Stochastic ensemble coupled modeling of pre-industrial control and 1% increasing CO2 scenarios with physically conservative machine learning emulators

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External partners

M²LInES GFDL LLNL

Who are we?

Allen Institute for AI (Ai2): a Seattle-based nonprofit funded by the Paul Allen estate

> Building breakthrough AI to solve the world's biggest problems

Ai2 Climate Modeling:

- We sit within "AI for the Environment" group at Ai2
- **Use machine learning to make faster, better, and easier-to-use climate models**
- **Partners**: NOAA-GFDL and DOE-LLNL (fellow atmosphere and climate modelers), M²LInES and NVIDIA (fellow machine learners)



M²LInES NVIDIA GFDL LLNL

Outline

- Overview of our published coupled emulator, SamudrACE v1
- Challenges in emulating 1% CO_2 forced trends
- Improvements in SamudrACE v2
- WIP results using SamudrACE for ENSO forecasting

Background: ACE and Samudra

- Independent groups developed atmosphere and ocean AI emulators



Chris Bretherton, Spencer Clark, Brian Henn, Anna Kwa, Jeremy McGibbon, Andre Perkins, Oli Watt-Meyer, Elynn Wu, James Duncan

→ ACE

Atmosphere AI model applied to AM4, ERA5 and other datasets.
Watt-Meyer et al. 2025, *Clark et al., 2025*



Surya Dheeshjith, Adam Subel, Alistair Adcroft, Laure Zanna, m²LInEs

→ "**Samudra**", a 3D emulator of GFDL's OM4 ocean model *Dheeshjith et al. 2025*

- Common features: **long-term stability, climate accuracy, fast prediction**

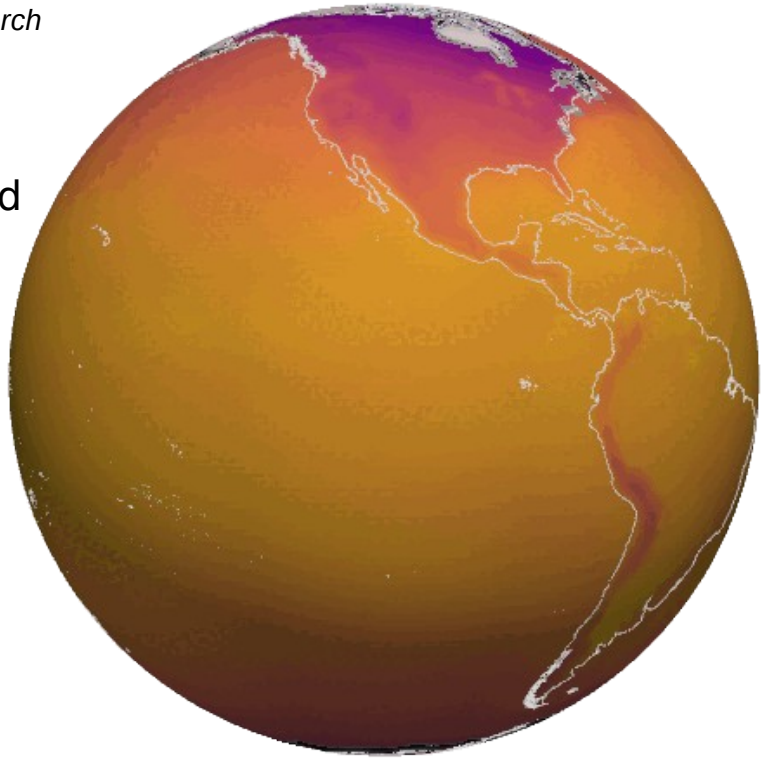
SamudrACE-v1

0312-02

Duncan, J., Wu, E., et al. **SamudrACE: Fast and Accurate Coupled Climate Modeling with 3D Ocean and Atmosphere Emulators**. *Geophysical Research Letters* (2026)

Trained on a 200-year NOAA GFDL-CM4.0 pre-industrial control (“piControl”) simulation run [Held et al. 2019]

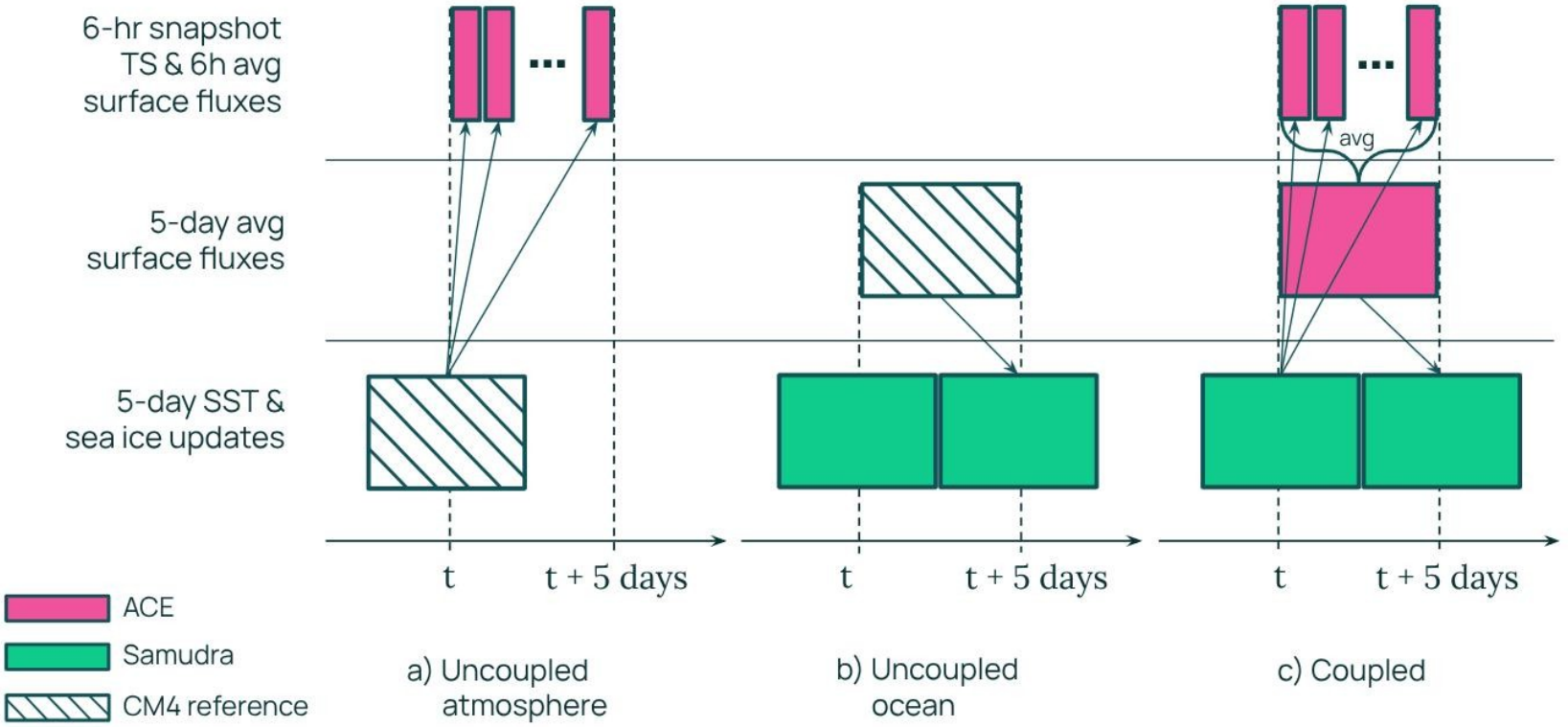
- Atmosphere + land (**ACE2**)
  - 6-hour time step
  - 8 vertical layers
  - 1° horizontal resolution
- Ocean + sea ice (**Samudral**)
  - 5-day time step
  - 19 vertical layers
  - 1° horizontal resolution (regridded from OM4 0.25° grid)



Monthly mean surface temperature and sea ice concentration from a 40-year rollout from SamudrACE-piControl

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SamudrACE coupling

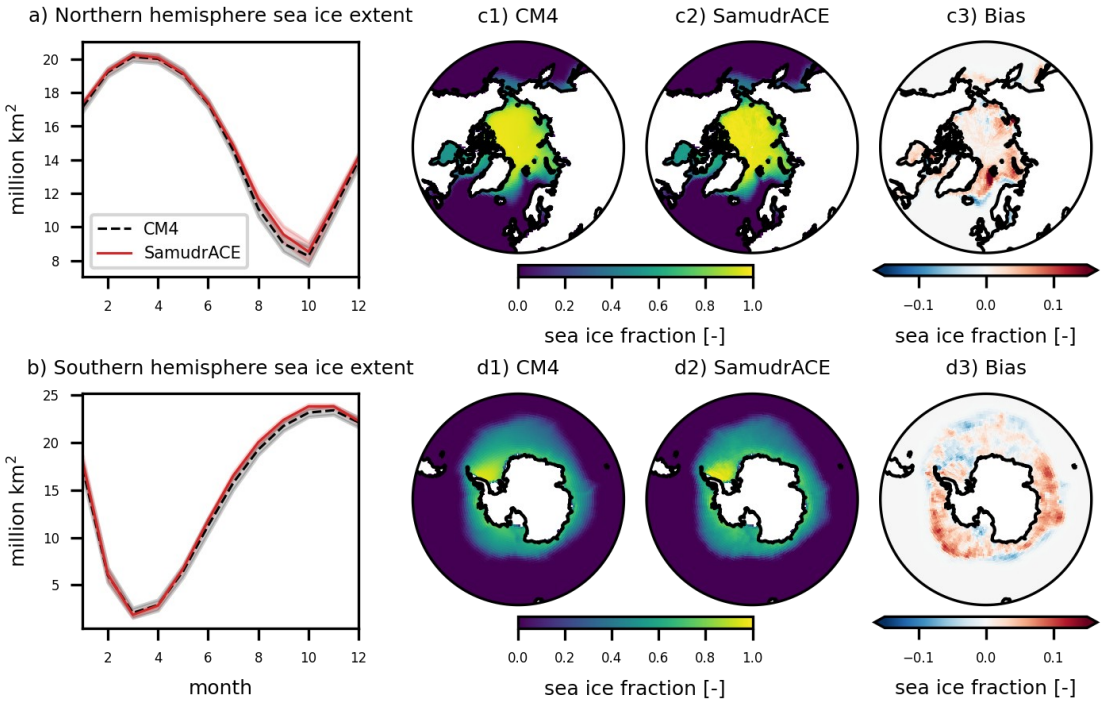


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Accurate sea ice climatology in SamudrACE-v1

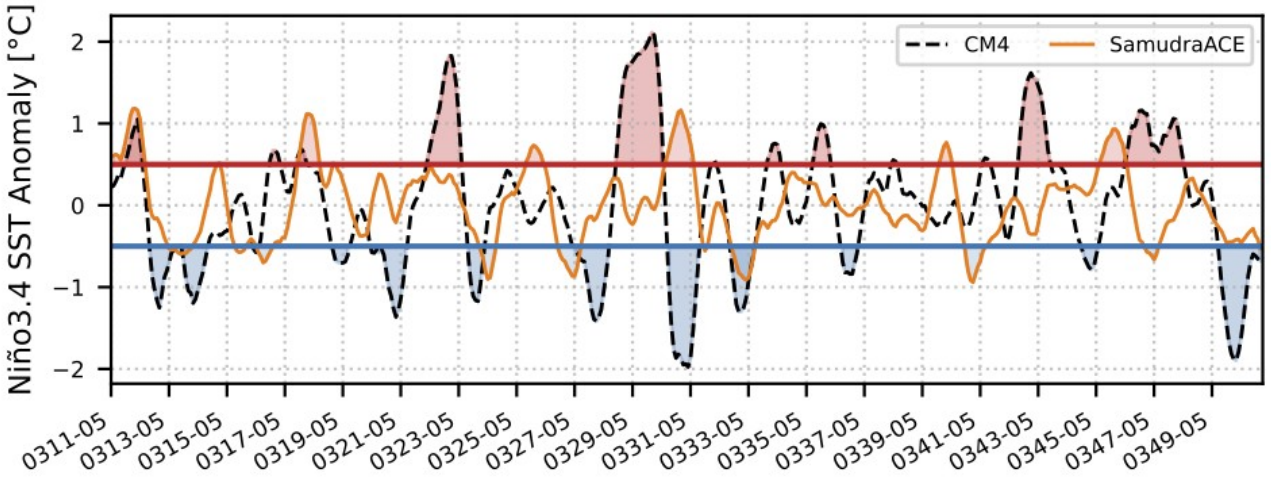
Duncan, J., Wu, E., et al. **SamudrACE: Fast and Accurate Coupled Climate Modeling with 3D Ocean and Atmosphere Emulators**. *Geophysical Research Letters* (2026)

- Sea ice concentration is a prognostic variable in our updated Samudra ocean model
- Maintains good sea ice climatology with accurate seasonal cycle
- Slightly underestimates interannual variability

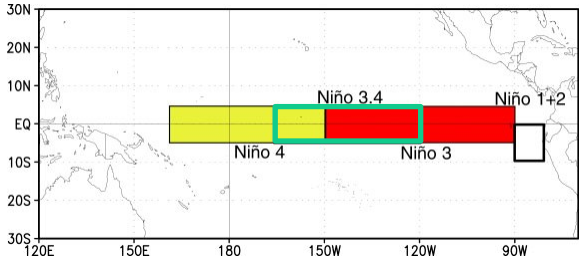


Emergent ENSO in SamudrACE-v1

Duncan, J., Wu, E., et al. **SamudrACE: Fast and Accurate Coupled Climate Modeling with 3D Ocean and Atmosphere Emulators**. *Geophysical Research Letters* (2026)



- Realistic emergent ENSO variability
- Too little at periods> 4 years.



M²LInES

GFDL NOAA

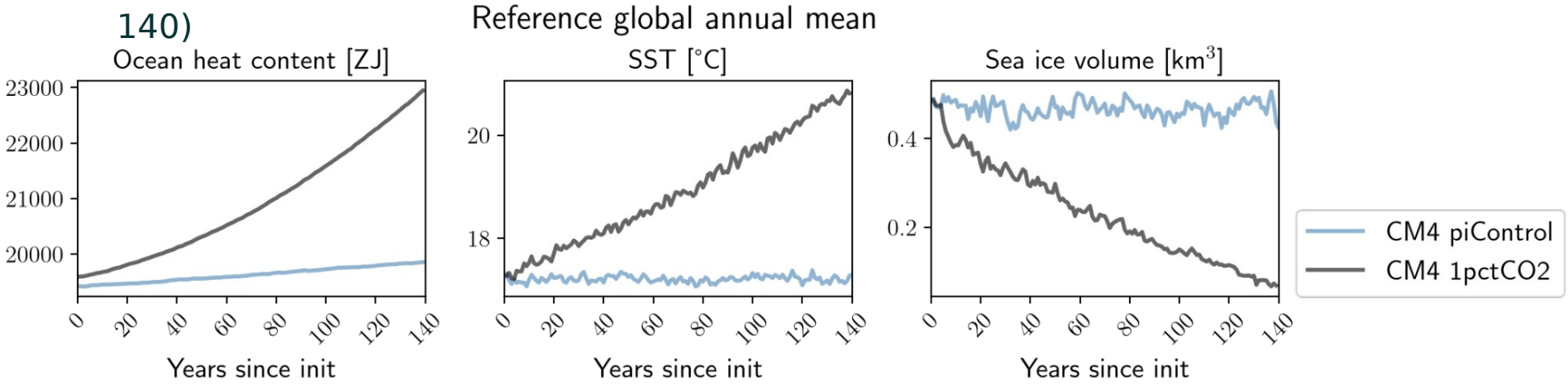
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Duncan et al. 2026, *GRL*

Generalization to changing climate scenarios

From pre-industrial control to 1% annual increasing CO_2

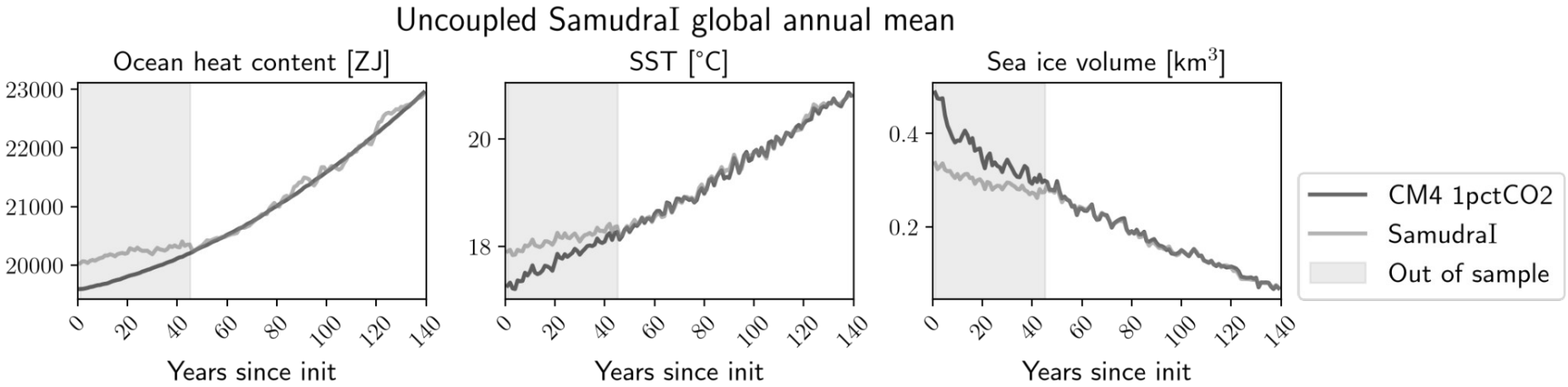
- In the 200-year piControl (blue line), CO_2 concentrations held fixed at pre-industrial levels.
- 140 year 1pctCO2 simulation (black line), 1% / year increase in CO_2 (4x CO_2 by year 140)



Learning the trend?

Training on years 46 to 140, years 1 thru 45 held out from training.

The SamudrACE-v1 training protocol is insufficient for **out-of-sample generalization in a changing climate**.



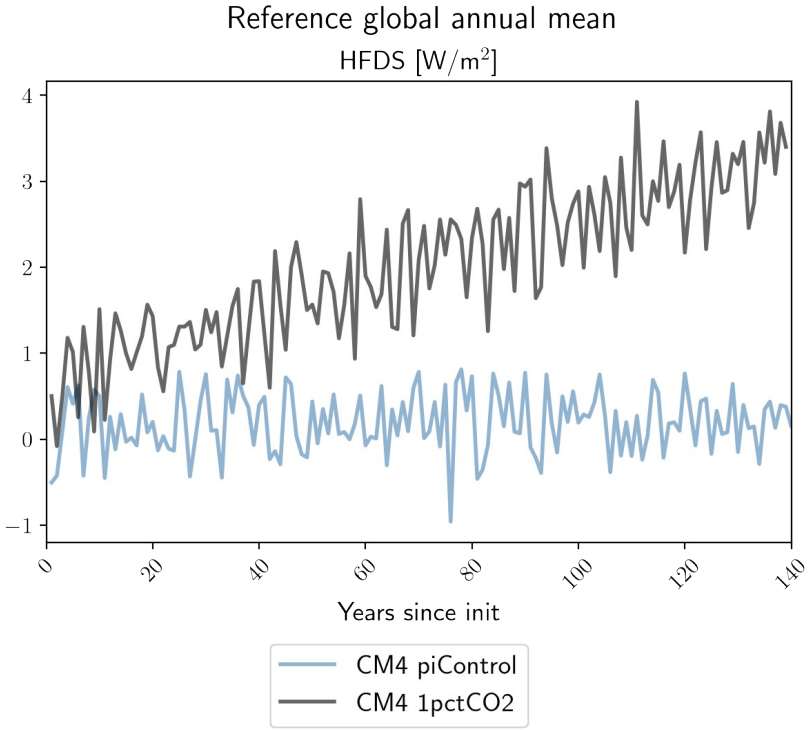
How can we make the ocean emulator respond correctly to the atmosphere surface forcings?

Conservation of ocean heat content

via a correction to the 3D potential temperature

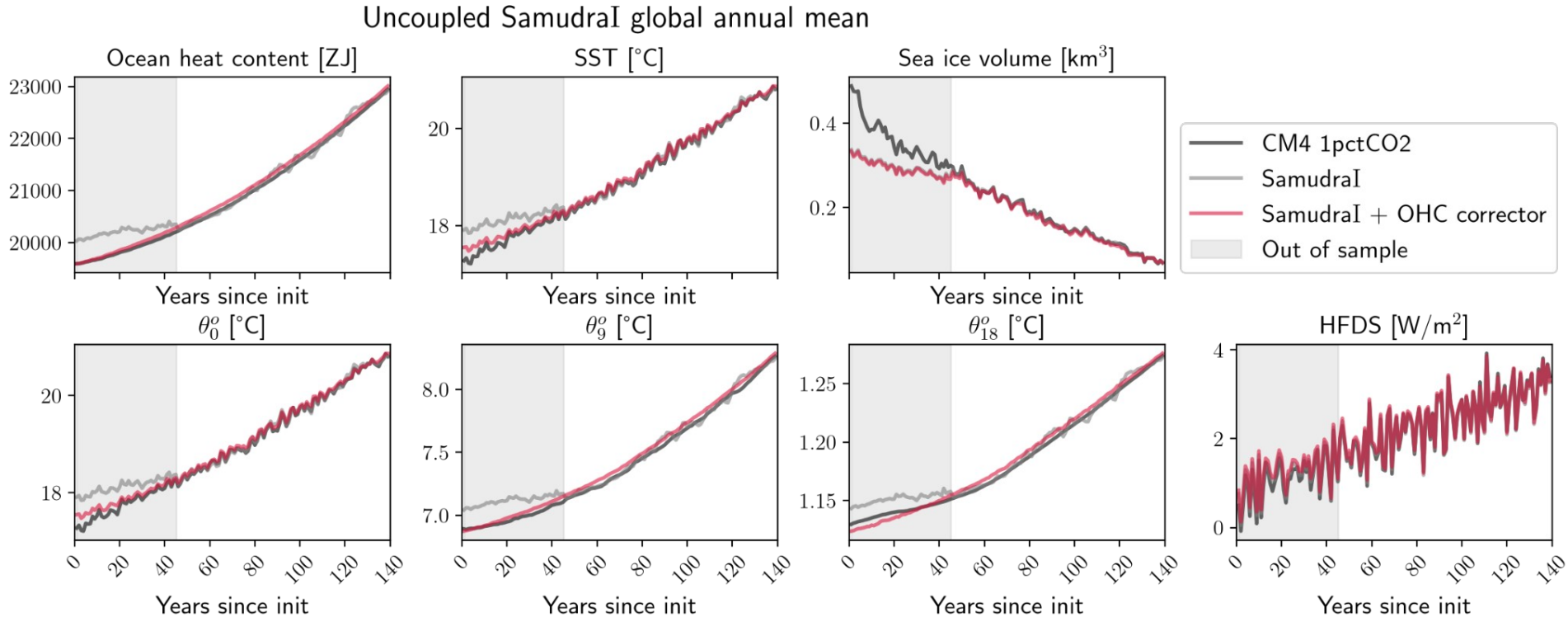
$$\theta^{\text{corr}}_{i,x,y} = \theta^{\text{pred}}_{i,x,y} \frac{\overline{\text{OHC}}_{\text{input}} + \overline{F_{\text{net}}}\,\Delta t}{\overline{\text{OHC}}_{\text{pred}}}$$

- HFDS: Ocean surface downward heat flux
- F_{net} = HFDS + bottom geothermal flux
- In coupled mode, we also include an atmosphere energy correction.



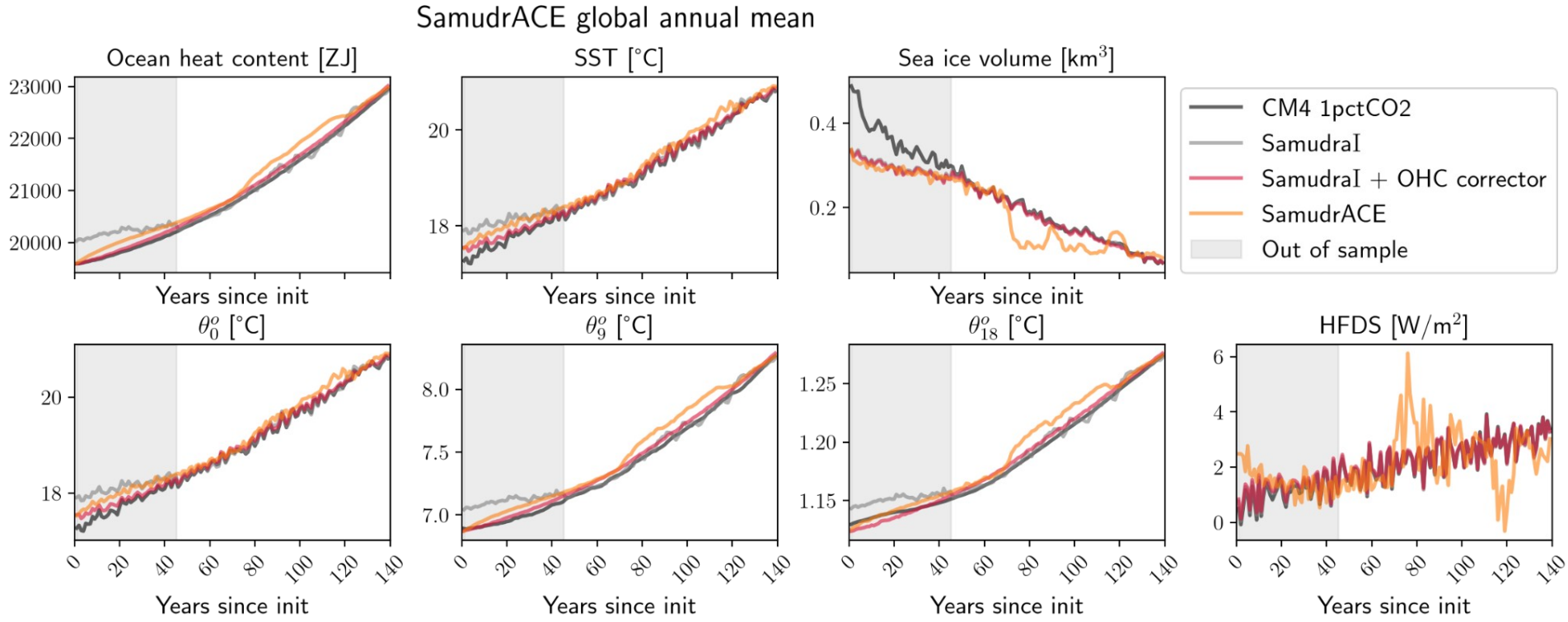
Learning the trend! But not sea ice

The OHC corrector leads to improved out-of-sample generalization for uncoupled SamudraI

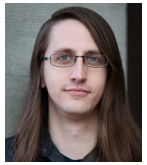


Learning the trend! But not sea ice and coupled is unstable

The OHC corrector leads to improved out-of-sample generalization for coupled SamudrACE



Key Update: Stochastic ACE



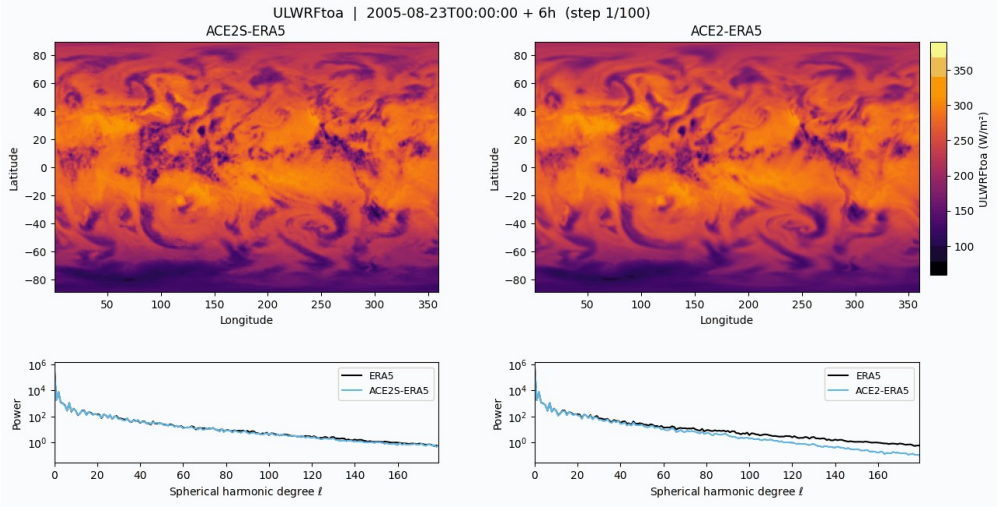
J. McGibbon

ACE2S (Stochastic ACE2): Random noise-conditioned Layer Norm with multi-timestep CRPS + spectral energy score loss

- ACE2S was developed as part of **downscaling** [Perkins et al. **HiRO-ACE**. arXiv:2512.18224 (2026)] -> 1 degree (~100 km) to 3km
- CRPS boosts small scale power
- Spectral energy score loss optimizes overall spectrum shape
- Reduction in 10-year time-mean RMSEs compared to ACE2 trained with MSE loss

Outgoing Longwave Radiation

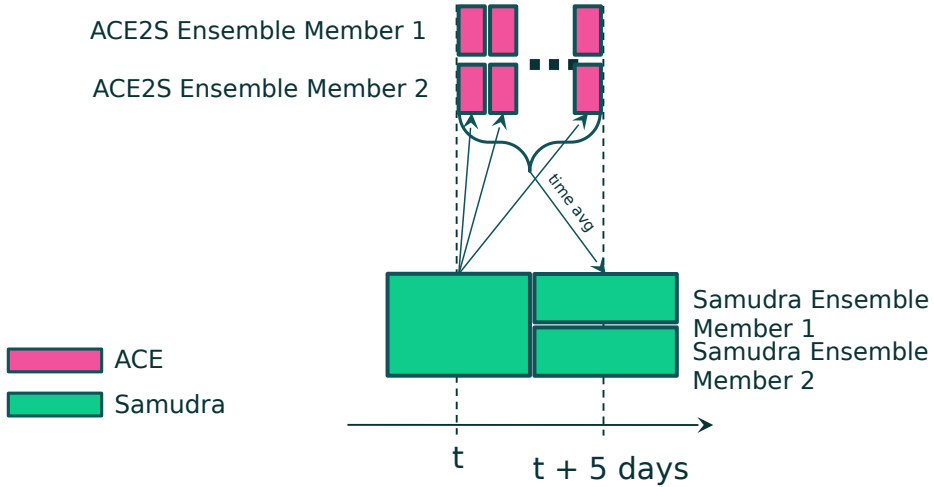
Stochastic | Deterministic



SamudrACE-E3SMv3-piControl: Key Updates

Wu, E., et al. **Stochastic Emulation of a Fully Coupled Preindustrial E3SMv3 Simulation**. [arXiv:2608.10277] (2026)

- **Stochastic Samudra** during coupled fine-tuning: sees two ensembles of ACE forcing and optimized with the same ensemble loss



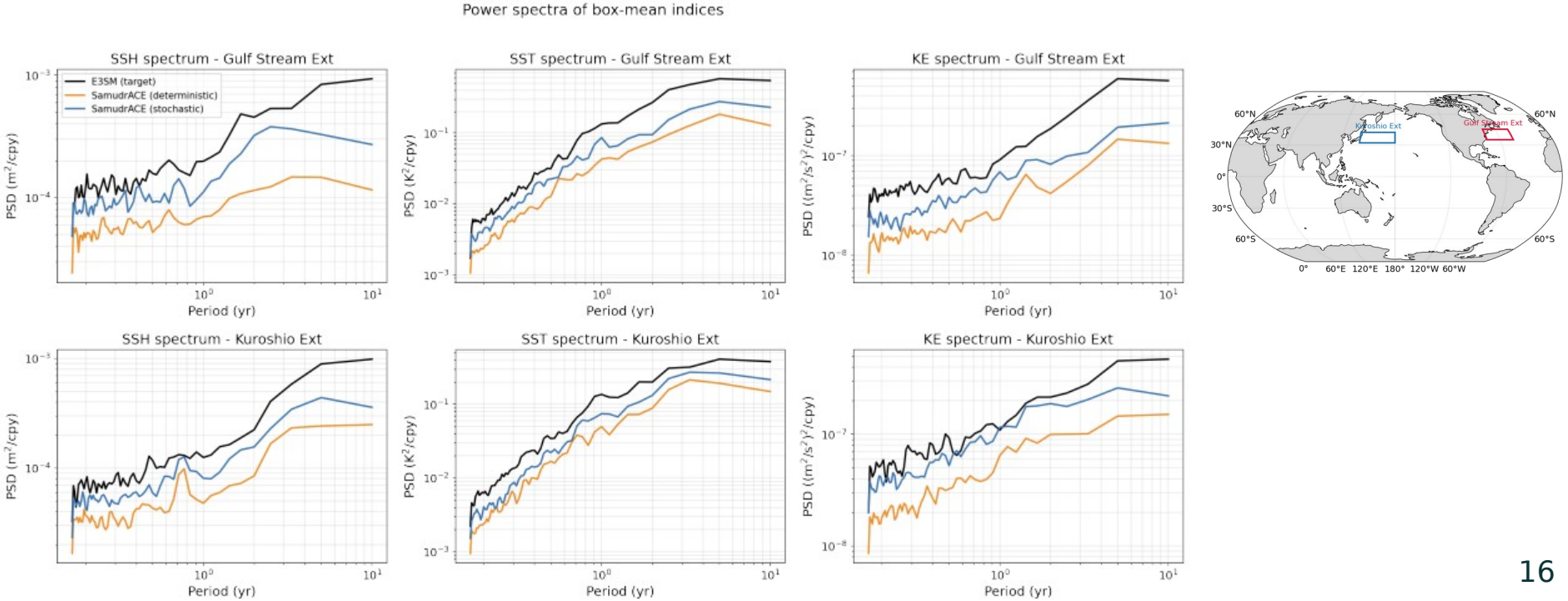
SamudrACE-E3SMv3-piControl: Key Updates



E. Wu

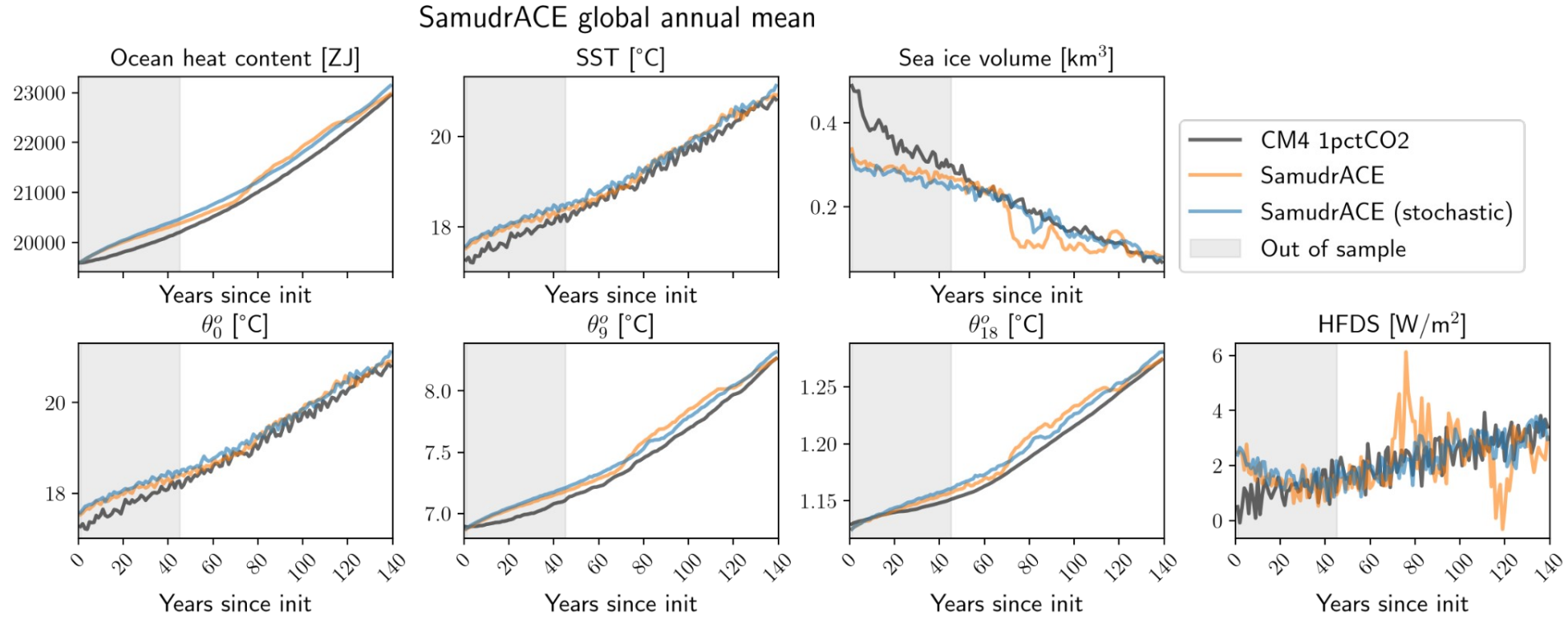
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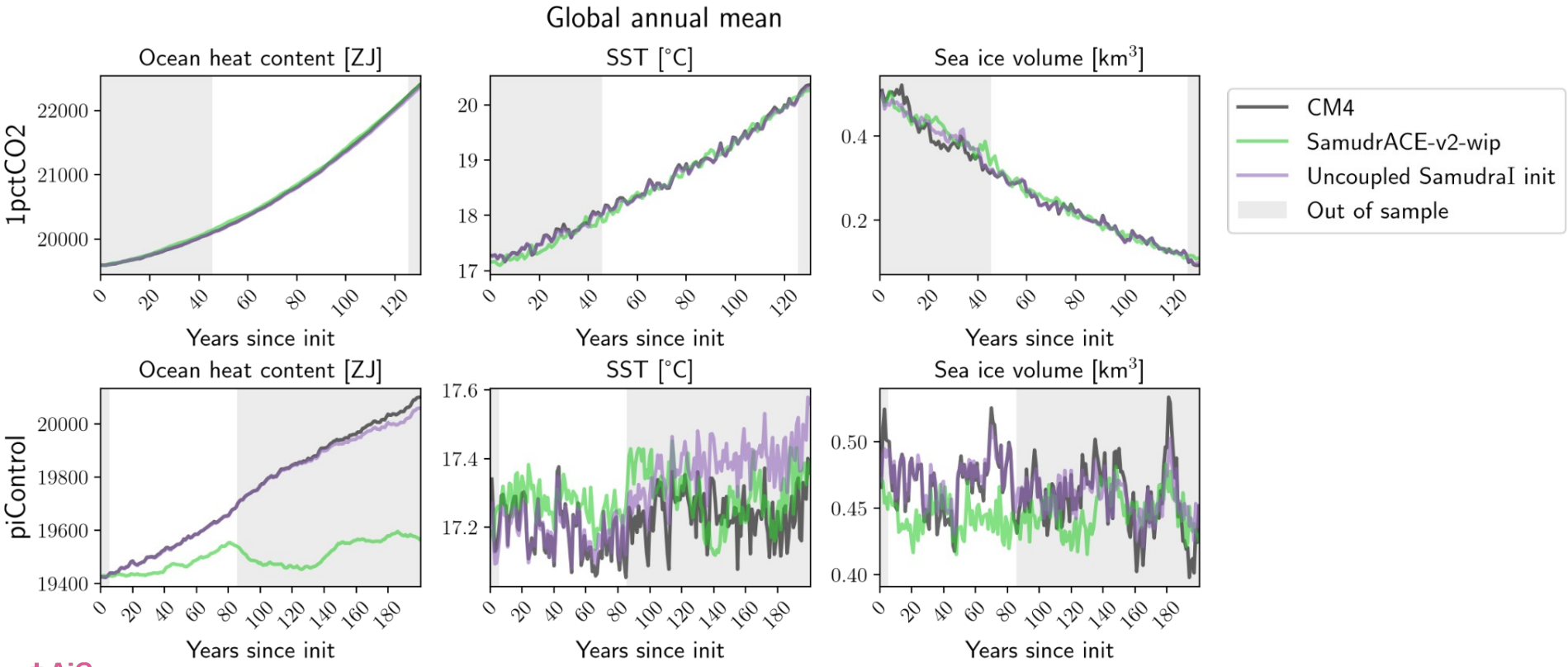
Learning the coupled trend stably! But not sea ice

Stochastic SamudraACE improves coupled model stability

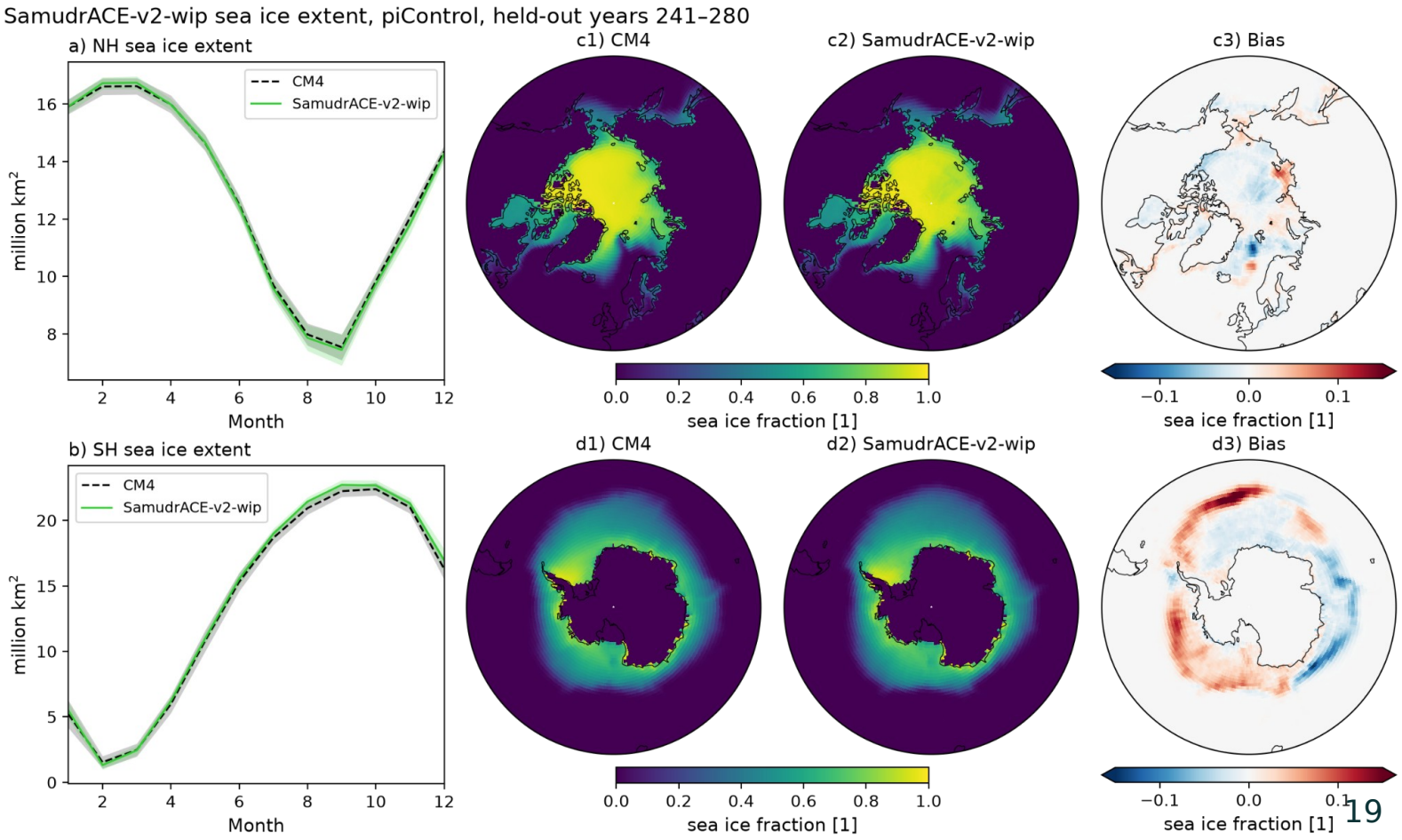


SamudrACE-v2-wip: trained on mix of piControl and 1pctCO2

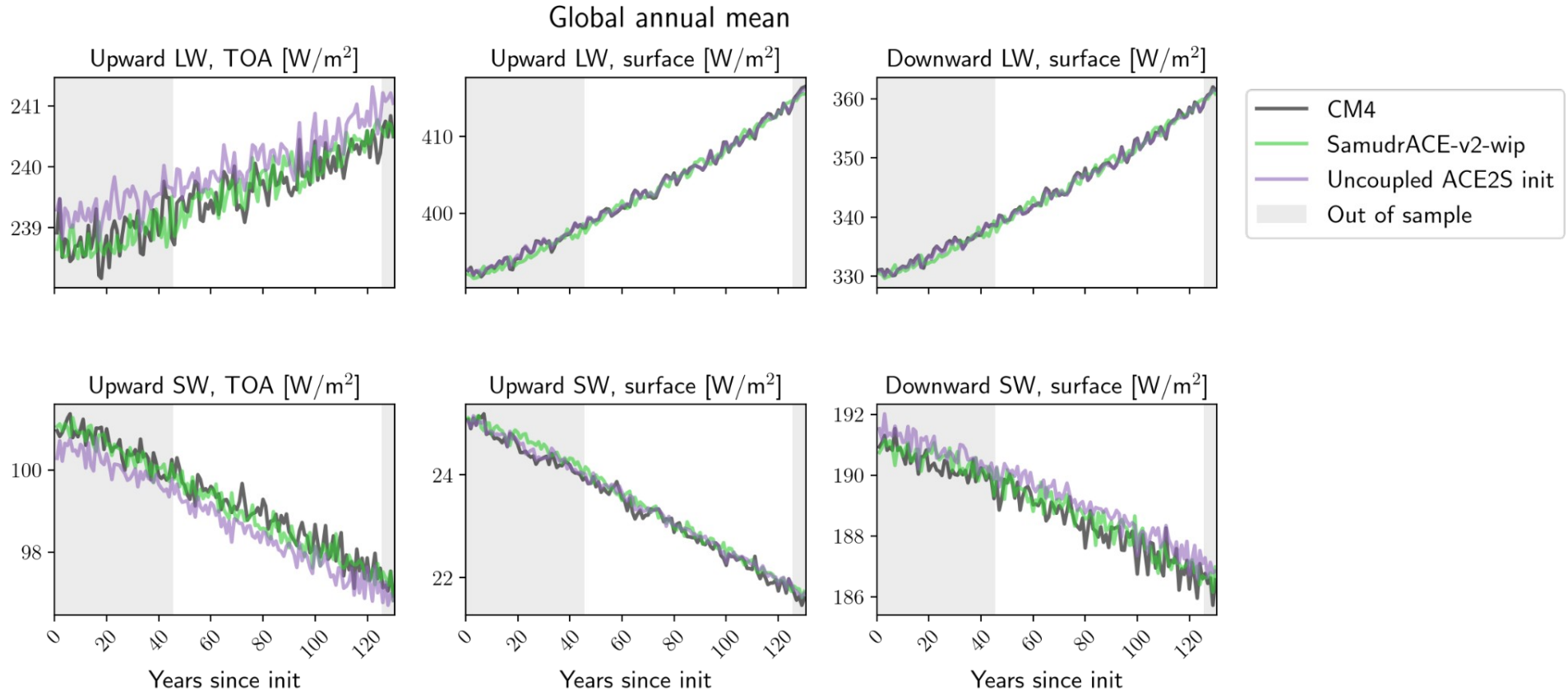
Mixed scenario training improves sea ice generalization: 80 years each of 1pctCO2 and piControl



Sea ice climatology skill in v2 similar to v1

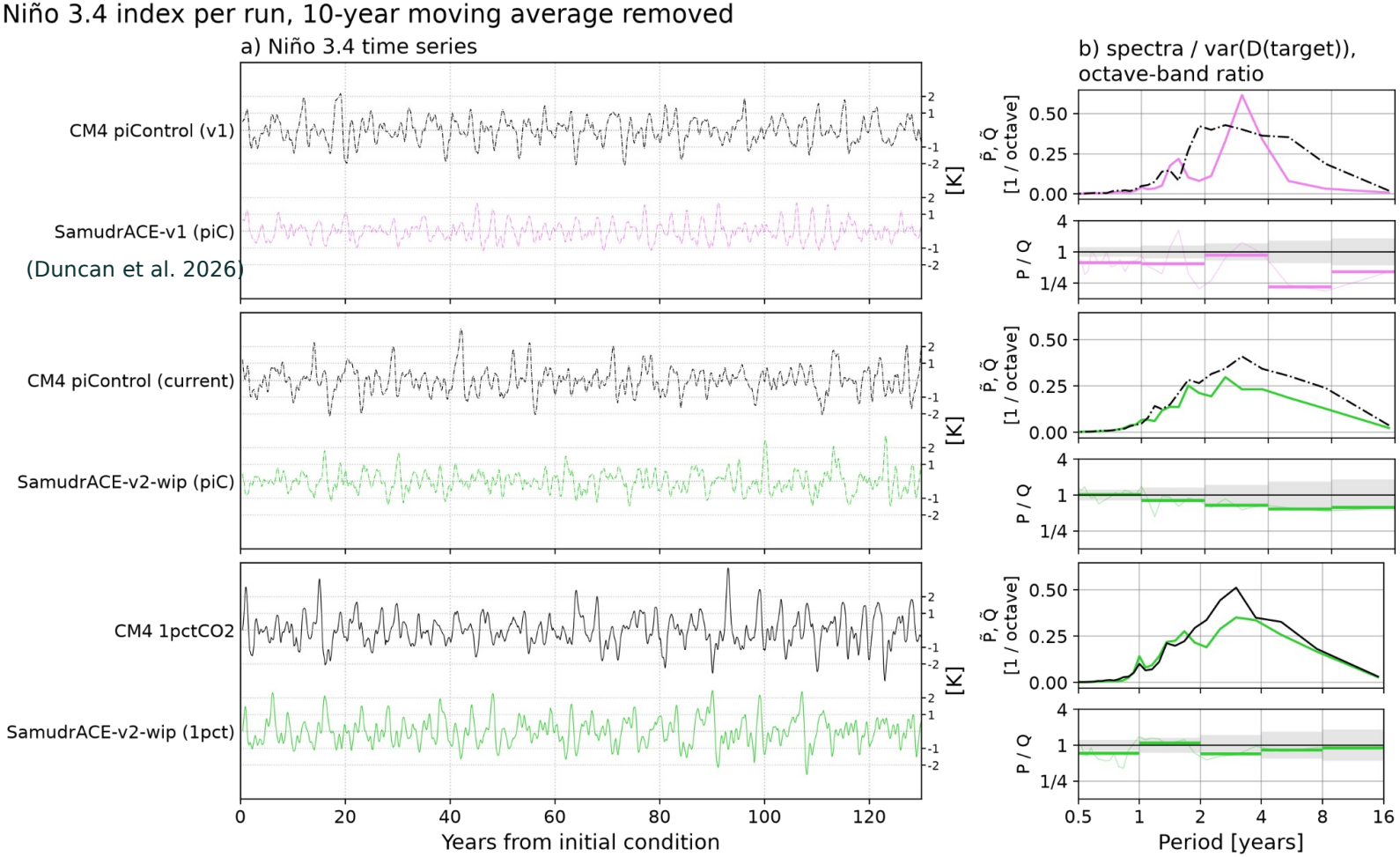


Improvement in atmosphere flux diagnostics



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ENSO improvements in v2-wip

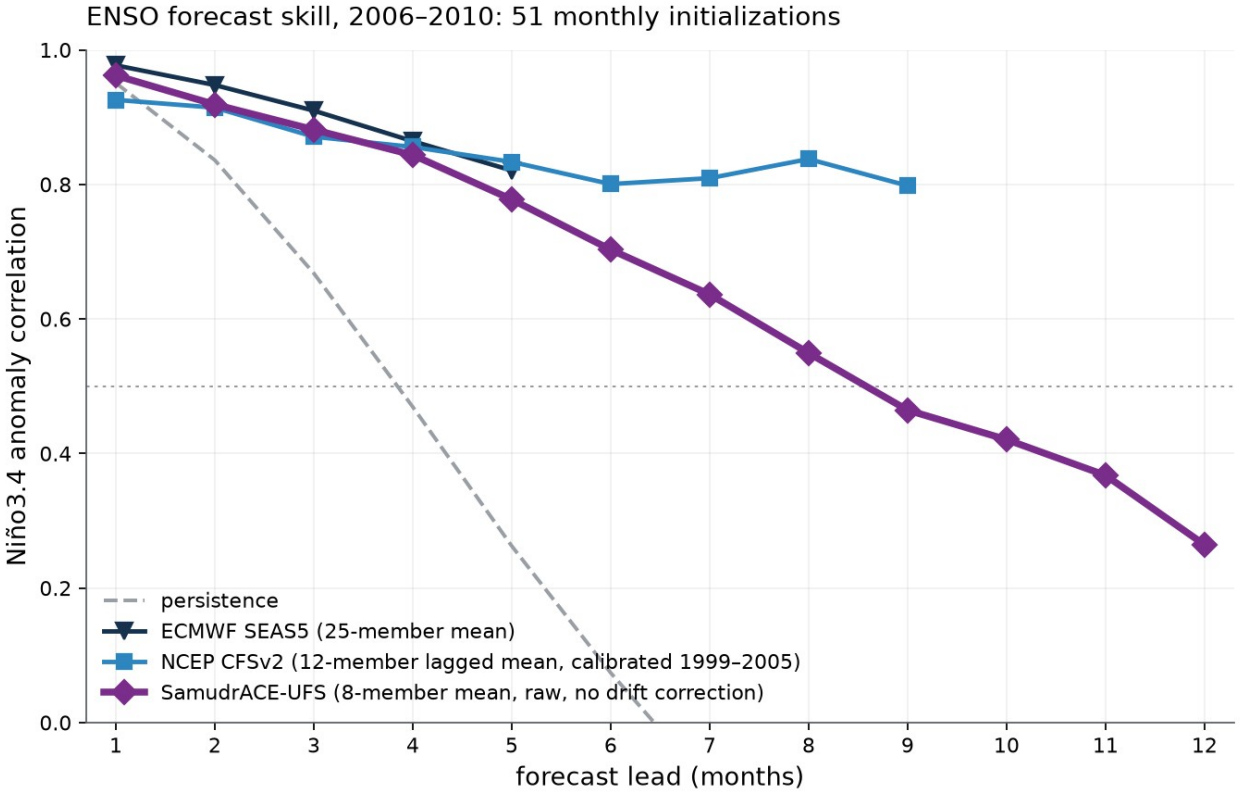


ENSO forecast skill on reanalysis



T. Arcomano

Preview of WIP results of SamudrACE trained on UFS-Replay

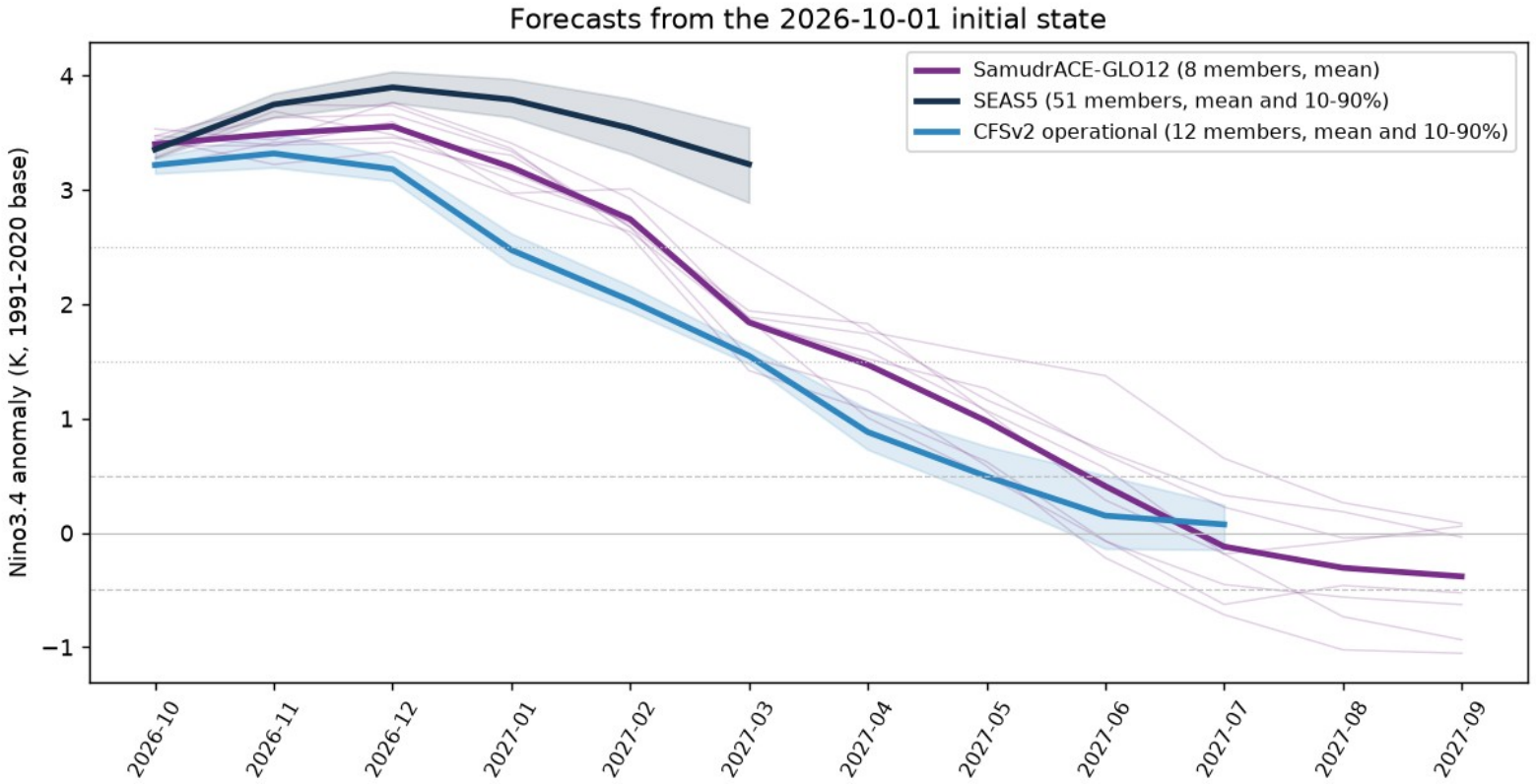


SamudrACE operational forecasts



T. Arcomano

Fine-tune on 4 years of GLO12 + pull near real-time GLO12 + ERA5 to initialize on-demand forecas



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Summary

SamudrACE is a 3D coupled atmosphere-ocean AI emulator that:

- maintains low climate biases comparable to its uncoupled component models
- generates emergent ENSO variability
- supports stochastic ensemble simulations
- **generalizes to out-of-sample (low CO_2) warming trends (interpolates sea ice)**

It is easier and more than 100x faster to run than the reference model!

- **1500 simulated years per day on an NVIDIA H100 GPU**
- Ongoing work includes training SamudrACE on reanalysis data
- Future work: Coupling to additional component emulators
  - e.g., the SIS2 emulator FloeNet [W. Gregory et al. 2026]

Open source code, data and models:
github.com/ai2cm/ace
huggingface.co/allenai/SamudrACE-CM4-piControl
(published v1 model)



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