# CATALYST

## *Cooperative Agreement To Analyze variabiLity, change and predictabilitY in the earth SysTem*

**Gerald Meehl**

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Boulder, CO

NCAR
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

U.S. DEPARTMENT OF ENERGY
Office of Science
Biological and Environmental Research
Regional and Global Model Analysis

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

## CATALYST represents a formal cooperative agreement between DOE and UCAR/NCAR

### Why a cooperative agreement?

**DOE and NCAR have shared scientific objectives,
so the combination of funding from DOE and NCAR leverages the efforts of a larger group of scientists than could be assembled from within each organization alone.**

The 22 members of the CATALYST team have funding from DOE (4 at 100%, 18 with partial DOE funding) with the remaining percentages of support coming mostly from UCAR/NCAR

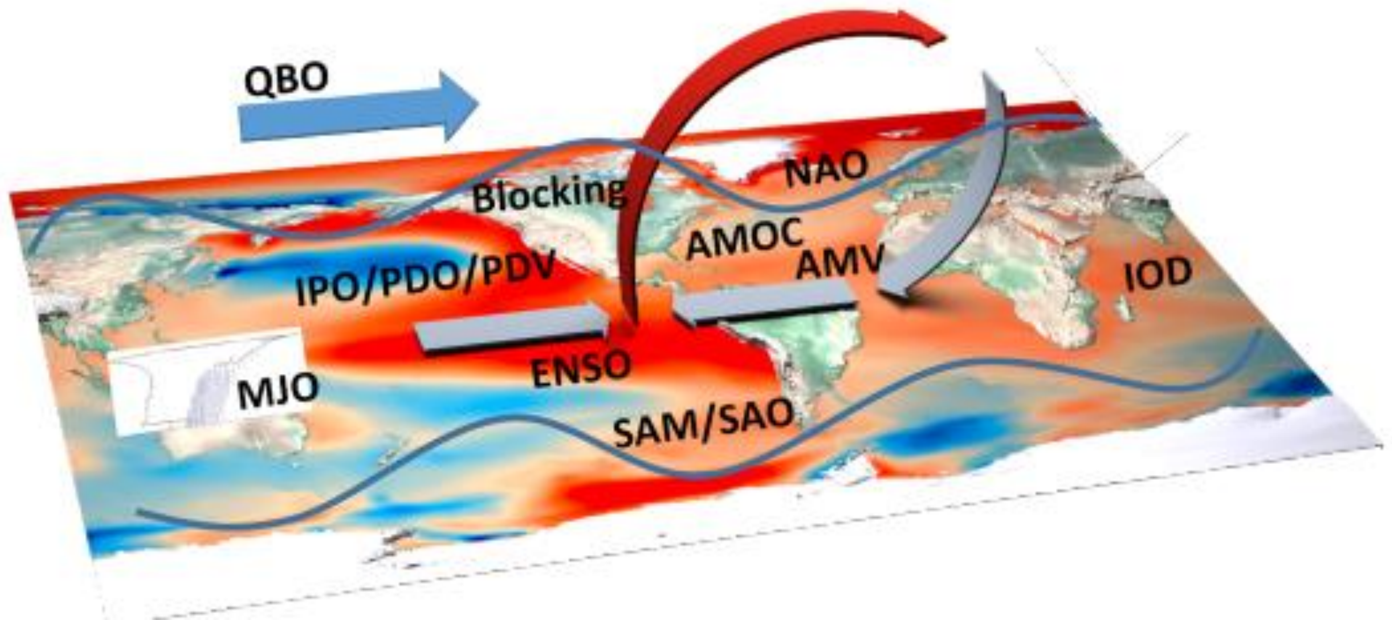
**Diversity:** CATALYST is committed to fostering diversity in the scientific community. The current CATALYST team includes 12 females and 10 males

# CATALYST science contributions to RGMA:

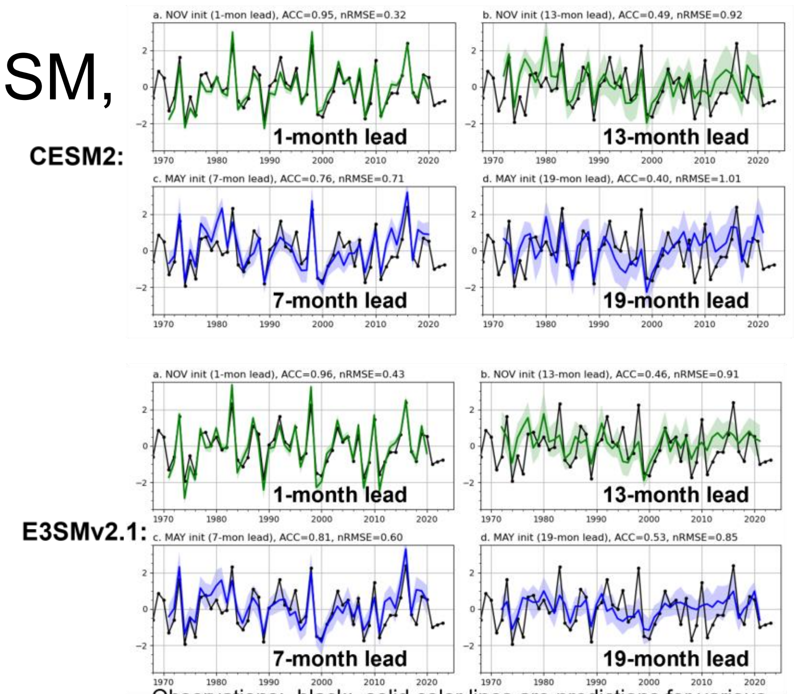
## --modes of variability (MOV)

## --Earth system prediction

(coordination focus with CASCADE, WACCEM, E3SM, SCREAM)




DJF Niño3.4:




Observations: black; solid color lines are predictions for various lead times; shading is ensemble range

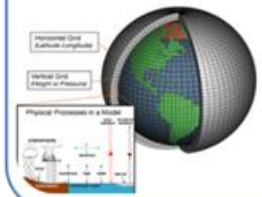
# catalyst

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

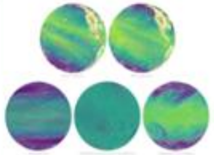
Focus on **modes of Earth system variability and change** to explore the limits to predictability, identify fundamental underlying mechanisms, quantify interactions among modes of variability and associated high impact events, and discover tipping points in the Earth system

**PI: Gerald Meehl co-PI: Jadwiga (Yaga) Richter project manager: Nan Rosenbloom**

**Joining Yaga as co-PI: Steve Yeager**



**Research Objective 1 (Lead: Aixue Hu)**
Use a combination of Earth system models and machine learning methods to understand modes of variability and their limits of predictability on subseasonal to decadal timescales



**Research Objective 2 (Lead: Brian Medeiros)**
Use a hierarchy of models to understand relevant processes and feedbacks related to how modes of variability interact with each other

**Research Objective 3 (Lead: John Fasullo)**
Examine the simulation of internal modes of variability, tipping points, and connections between them in a changing climate

**Research Objective 4 (Lead: Christine Shields)**
Use high resolution ESMs, RRMs, and ML methods to investigate the relationships between high impact events, the synoptic systems that produce them, and their interactions with modes of variability

## Research themes across CATALYST:

- **Two-model analysis of modes of variability with E3SM and CESM**
- **Initialized Earth system prediction with E3SM and CESM**
- **Machine learning analysis and prediction of modes of variability**
- **Antarctic atmospheric rivers and extremes, E3SM and CESM analyses complement machine learning methods**

# CATALYST E3SM simulations

Web page listing E3SM simulations available for analysis by the community:
**https://project.cgd.ucar.edu/projects/CATALYST**

**E3SM large ensembles:**

- 20-member E3SMv2 future climate (SSP3.70) ensemble
- 20-member historical+future large ensemble with E3SMv2 (collaboration with Chris Golaz, LLNL)
- Collaborated with Samantha Stevenson (UCSB) and contributed to the completion of ensemble members for E3SMv1-LE

(Stevenson et al., 2023, *JAMES*; **Fasullo** et al., *Earth Sys. Dyn*., 2024*;* *J. Climate*, 2024)

**E3SMv2 Smoothed Biomass Burning Large Ensemble**

- explore the sensitivity of E3SMv2 to the CMIP6 prescription of biomass burning emissions:
  21 members,1990 to 2085 using "smoothed" climatological satellite-era CMIP6 biomass emissions

**Initialized Earth system prediction, Seasonal to Multi-Year Large Ensemble (SMYLE):**

- recently completed 20-member ensemble hindcasts with E3SMv2.1 initialized quarterly between 1970-2019 (four start dates per year) and integrated for 24 months (SMYLE methodology: **Yeager, Rosenbloom, Glanville, Molina, Richter, Strand, King** and coauthors, GMD, 2022).

**Initialized Earth system prediction, S2S-control:**

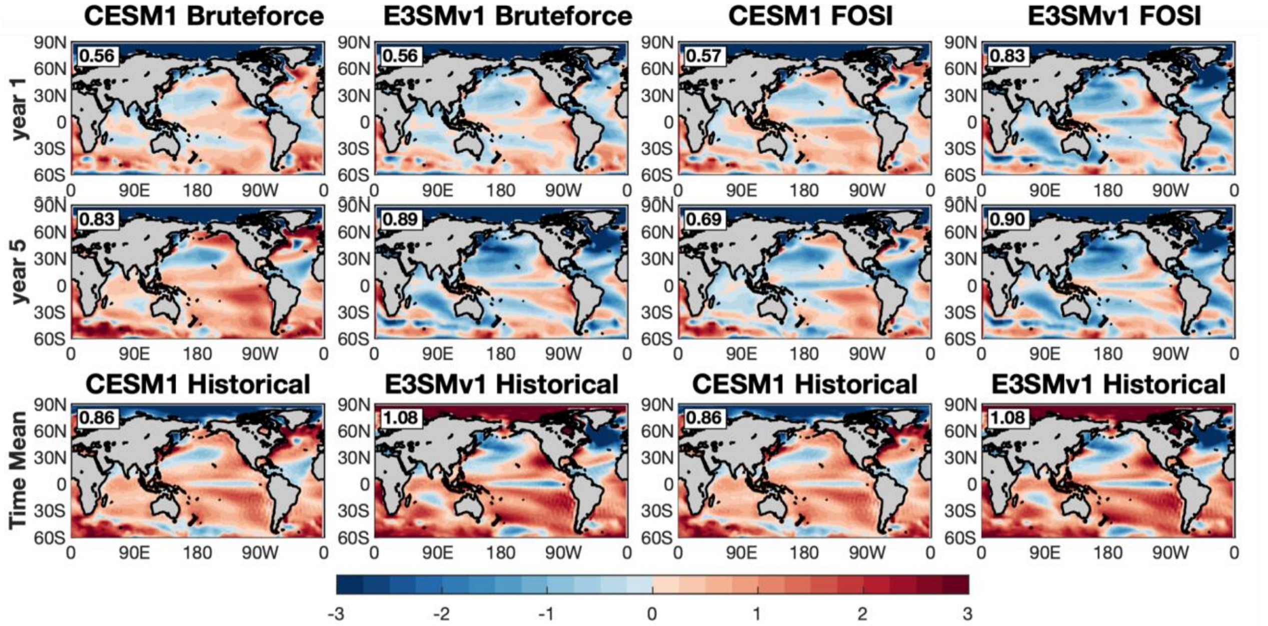
- In progress: E3SMv2.1 subseasonal reforecasts, initialized with observed and analysis-based atmospheric, ocean and sea ice, and land ICs; weekly starts between October and March from 1999 to 2022; 45-day simulations, 11-member ensembles (S2S methodology: **Richter** et al., Weather and Forecasting, 2022)

# Initialized Earth system prediction with E3SM:  removing bias and drift in hindcasts

Using historical large ensembles to compute model climatology produces similar drift patterns compared to the initialized hindcasts in both the 1 degree and high res versions of E3SMv1 and CESM1

**This result opens up whole new possibilities of being able to perform hindcast case studies without re-running an entire hindcast set, and could facilitate greater use and application of Earth system prediction science**

Drift pattern in year 1, year 5, and mean of historical large ensemble is similar (~0.9 pattern correlation), with only the expected larger amplitude in the LE;
**hindcasts with 2 initialization methods in E3SMv1 and CESM1, 1 degree versions**




*(**Meehl**, Kirtman, **Richter, Glanville, Rosenbloom, and Yeager**, 2023, Cli.Dyn,)*

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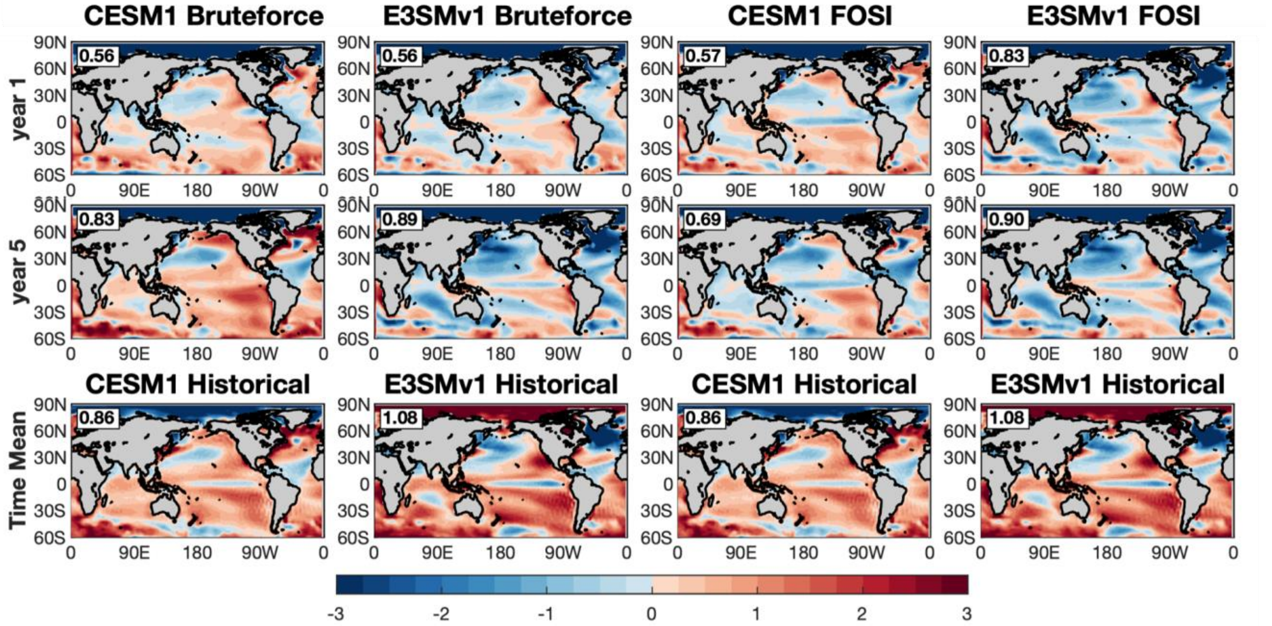
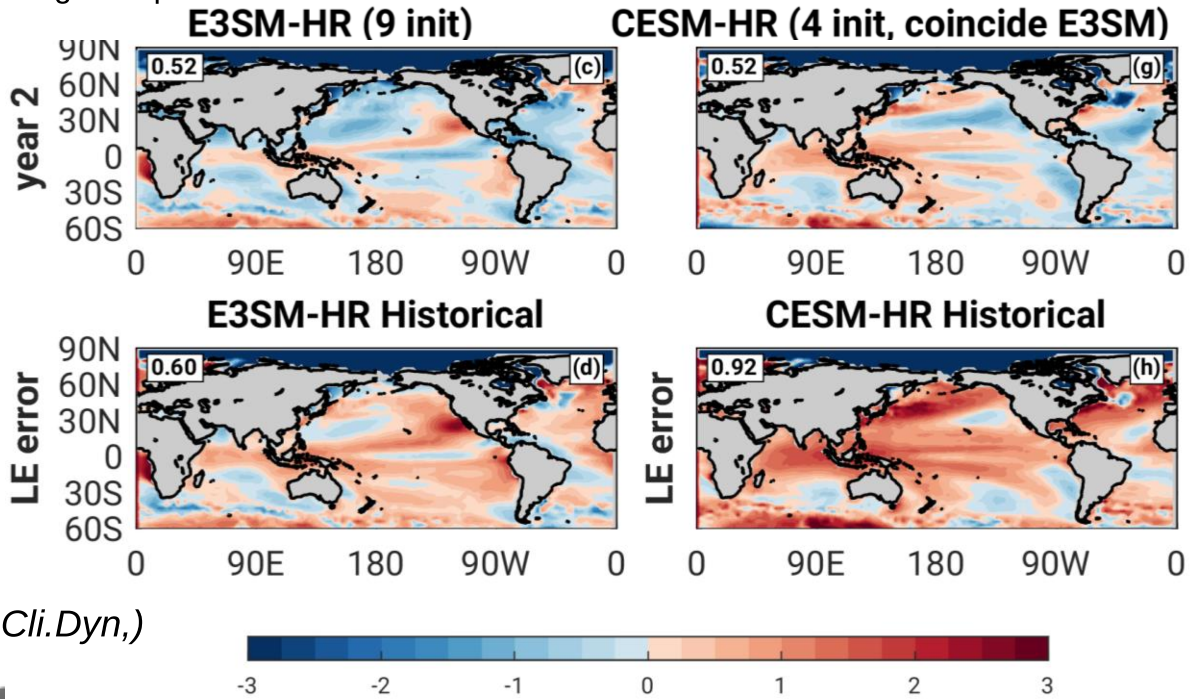



*(Meehl, Kirtman, Richter, Glanville, Rosenbloom, and Yeager, 2023, Cli.Dyn,)*

As in the 1 degree versions, **in high res versions of E3SMv1 and CESM1.3** (1/4 degree atmosphere, 1/10 degree ocean) drift pattern in year 2 and mean of historical large ensemble is similar (~0.9 pattern correlation), with only the expected larger amplitude in LE error

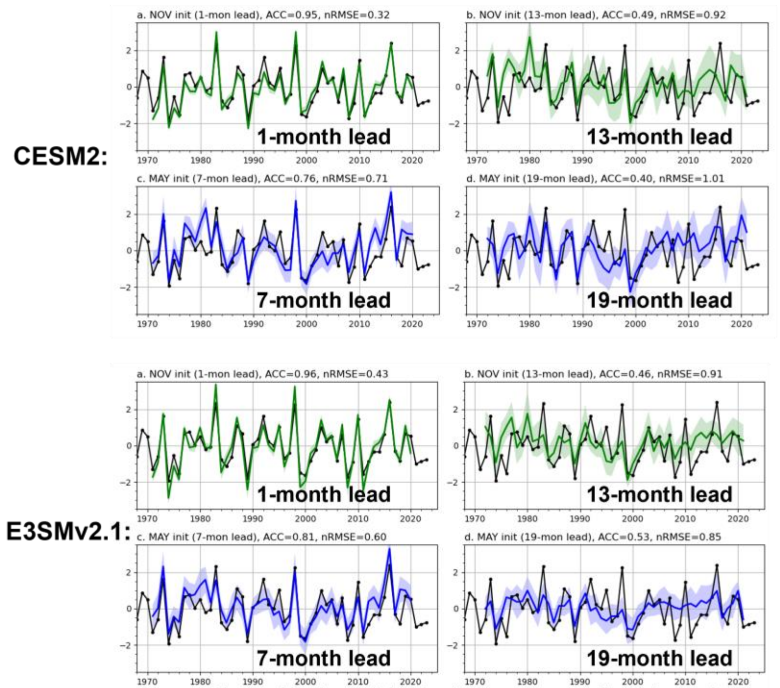


# Initialized Earth system prediction with E3SM: predicting modes of variability, ENSO and IPO

**First results from SMYLE ENSO hindcasts with E3SMv2.1 compared to CESM2:**

**Despite markedly different mean state biases (and associated drift), full field initialized hindcasts using CESM2 and E3SMv2.1 show considerable skill at forecasting winter Niño3.4 out to 19 month leads**

DJF Niño3.4:



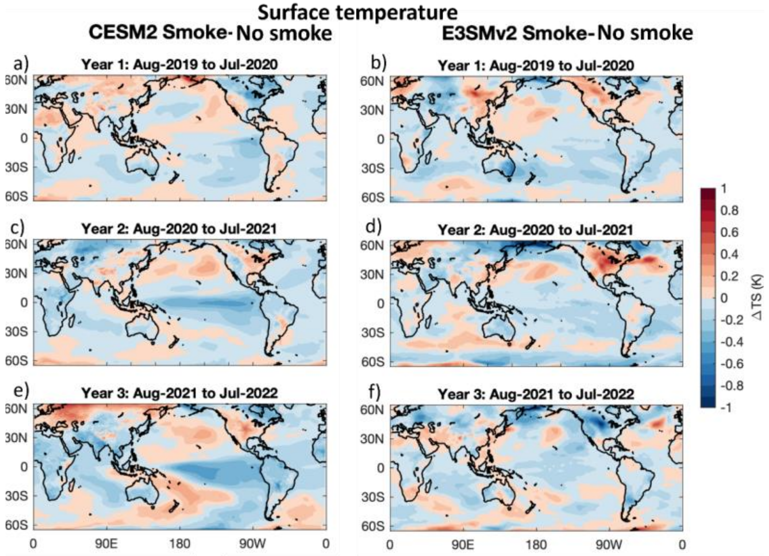

Observations: black; solid color lines are predictions for various lead times; shading is ensemble range

*(SMYLE description: Yeager et al., 2022, GMD; new results; Yeager et al., 2024, pending)*

# Initialized Earth system prediction with E3SM: predicting modes of variability, ENSO and IPO

**First documentation of the effects of wildfire smoke on a mode of variability: ENSO**

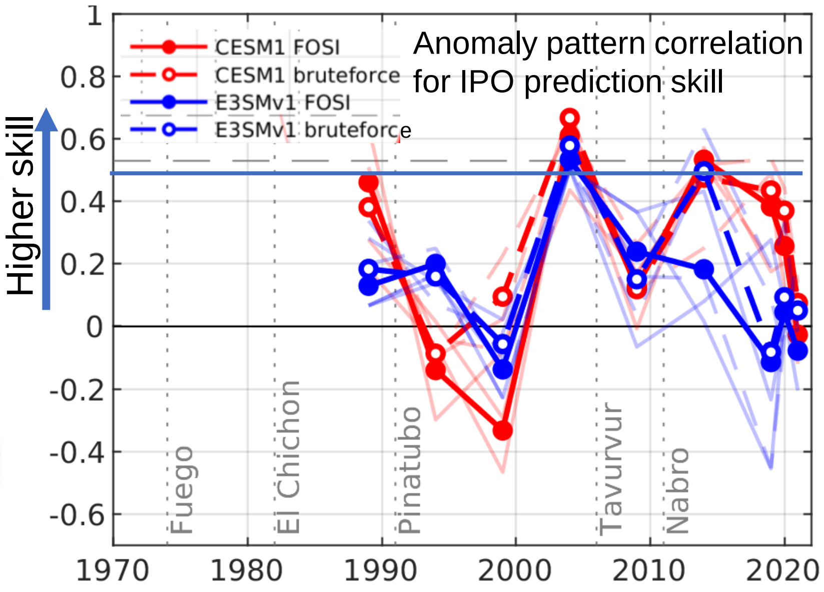
3-year hindcast case study with **E3SMv2 and CESM2 showed the 2019-2020 Australian wildfire smoke triggered coupled processes that produced a multi-year La Niña**




*(Fasullo et al., 2023, Sci. Adv.; Meehl et al., 2024, pending)*

# Initialized Earth system prediction with E3SM: predicting modes of variability, ENSO and IPO

**E3SMv1 and CESM1 show comparable skill in predicting the IPO at lead years 3-5** using two different initialization methods, with decreases of skill after large volcanic eruptions




(*Meehl, Kirtman, Richter, Glanville, Rosenbloom, and Yeager, 2023, Cli.Dyn.*; *Wu, Yeager, Deser, Rosenbloom, and Meehl, 2023, Sci. Adv.*)

# Quantifying sources of subseasonal prediction skill

**J. H. Richter**, **A. A. Glanville**, …, **Stephen G. Yeager … Julie M. Caron**, et al.(2024):
*Nature Climate and Atmospheric Science, 7:59,* https://doi.org/10.1038/s41612-024-00595-4

***OBJECTIVE***

To to quantify the respective roles of atmosphere, land, and ocean initial conditions on subseasonal prediction skill.

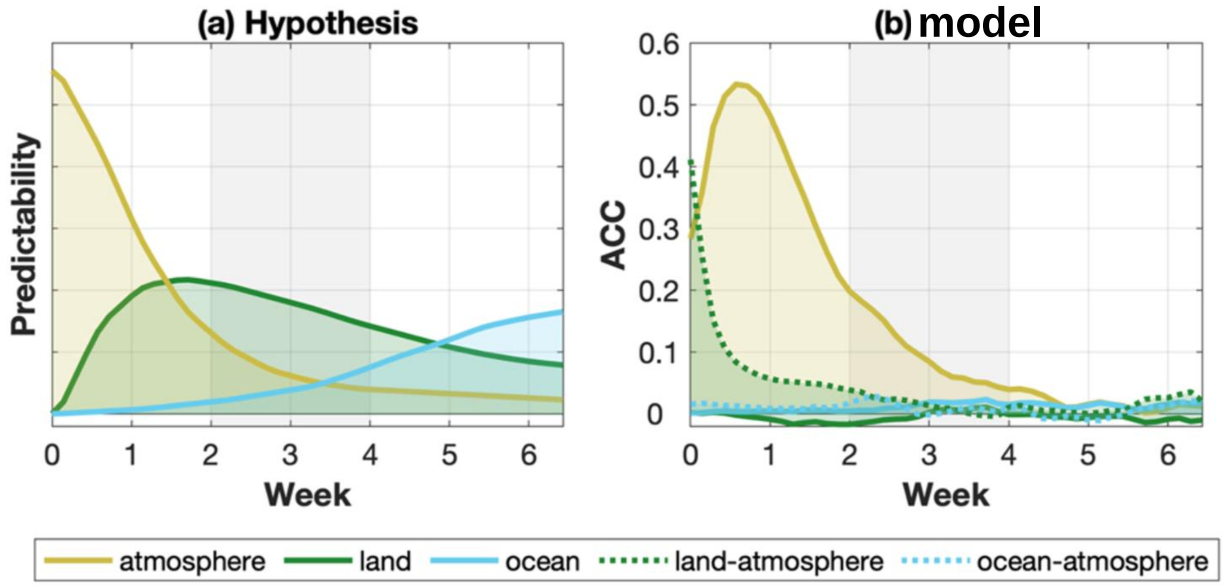
***APPROACH***

We use a suite of subseasonal reforecast experiments with initial conditions for one or more model components set to climatology.

***IMPACT***

**The majority of prediction skill for global surface temperature in weeks 3–4 comes from the atmosphere, while ocean initial conditions become important after week 4, especially in the Tropics.**

**Subseasonal precipitation prediction skill also comes primarily from the atmospheric initial condition, except for the Tropics, where after week 4 the ocean state is more important.**




Sources of subseasonal predictability of temperature. Predictability coming from the atmosphere (yellow), land (green), and ocean (blue) as a function of forecast time for annual mean 2 m temperature from 30ºN to 60ºN over land regions only: a) Hypothesis, adapted from a graphic by Paul Dirmeyer, (b) derived from simulations Panel (b) includes additional two coupling terms: land- atmosphere (green dashed) and ocean-atmosphere (blue dashed).

# Using ML to explore the relative importance of the MJO and ENSO to North Pacific subseasonal predictability

### *OBJECTIVE*

To separate the relative contribution of two tropical modes of variability to North Pacific subseasonal predictability: the Madden-Julian Oscillation (MJO) and the El Nino Southern Oscillation (ENSO).

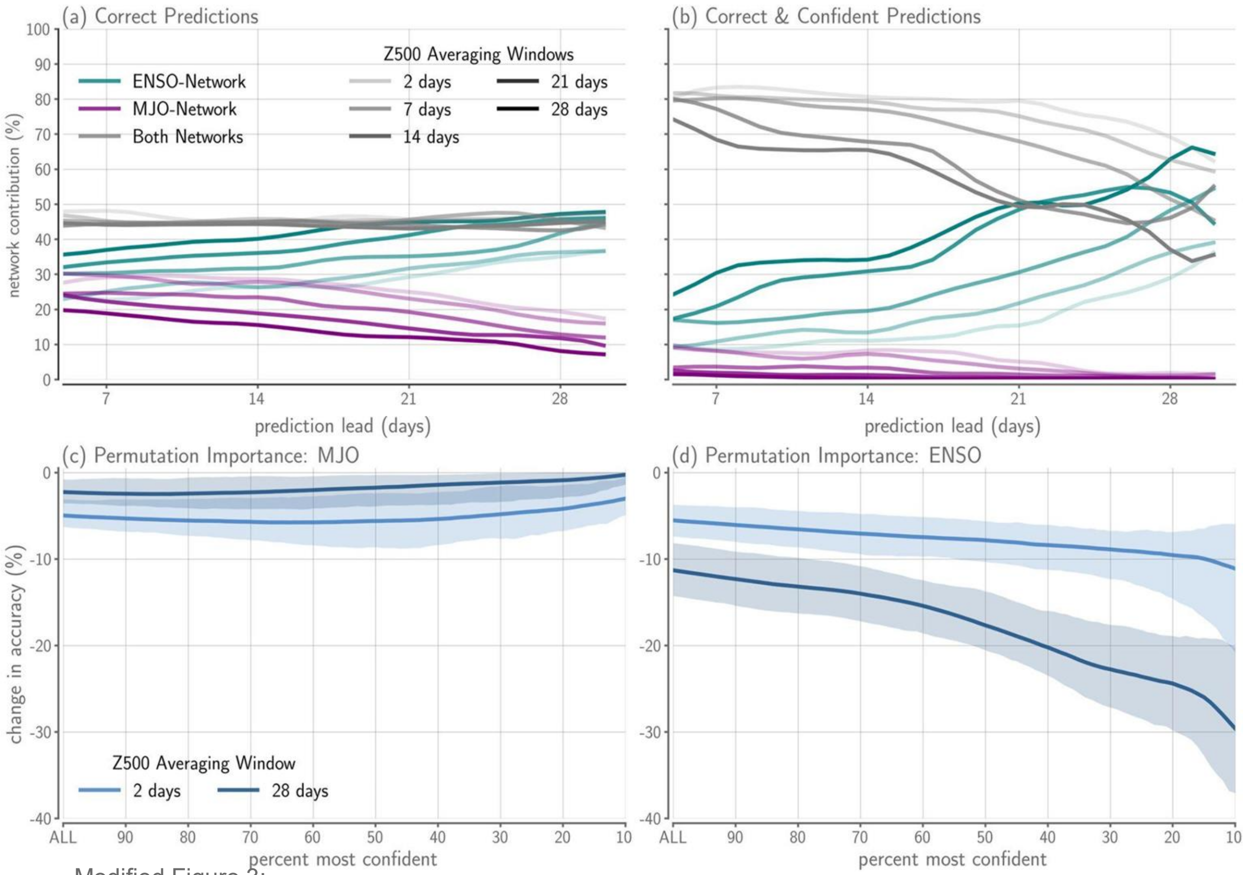
### *APPROACH*

**Utilize an interpretable neural network to disentangle the relative importance of the state of the MJO and ENSO for subseasonal predictability atmospheric circulation at 500 hPa over the North Pacific.**

### *IMPACT*

**The state of ENSO alone provides more subseasonal predictive information than the MJO on a variety of subseasonal lead times, particularly during network identified forecasts of opportunity, but during ENSO-neutral the MJO is more important**

(**Mayer,** Chapman, Manriquez, 2024. *Geophysical Research Letters)*




Modified Figure 3:
The frequency of a correct prediction provided by *either* the MJO- (purple) or ENSO-network (teal) or by *both* MJO- and ENSO-networks (gray) for each prediction lead. Lighter (darker) lines indicate shorter (longer) Z500 averaging windows. (b) As in (a) but for forecasts of opportunity (20% most confident predictions). (c,d) Change in accuracy across confidence thresholds after permuting (c) RMM and (d) ENSO index input. The light/dark blue lines represent the mean of a 2 days/28 days Z500 averaging window across all lead times and the associated range of change in accuracy is represented by the shading.

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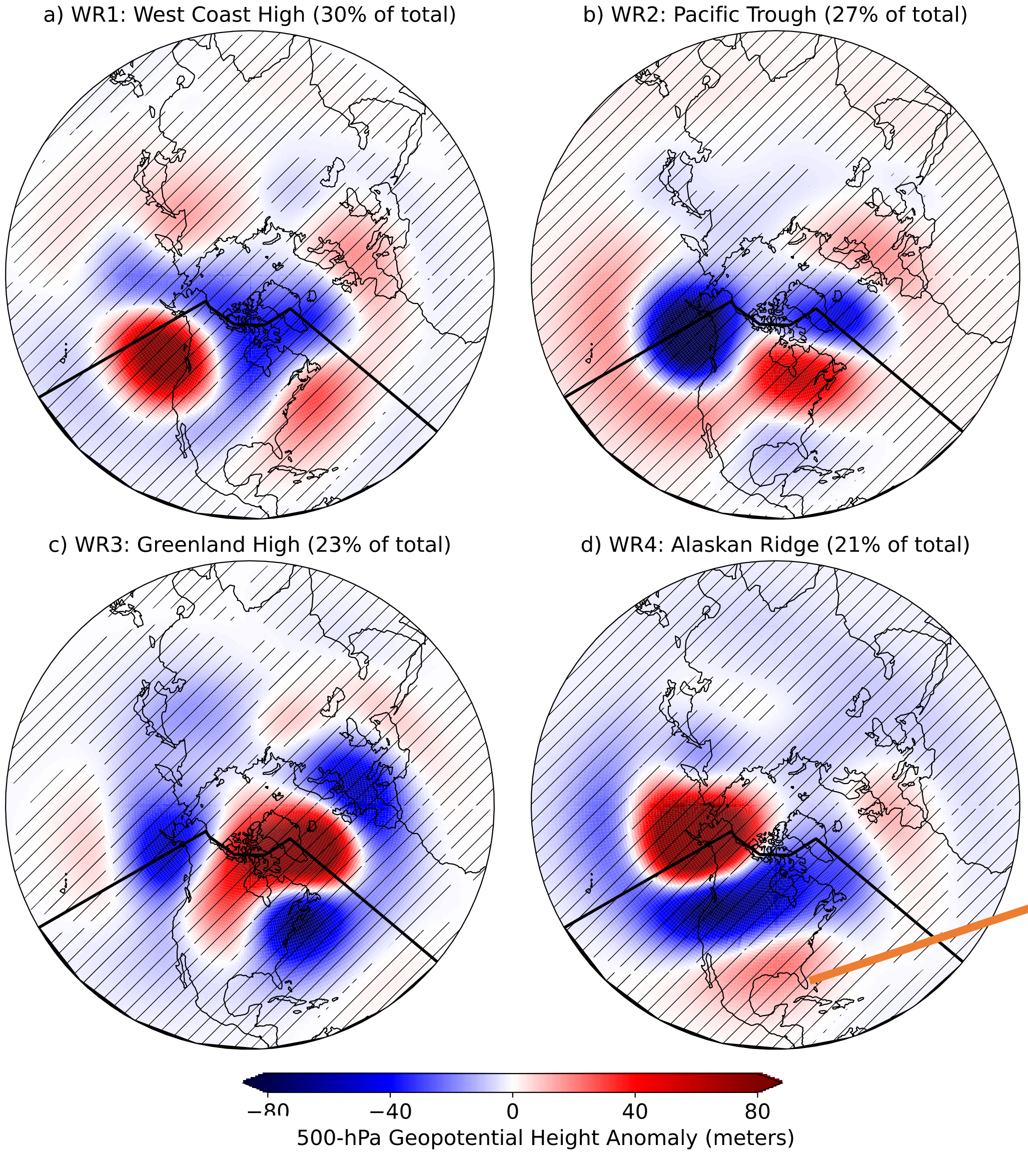
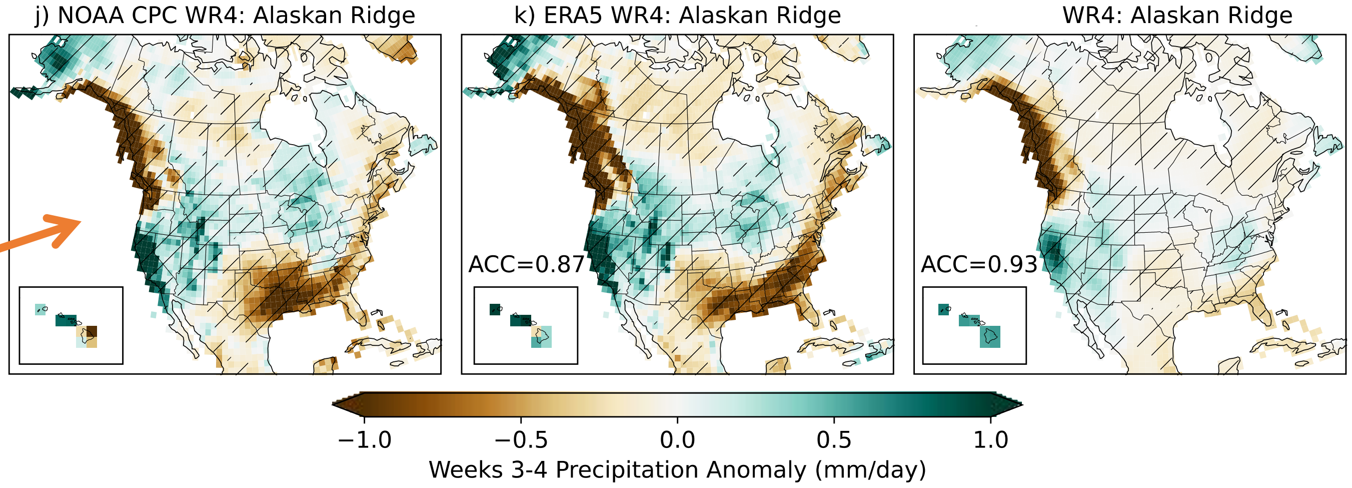



# Using unsupervised learning for signal extraction with K-means clustering for climate prediction

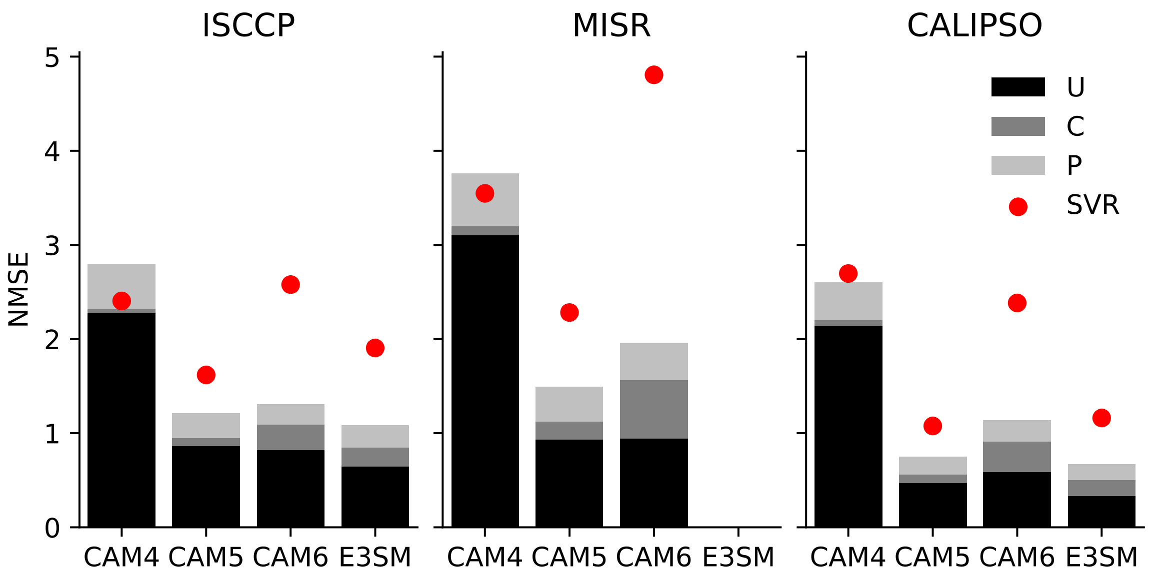
Skillful predictions of large-scale circulation patterns can be used to derive predictions of precipitation




(**Molina, Richter, Glanville, Dagon**, Berner**, Hu, Meehl**, 2023, *AMS AI for the Earth Systems*).

# Analysis of processes in E3SM compared to CESM

## E3SMv1, CAM5, and CAM6 show large improvements in simulated cloud cover compared to CAM4




(**Medeiros** et al., 2023, *Earth and Space Science*)

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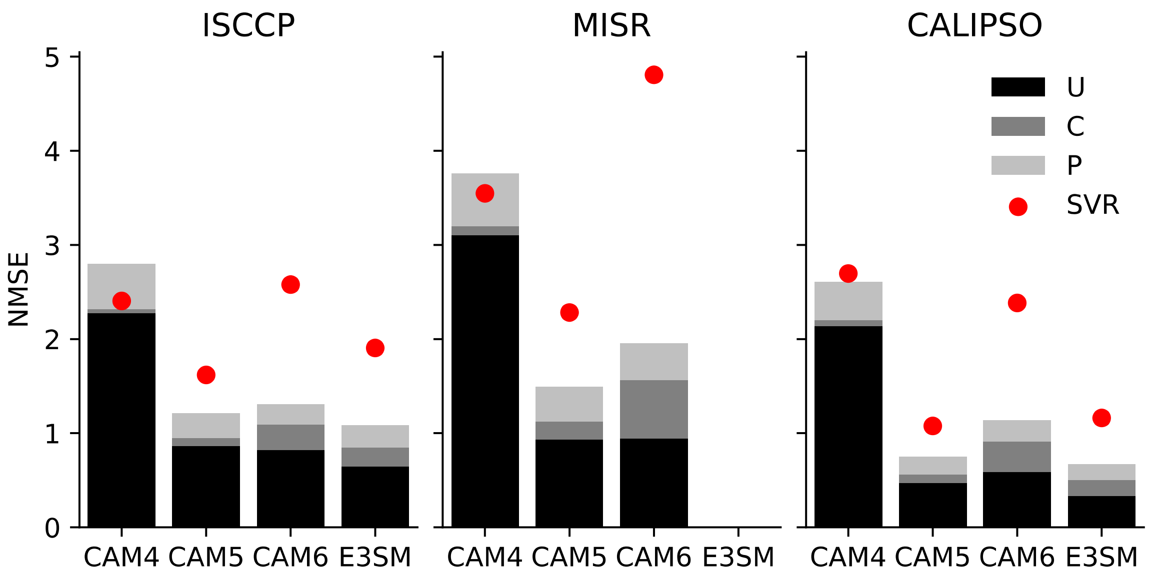
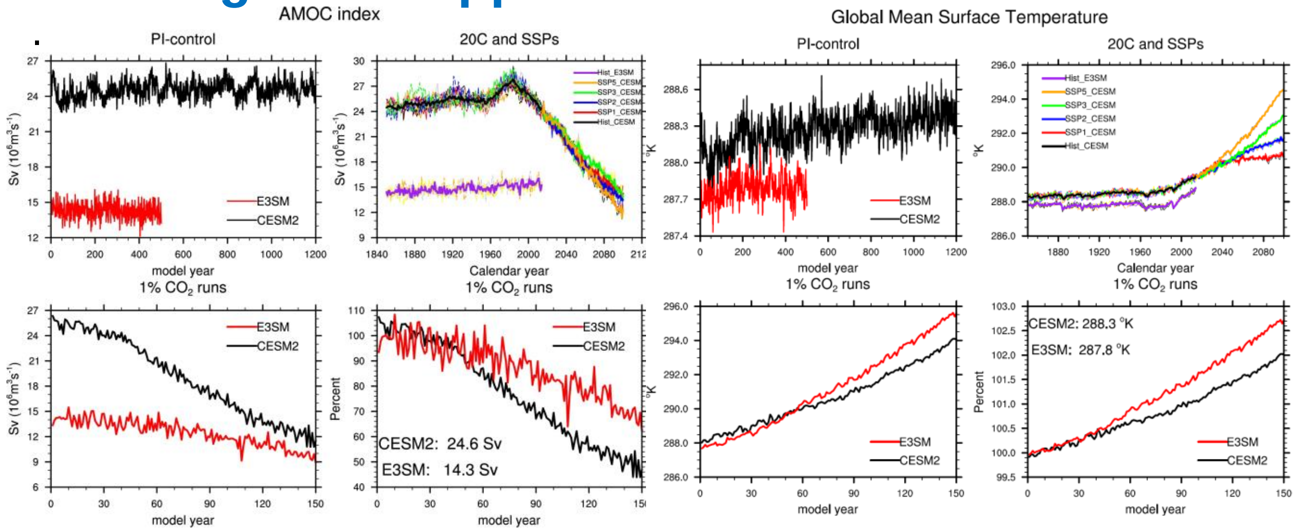


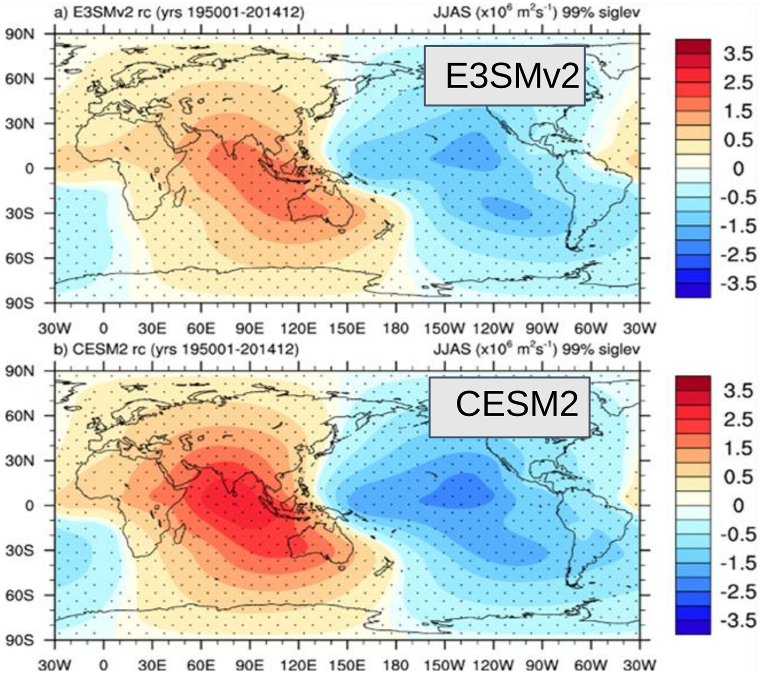

(**Medeiros** et al., 2023, *Earth and Space Science)*

## E3SMv1 and CESM2 have a similar equilibrium climate sensitivity, but a weaker AMOC in E3SMv1 contributes to a higher transient climate response: the surface water stays in contact with the atmosphere longer allowing a faster warming of the upper ocean in E3SMv1




(**Hu,** van Roekel,Wei jer, Garuba, Cheng, Nadiga, 2020, *J. Climate)*

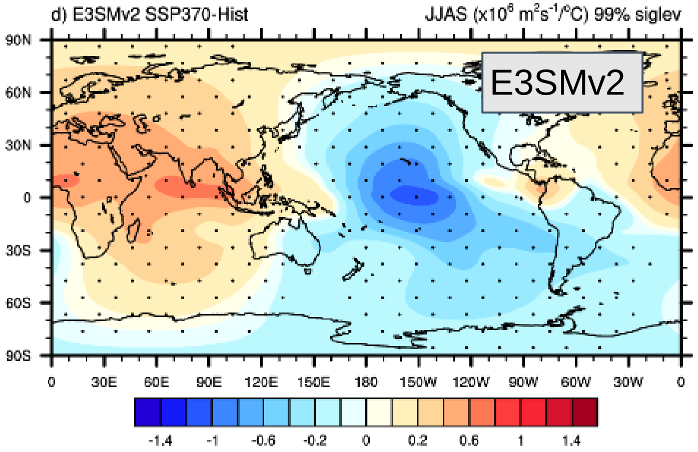
# Processes and modes of variability: ENSO-monsoon connection




Regression of 200 hPa velocity potential during JJAS onto Nino3.4

**Present-day: E3SMv2 has a weaker ENSO influence on the South Asian monsoon compared to CESM2**

Difference between E3SMv2 and CESM2 pacemaker (which has much more comparable ENSO variability) Analyses suggest ***about half due to lower ENSO amplitude, and half due to the cooler tropical Pacific mean state in E3SMv2***



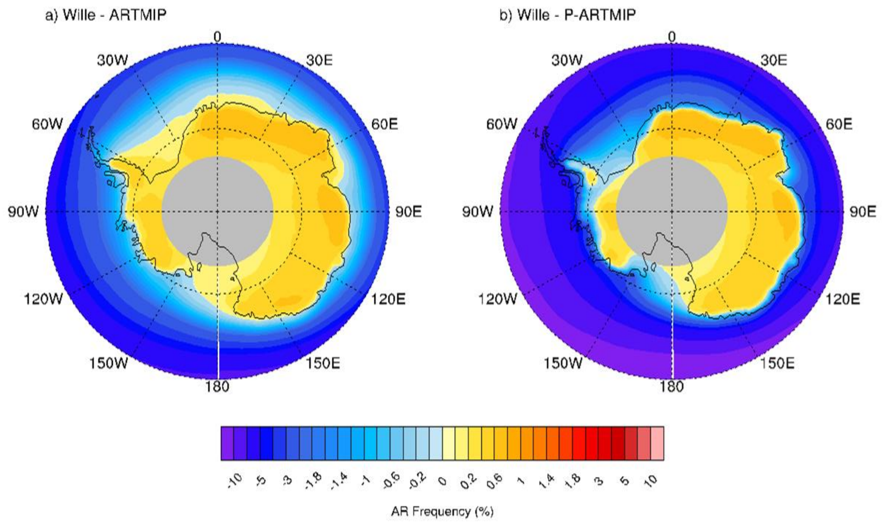

**Future: Strengthened monsoon-ENSO connection in E3SMv2 compared to CESM2:**

1. **Larger future El Niño-like SST response in CESM2 shifts the anomalous Walker Circulation eastward and weakens the monsoon-ENSO connection in CESM2 compared to E3SMv2**
2. **Larger amplitude increase in future ENSO in E3SMv2 strengthens the monsoon-ENSO connection compared to CESM2**

(Monsoon analysis team: CATALYST, E3SM and university scientists: GRL, 2023, 2024)

# Synoptic weather events and modes of variability

**Antarctic atmospheric rivers and MOV:**
**Must use an Antarctic-specific ARDT (AR detection tool) to capture Antarctic ARs;**
**One of the first studies to show that a variety of MOVs (not just SAM) can contribute to Antarctic ARs**




Composite difference heatmaps of AR frequency in % time (relative to full ARTMIP MERRA-2 period (1980-2016)

**(Shields** et al., 2022, GRL)

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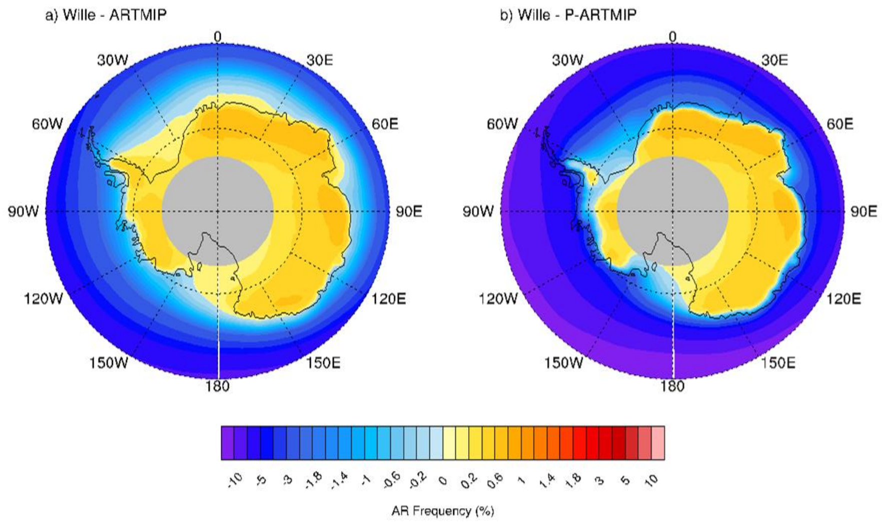
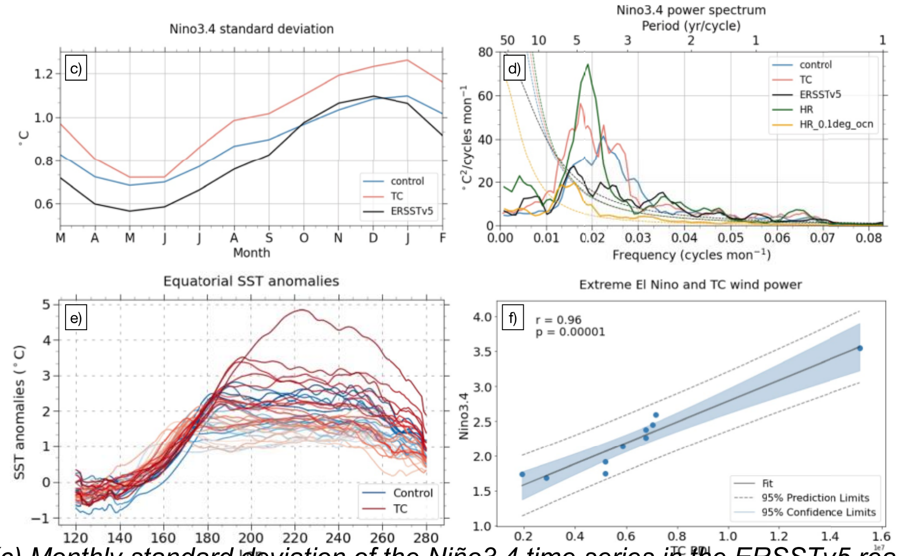



Composite difference heatmaps of AR frequency in % time (relative to full ARTMIP MERRA-2 period (1980-2016)

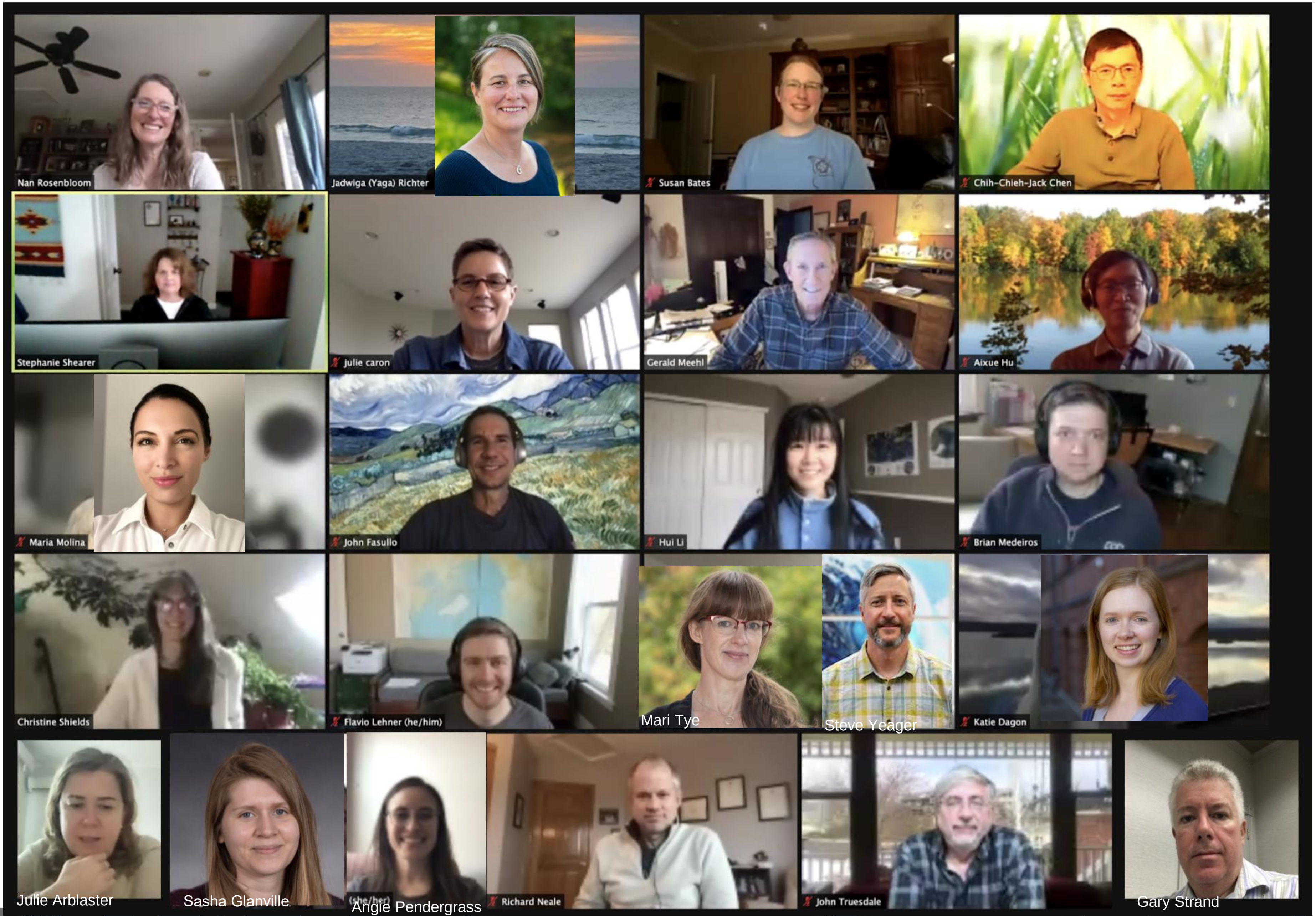
**(Shields** et al., 2022, GRL)

**Tropical cyclones (TCs) actively affect ENSO:**
**High resolution TC winds are combined with a low resolution model to show that TCs play a fundamental role in producing the observed ENSO characteristics in the climate system and point to a two-way climatological interaction between TCs and ENSO**




*(c) Monthly standard deviation of the Niño3.4 time series in the ERSSTv5 reanalysis (black), LR-ctrl (blue) and the LR-TC (red). (d) Power spectrum of the Niño3.4 index in the ERSSTv5 reanalysis (black), the LR-ctrl (blue), the LR-TC (red), the HR (green), and the HR_0.1 with eddy resolving ocean (orange). (e) SST anomalies along the equatorial Pacific for each El Niño event in the LR-ctrl (blue) and the LR-TC (red). (f) Scatterplot of the Niño3.4 index of strong El Niño events against the TC power dissipation index Integrated from May to December over the west equatorial Pacific.*

**(Li** et al., 2023, GRL)

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