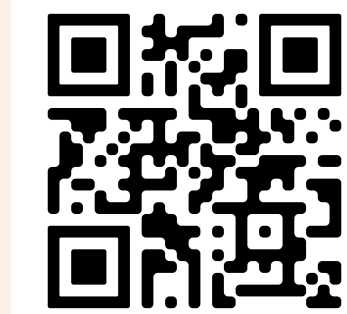
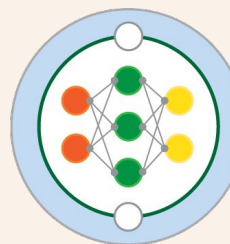


SamudrACE– Coupled Climate Simulations with ACE and Samudra



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Scan to explore the model and paper!

Overview

- Our long-term goal is to build a global climate emulator capable of running the Coupled Model Intercomparison Program (CMIP) DECK [1] simulation suite
- Use coupled emulator to learn and generate realistic climate trends including physical phenomena that emerge through the interaction of atmosphere and ocean (e.g. ENSO)

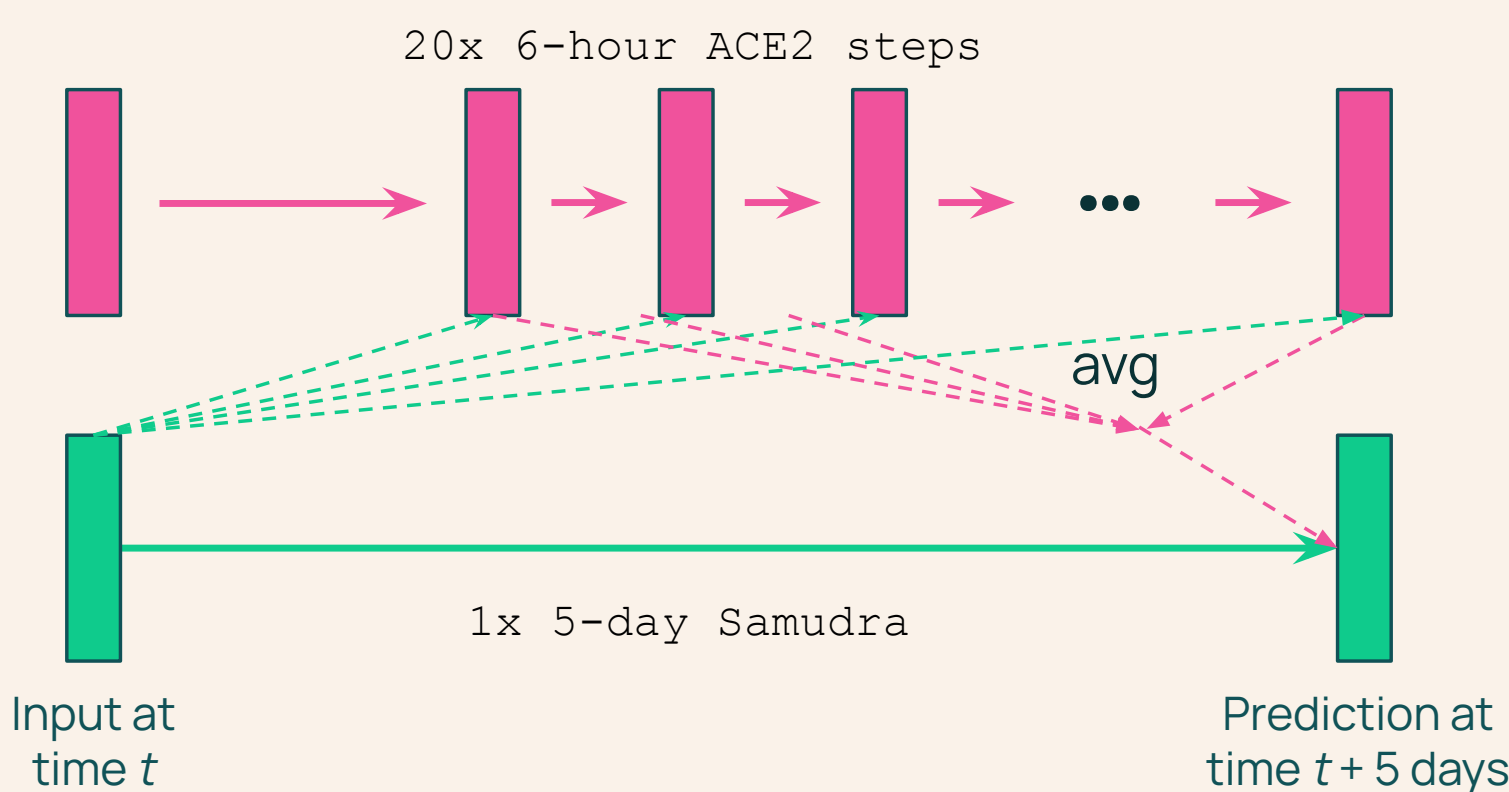


Figure 1: A single forward step of SamudrACE. ACE2 is forced by 5-day average SST and sea ice and steps forward 6 hours at a time for 5 days. Wind stress, precipitation, and surface fluxes are averaged and input as forcings to Samudra, which takes a single 5-day step forward.

Realm	Emulator	Temporal resolution	Horizontal resolution	Vertical resolution	Variables
Atmosphere	ACE2 [1]	6 hours	1°	33 levels coarsened to 8 levels	<u>3D prognostic</u> : T, Q, U, V <u>2D prognostic</u> : Surface temperature of land and sea ice, TMP2m, Q2m, U2m, V2m <u>2D diagnostic</u> : Upward/downward SW/LW flux at surface , upward SW/LW flux at TOA, precipitation , advective tendency of TWP, latent & sensible heat flux , Z500, T850, meridional & zonal wind stress
Ocean & sea ice	Samudra [2]	5 days	1/4° coarsened to 1°	75 levels coarsened to 19 levels	<u>3D prognostic</u> : Sea water potential temperature, salinity, zonal & meridional velocity <u>2D prognostic</u> : Sea surface temperature , sea surface height, sea ice fraction , sea ice thickness

Table 1: Atmosphere, ocean, and sea ice variables and their temporal, horizontal, and vertical resolutions as emulated by ACE2 and Samudra in uncoupled and coupled modes. Variables in **bold** act as surface boundary conditions.

Data and Methods

- 200-year pre-industrial control simulation from GFDL's Climate Model v4 (piCM4)
- Use the first 155 years of output for training, the next 5 years for validation, and hold out the remaining 40 years of data for testing
- Pretrain the atmosphere and ocean separately following ACE2 and Samudra's training protocols then do coupled fine-tuning
 - Include sea ice as prognostic variables in Samudra
 - Ocean is forced by 5-day average of atmosphere surface fluxes

Results

- The emulator has good long term climate skill – precipitation biases are concentrated in the tropics and surface temperature biases are largest in areas of sea ice and topographic features
- Maintains good sea ice climatology but underestimates interannual variability in the SH
- Different coupled fine-tuning strategies can impact ENSO response, SamudrACE loses low-frequency power beyond periods of 4 years

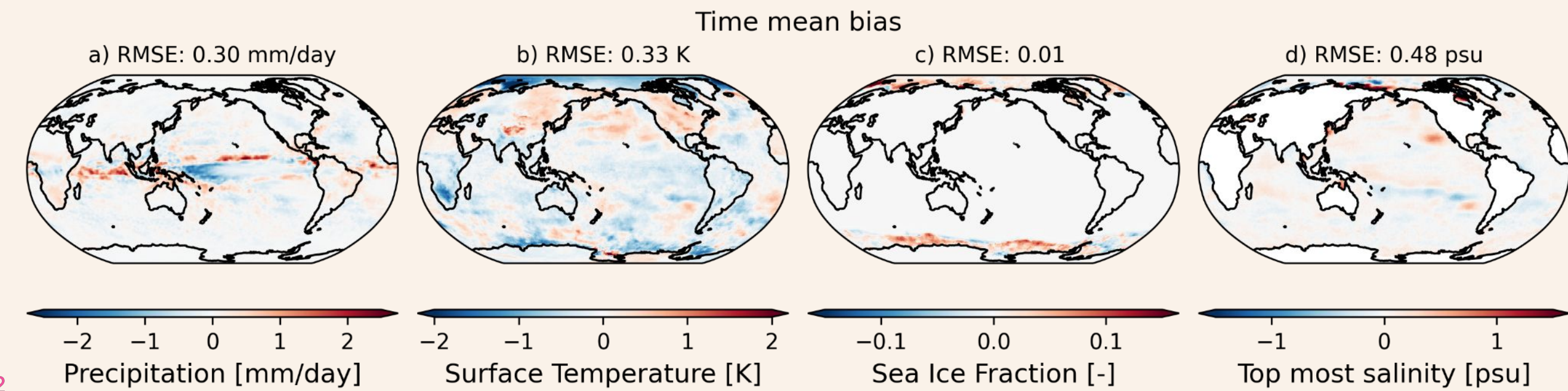


Figure 2: Time-mean bias of precipitation, surface temperature, sea ice fraction, and sea-surface salinity over the 40-year held-out inference period between SamudrACE and the piCM4 reference model.

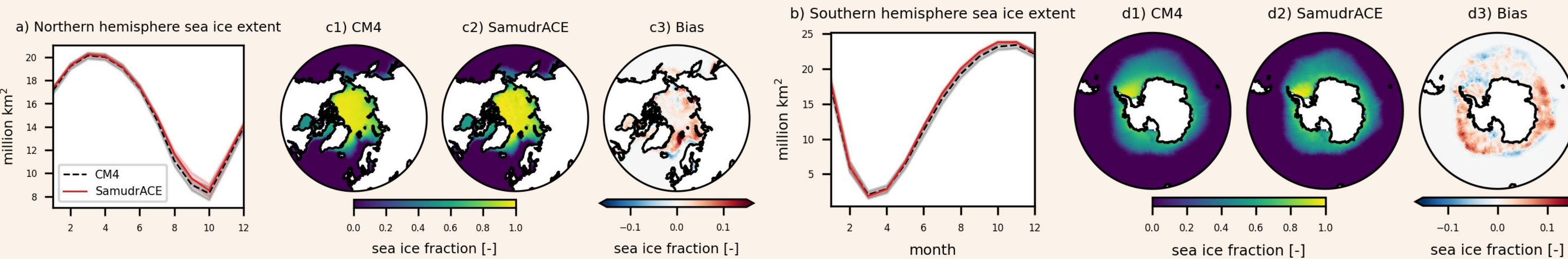


Figure 3: Monthly mean over the 40-year held-out period of (a) Northern and (b) Southern Hemisphere sea ice extent. Shading denotes the interannual standard deviation over 40 years. Panel c-d shows the time mean sea ice fraction over the same time period for the CM4 target, SamudrACE, and its bias.

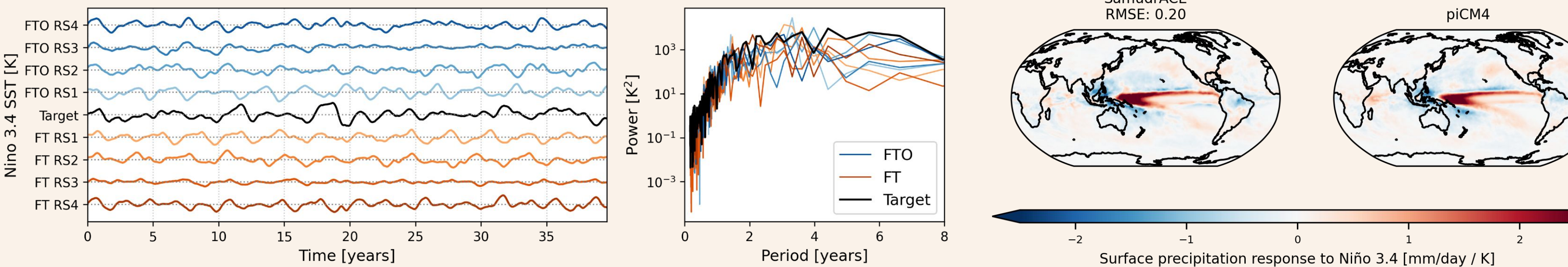


Figure 4: (left) Time series of monthly Niño3.4 index with coupled fine-tuning where only ocean MSE contribute to training losses (FTO) or both ocean and atmosphere MSE are considered (FT) for 4 different random seed each and their corresponding temporal power spectra. (right) Maps of surface precipitation response to Niño3.4 index for FTO RS1.

Summary

- SamudrACE maintains low climate biases comparable to its uncoupled component models while running 100x faster and 7350x less energy intensive than the reference numerical model
- SamudrACE generates realistic ENSO variability including the associated teleconnections to global precipitation patterns
- SamudrACE generally underestimates low-frequency variability on time scales longer than 4 years

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- [2] Held, I. M., Guo, H., Adcroft, A., Dunne, J. P., Horowitz, L. W., Krasting, J., et al. (2019). Structure and performance of GFDL's CM4.0 climate model. Journal of Advances in Modeling Earth Systems, 11, 3691–3727. <https://doi.org/10.1029/2019MS001829>
- [3] Watt-Meyer, O., Henn, B., McGibbon, J. et al. ACE2: accurately learning subseasonal to decadal atmospheric variability and forced responses. npj Clim Atmos Sci 8, 205 (2025). <https://doi.org/10.1038/s41612-025-01090-0>
- [4] Dheeshjith, S., Subel, A., Adcroft, A., Busecke, J., Fernandez-Granda, C., Gupta, S., & Zanna, L. (2025). Samudra: An AI global ocean emulator for climate. Geophysical Research Letters, 52, e2024GL114318. <https://doi.org/10.1029/2024GL114318>