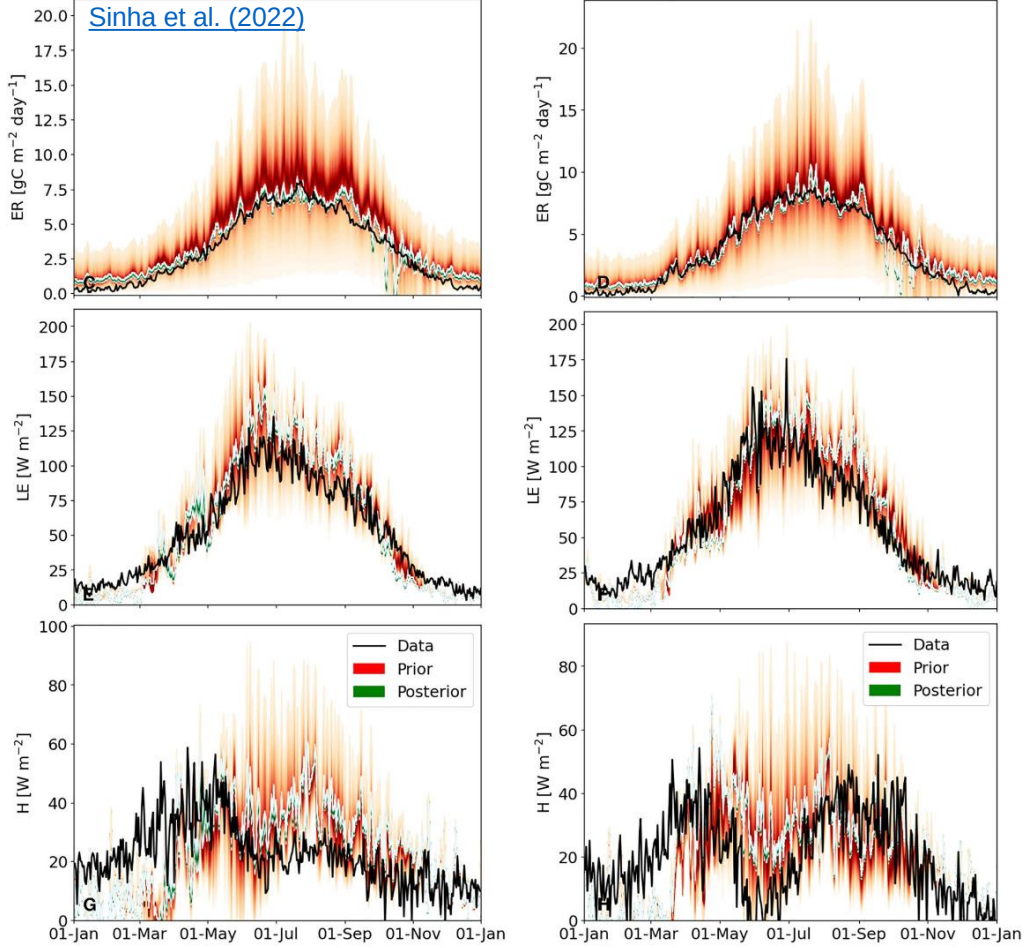
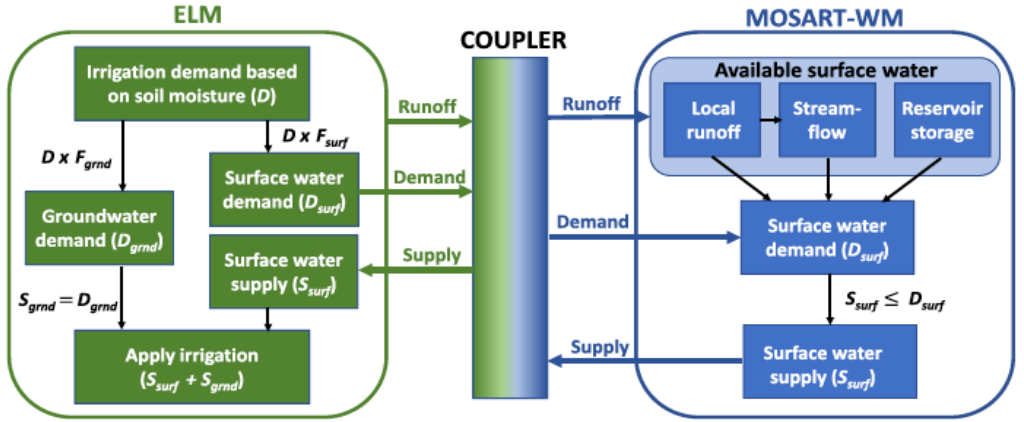
HES: Improved and performant climate- and human-relevant features

Clockwise from below: realistic ocean temperatures; bioenergy crop modeling; MOSART water irrigation coupling.







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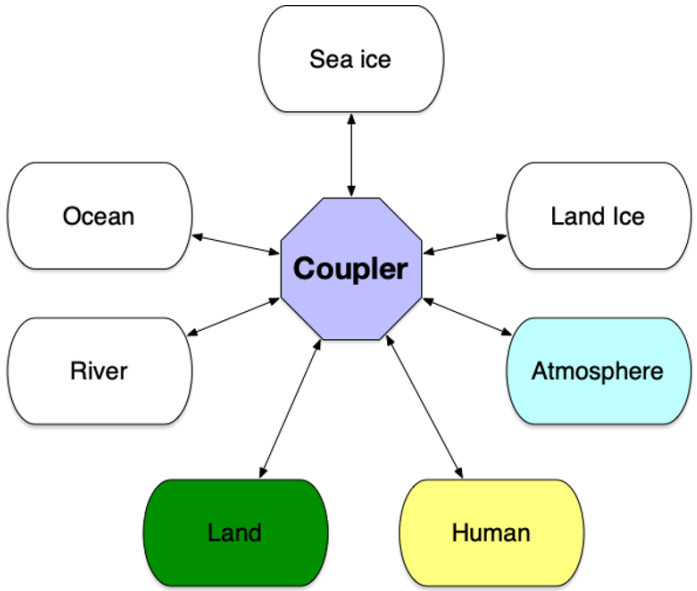
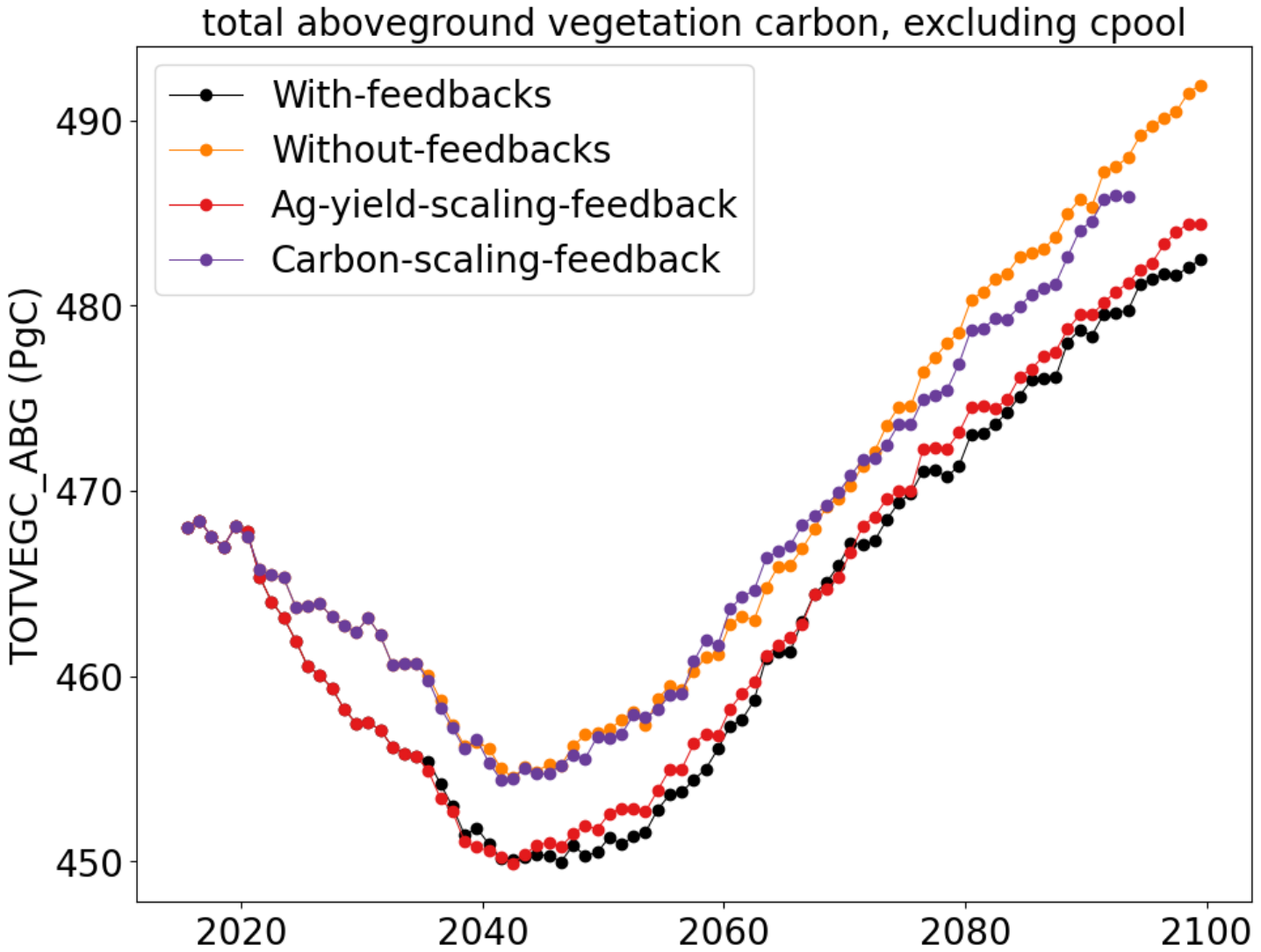
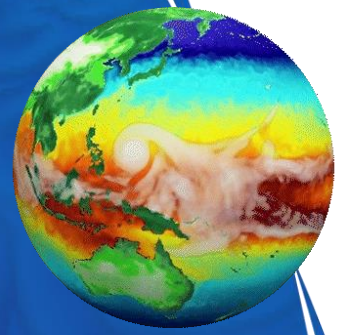
HES: An operational, fully coupled human systems model

Design of the atmosphere-land-human model coupling (below); agricultural yield changes drive initial coupling differences (right).





Water Cycle Changes and Impacts Group



Bryce Harrop, Group Lead (GL)

Claudia Tebaldi, Deputy GL

Water Cycle Changes and Impacts accomplishments

- Paper highlights

Geophysical Research Letters

Research Letter | Open Access

Influence of Eastern Pacific Hurricanes on the Southwest US Wildfire Environment

Karthik Balaguru, Sally S.-C. Wang, L. Ruby Leung, Samson Hagos, Bryce Harrop, Chuan-Chieh Chang, Sandro W. Lubis, Oluwayemi A. Garuba, Sourav Taraphdar

First published: 13 February 2024 | https://doi.org/10.1029/2023GL106774

JAMES | Journal of Advances in Modeling Earth Systems

Research Article | Open Access

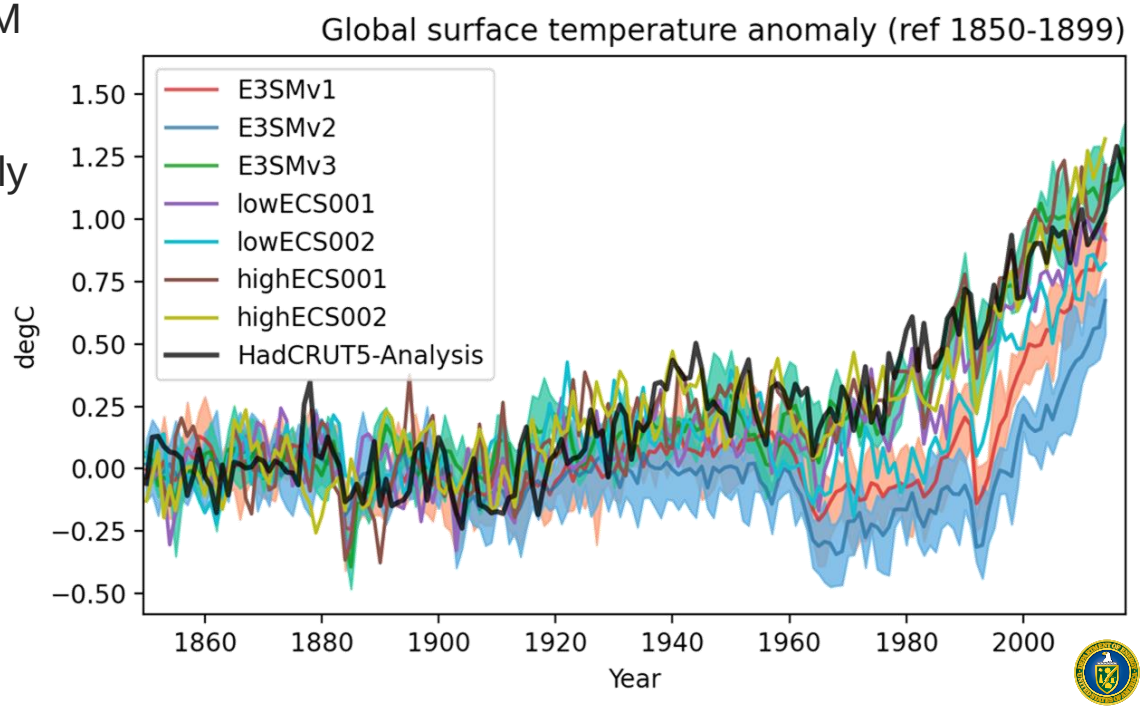
Evaluating the Water Cycle Over CONUS at the Watershed Scale for the Energy Exascale Earth System Model Version 1 (E3SMv1) Across Resolutions

Bryce E. Harrop, Karthik Balaguru, Jean-Christophe Golaz, L. Ruby Leung, Salil Mahajan, Alan M. Rhoades, Paul A. Ullrich, Chengzhu Zhang, Xue Zheng, Tian Zhou ... See all authors

First published: 27 November 2023 | https://doi.org/10.1029/2022MS003490

- WCCI simulation campaign setup (see Harrop's poster):
  - Employed machine learning approach on an E3SM emulator to identify candidate E3SM parameterization with ECS significantly lower or higher than standard but still performing acceptably compared to observations;
  - Ran E3SM under candidate parameter settings (piControl; abrupt4xCO2; historical) and analyzed behavior of coupled model;

Default v3 – estimated ECS = 3.89 K
HighECS001 – ECS = 4.52 K (+0.63 K)
LowECS001 – ECS = 2.69 K (-1.20 K)
HighECS002 – ECS = 4.15 K (+0.26 K)
LowECS002 – ECS = 3.11 K (-0.78 K)

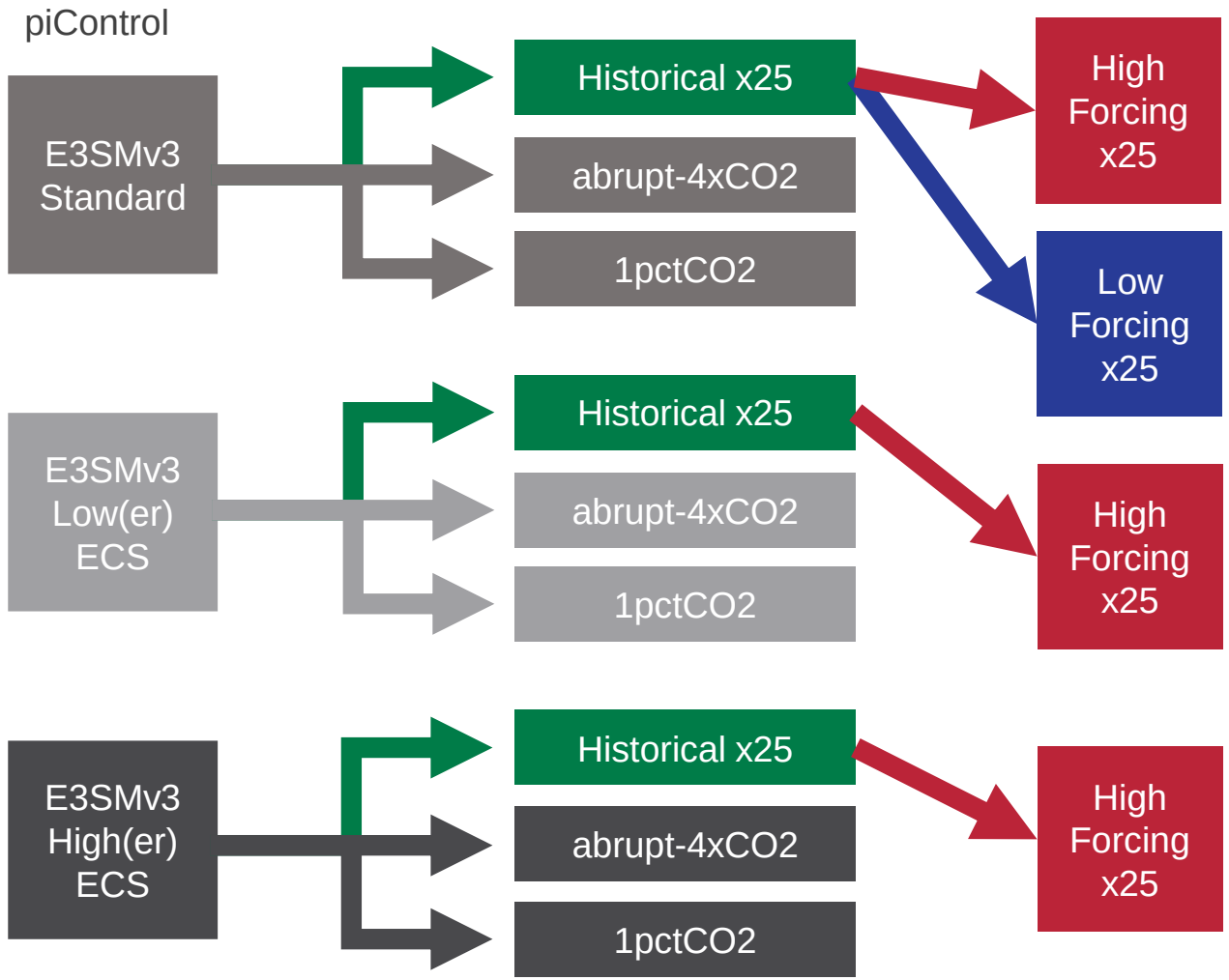


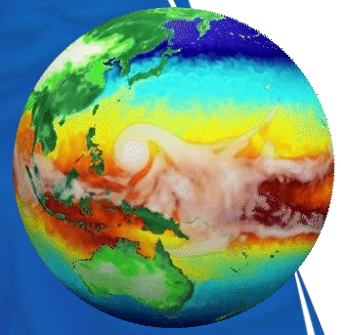
Water Cycle Changes and Impacts road map

Continue paper writing

Simulation campaign:

The goal of the WCCI simulation campaign is to create a large ensemble that examines uncertainty related to both internal variability and climate sensitivity





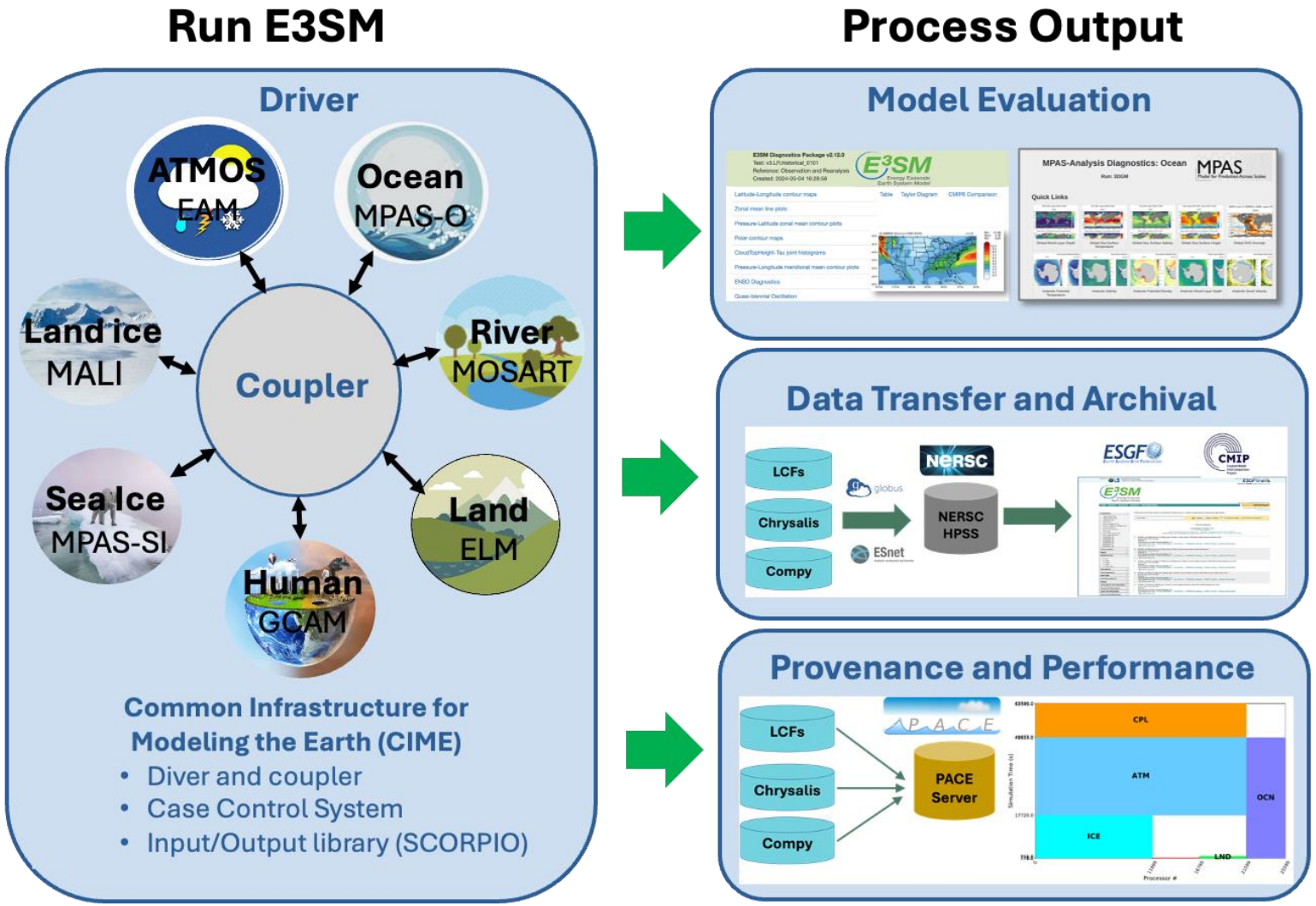
Infrastructure, Performance and Data Group

Rob Jacob, Group Lead (GL)

Jill Zhang, Sarat Sreepathi, Deputy GL

Infrastructure, Performance and Data Group

Robert Jacob, Jill Zhang, Sarat Sreepathi (Performance Coordinator)



Build and maintain a robust model infrastructure that support every phase of E3SM development

Define processes to scale E3SM development and to enable the project's open development vision

Open source code

Open data: ESGF/CMIP

IPD Progress

New and improved diagnostic/analysis tools:

- New standard diagnostics capabilities in **NCO, E3SM Diags, MPAS-analysis**
  - i.e. New variability analysis, ARM Diags, compare with CMIP results.
- New standard python tool **xCDAT**
- New end-to-end diagnostics workflow tool **zppy** that leverages other packages, ChemDyg, ILAMB
- Updated platform support tool **e3sm_unified** with **mache**
- Globus transfer capability integrated with **zstash** archiving tool
- Web-browsable performance data through **PACE**

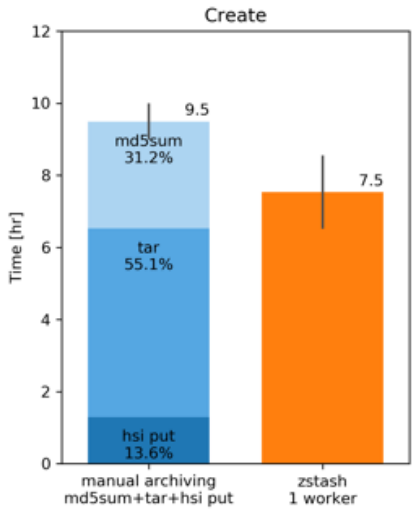
Model development and operations progress:

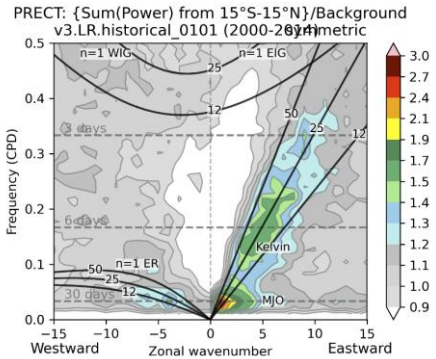
- Additional **tests** added for performance, non-BFB, super-BFB.
- Now using **containerized testing** with each PR.
- **SCORPIO** library supports ADIOS and HDF formats for output (and ADIOS for input)
- **MOAB coupler** works with v3 fully coupled cases.

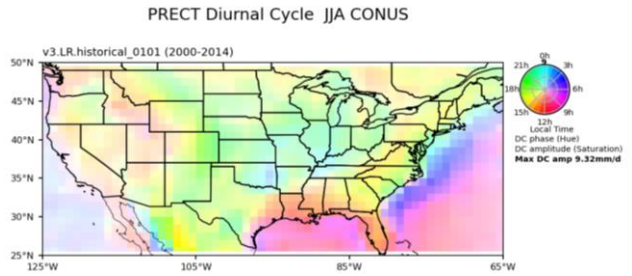
Data published:

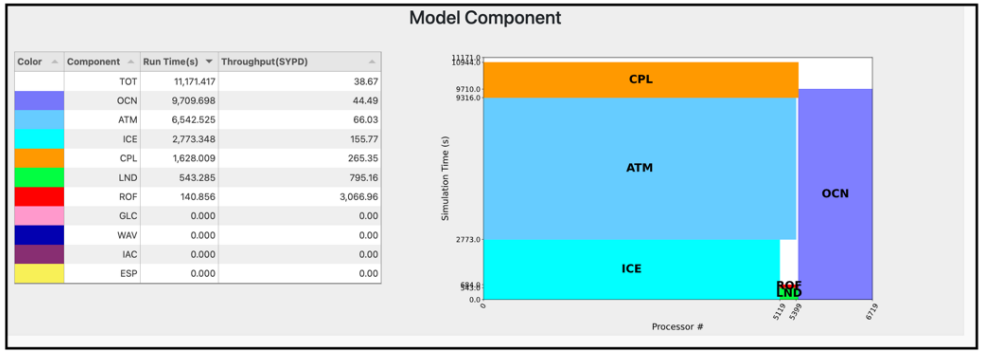
- All of version 2 simulation campaign data published. (LR DECK, LR LENS and NARRM) are published on ESGF.
  - ✓ 1497 TB total to E3SM Project Space
  - ✓ 48.4 TB total to CMIP

  Updated tool for data publication: **e3sm_to_cmip**





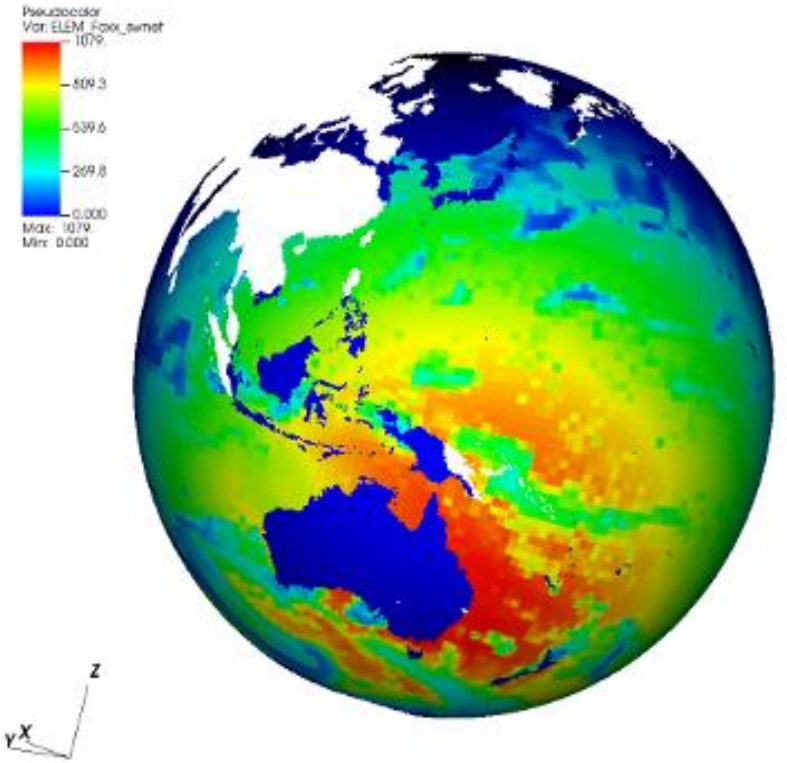




IPD Outlook

Near term goals:

- Publication of v2.1 data to ESGF
- CMOR-ization of v3 data
- More post-processing and analysis support for EAMxx component.
- Port MOAB-based coupler to EAMxx, land-ice, waves; validate; make default
- Complete refactoring E3SM Diags with xarray/xCDAT
- Additional use of containers.
- Continue supporting model development (testing, integration)
- Add new capabilities in standard analysis, such as PMP

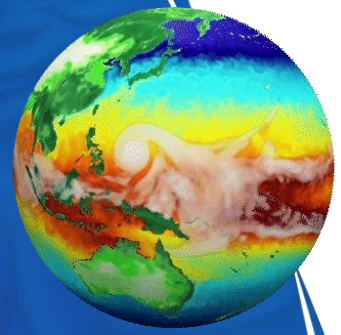


Long term goals:

- More parallelization in analysis tools
- Introduce UXarray in to E3SM diags
- Refactor CIME Case Control System to be more pythonic.
- Support asynchronous I/O
- Continue supporting model development (testing, integration)
- Redesign input data tools

Connections to breakout topics: The IPD group's work is featured in the Metrics, Benchmarks and Credibility and Innovative Tech breakout topics. Also related to Methods in Model integration.

E3SM
Energy Exascale Earth System Model



Coupled Model Group

Chris Golaz, Group Lead (GL)

Wuyin Lin, Deputy GL

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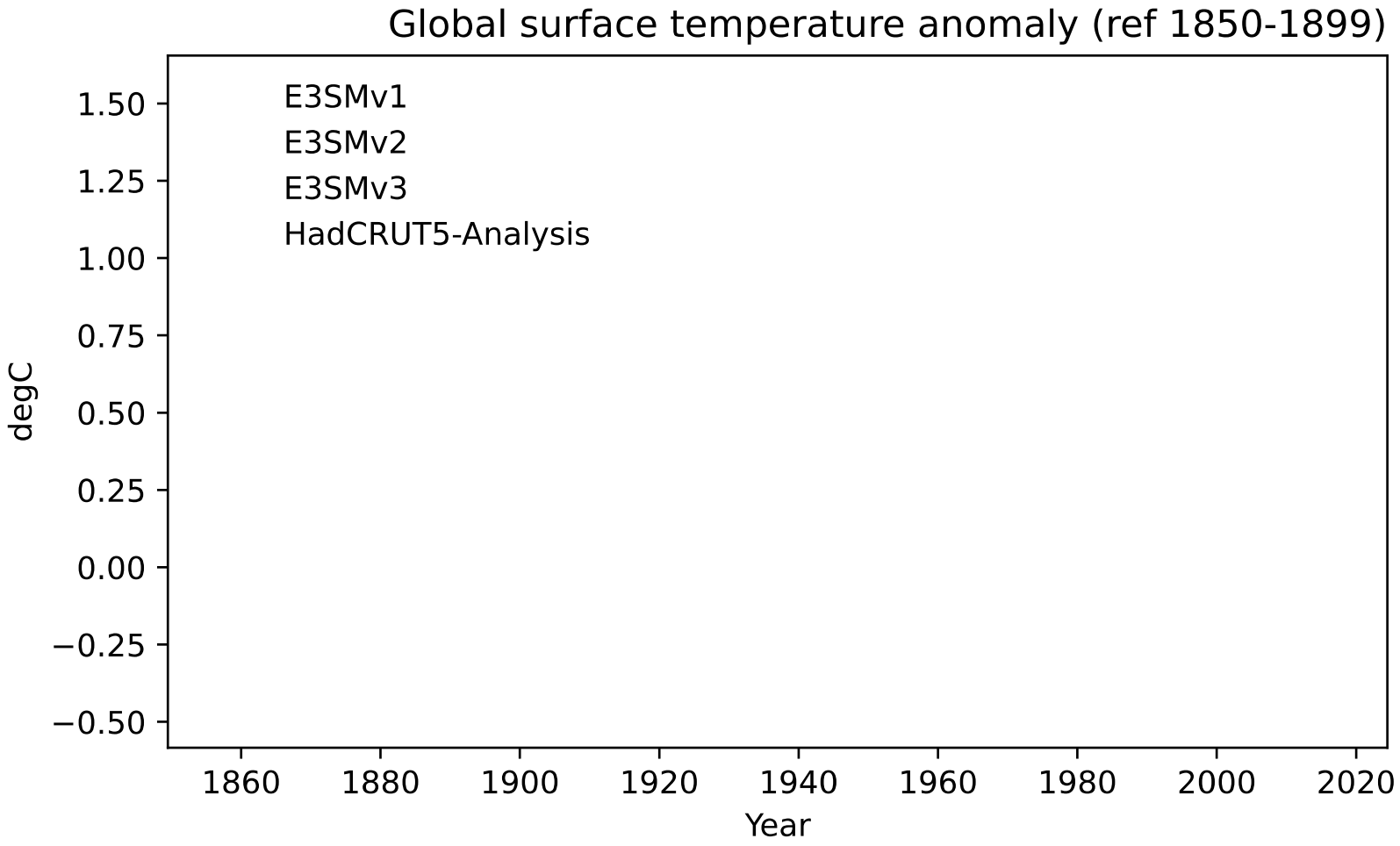
Coupled Group: accomplishments

E3SMv3.LR

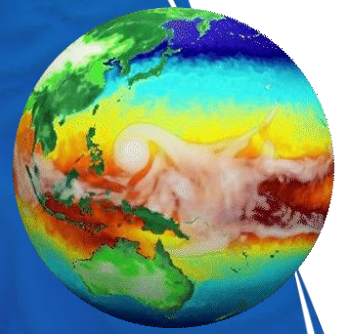
- Tri-grid, with higher-order non-linear remapping.
- Land: BGC mode (instead of SP), TOP parameterization.
- Atmosphere: more than a dozen new features; significant improvements with respect to tropical atmosphere variability, aerosols, chemistry.
- Ocean: higher resolution mesh (21-30 km), more efficient time stepping, improved physics.
- Sea-ice: Icepack, and many other improvements.
- More…



Coupled Group: outlook

- Complete **E3SMv3.LR simulation campaign**
  - Historical large-ensemble (targeting 30 members)
  - Single forcing simulations: RFMIP, DAMIP, …
  - Publication of overview manuscripts and simulation data.
- **E3SMv3.NARRM**
  - North America atmosphere (110 → 25 km), ocean and sea-ice as LR, ¼ land and river.
- **E3SMv3.HR**
  - 25 km atmosphere, 6-to-18 km ocean and sea-ice, ¼ land and river.
- **Ultra-high res coupled simulations**
  - 3 km EAMxx (SCREAM) coupled to 6-to-18 km ocean, sea-ice.
- **E3SMv4**
  - Next generation fully coupled model with EAMxx and OMEGA (both C++/kokkos).
  - There will be a lower resolution configuration capable of running 1000s years.

E3SM
Energy Exascale Earth System Model



Atmosphere (EAM) Group

Shaocheng Xie, Group Lead (GL)

Susannah Burrows, Deputy GL

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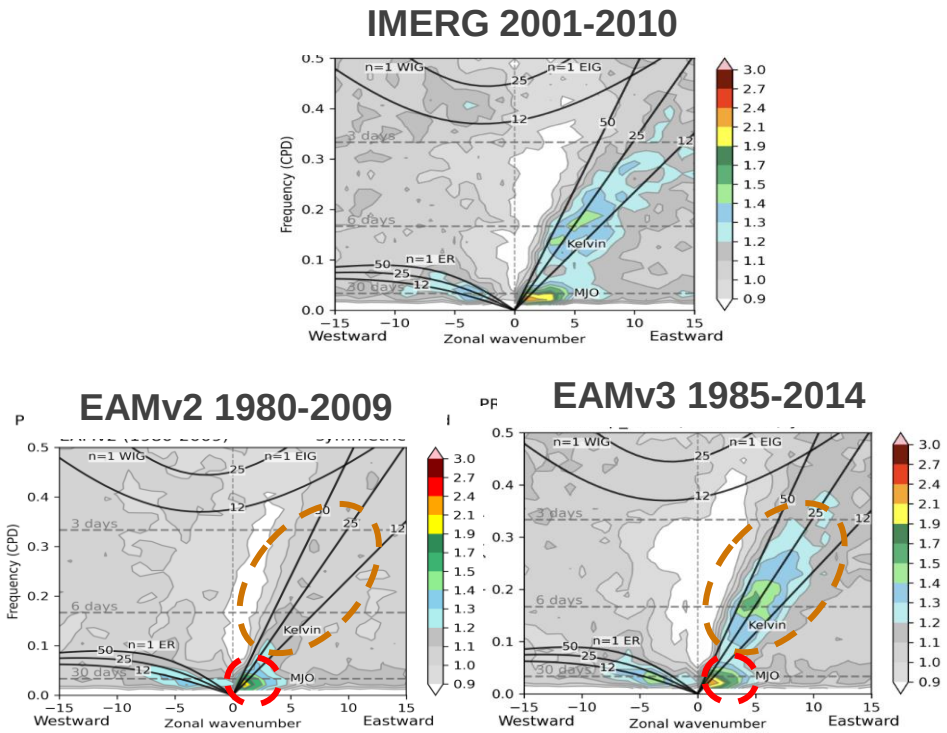
Update on EAMv3

Shaocheng Xie, Susannah Burrows, and Chris Terai

Significantly improved atmosphere physics - total 13 new features

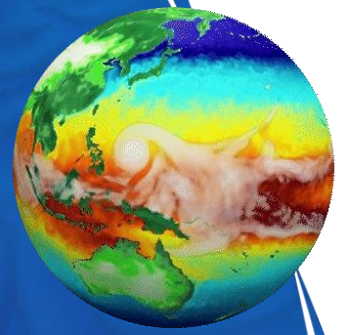
- Significantly enhanced model capabilities for coupling across aerosol, chemistry and BGC and improved aerosol forcing
  - Interactive atmospheric chemistry (chemUCI)
  - Improved aerosol/dust physics/capability (Nitrate aerosols, SOA, Stratosphere sulfate aerosols, aerosol dry and wet removal, dust emission, numerical coupling)
- Significantly improved cloud and convective processes
  - Improved cloud microphysics for both stratiform clouds (P3) and convective clouds (a two-moment microphysics)
  - Improved convective processes (meso-scale heating and large-scale controls on deep convection)
- Increased vertical resolution from 72 layers to 80 layers leading to a significantly improve Quasi Biennial Oscillation
  - Added additional 8 layers in lower stratosphere



(above) Wheeler-Kiladis diagram shows much improved tropical variability (Kelvin wave and MJO) in EAMv3 compared to EAMv2

Ongoing and Future Plan

- EAMv3
  - Document EAMv3 in peer-reviewed papers
  - Support development of E3SMv3.HR (0.25 degree)
  - Support scientific applications of using E3SMv3 in E3SM science groups
    - Coupling dust and iron deposition from atmosphere to the ocean and sea ice
  - Maintenance and update
    - Update COSP satellite simulators by adding new diagnostics for cloud phase
    - Improve the coupling of atmospheric chemistry and aerosols
    - Physically address the high occurrences of low cloud droplet number concentration
- EAMxx
  - Support the development of low-res version of EAMxx
    (e.g., GWD, ZM, ice cloud fraction, coupling of SHOC with ZM)
  - Perform evaluation of EAMxx simulated clouds and precipitation
  - Work with the EAMxx team to address outstanding biases in EAMxx
    (e.g., popcorn convection, midlevel dry bias, moist upper troposphere, surface warm bias, etc.)
  - Develop new cloud/aerosol diagnostics critical for EAMxx
  - Develop aerosol/chemistry strategy for EAMxx



EAMxx Group

Peter Caldwell, Group Lead (GL)

Susannah Burrows, Deputy GL

EAMxx/SCREAM Achievements

- Built new atm model in C++ in 4.5 yrs with 6 FTEs
- Won 2023 Gordon Bell Prize for Climate Modeling
  - Max 1.26 simulated years per wall day (SYPD)
  - 0.4 SYPD in practice (on 2048 Frontier nodes)
- Completed runs:
  - 40 day runs for each season
  - 2x 13 mo climate sensitivity runs
  - 2x 13 mo aerosol sensitivity runs
  - currently working on 10 yr current-climate run
- Budget configurations:
  - regionally-refined grids
  - Doubly-periodic patch for 30+ ARM case studies

Fig: Diurnal cycle of clouds in 3.25 km SCREAM. Created by Kristin Chang

Future EAMxx/SCREAM Tasks

- Improve model climate and computational performance
- Extend to low resolution (replacing the Fortran-based atm model in E3SMv4)
- Develop coupled km-scale capability
- Perform realistic future climate projections
- Add prognostic aerosol (MAMxx) from EAGLES project

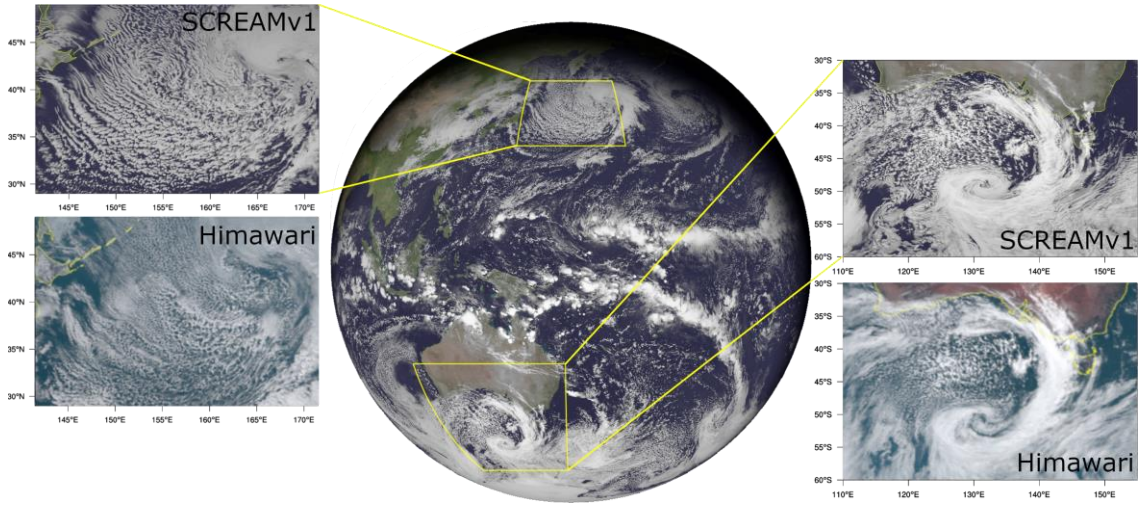


Fig: Upwelling shortwave radiation at model top taken two days into SCREAM simulation

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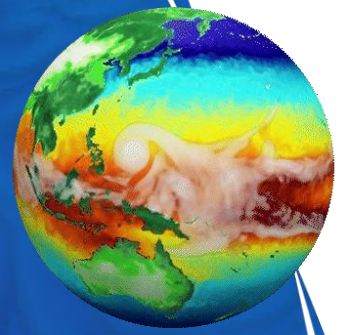

Omega Group

Luke van Roekel, Group Lead (GL)

Steve Brus, Mark Petersen, Deputy GL

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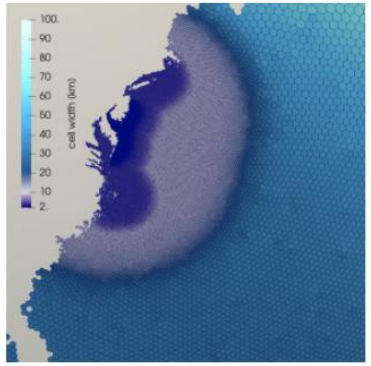
E3SM
Energy Exascale Earth System Model

Why OMEGA?

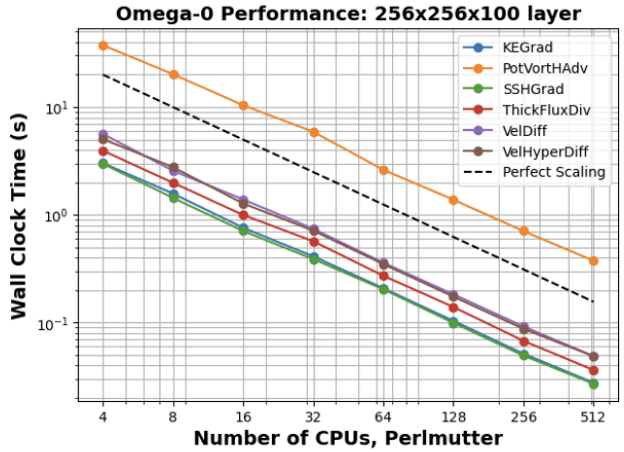
- Nearly all DOE HPC resources are GPU enabled
  - NVIDIA, AMD, Intel
- openACC support lags on these systems
- MPAS Ocean
  - Framework not well designed for GPU



- An exascale ready ocean allows us to push the resolution frontier
  - E.g. Base of RRS6to18 with RRM to finer scales

Initial Performance

- Tests showing good scaling and 9-10x speed up over CPU
  - 1.3-1.5x
- MPAS-O saw ~1.3x speedup on GPU



OMEGA Release Schedule

OMEGA-0 (Stacked SSW) Summer 2024 → OMEGA-1 (Primitive Eq) Summer 2025 → OMEGA-v1 (E3SM; HR only) Spring 2026

→ OMEGA-v2 (eddy param.) Late 2026 → OMEGA-v3 (BGC ready) Late 2027

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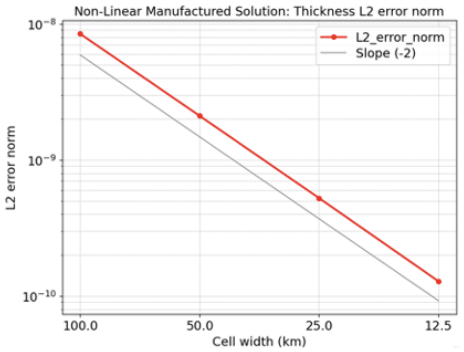
E3SM Energy Exascale Earth System Model

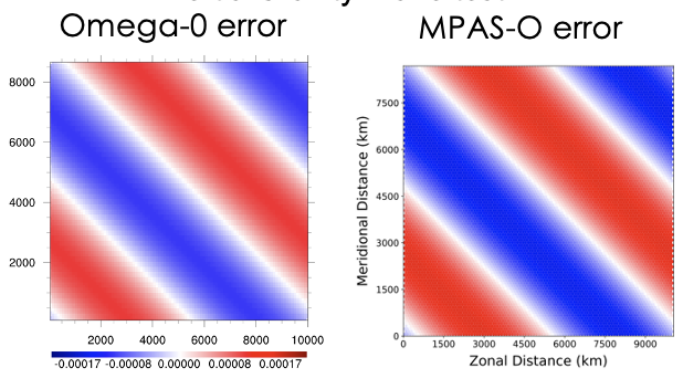
Testing and Documentation

Testing is through Polaris, a python package originally developed for MPAS-Ocean mesh generation, initialization, and testing

Manufactured solutions test



Inertia Gravity Wave test



Every development includes a Design Doc, Users Guide, and Developers guide written in markdown. Each is required before merging

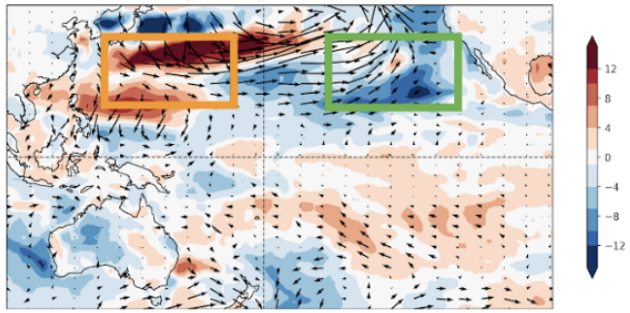
Model Configuration (Config)

Model configuration refers to all of the necessary variables to configure and run the model. It contains all the input parameters, choices of methods, physical coefficients for parameterizations and various options for I/O. Typically, this is read as a single input file that can serve as a description of the configuration for provenance as well.

Wave Modeling

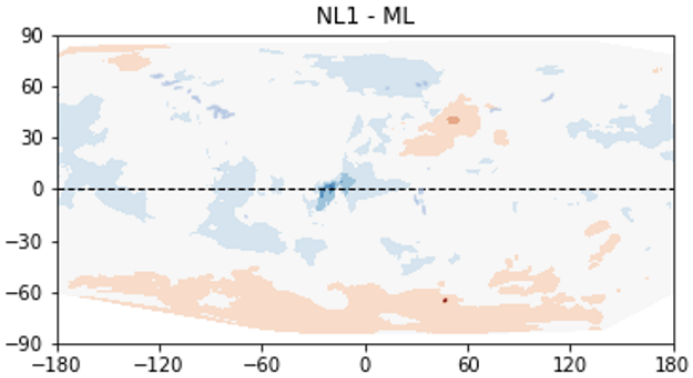
Examination of wave dependent fluxes reveals interesting relationships. For example, MJO propagation is modified due to the surface wave field.

COARE3.0a_Wave – COARE3.0a



- Windstress (vectors) and LH flux in shading)
- Wave field reduces LH via change in easterlies (green box)

- Use of ML approaches to emulate expensive source terms
- Error relative to current source term is very low (right)



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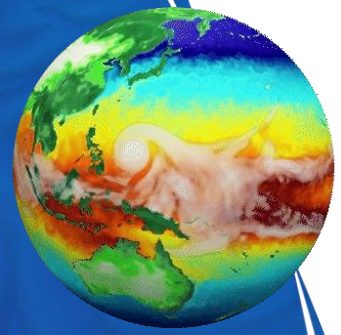
E3SM
Energy Exascale Earth System Model



Ice Group

Darin Comeau, Deputy GL

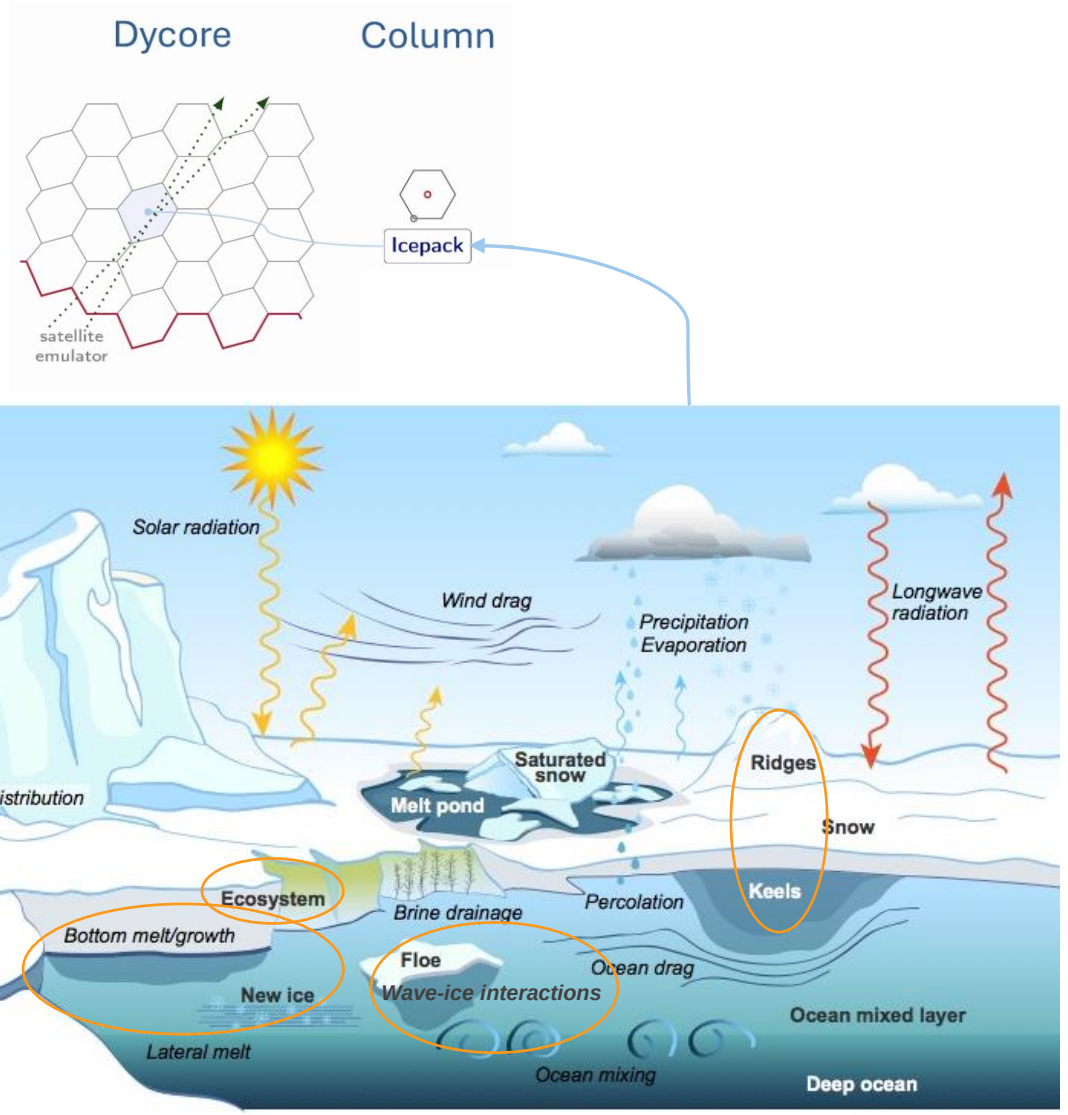
Elizabeth Hunke, Group Lead (GL)

U.S. DEPARTMENT OF ENERGY

Sea ice development in E3SM

Posters:
A. Roberts
E. Thomas

- **Achievements:**
  - Icepack integration for column physics (CICE Consortium)
    - Floe size distribution
    - Advanced snow physics
    - 5 band radiation (SNICAR-AD)
    - BGC
  - Quality control testing
- **Current and Future Work Towards v4:**
  - Wave-sea ice interactions (w/ InteRFACE)
  - Aerosols in standard physics runs
  - Landfast Ice (via InteRFACE)
  - Sea ice macroporosity, ridge statistics
  - Improved salinity coupling
  - BGC/frazil coupling consistency
  - Performance
  - Dual dycore options:
    - Improved EVP
    - Material Point Method (SciDAC)



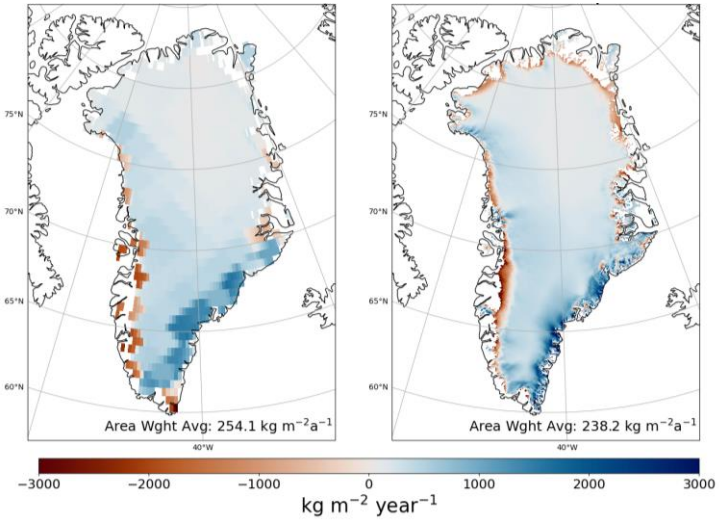
Physical processes represented with Icepack

Dynamic Greenland Ice Sheet

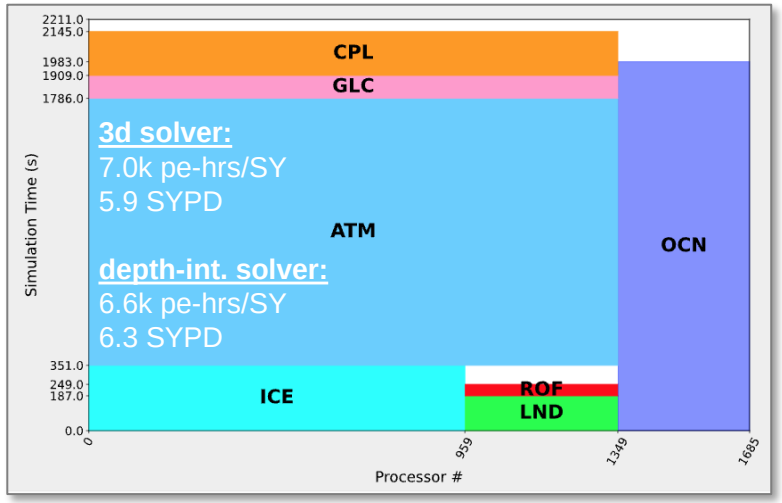
Posters:
A. Nolan
C. Whicker-Clarke

- **New infrastructure:**
  - IG, BG cases; low-res. v3 + 20km or 1-to-10km GIS; regular testing
  - ERA5 atmos. forcing; 1000 yr spun-up land & deep snowpack
- **New development:**
  - 16-layer snowpack with GIS-appropriate albedo, compaction, etc.
  - spun-up init. conds. for ice sheet snowpack (GIS & AIS)
  - improved init. conds. for 1-to-10km res. GIS
  - evaluation of, & coupling to, E3SM ocean thermal forcing (ongoing)
- **Evaluation via ERA5-forced historical runs:**
  - validation of surface climate using LIVVkit (upper-right fig)
  - validation & tuning for accurate GIS transient behavior (ongoing)
- **Performance:**
  - default layouts for 20km & 1-to-10km configs. on *Chrys* & *PM-cpu*
  - much improved perf. of 1-to-10km GIS config. (lower-right fig)
  - MALI is CPU+GPU ready & running on *Perlmutter* and *Frontier*
- **Goal:** scientifically supported, coupled simulations using **E3SM v3.X**

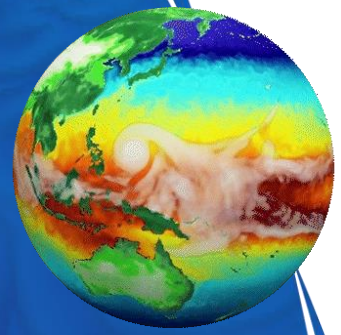
LIVVkit surface mass balance validation: low-res. E3SM (left), RACMO 2.3 (right).



PACE plot for coupled, low-res. V3 config. with high-res. GIS component (BG).



E3SM
Energy Exascale
Earth System Model



Land Group

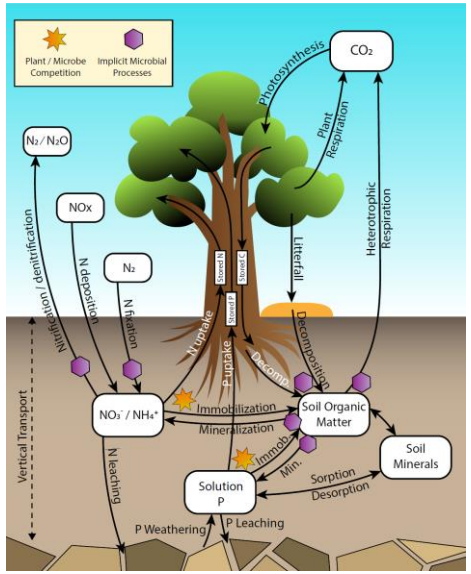
Peter Thornton, Group Lead (GL)

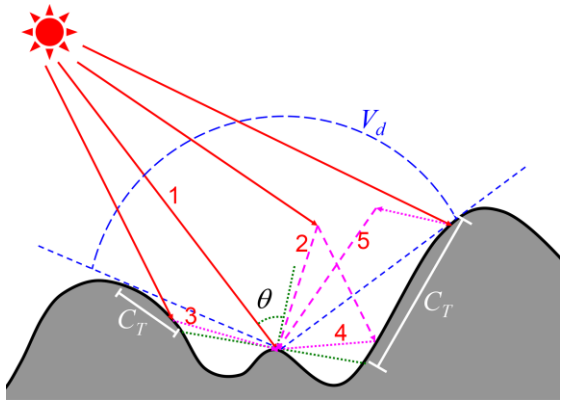
Gautam Bisht, Deputy GL

U.S. DEPARTMENT OF
ENERGY

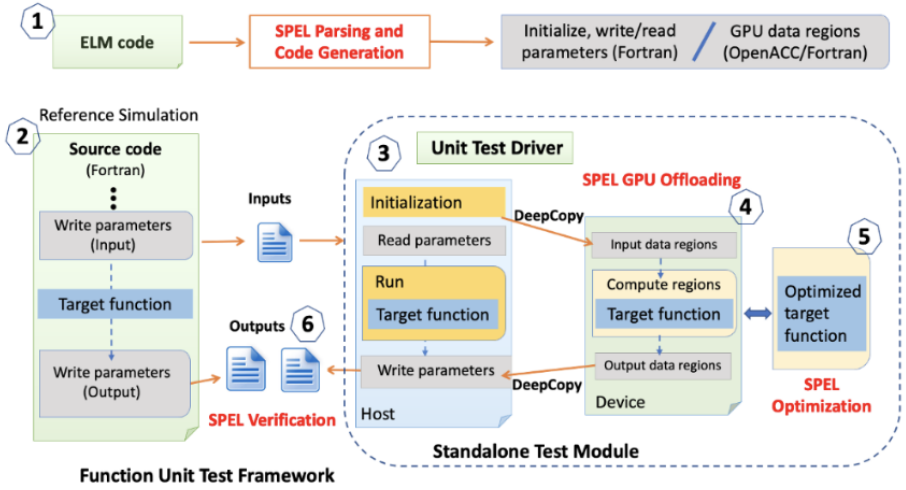
Land, River, and Human Systems

- Achievements
  - **Dynamic land biogeochemistry** is now the default configuration for coupled E3SM simulations
    - Includes carbon, nitrogen, and phosphorus cycles, fire, and land management (e.g. forest harvest, conversion of forest to agriculture)
  - **Radiation downscaling** is enabled by default for coupled simulations
    - Gridcell-level accounting for slope, aspect, and sky-view factors
  - **Code port to GPUs** is complete on development branch, being integrated to main branch
    - Uses OpenACC, implementation tested on Summit and Perlmutter
    - 3x speedup compared to CPU-only code





Hao, Bisht, et al. 2021



Wang, Schwartz, et al. 2022

Land, River, and Human Systems

- Ongoing work and future outlook
  - V3 Human Earth System (HES) campaign will include several new land-river-human system features
    - Introduction of topographic units as a new level of the ELM nested subgrid hierarchy
    - Topographic downscaling of temperature, precipitation, and humidity
    - Two-way coupling of water fluxes between land and river
    - Explicit vegetation hydraulics
  - Multiple developments from BER-sponsored “ecosystem projects” are being integrated into ELM
    - NGEE Tropics, NGEE Arctic, SPRUCE, COMPASS FME, COMPASS GLM
  - 1km continental-scale simulations running on Summit (and later Perlmutter, Frontier)
  - SPEL (Software tool for Porting E3SM Land model) is being used to automate multiple tasks
    - Code porting to GPU with OpenACC
    - Functional unit development for testing and debugging
    - Tracking of read and write dependencies for all variables
    - Generation of user-friendly documentation (e.g. html version of ELM calling tree)
  - Integration of ELM diagnostics into E3SM_diags (including iLAMB)

e3sm.org