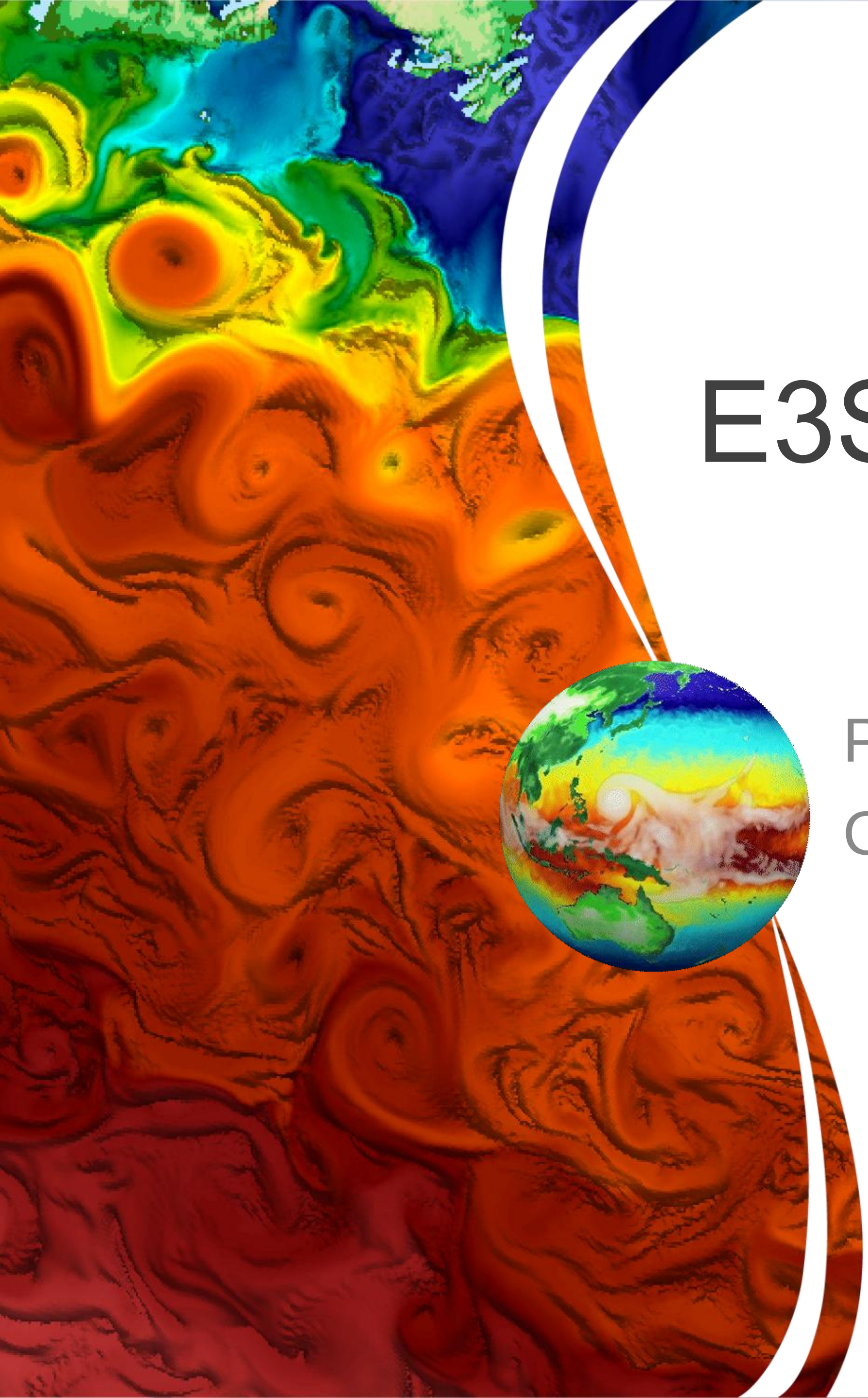

E3SM's Push to High Resolution

Peter Caldwell (E3SM PI)

CESM Workshop 6/11/25

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The Plan

- High res is a central focus for the Energy **Exascale** Earth System Model

- Strategy = rewriting code in C++ & using Kokkos for **performance portability**
  - DOE needs to use all 3 exascale architectures + provides future proofing
  - Domain-Specific Language (DSL) would be better if it was mature tech

- E3SMv4 (2028 release) will consist of:
  - EAMxx/SCREAM atm (already in C++, adding ZM convection now)
  - OMEGA ocean (currently being written in C++)
  - Existing F90 sea ice model
  - Existing F90 land model
  - “Low-res” = 12 km atm, 6-18 km ocean/ice, and 5 km land
  - “High-Res” = 3 km atm and 2-18 km surface components
  - All surface models will use a single MPAS grid

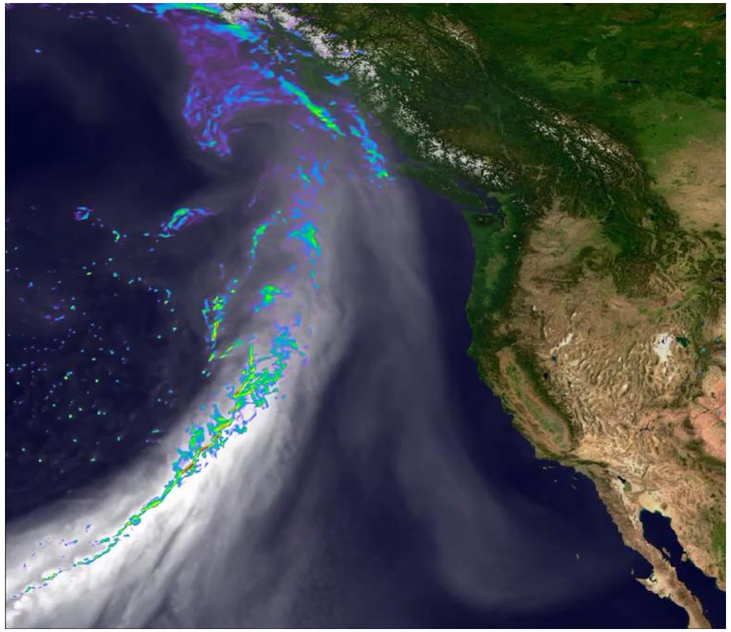
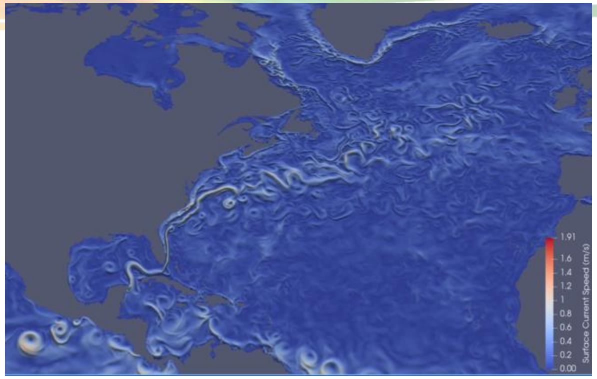


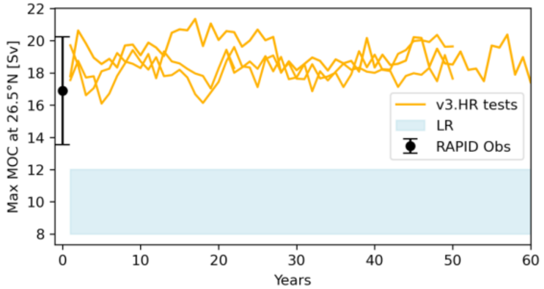
Fig: An atmospheric river making landfall on the US West Coast as simulated by SCREAM

Near Future: E3SMv3.HR

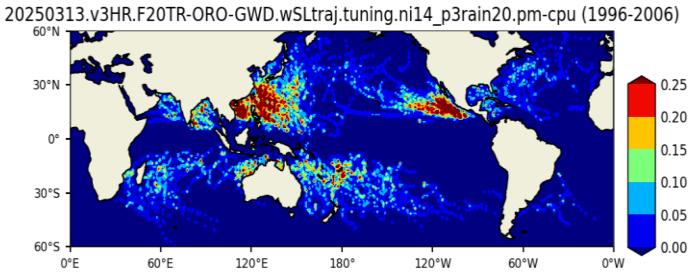
- Model Configuration
  - Atmosphere (~27 km, ne120pg2)
  - 18-to-6 km ocean and sea-ice
  - Land and river on ¼ deg lat-lon grid
- Advantages of higher resolution
  - Improved ocean mesoscale eddy-driven flows (e.g., AMOC, ACC, Gulf Stream)
  - Better skill for extreme events
  - Better overall mean climatology
  - Tighter ocean-sea ice-atmos coupling
- Status
  - Model is nearing finalization
  - Planned simulation campaign: CMIP7 DECK



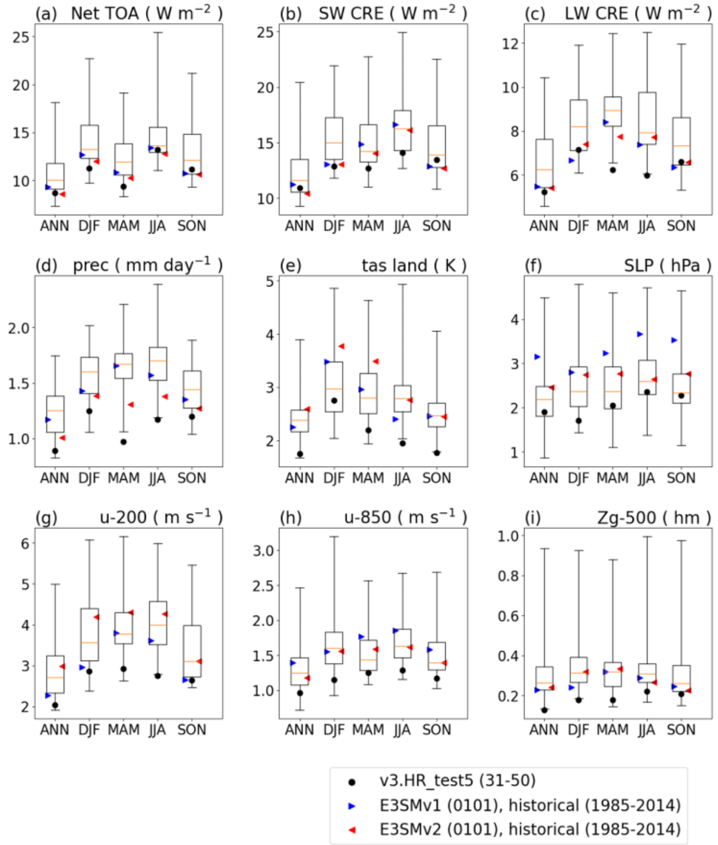
Resolved eddies on the surface current speed map



Enhanced AMOC



TC Tracks Density

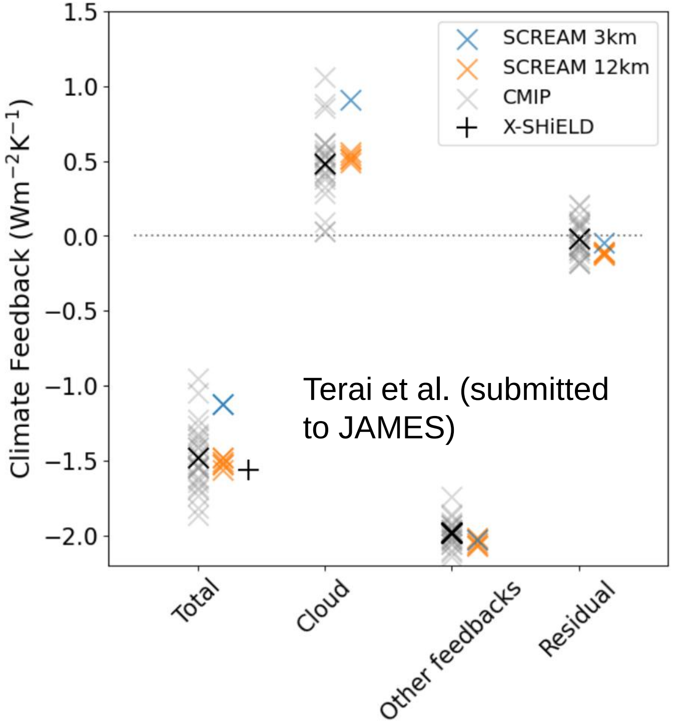


piCtl coupled test

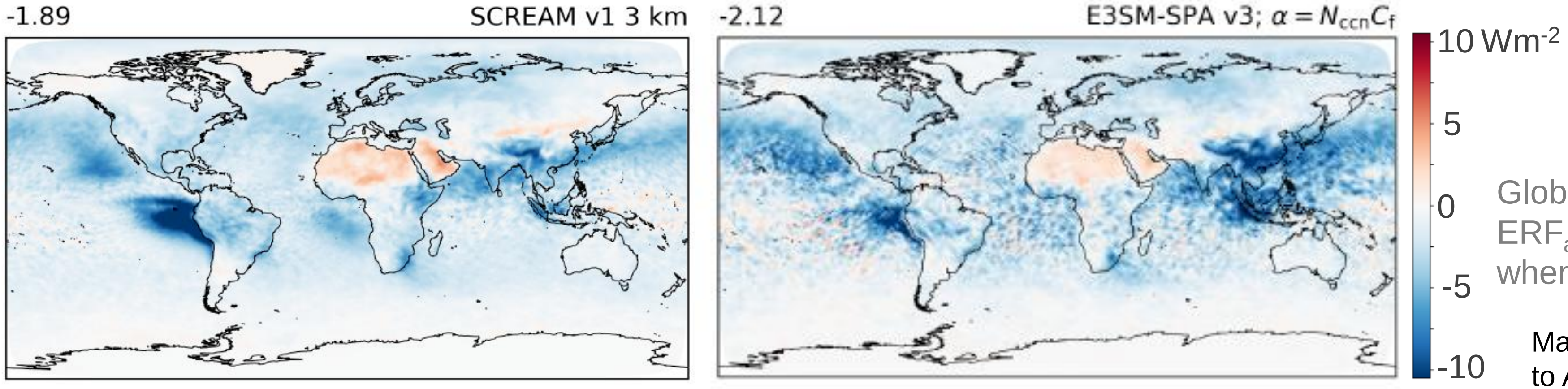
3 km SCREAM Simulation Campaigns

Science campaign	Length	What we've found
Four Seasons	4 x 40 days	Km-scale improves many features but also causes biases
Cess (+4K SST)	2 x 13 months	Cloud feedback at 3 km is very strong, 12 km is weaker
Prescribed Aerosol (PD/PI)	2 x 13 months	PD-PI ERF_{aci} is sensitive to activation assumptions but can be tuned to EAMv3
Decadal	10 years	Will examine storm statistics, variability + extremes, ENSO, …

Globally averaged feedbacks in SCREAM 3km, SCREAM 12km, CMIP5/6 models, and X-SHiELD.



Terai et al. (submitted to JAMES)



Globally averaged and spatial distribution of ERF_{aer} in SCREAM 3km (left) and E3SMv3 (right) when forced to use the same prescribed aerosol.

Mahfouz et al. (submitted to ACP)

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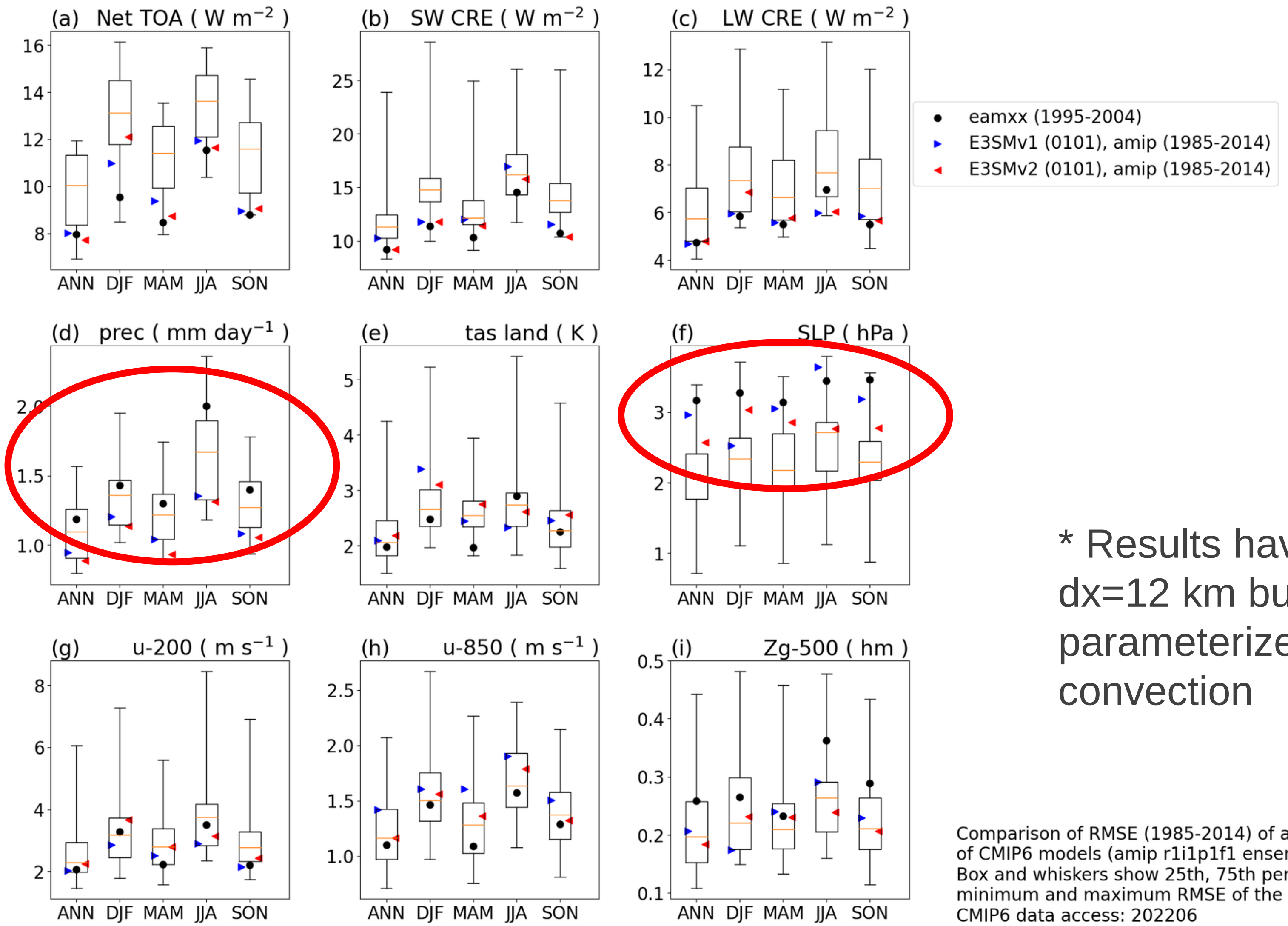
12 km SCREAM Skill

- In addition to improved orographic effects and storms, very high res improves some global fields… but not all (see graphic)

- Tuning global km-scale models is a grand challenge
  - Slow-evolving features like surface T => short hindcasts are insufficient
  - Multi-resolution autotuning seems like the way to go



Comparison of RMSE (1985-2014) of an ensemble of CMIP6 models (amip r1i1p1f1 ensemble). Box and whiskers show 25th, 75th percentile, minimum and maximum RMSE of the ensemble. CMIP6 data access: 202206

* Results have dx=12 km but no parameterized convection

Exascale = Exa-lent Chance of Fails

- SCREAM can run at 1 simyear/wallday… but it took 8 wall months to complete our decadal run (all on OLCF Frontier)
  - Lots of nodes => lots of node failures
  - Bleeding-edge computers are fragile
  - Machine updates kept breaking our code

Better tools for job resiliency are needed

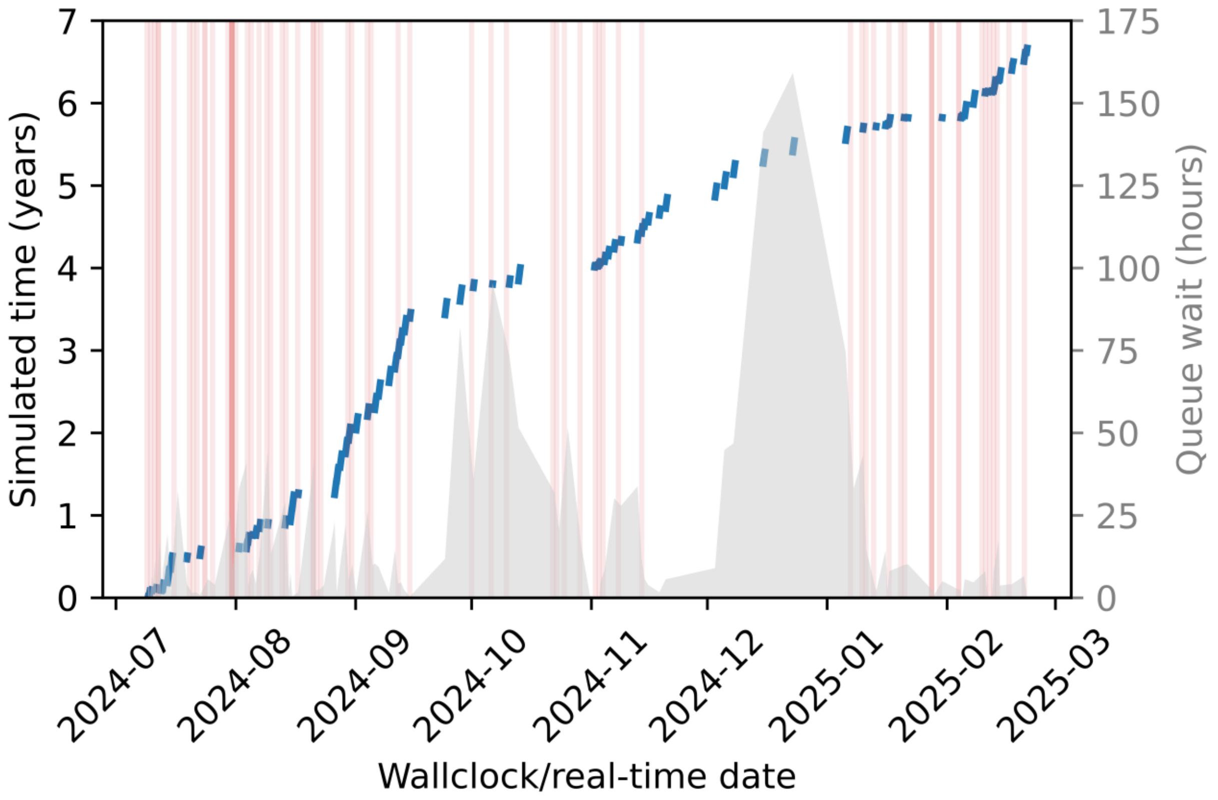


Fig: Decadal simulation progress versus real-world time. Blue lines are progress during a simulation, red lines are job failures, and gray shading indicates queue wait time. Graphic by Ben Hillman

SCREAM Budget Options

- **Doubly-Periodic (DP)** mode is an economical way to develop and test EAMxx. It:
  - runs the full model on a rectangular plane
  - takes advantage of E3SM's library of ~30 ARM single-column model case studies

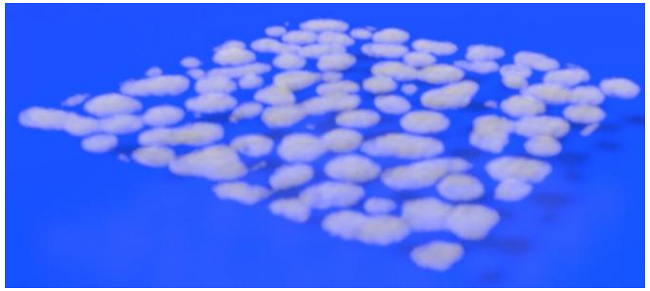
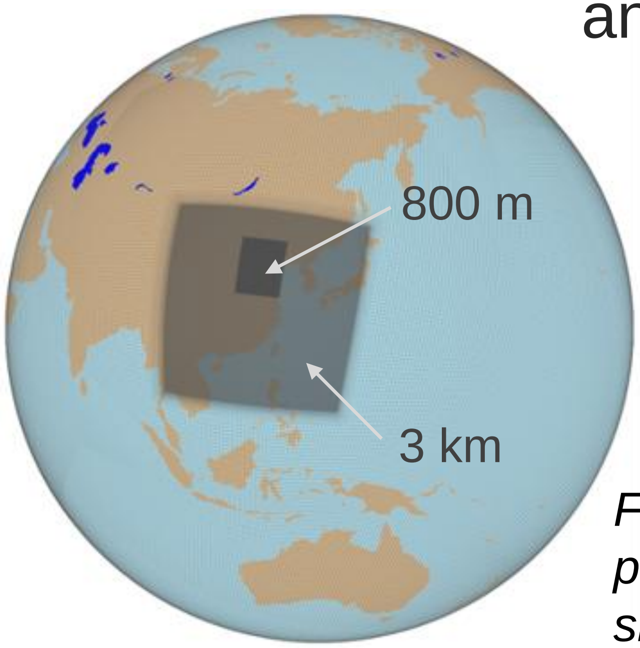


Fig: DP in action

- EAMxx can also run in **regionally-refined mode (RRM)** with fine Δx in a small region and coarse Δx (and nudging) elsewhere

- For debugging and exploration, individual SCREAM **processes can be called interactively from python**



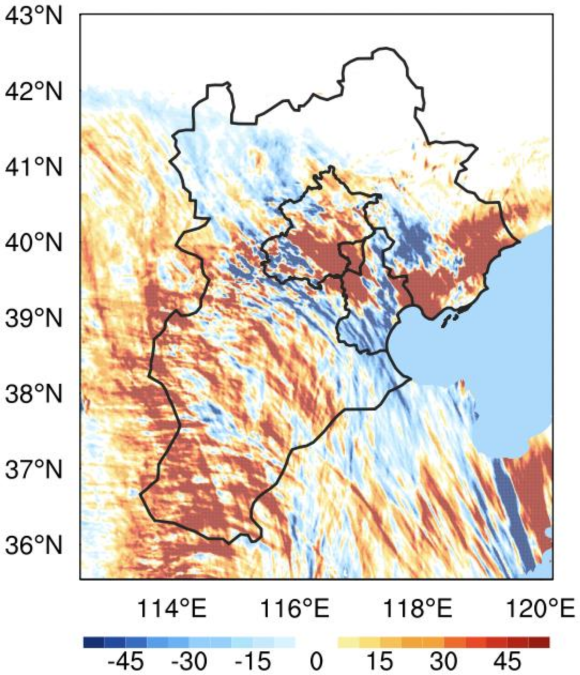


Fig: an RRM grid (left) and the change expected in precipitation if the 2023 Beijing flood happened in 2050 (as simulated by EAMxx RRM)

Ocean Model for E3SM Global Applications (OMEGA)

- C++ version of MPAS-Ocean
  - Focused on eddy-resolving resolutions (no GM)
  - Uses non-Boussinesq dynamics and updated equation of state (TEOS-10) to improve sea-level change projections

- Development steps:
  - Stacked shallow water (done)
  - Standalone ocean Model (due Dec)
  - First draft in E3SM (June 2026)
  - v4 release candidate (Dec 2026)

- Stacked shallow water model is
  - 1.5x faster than MPAS-Ocean on CPUs
  - 30x faster on GPUs than CPUs

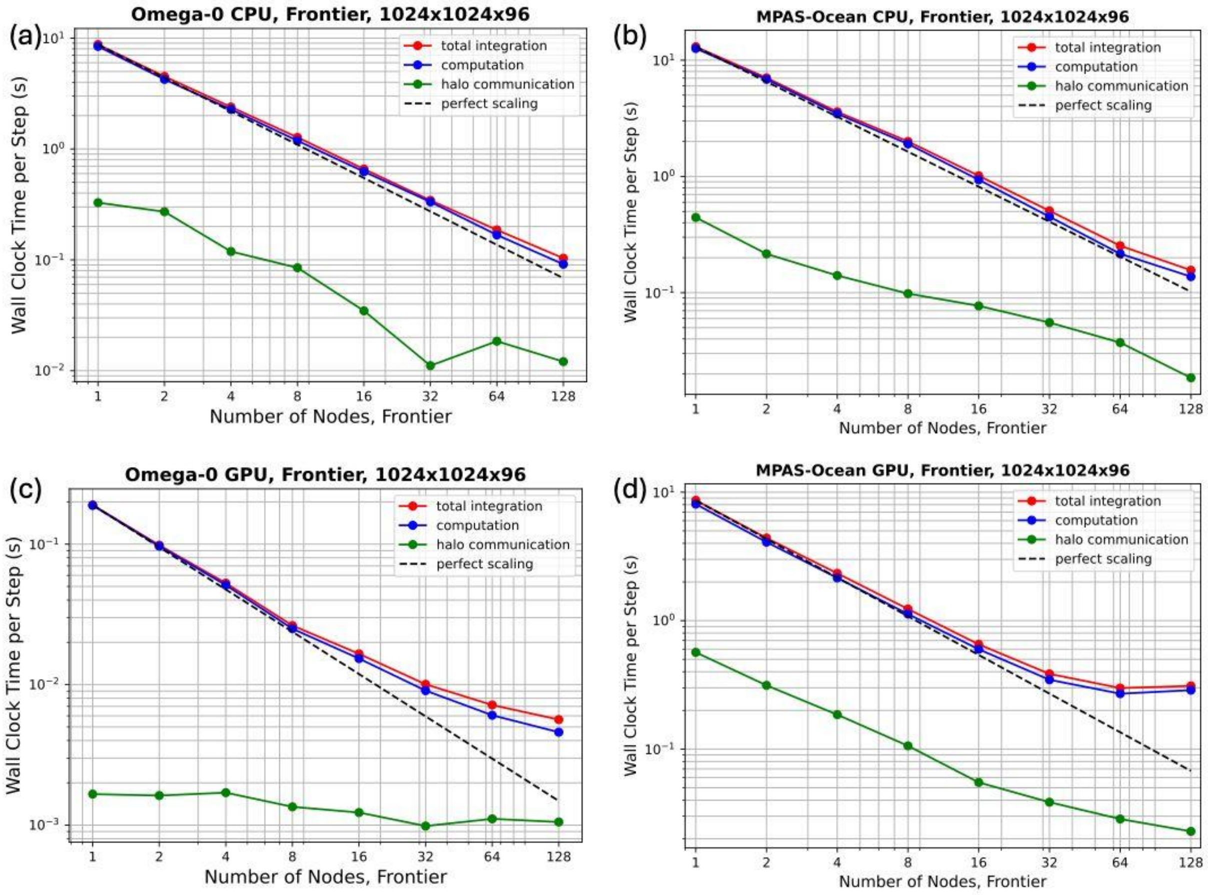
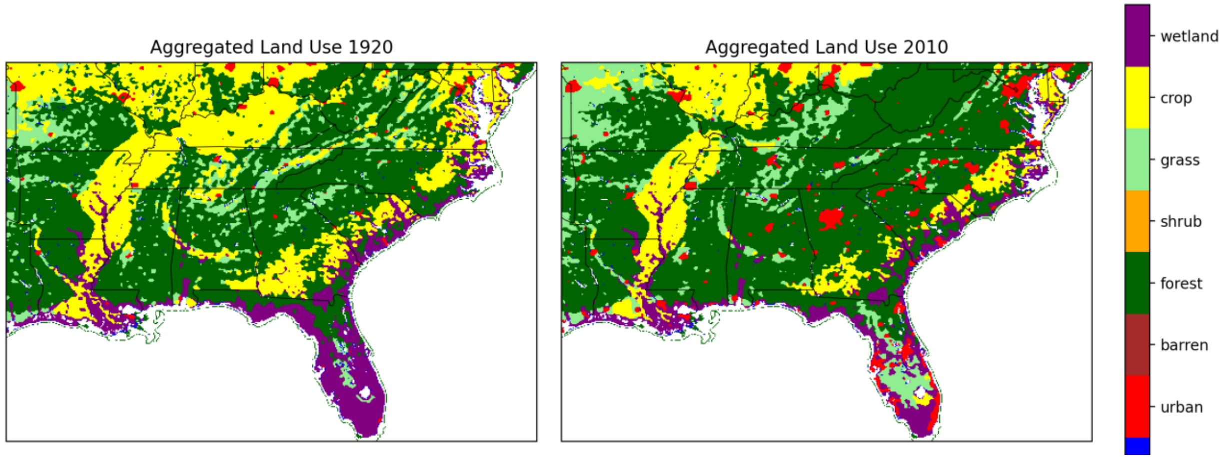
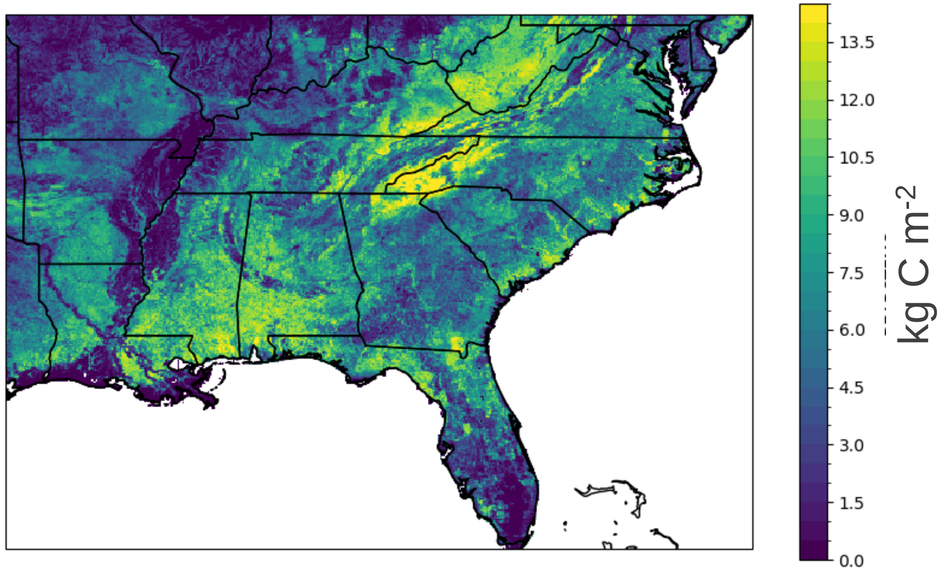


Fig: Speed vs node count for stacked shallow water OMEGA (left) and MPAS-Ocean (right). CPU values are on the top row and GPU timings are on the bottom. Note different vertical axis scaling.

High-Resolution Land Efforts





- Generating km-scale land inputdata has been a major effort
- Km-scale land-only simulations have realistic carbon, water table depth, etc
- AI-based spin-up techniques are critical for making high-res possible

Fig: AI-based downscaling of land use timeseries (top) and present-day carbon in trees from a CONUS transient simulation forced by atmospheric reanalysis

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