**NOAA S2S Community Workshop:**
**Toward Minimizing Early Model Biases and Errors in S2S Predictions**
**Boulder, CO**
**June 5, 2024**

# Towards Reduced Error in Climate Forecasts: A CESM Perspective

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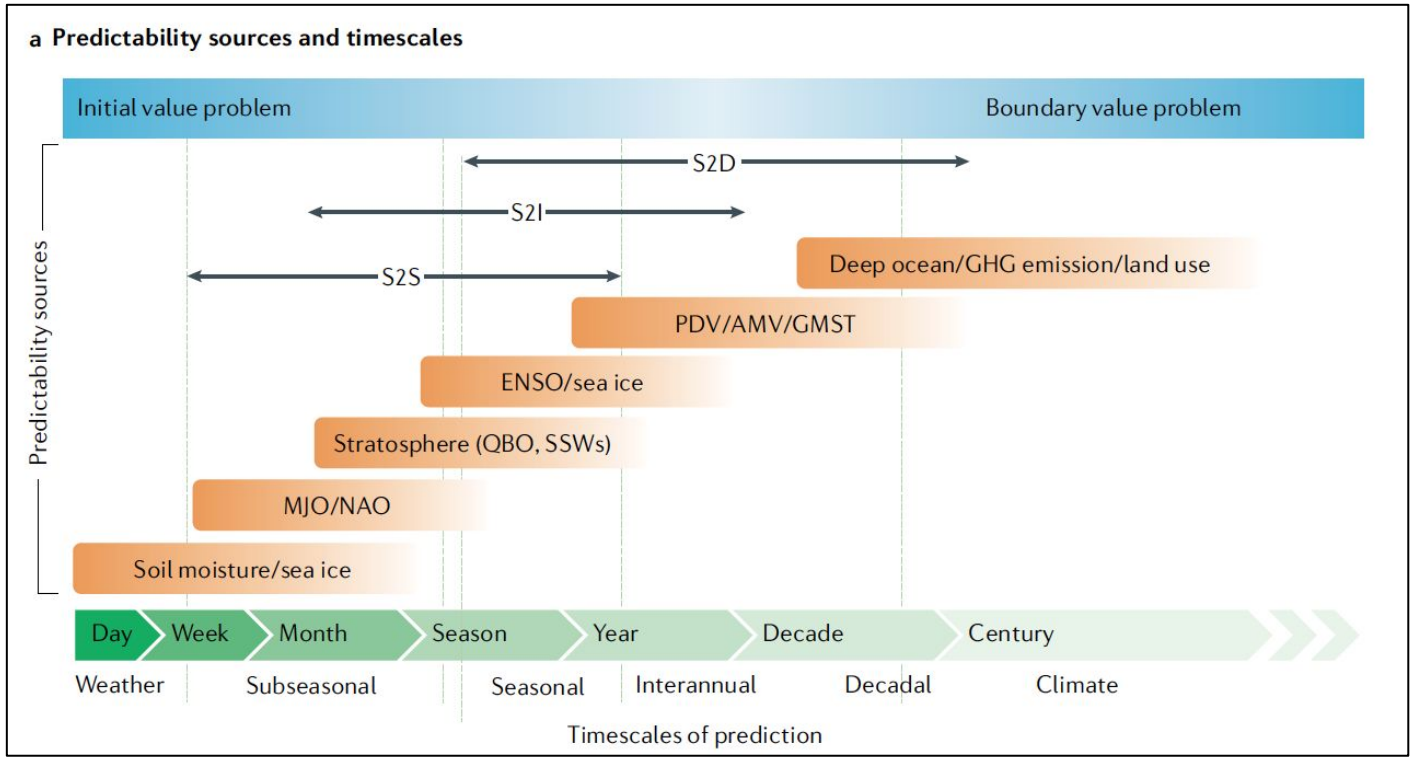
# Initialized Earth System Prediction with CESM

- CESM's Earth System Prediction Working Group (ESPWG) was founded in 2020 to coordinate initialized prediction research across the CESM community

- Provides a community nexus for climate prediction research:

  - fundamental origins, mechanisms, and limits of Earth system predictability
  - fidelity of coupled model behavior
  - potential to deliver reliable, actionable advanced warning of near-term regional environmental change

**Initialized Prediction** **Forced Projection**




Meehl et al. (2021, *Nature Reviews*, 10.1038/s43017-021-00155- x)

# Initialized Earth System Prediction with CESM

## PREDICTING NEAR-TERM CHANGES IN THE EARTH SYSTEM

### A Large Ensemble of Initialized Decadal Prediction Simulations Using the Community Earth System Model

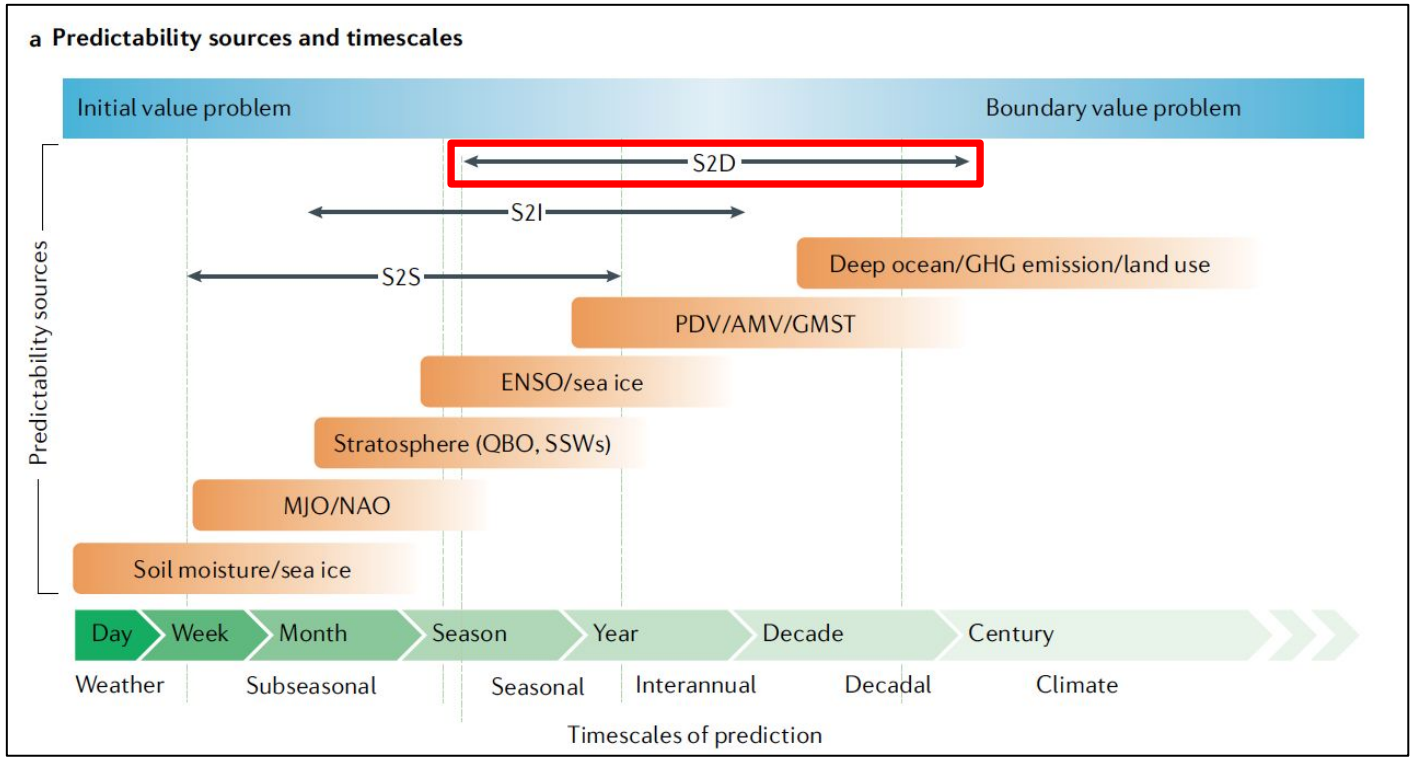
S. G. Yeager, G. Danabasoglu, N. A. Rosenbloom, W. Strand, S. C. Bates, G. A. Meehl, A. R. Karspeck, K. Lindsay, M. C. Long, H. Teng, and N. S. Lovenduski

Yeager et al. (2018, *BAMS*, 10.1038/s41612-019-0071-y)

S2D system design (WCRP-DCPP protocol):

- Annual initializations (Nov. 1st 1954-2020)
- 122-month simulations
- 40-member ensembles

 ~27,000 sim-years




Meehl et al. (2021, *Nature Reviews*, 10.1038/s43017-021-00155- x)

# Initialized Earth System Prediction with CESM

Geosci. Model Dev., 15, 6451–6493, 2022
https://doi.org/10.5194/gmd-15-6451-2022


Geoscientific Model Development
Open Access
EGU

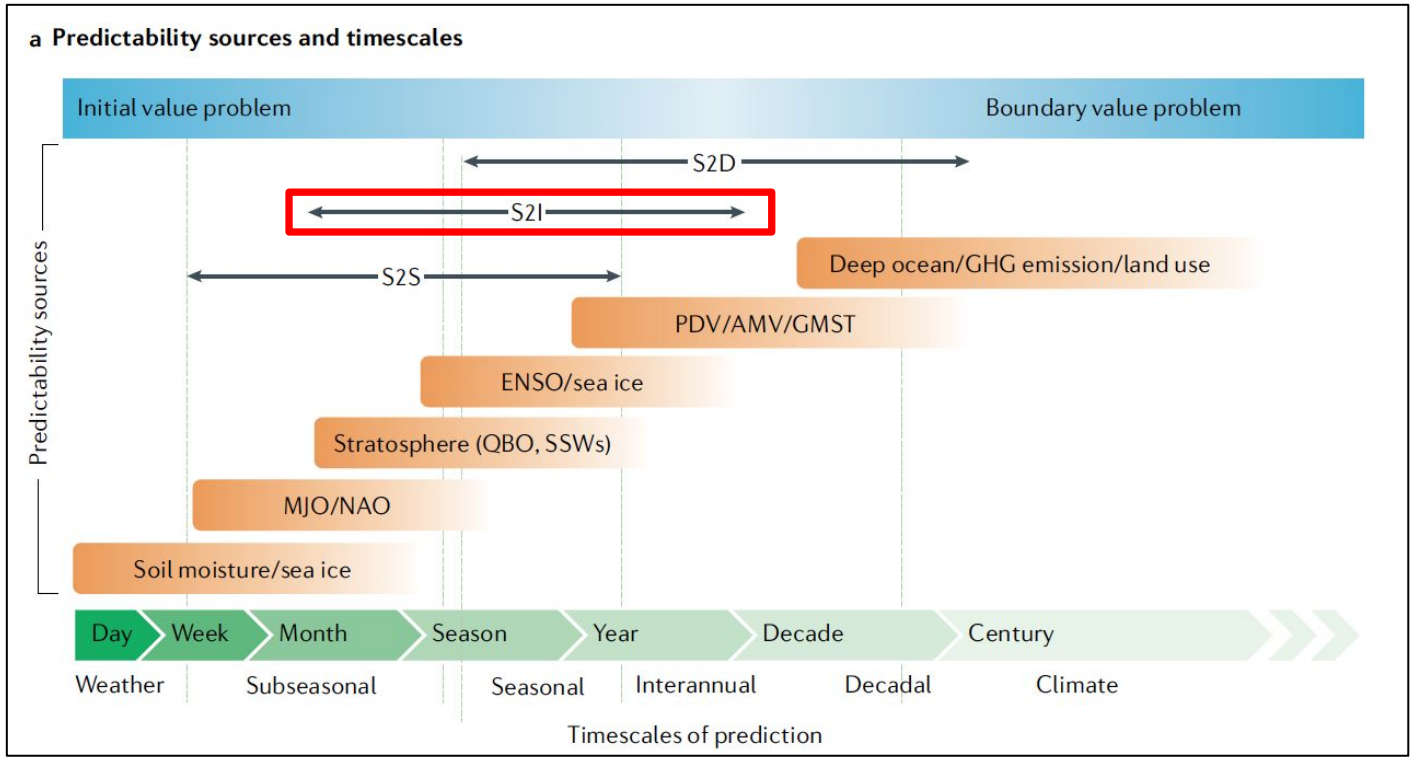
## The Seasonal-to-Multiyear Large Ensemble (SMYLE) prediction system using the Community Earth System Model version 2

Stephen G. Yeager[1], Nan Rosenbloom[1], Anne A. Glanville[1], Xian Wu[1], Isla Simpson[1], Hui Li[1], Maria J. Molina[1], Kristen Krumhardt[1], Samuel Mogen[2], Keith Lindsay[1], Danica Lombardozzi[1], Will Wieder[1], Who M. Kim[1], Jadwiga H. Richter[1], Matthew Long[1], Gokhan Danabasoglu[1], David Bailey[1], Marika Holland[1], Nicole Lovenduski[2], Warren G. Strand[1], and Teagan King[1]

S2I system design (emerging protocol):

- Quarterly initializations (1st of Nov/Feb/May/Aug 1958-2020)
- 24-month simulations
- 20-member ensembles

□ ~10,000 sim-years




Meehl et al. (2021, *Nature Reviews*, https://doi.org/10.1038/s43017-021-00155- x)

# Initialized Earth System Prediction with CESM

VOLUME 37 WEATHER AND FORECASTING JUNE 2022

**Subseasonal Earth System Prediction with CESM2**

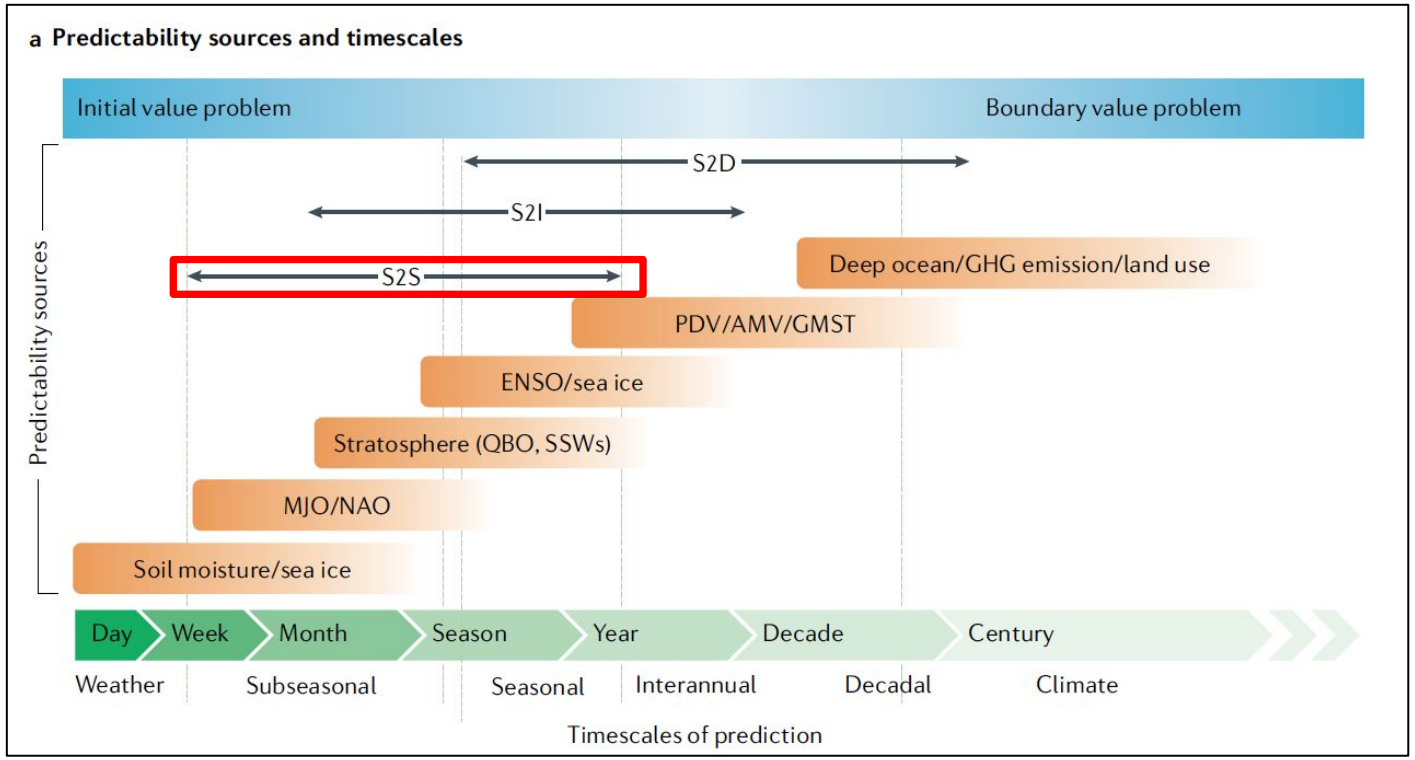
JADWIGA H. RICHTER,[a] ANNE A. GLANVILLE,[a] JAMES EDWARDS,[a] BRIAN KAUFFMAN,[a] NICHOLAS A. DAVIS,[b] ABIGAIL JAYE,[c] HYEMI KIM,[d] NICHOLAS M. PEDATELLA,[e] LANTAO SUN,[f] JUDITH BERNER,[c,a] WHO M. KIM,[a] STEPHEN G. YEAGER,[a] GOKHAN DANABASOGLU,[a] JULIE M. CARON,[a] AND KEITH W. OLESON[a]

Richter et al. (2022, *Wea. Forecasting*, 10.1175/WAF-D-21-0163.1)

S2S system design (SubX protocol):

- Weekly initializations (1999-2020)
- 45-day simulations
- 11-member ensembles

 ~1,600 sim-years




Meehl et al. (2021, *Nature Reviews*, 10.1038/s43017-021-00155- x)

# ESPWG Common Elements Across Timescales

- Use of fully-coupled “workhorse” (~1°) CESM model to produce baseline climate hindcast datasets

- Full field initialization:
  - Ocean/Ice: CESM forced ocean/sea-ice (FOSI) simulations (OMIP1, OMIP2)
    - leverages experience/expertise of CESM-OMWG
  - Land: CESM forced land-only simulations
    - leverages experience/expertise of CESM-LMWG
  - Atm: Interpolated atmospheric analysis products (ERA-I, JRA55, MERRA-2)

- Sharing of data, tools, experimental frameworks, compute resources

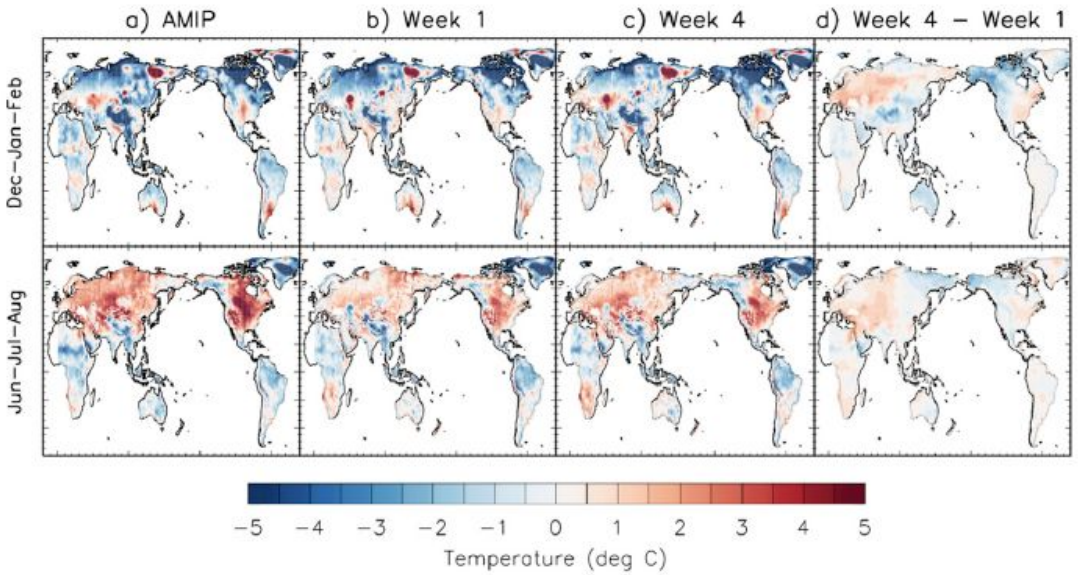
- Focus on facilitating basic predictability research & engagement with interdisciplinary CESM community:
  - emphasis on agile experimentation & exploration of mechanisms
  - interest in real-time predictions for research applications

- Limited efforts thus far to document/understand/address the impacts of model bias & time-dependent error
  - focus on bias-corrected anomaly skill

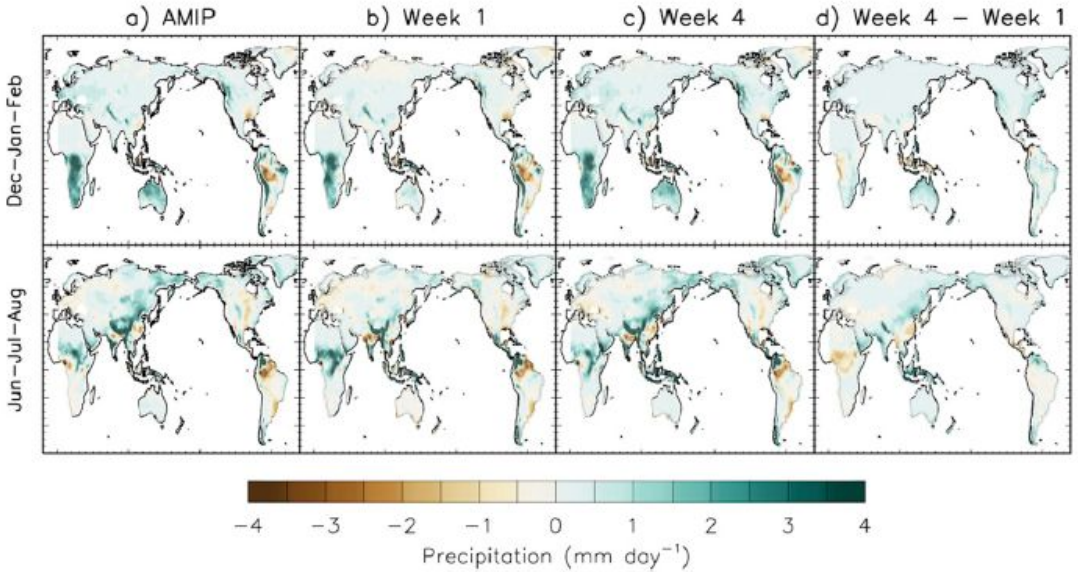
# CESM-S2S

- Rapid (week 1) development of AMIP-like bias in CESM1-S2S hindcasts highlights (fast physics) errors intrinsic to atmosphere model

**Temperature Bias:**



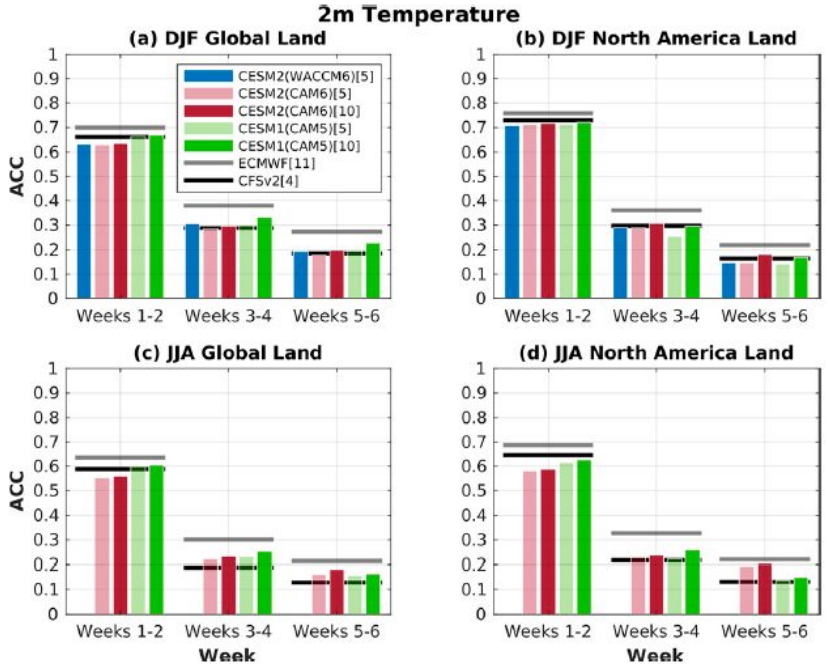

**Precipitation Bias:**




Richter et al. (2020, *Weather and Forecasting*)

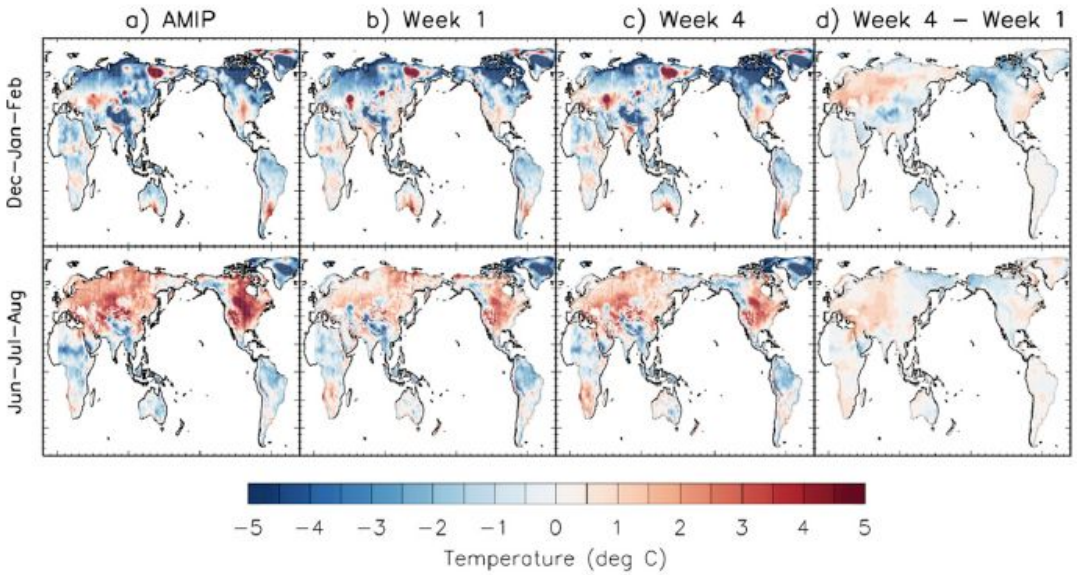
# CESM-S2S

- After removing mean bias, CESM S2S skill is competitive and relatively insensitive to model version (CESM1 outperforms CESM2 despite substantial model improvements: see Danabasoglu et al. 2020; Simpson et al. 2022).

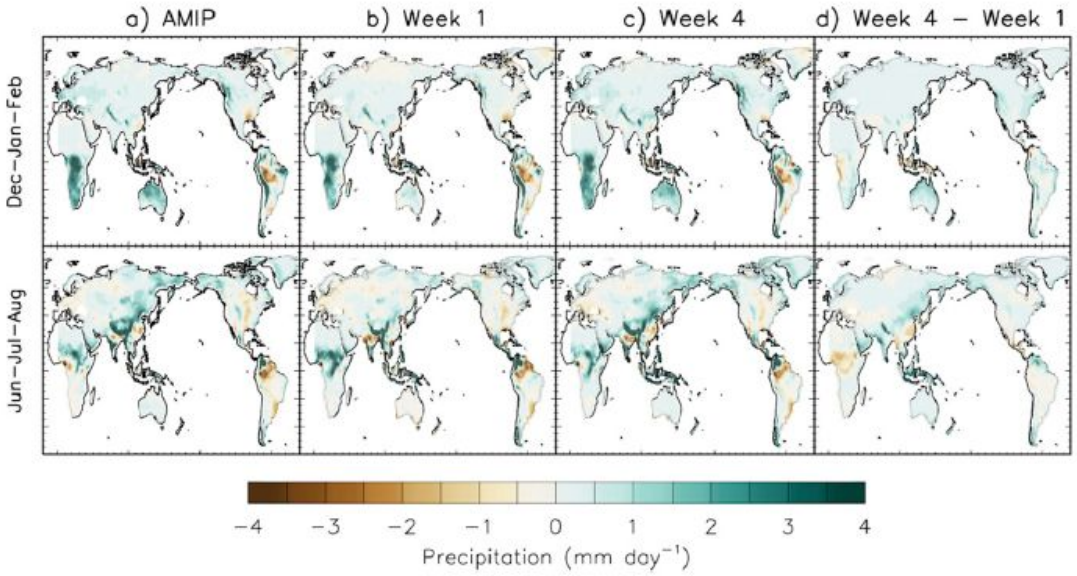



Richter et al. (2022, *Weather and Forecasting*)

**Temperature Bias:**




**Precipitation Bias:**

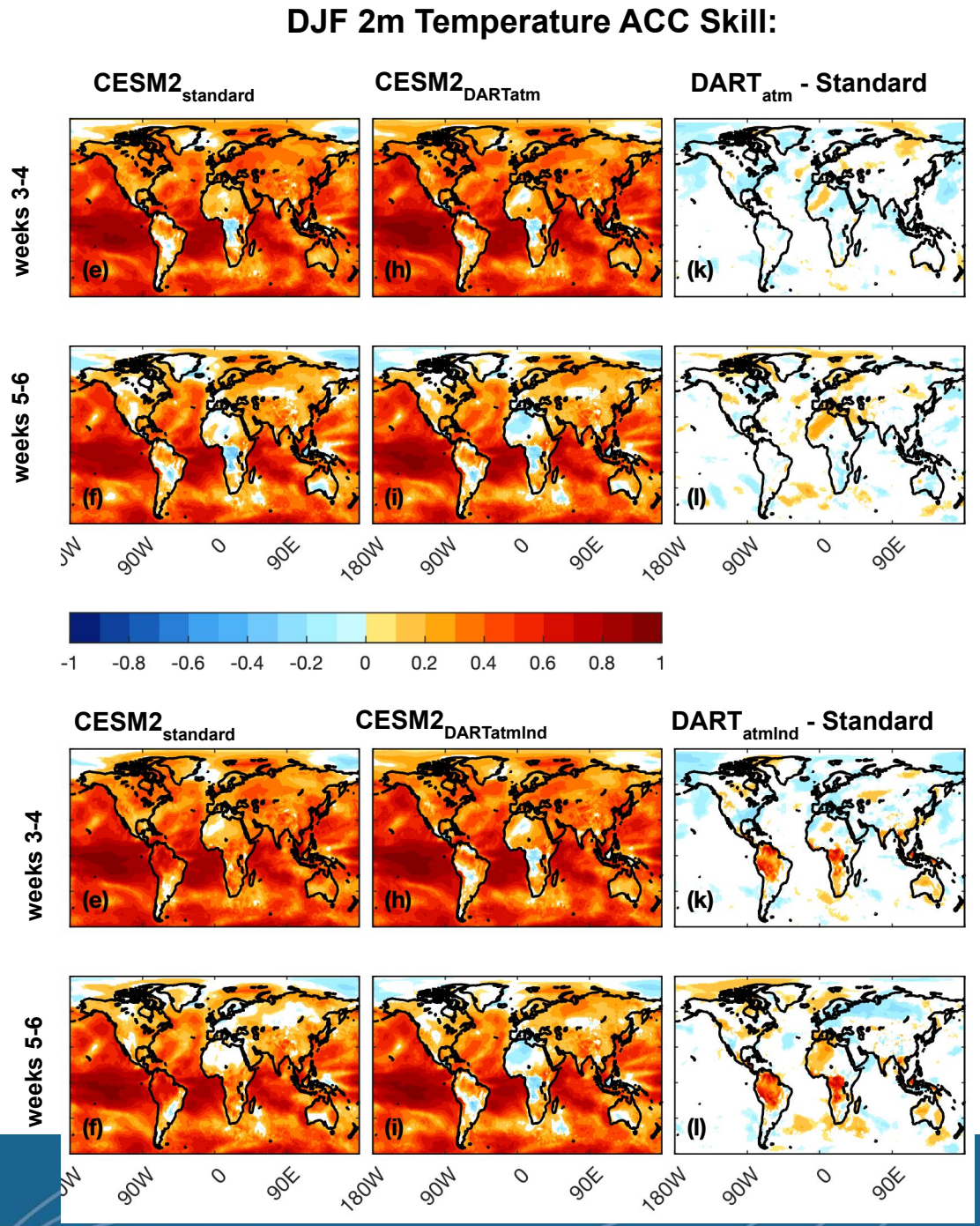



Richter et al. (2020, *Weather and Forecasting*)

# CESM-S2S

Ongoing efforts to improve CESM-S2S skill include:

- Initialization from CESM land/atm data assimilation (DART) (Glanville/Raeder)
- Inclusion of stochastic parameterization & online nudging (Berner/Chapman)
- ML-based offline bias correction (Mayer/Molina)
- Improved land-atmosphere coupling (Richter/Fowler)



# Skill of North American Subseasonal Prediction Systems

- Coordinated protocols permit multi-model ensembles that consistently outperform single-model systems.

SubX: Pegion et al. (2019, *BAMS*)
NMME: Becker et al. (2020, *GRL*)
DCPP: Smith et al. (2020, *Nature*)

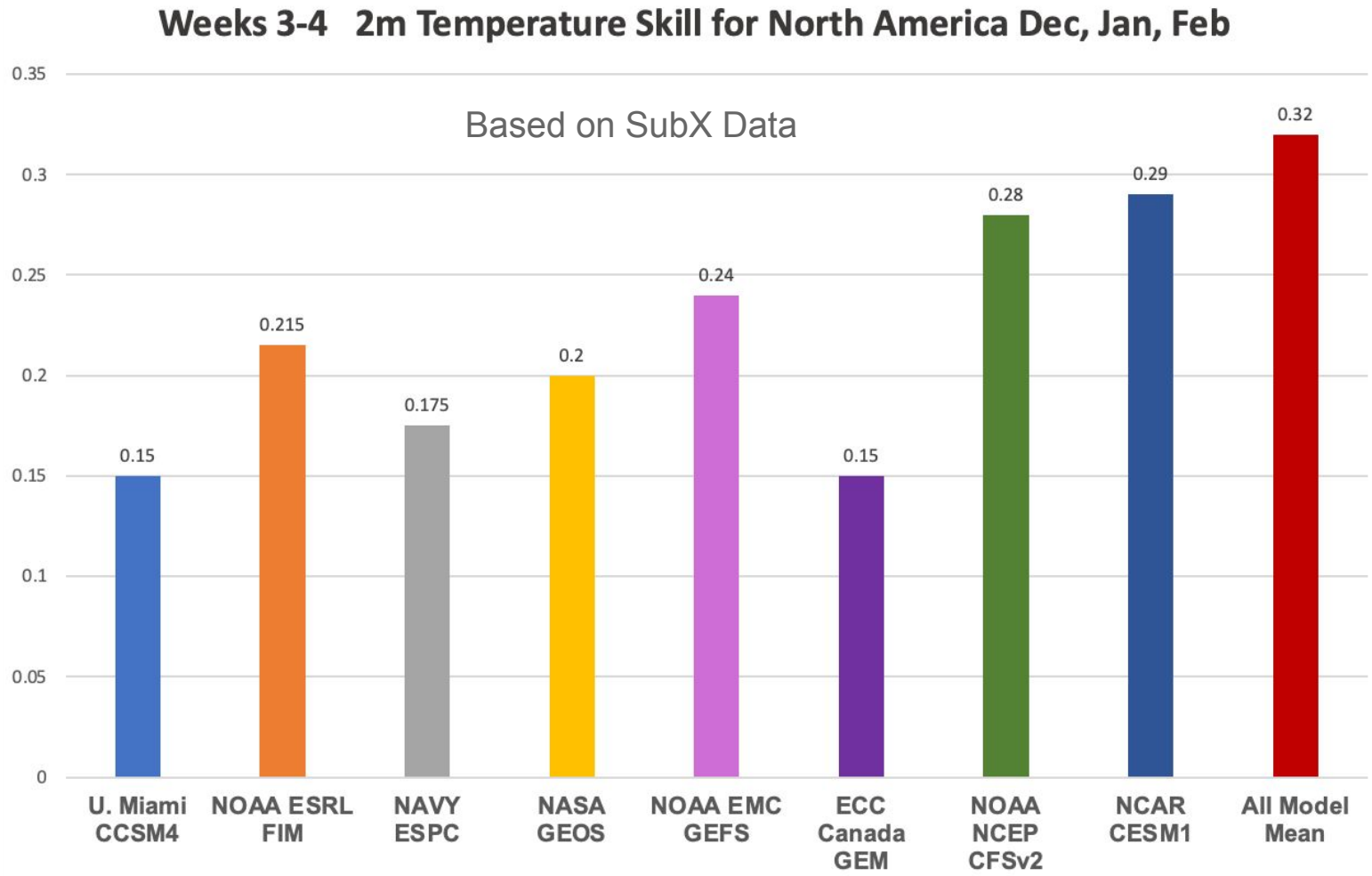
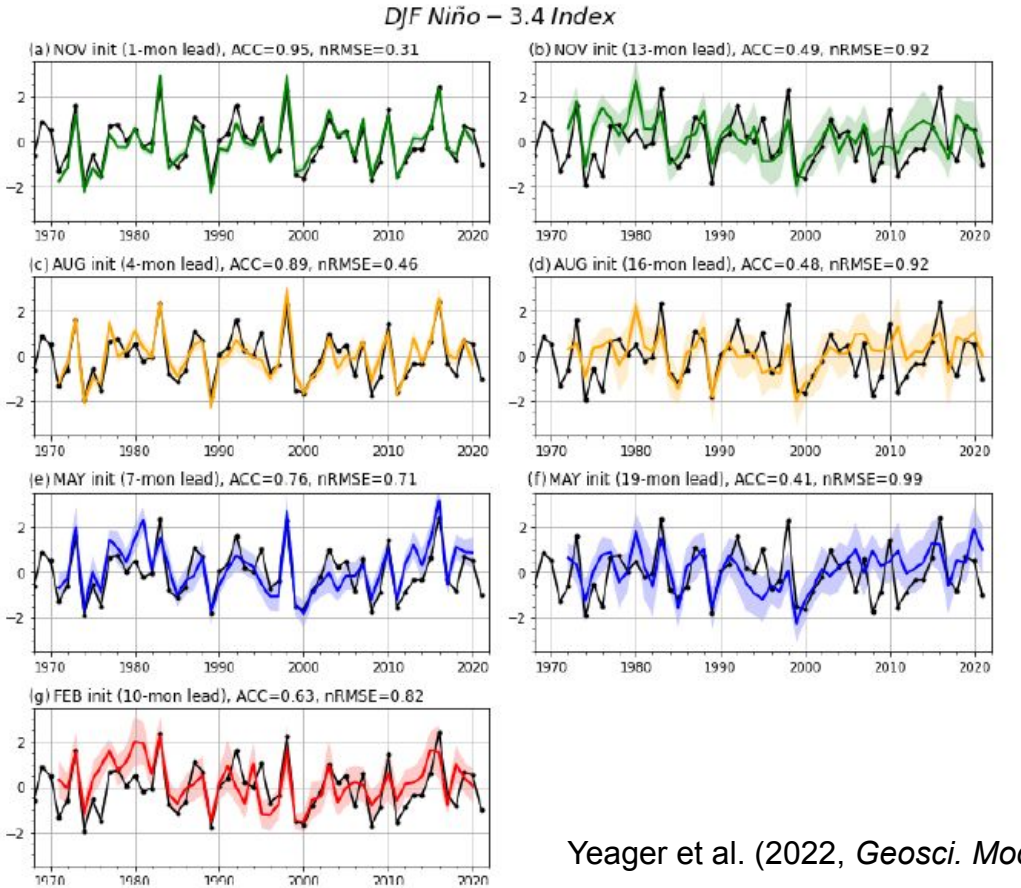



Figure from Kathy Pegion

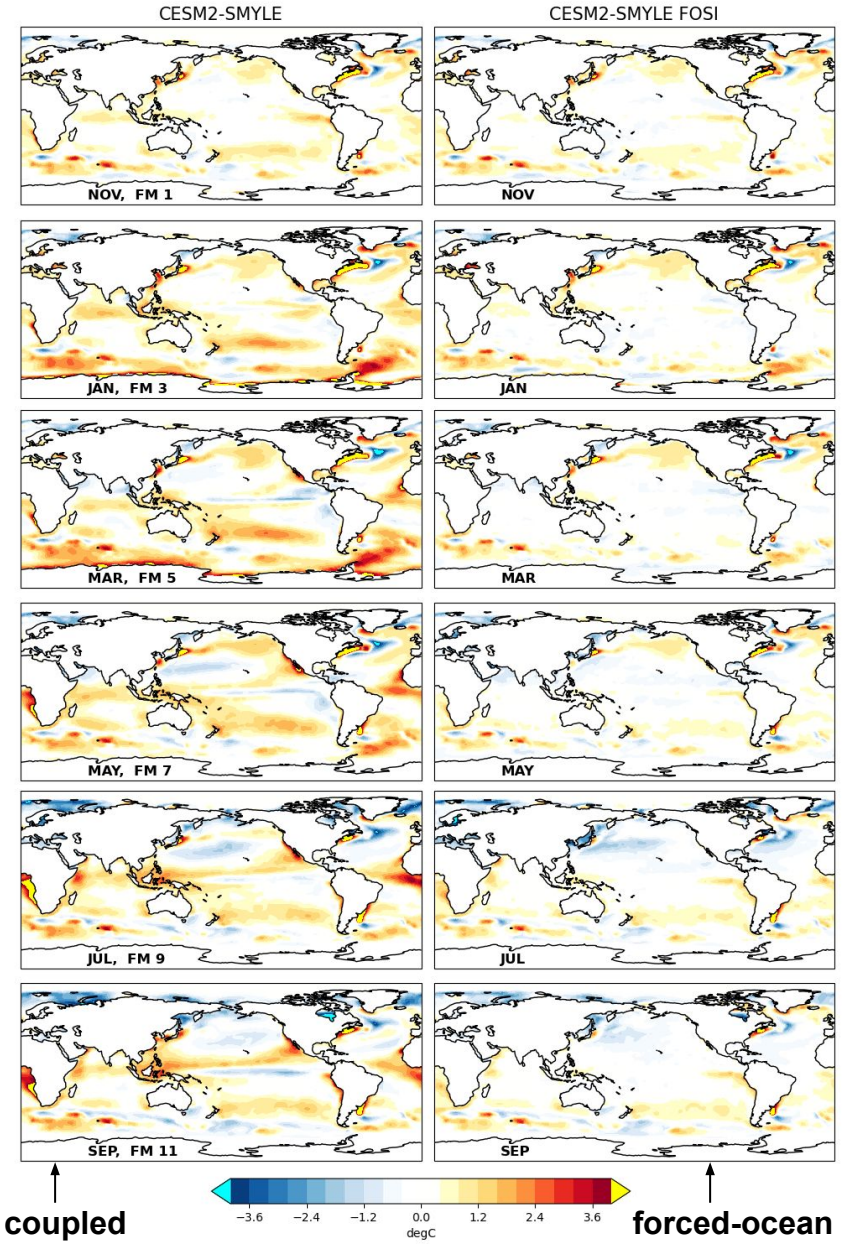
# Extended Seasonal

- CESM2-SMYLE has competitive ENSO skill despite imperfect initialization & rapid growth of coupled model bias




Yeager et al. (2022, *Geosci. Mod. Dev.*)

**CESM2-SMYLE SST Bias (NOV init):**



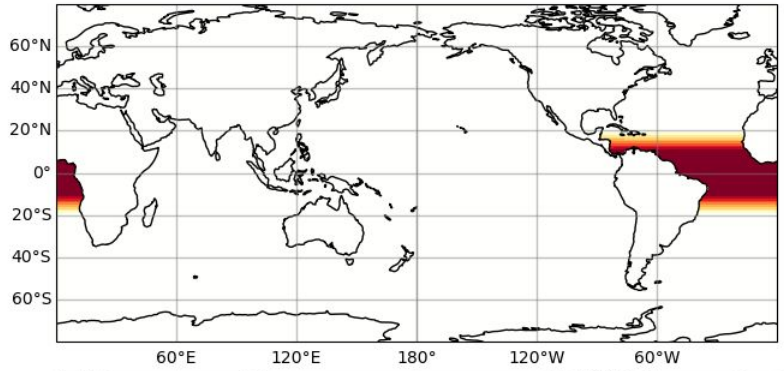
# Extended Seasonal

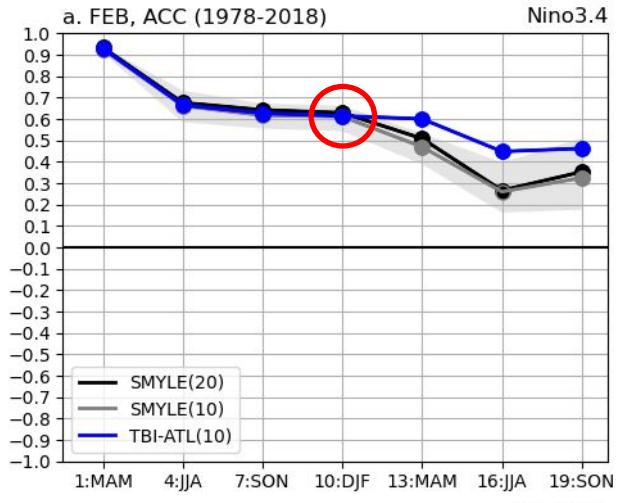
What is the impact of time-dependent SST error?

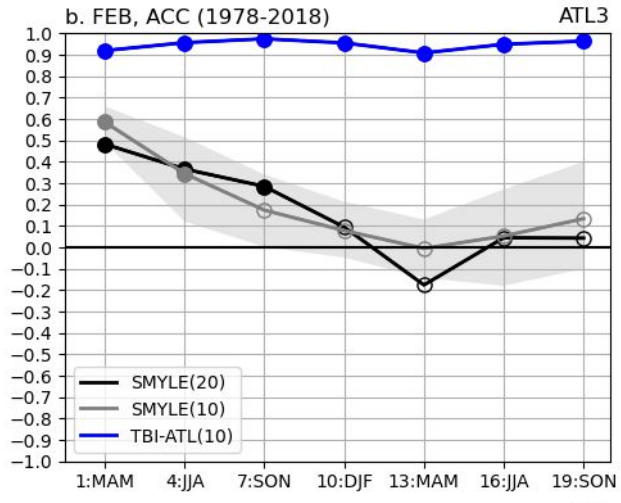
- CESM contribution to CLIVAR Tropical Basin Interaction (TBI) Panel coordinated seasonal hindcast pacemaker experiments

 CESM2-SMYLE DJF Niño3.4 skill is not enhanced by tropical Atlantic restoring (Feb init, 10-month lead)

**TBI-ATL**
Restoring Region:

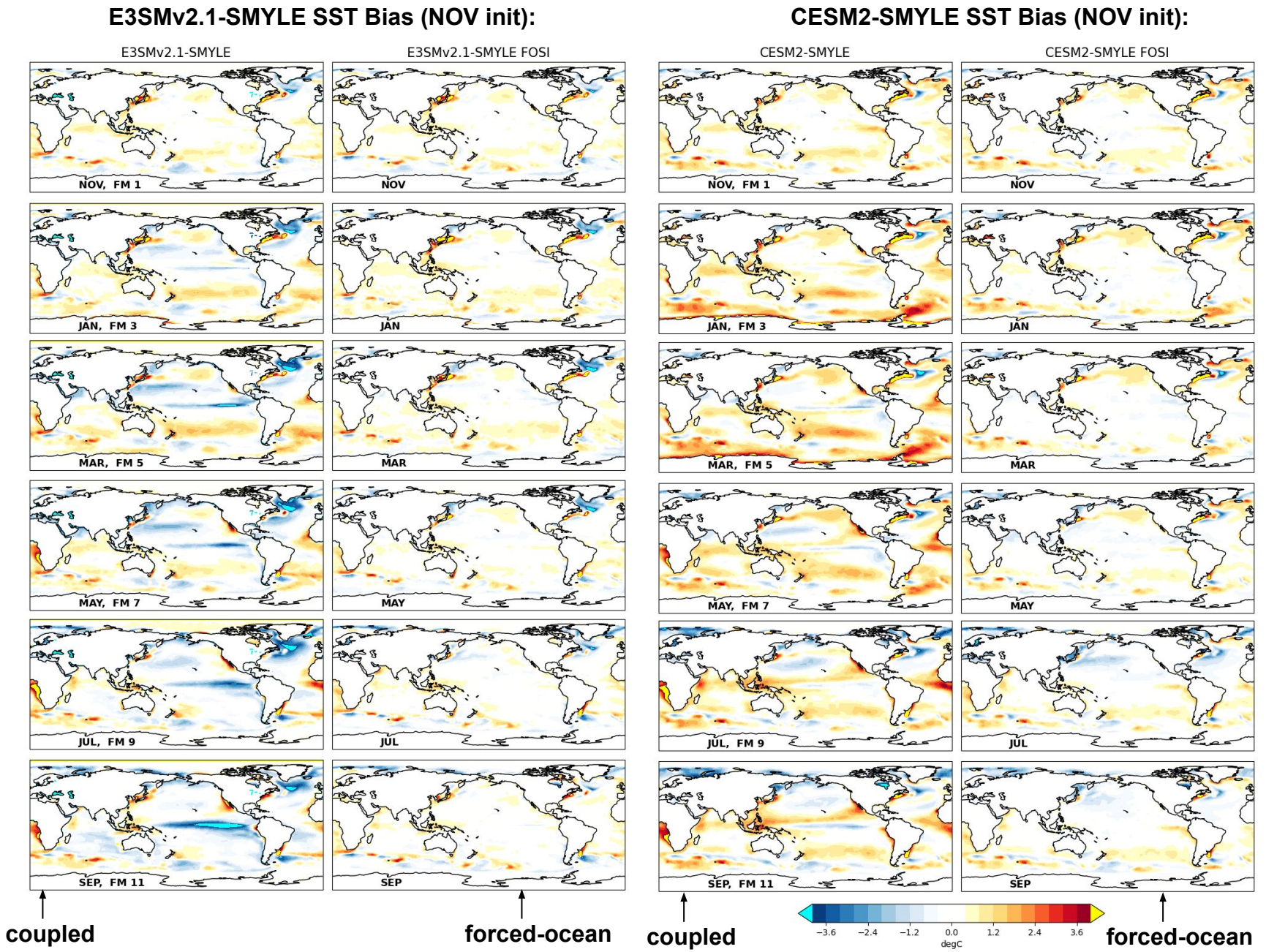


# Extended Seasonal

- New E3SMv2.1-SMYLE system has very different bias/error characteristics



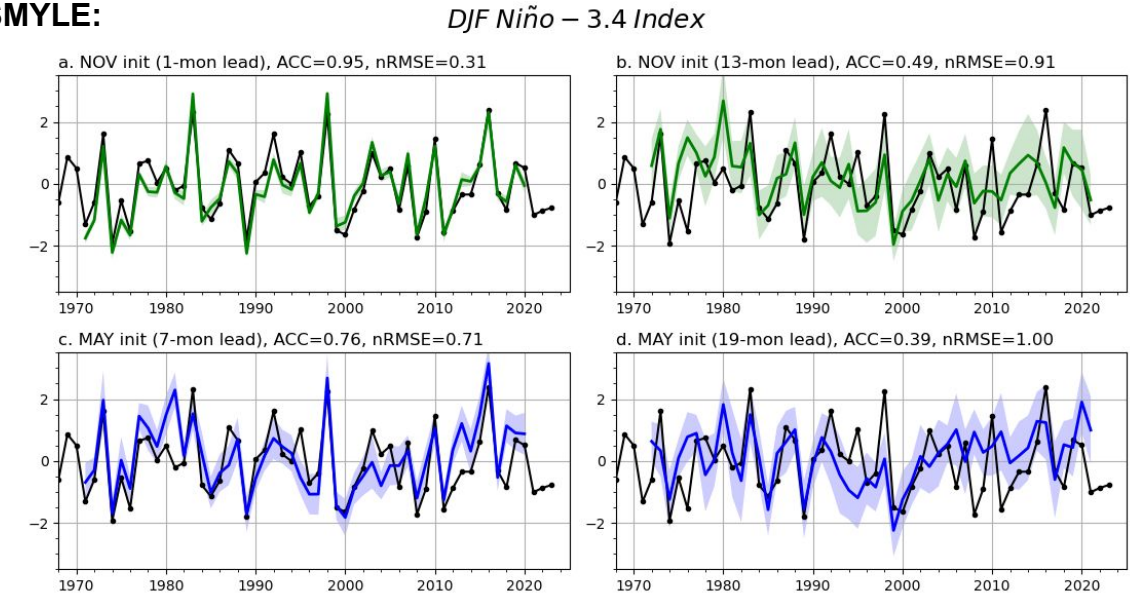

catalyst
Cooperative agreement to analyze variability, change and predictability in the earth system

# Extended Seasonal

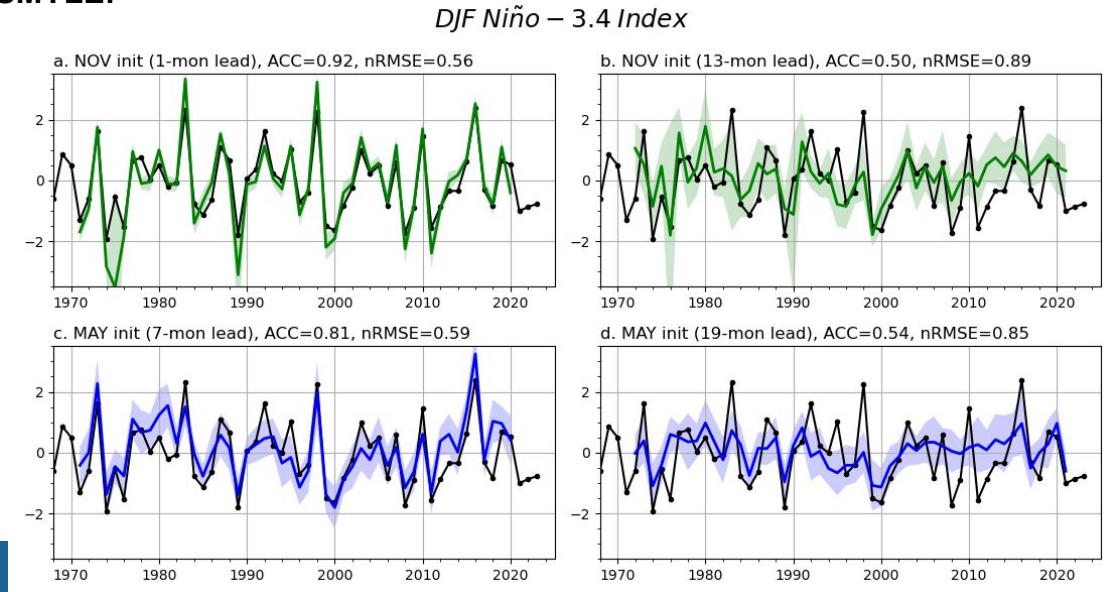
- New E3SMv2.1-SMYLE system has very different bias/error characteristics
- Near-equivalent skill for DJF Niño3.4
- Combined multi-model ensemble generally outperforms either individual system for climate impacts

 In-depth comparison of twin prediction systems could yield insights into how model process representation/error relates to skill

**CESM2-SMYLE:**




**E3SMv2.1-SMYLE:**



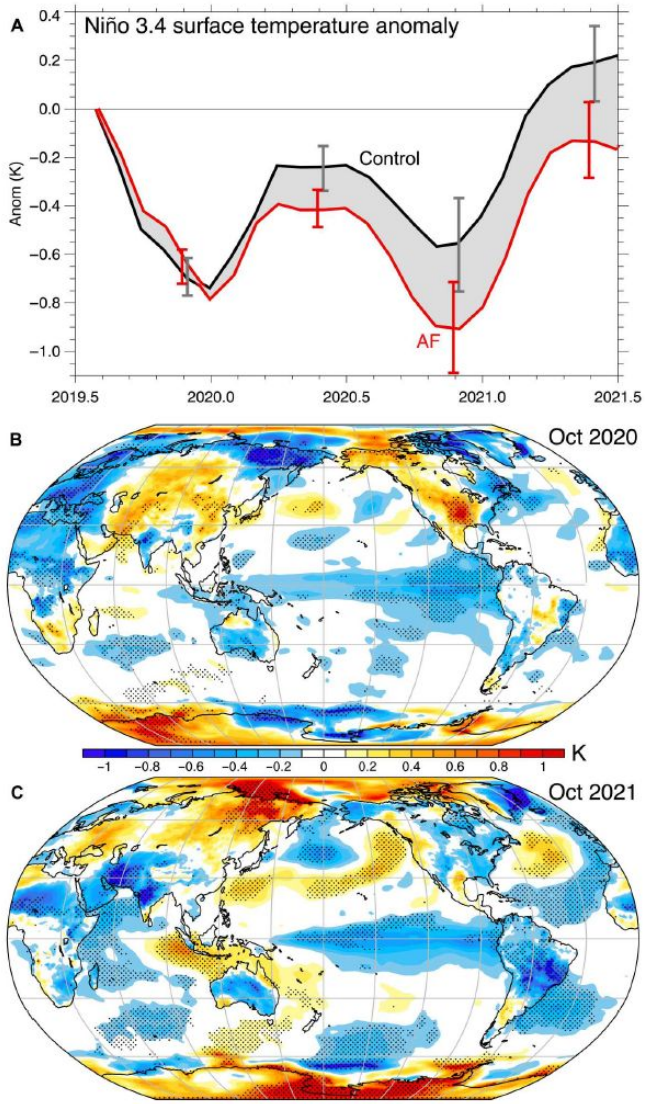

catalyst
Cooperative agreement to analyze variability, change and predictability in the earth system

NSF NCAR Operated by UCAR

# Extended Seasonal

Other efforts to improve understanding of error/bias in CESM-S2I include:

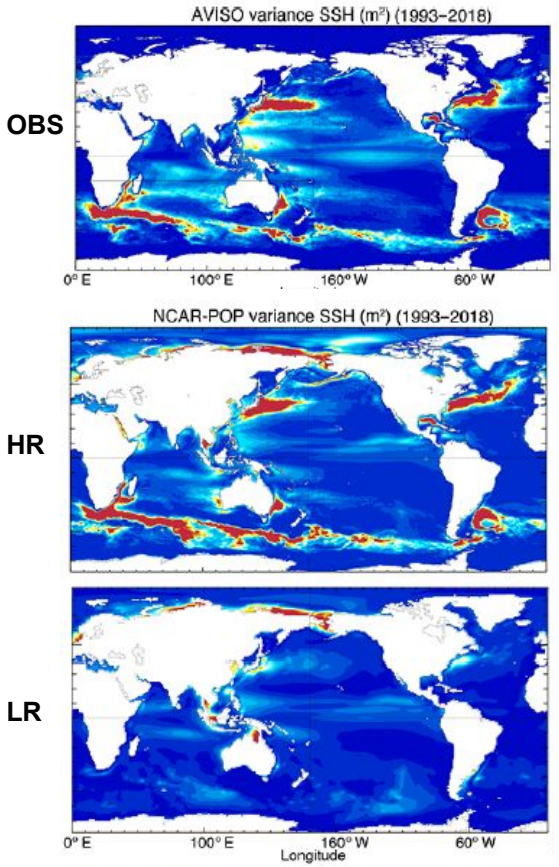
- SMYLE with high-top atmosphere (collaboration between Scripps CW3E & NCAR)
- SMYLE with more realistic aerosol radiative forcing (Fasullo)




Fasullo et al. (2023, *Sci. Adv.*)

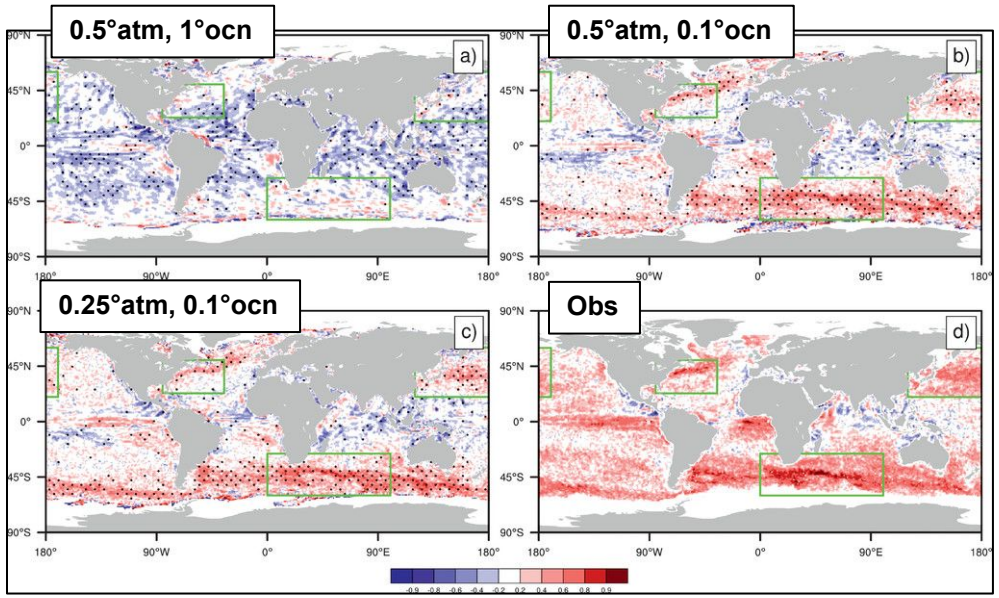
# Decadal

Improved ocean variability:



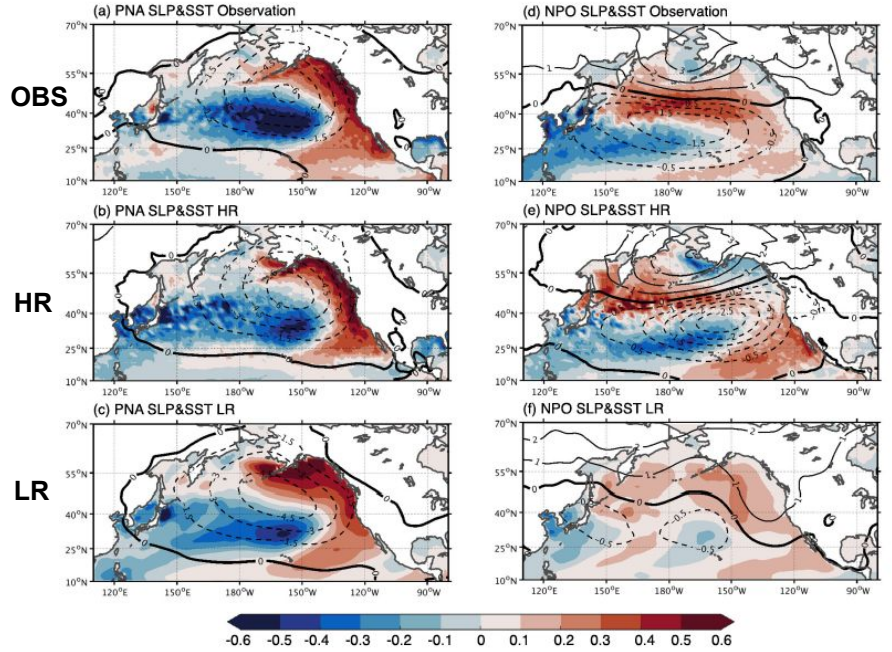

Chassignet et al. (2020)

More realistic air-sea interaction:




Bryan et al. (2010), Small et al. (2019), Laurindo et al. (2022)

Improved MoV:



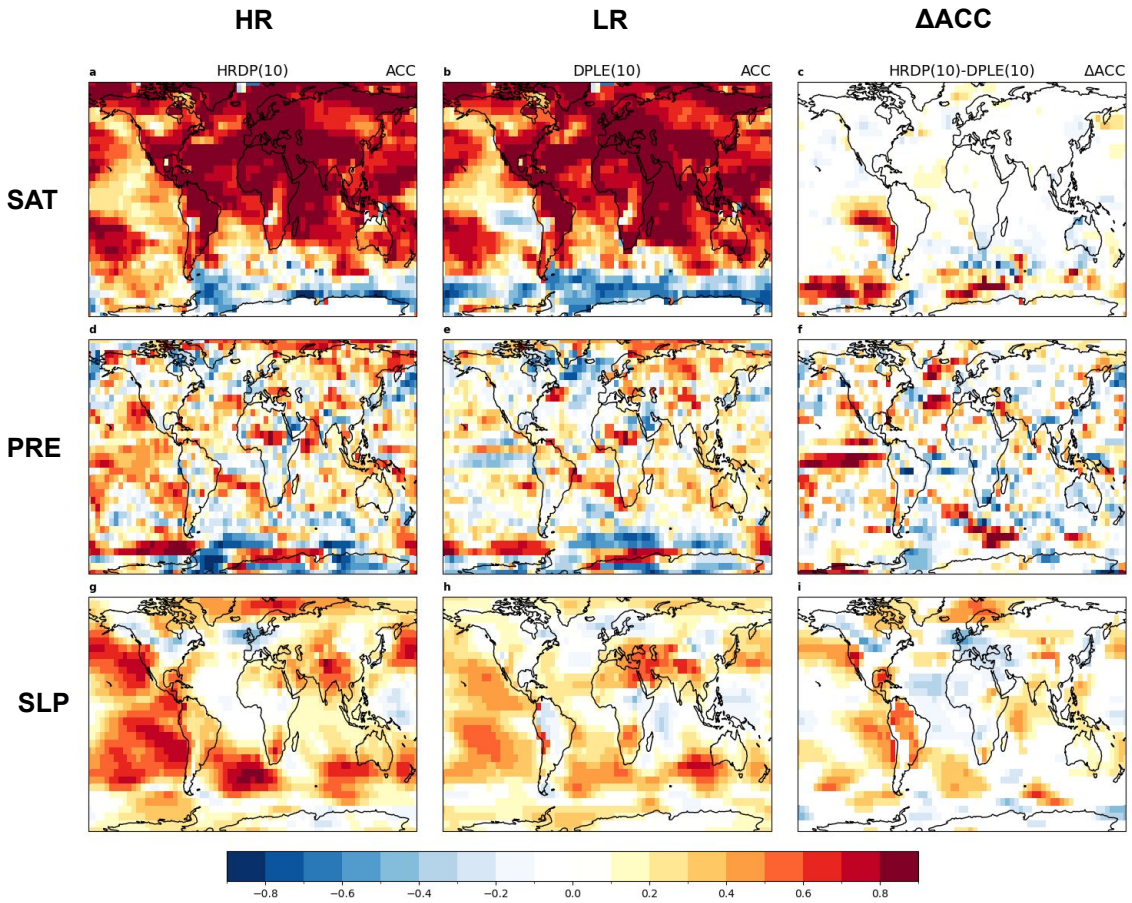

Chang et al. (2020)

- Abundant and growing evidence that high-resolution (~0.1° ocean; ~0.25° atmosphere) significantly improves process representation and reduces bias

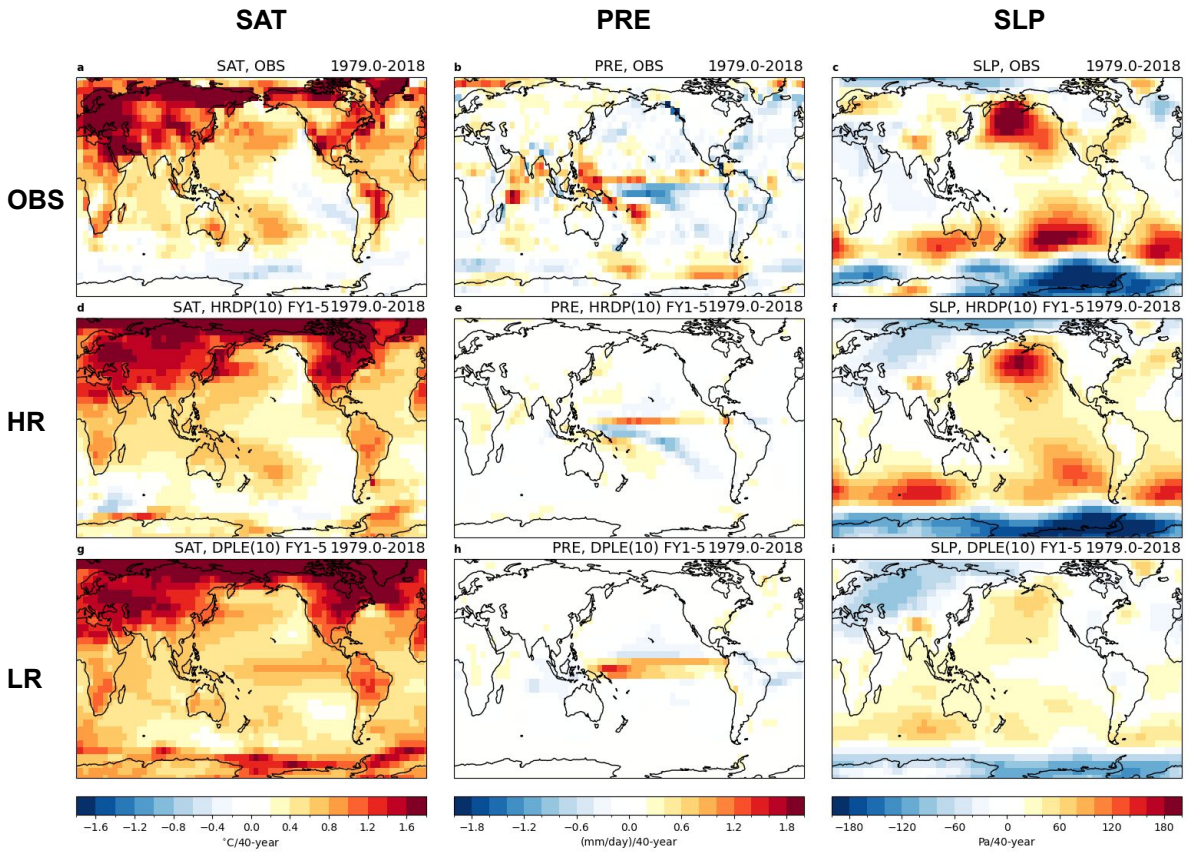
**Hypothesis**: Improved simulation fidelity with high-resolution will translate into more skillful and useful regional S2D predictions.

# Decadal

ACC Skill:




Multidecadal Trends:




- Widespread skill increase in CESM1 HR decadal prediction system compared to LR.

- Amelioration of longstanding Pacific trend bias

Yeager, Chang, Danabasoglu, et al. (*npj Clim Atm Sci,* 2023, https://doi.org/10.1038/s41612-023-00434-y)

# CESM Lessons Learned

- Community input is crucial
  - data/framework sharing
  - technical support for broad CESM community to test new ideas
  - entrainment of early career researchers

- Significant progress can be made with non-operational, research-oriented prediction systems
  - current methods work well for basic research & exploration of novel capabilities (e.g., HR, ocean BGC)
  - further advancements will likely require formal DA native to CESM

- Coordinated multi-model prediction experiments provide useful insight
  - multi-model means remain the lowest hanging fruit for addressing model bias/error
  - multi-model comparisons help to advance understanding

- Unified {subseasonal, seasonal-to-multiyear, decadal} effort is advantageous
  - Seamless system promotes cross-fertilization

- High-resolution may offer a step-change in process representation and climate prediction skill
  - more impactful than incremental improvements in LR?
  - will improvements seen in HR decadal translate to S2S?