10 July 2026

2026 CESM Tutorial

Earth System Prediction

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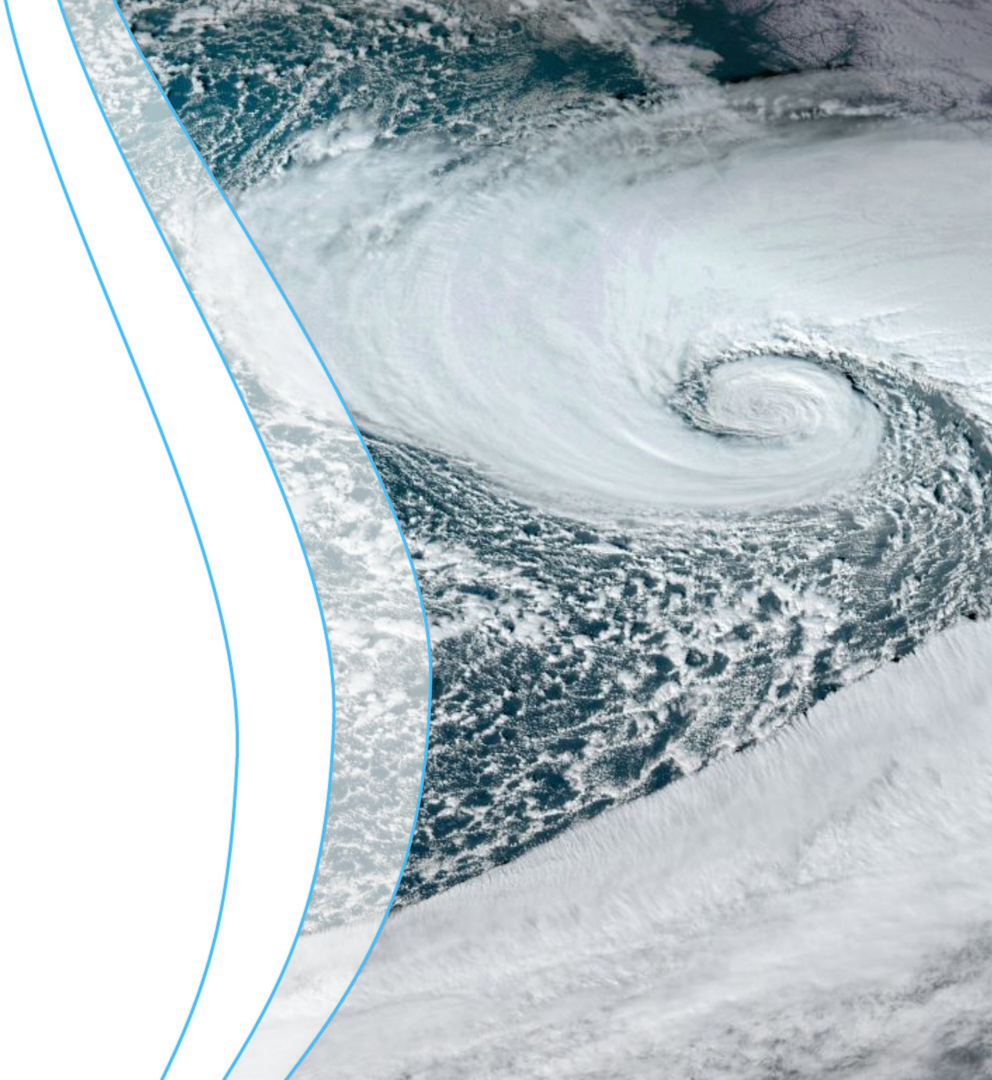
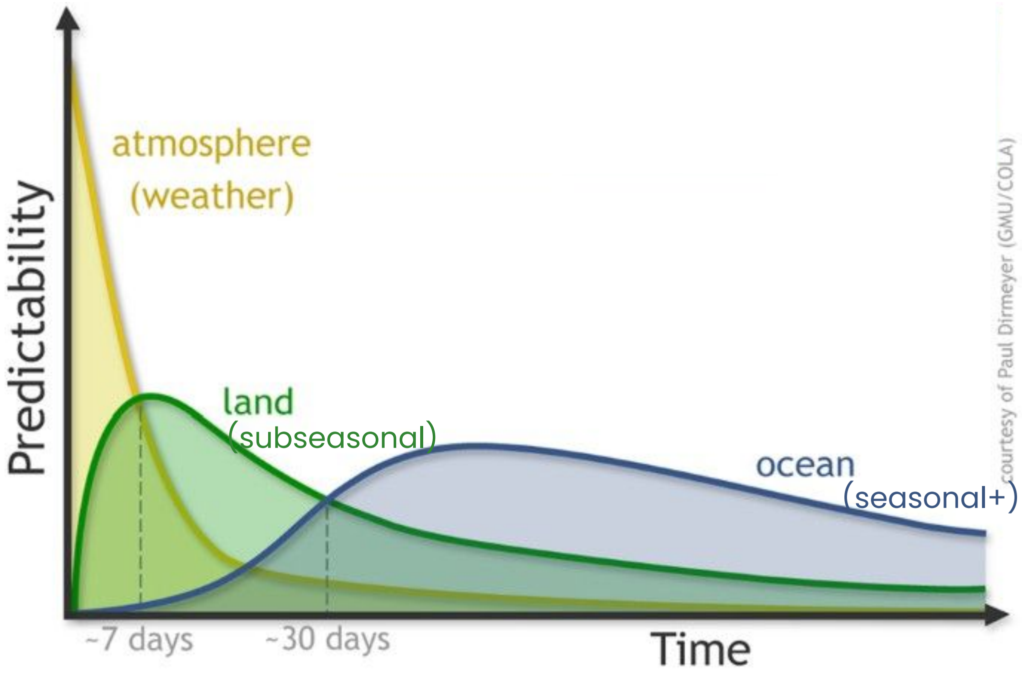
Original slides provided by Steve Yeager



Sources of Predictability



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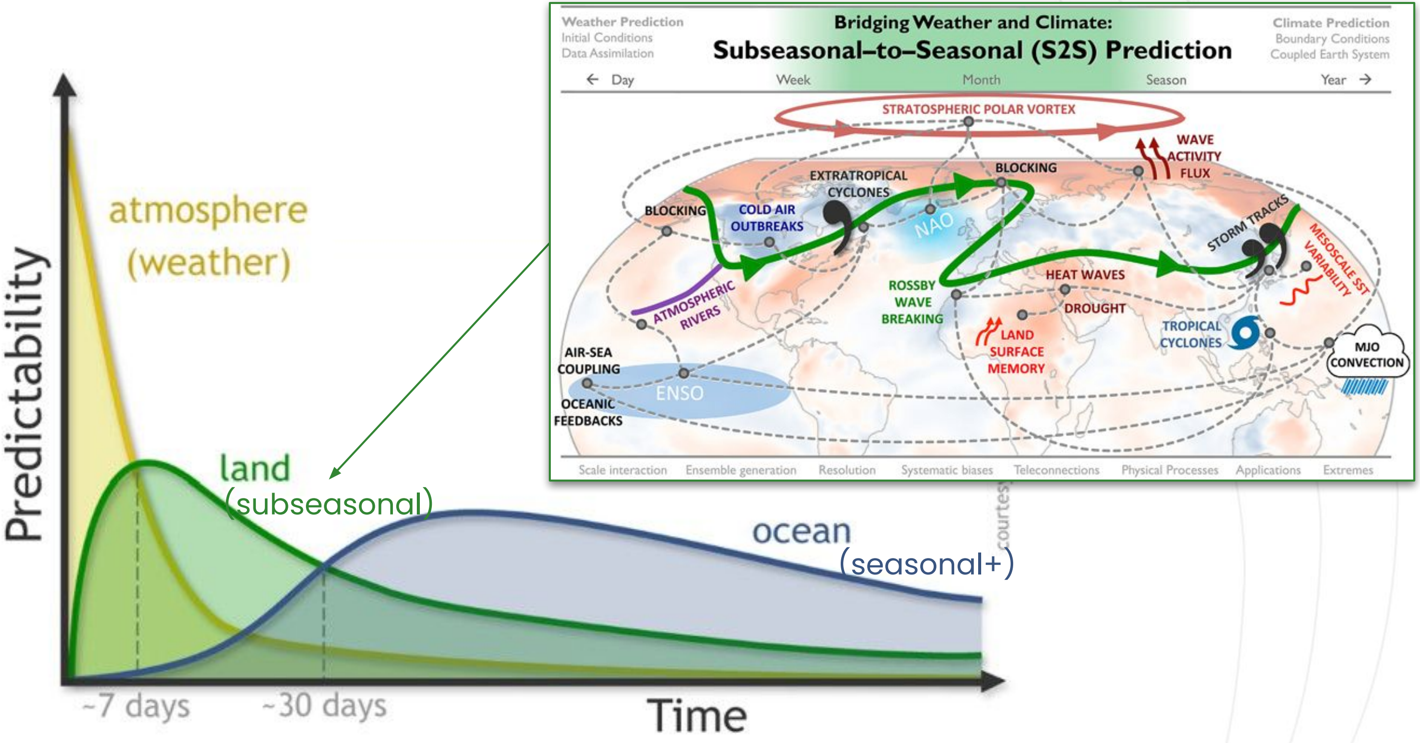

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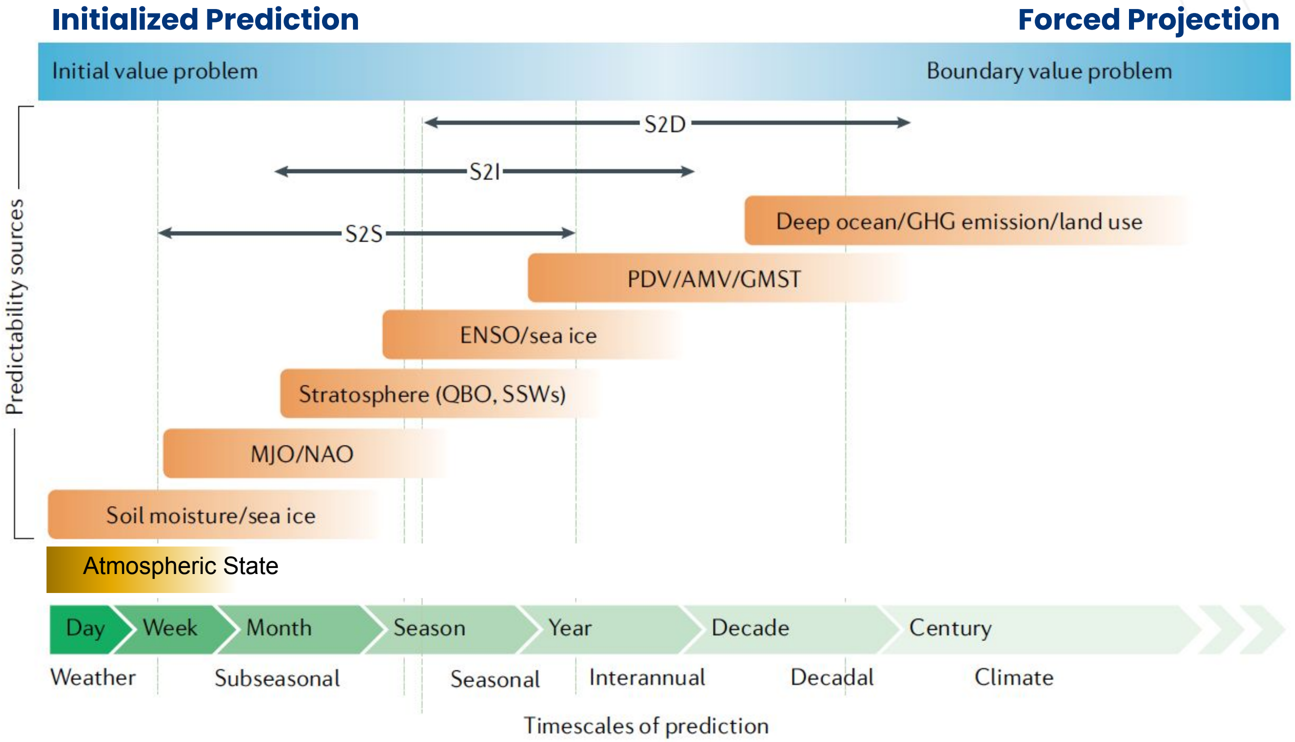
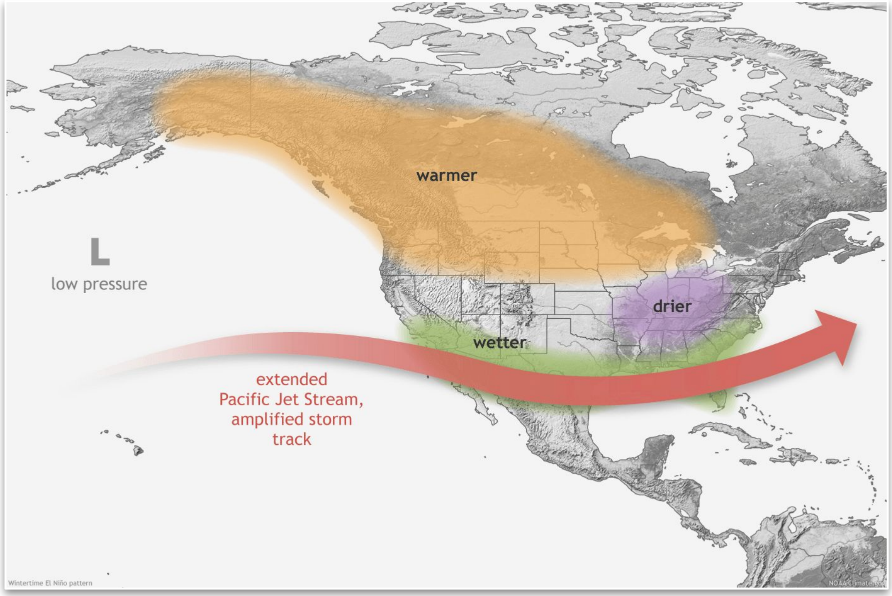


Merryfield et al. (2020, 10.1175/BAMS-D-19-0037.1)
Meehl et al. (2021, 10.1038/s43017-021-00155- x)

Prediction

Average DJF North American Response to El Nino



Prediction

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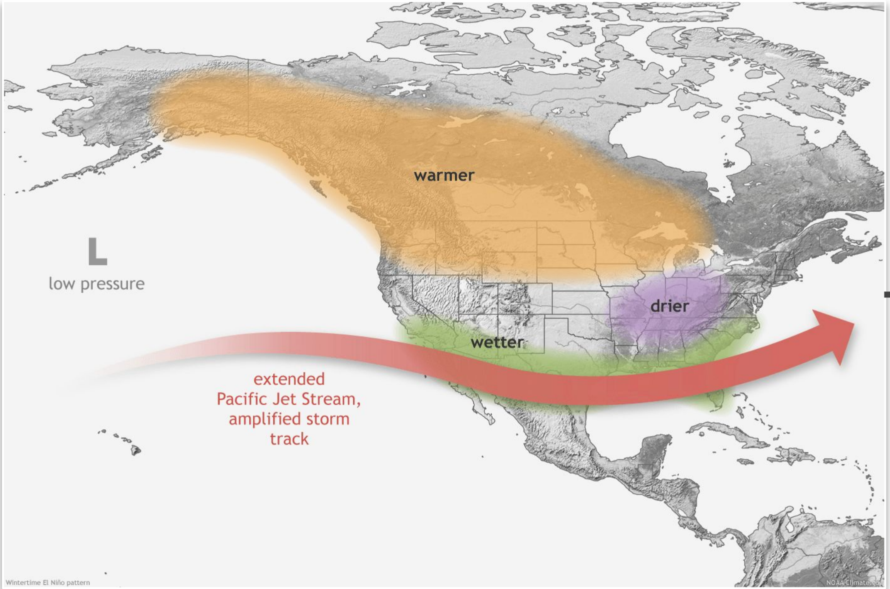
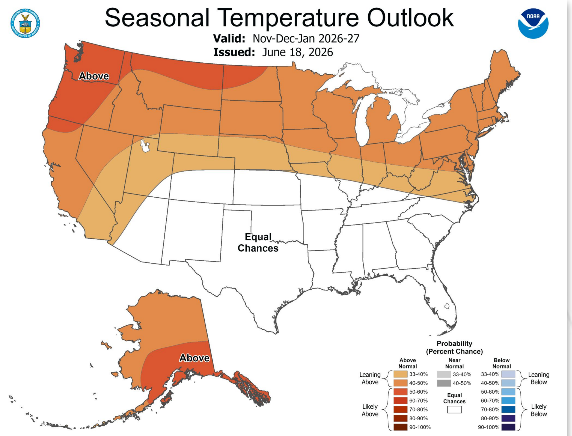
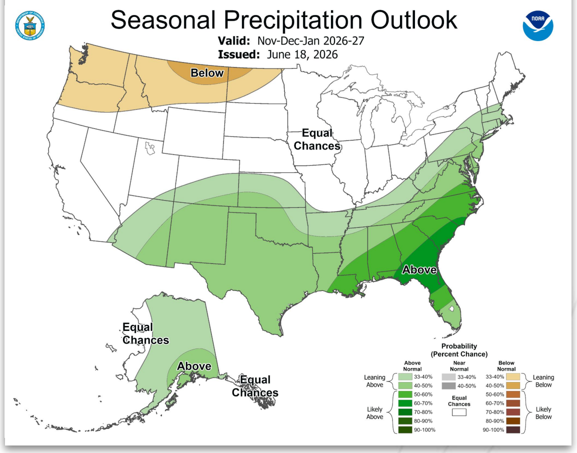


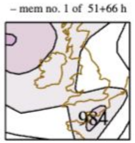




Initialized Prediction

Modified Figure from Slingo & Palmer (2011, doi:10.1098/rsta.2011.0161)

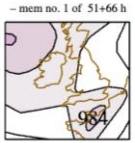
Initialized Prediction



"The **advantages of ensemble forecasting** became readily apparent in the case of the October 1987 storm when Michael Fish, a BBC weather forecaster, was famously quoted as saying **'…a woman rang the BBC and said she had heard that there was a hurricane on the way. Well if you [the woman] are watching, don't worry there isn't'"**

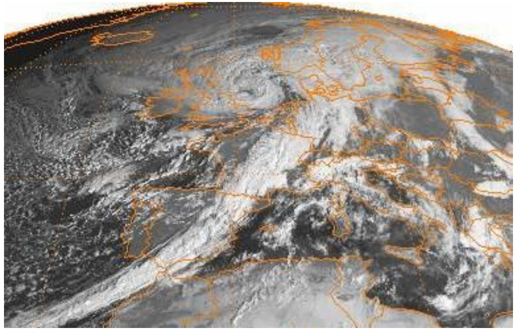
Modified Figure from Slingo & Palmer (2011, doi:10.1098/rsta.2011.0161)

Initialized Prediction



"The **advantages of ensemble forecasting** became readily apparent in the case of the October 1987 storm when Michael Fish, a BBC weather forecaster, was famously quoted as saying **'…a woman rang the BBC and said she had heard that there was a hurricane on the way. Well if you [the woman] are watching, don't worry there isn't'**"

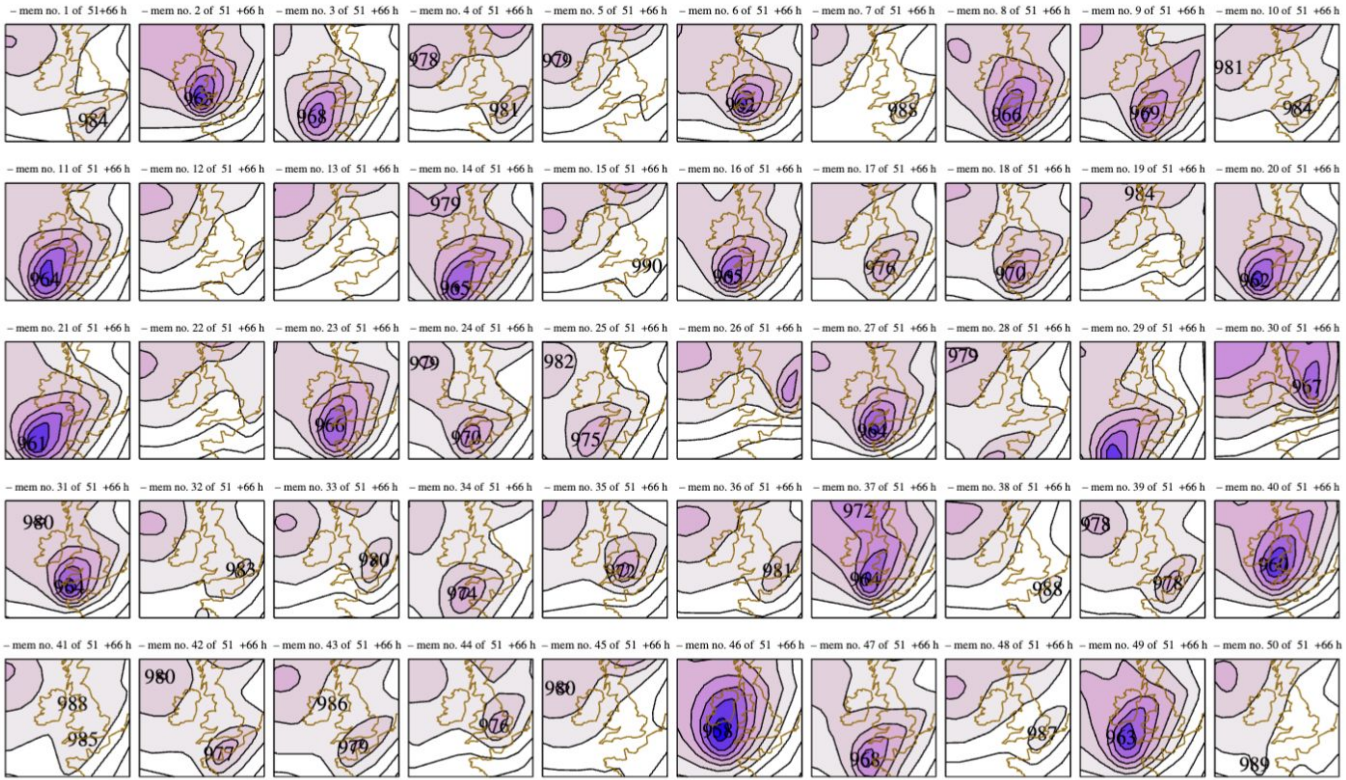
… there was:



The **great storm of 1987** was a violent extratropical cyclone that occurred on the night of 15–16 October, with **hurricane-force winds** causing casualties in England, France, and the Channel Islands as a severe depression in the Bay of Biscay moved north east. Among the **most damaged areas were Greater London, Kent, the East Anglian coast, …** all of which weathered **gusts with a return period of 1 in 200 years**. [wikipedia]

Modified Figure from Slingo & Palmer (2011, doi:10.1098/rsta.2011.0161)

Initialized Prediction



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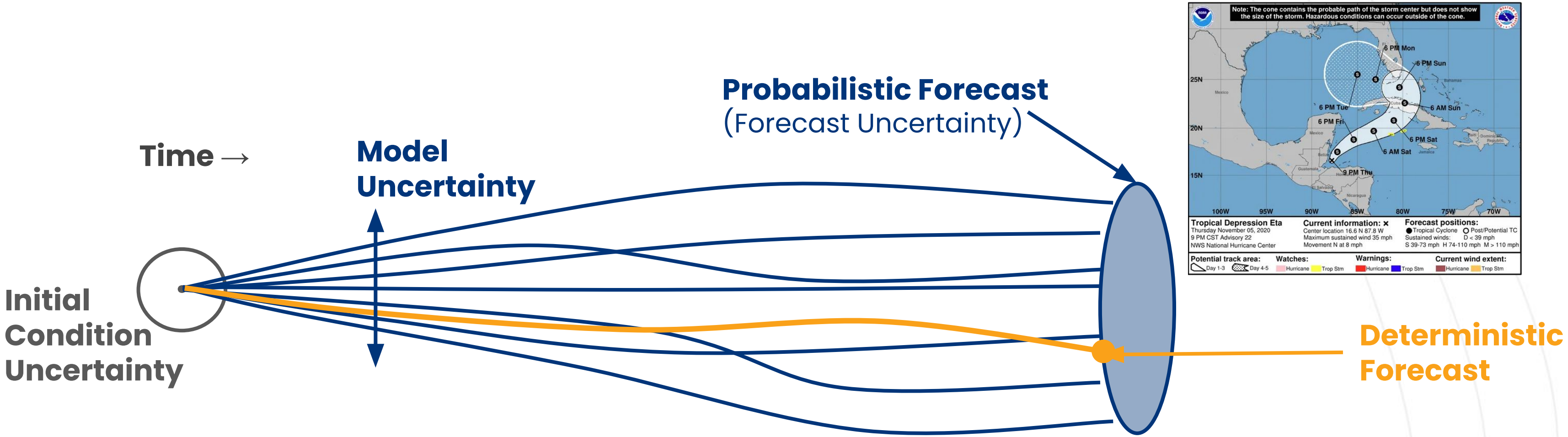
Initialized Prediction



- Initialized ensembles generate probability distributions of future states
- Ensemble mean: most likely outcome (deterministic forecast, “**signal**” that is common across ensemble members)

Modified Figure from Slingo & Palmer (2011, doi:10.1098/rsta.2011.0161)

Forecasts of Opportunity

Time →

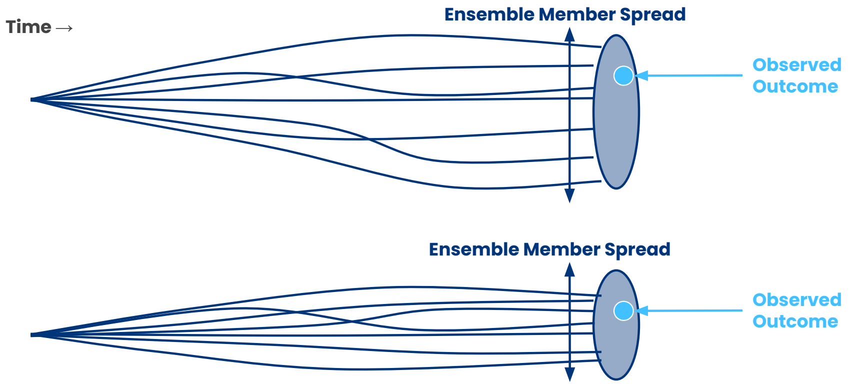
State-Dependent Prediction

Occasionally, we have time periods when the state of the Earth System can extend the limits of atmospheric predictability beyond ~2 weeks – Forecasts of Opportunity

How do we know when these occur?

Forecasts of Opportunity

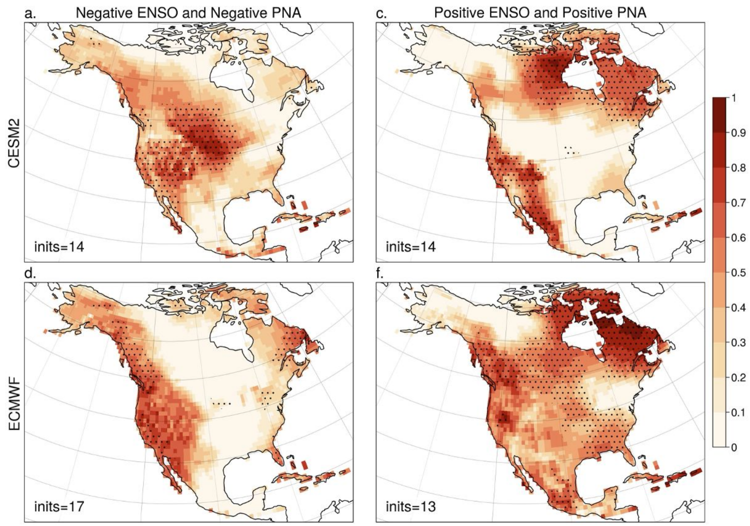
1. Look at the spread of ensemble members
   a. There *can* be a relationship between the ensemble member standard deviation and forecast performance
      i. Only useful if the model is “reliable”

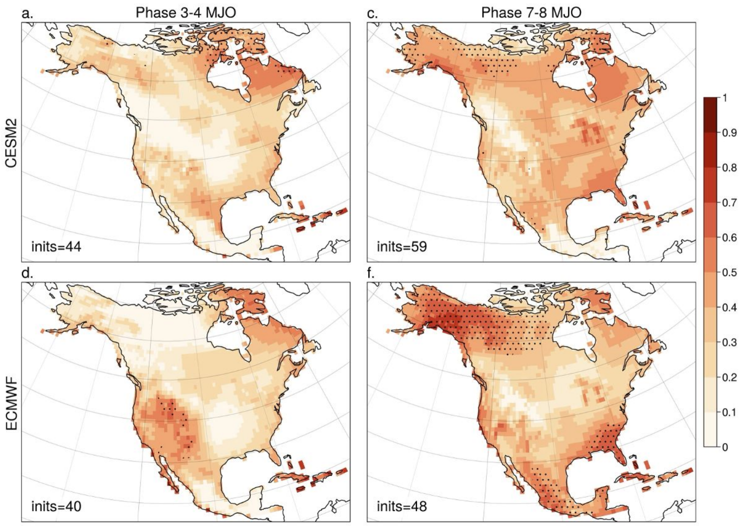


Forecasts of Opportunity

1. Look at the spread of ensemble members
   a. There *can* be a relationship between the ensemble member standard deviation and forecast performance

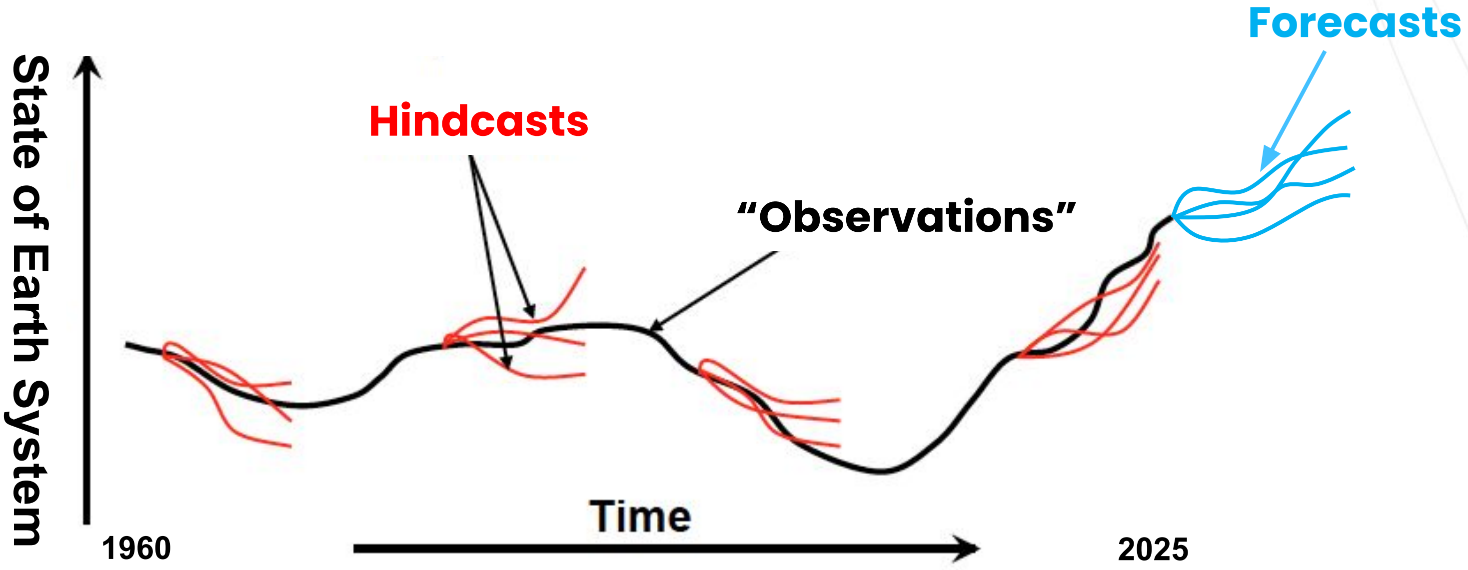
2. Look at historical skill based on certain conditions





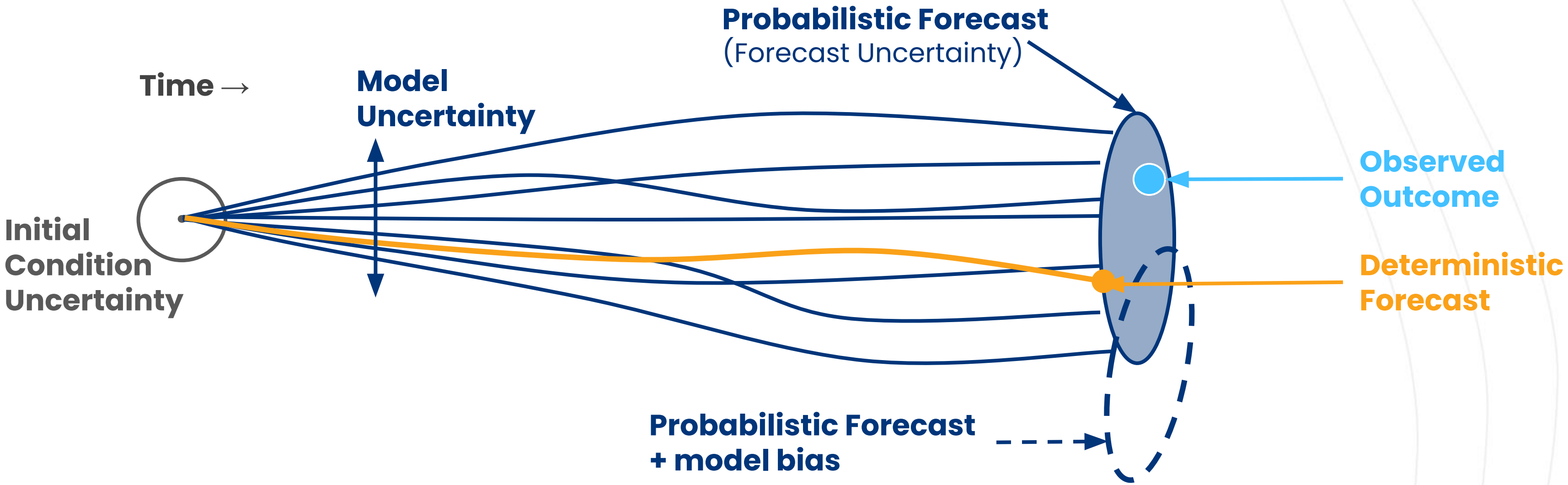
Berner and Jaye 2026; under review

Initialized Prediction



1. **Initialize** climate model simulations from best estimates of the Earth system state
2. **Force** the simulations with observed external forcings
3. **Repeat** steps #1-2 many times, to generate a collection of “hindcasts”.
4. Use hindcasts to **evaluate** model skill at predicting past change.
5. If model has hindcast skill, then **forecast**s (using projected forcings) of future change are more credible.

Initialized Prediction



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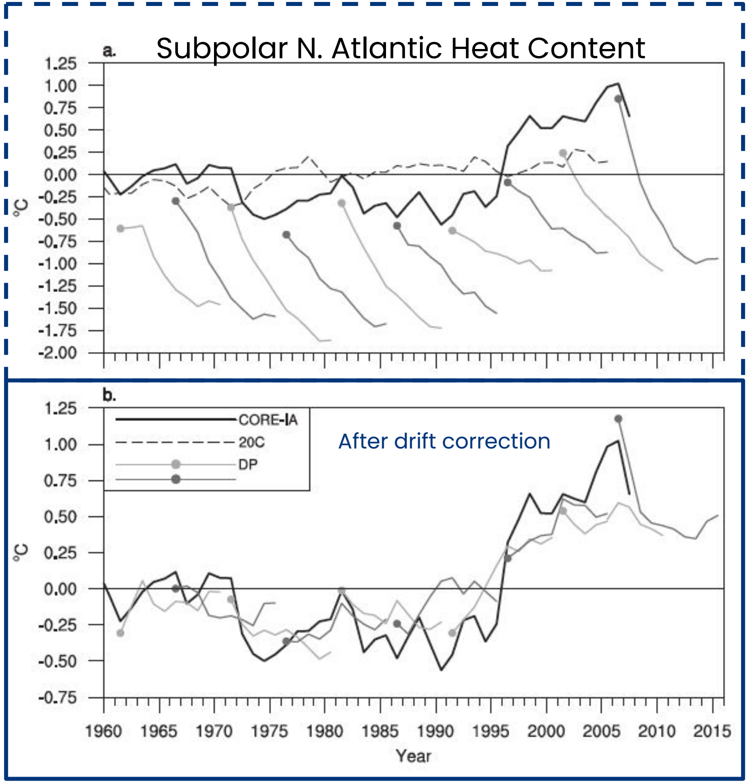
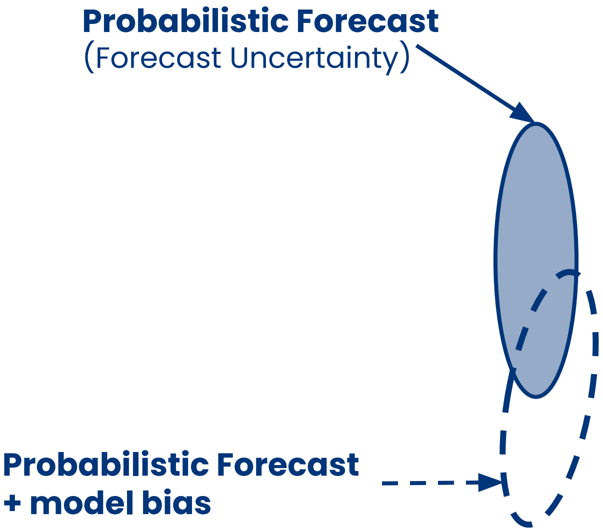
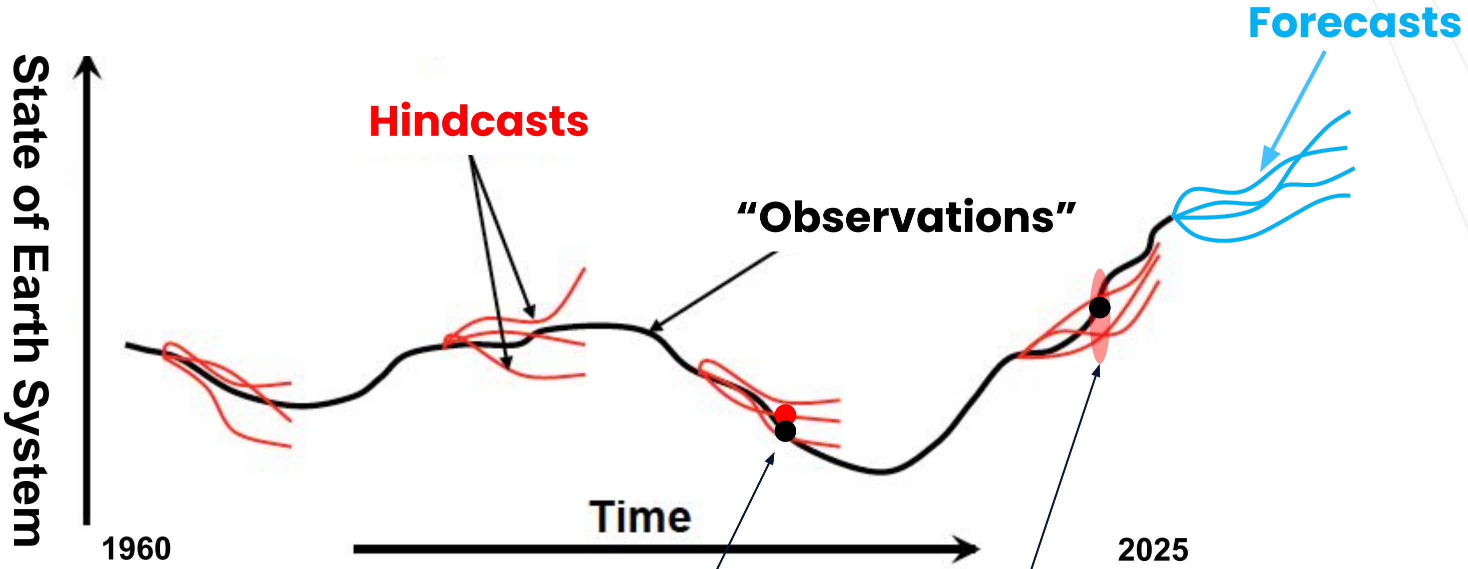




Yeager et al. (2012, https://doi.org/10.1175/JCLI-D-11-00595.1)

Initialized Prediction: Evaluation of Hindcasts/Forecasts



Deterministic: Anomaly Correlation Coefficient (ACC)

Probabilistic: Brier Skill Score (BSS)

Prediction Baselines

Modified Figure from Slingo & Palmer (2011, doi:10.1098/rsta.2011.0161)

Initialized Prediction in CESM

Subseasonal to Seasonal

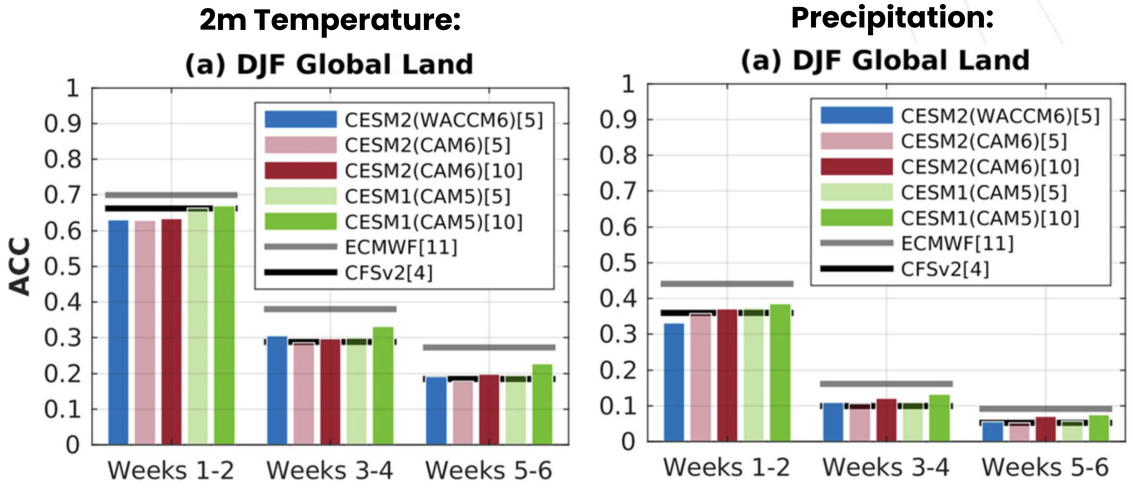
S2S

S2S Reforecasts - CESM2
Richter et al. 2022

- Weekly initializations
  - 1999-2020
- 45-day simulations
- 10-member ensembles

Land-Atmos Interactions

- Meg Fowler



- Much lower skill for precipitation than temperature
- CESM systems comparable to CFSv2; slightly lower than ECMWF

Initialized Prediction in CESM

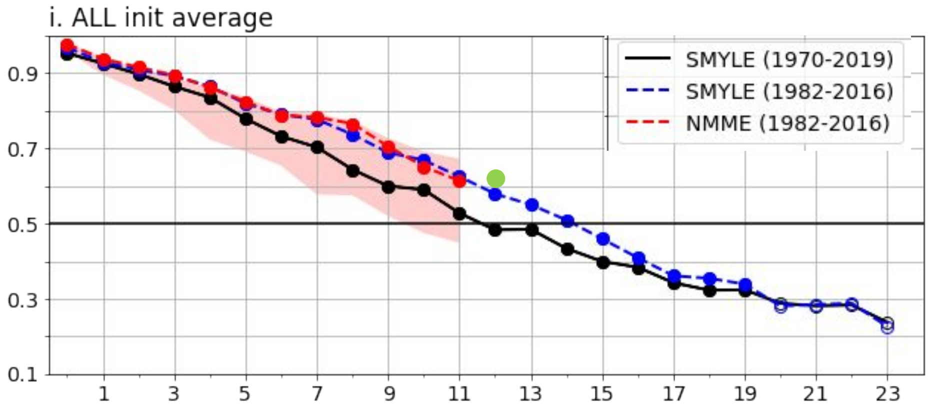
Seasonal to Interannual

S2I

SMYLE - CESM2
Seasonal-to-Multiyear Large Ensemble
Yeager et al. 2022

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

Nino3.4 Correlation Skill:



CESM2-SMYLE is competitive with other leading ENSO prediction systems (NMME, ECMWF)

Initialized Prediction in CESM

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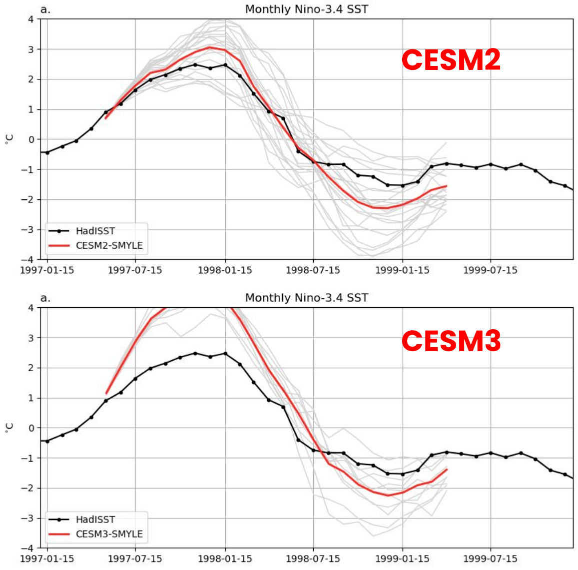
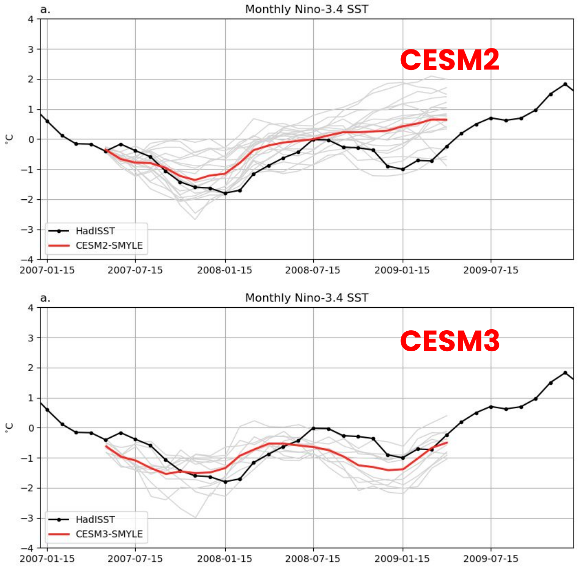
05/01/1997 Initialization:

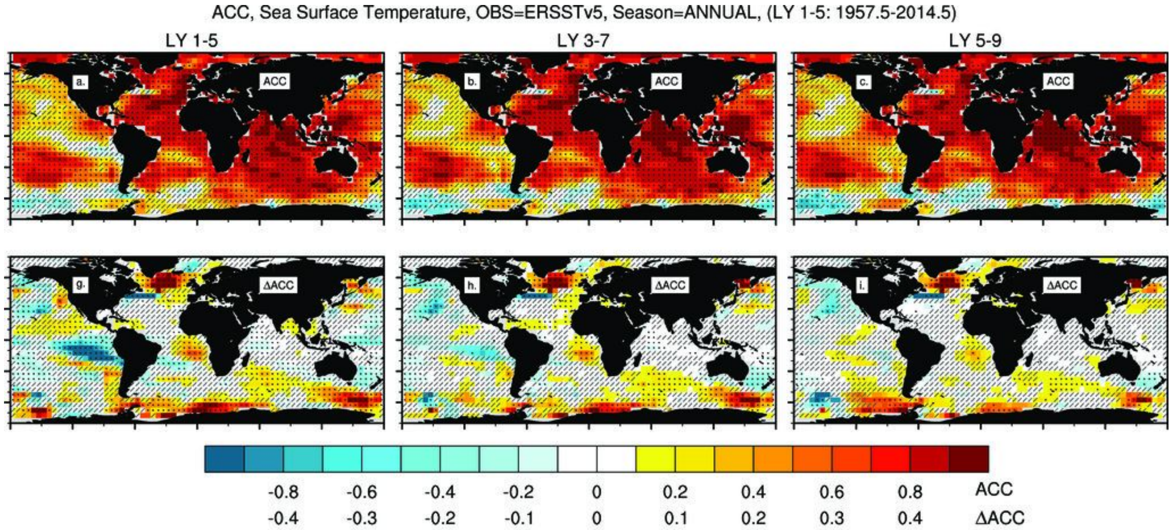


05/01/2007 Initialization:



- Work is ongoing to **assess the performance of CESM3** in “SMYLE” configuration.
- Preliminary comparison of 10-member CESM3 to 20-member CESM2 reveals **mixed results for Niño3.4**

Initialized Prediction in CESM



High skill and clear benefit of initialization (e.g. North Atlantic)

(a)–(c) ACC of annual SST
(g)–(i) ACC differences between CESM-DPLE and CESM-LE

Seasonal to Decadal

S2D

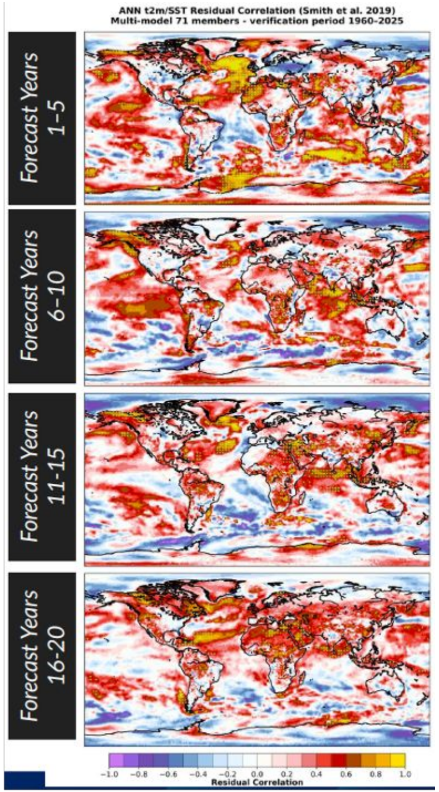
DPLE - CESM1
Decadal Prediction Large Ensemble
Yeager et al. 2018

- Initialized on November 1st
  - 1954-2015
- 40-member ensemble
- 122-months simulations

DP-CESM2

- Initialized on November 1st
  - 1958-2023
- 20-member ensemble
- 122-months simulations

Initialized Prediction in CESM



2m Temperature/SST residual correlation reveals promising **impact of initialization** even **out to forecast year 20**

Multi-Decadal

MD

MDP - CESM2
Multi-Decadal Prediction

- Nov 1st 1960-2015
  - every 5 yrs
- 242-month simulations
- 10-member ensemble

Nicoli et al. (2026, in prep)

Initialized Prediction in CESM

Subseasonal to Seasonal

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Multi-Decadal

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Initialized Prediction... with CAMulator

Subseasonal to Seasonal

S2S

S2S Reforecasts
CAMulator

- Daily reforecasts
- 1999-2020
- 11-member ensemble
- CFSv2 initial conditions
- SST evolves w/ reanalysis
- ICEFRAC persisted

Initialized Prediction... with CAMulator

Subseasonal to Seasonal

S2S

S2S Reforecasts
CAMulator

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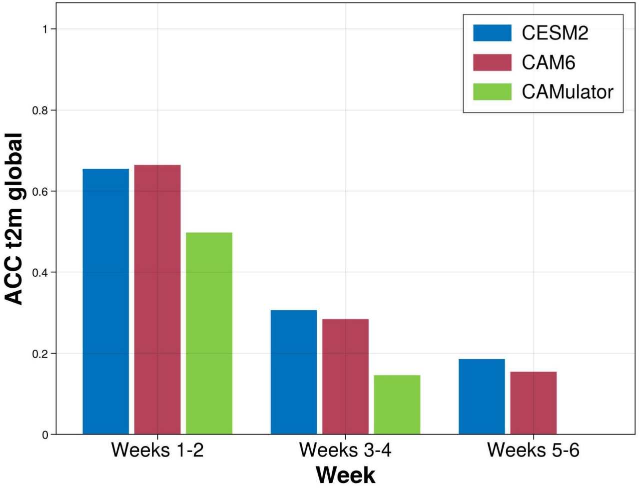
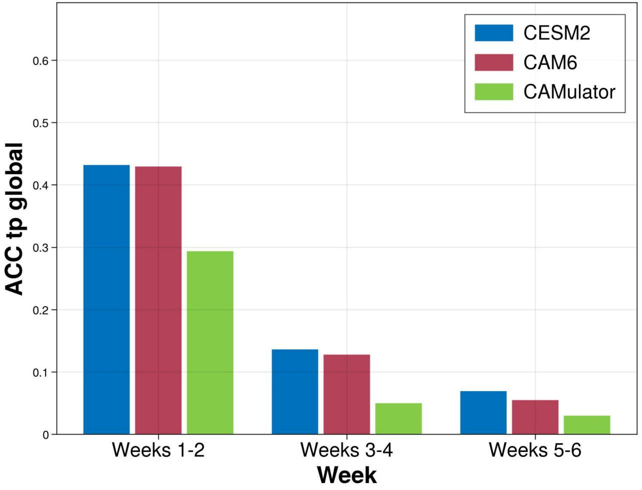
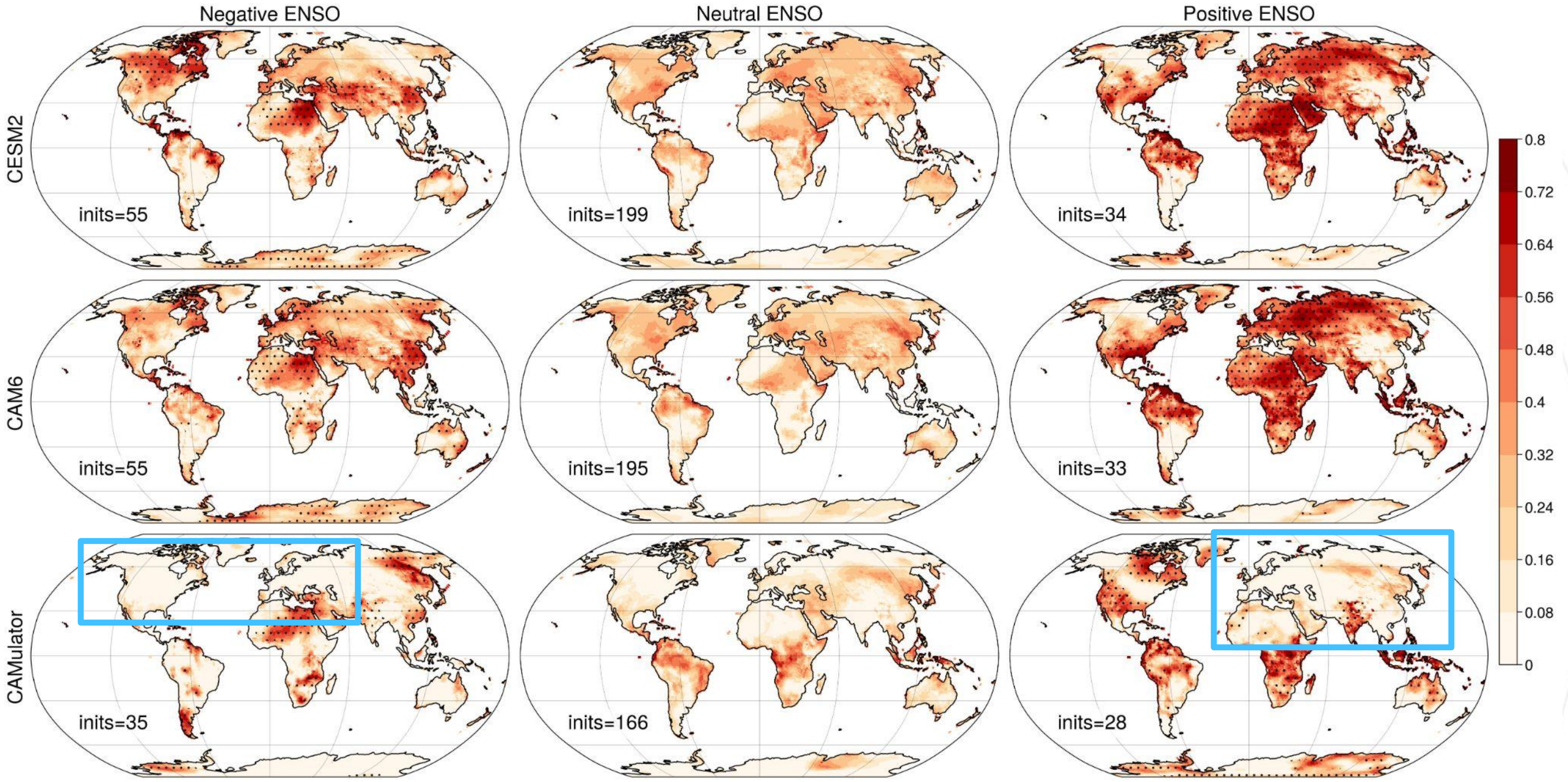




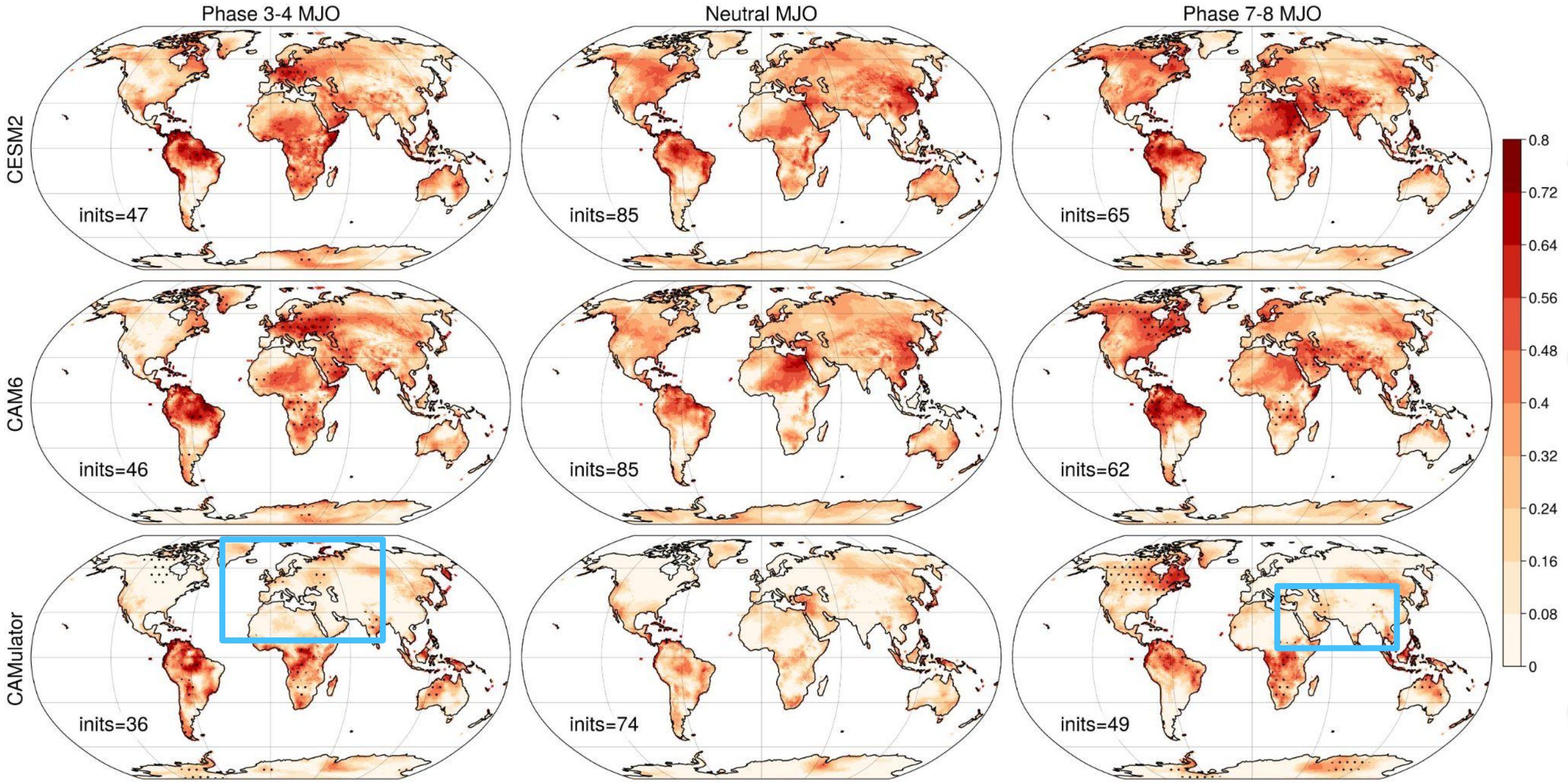
preliminary results from Abby Jaye

CAMulator: DJF ENSO Week 3-4



preliminary results from Abby Jaye

CAMulator: DJF MJO Week 3-4



preliminary results from Abby Jaye

ML-Based Prediction

Coming Soon

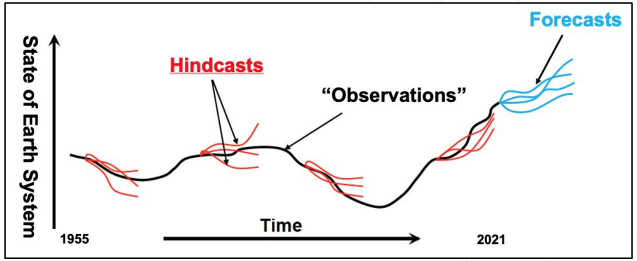
CAMulator Hindcasts

subCESMulator Hindcasts

Two Types of Prediction Systems with CESM

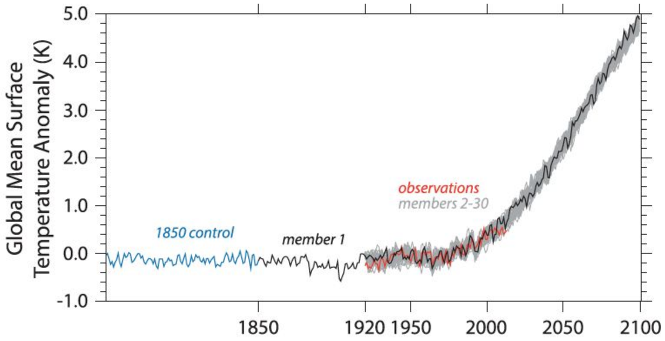
"Initialized"

- Skill comes from accurately simulating both **forced** & **internal** components
- Expect improved skill for short timescales, small spatial scales
- Examples:
    - CESM2 S2S (Richter et al., 2021, 10.1175/WAF-D-21-0163.1)
    - CESM2 SMYLE (Yeager et al., 2022, 10.5194/gmd-15-6451-2022)
    - CESM1 DPLE (Yeager et al., 2018, 10.1175/BAMS-D-17-0098.1)



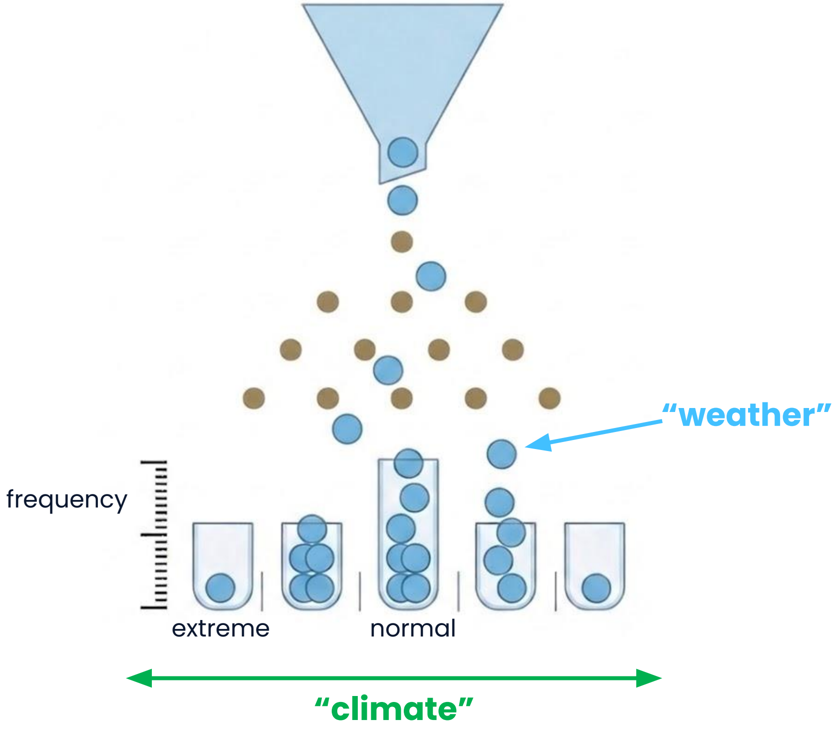
"Uninitialized"

- Skill from accurately simulating forced variability & change
- Expect skill for long timescales, large spatial scales
- Explore modes of variability
- Examples:
    - CESM1 LE (Kay et al., 2015, 10.1175/BAMS-D-13-00255.1)
    - CESM2 LE (Rodgers et al., 2021, 10.5194/esd-12-1393-2021)
    - CESM3 (coming soon!)



Weather vs Climate

Climate is the background probability distribution of weather



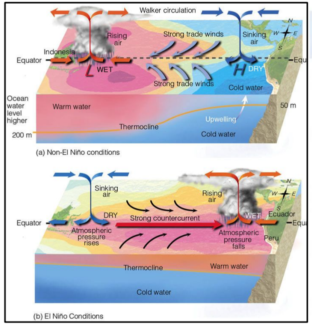
Weather vs Climate

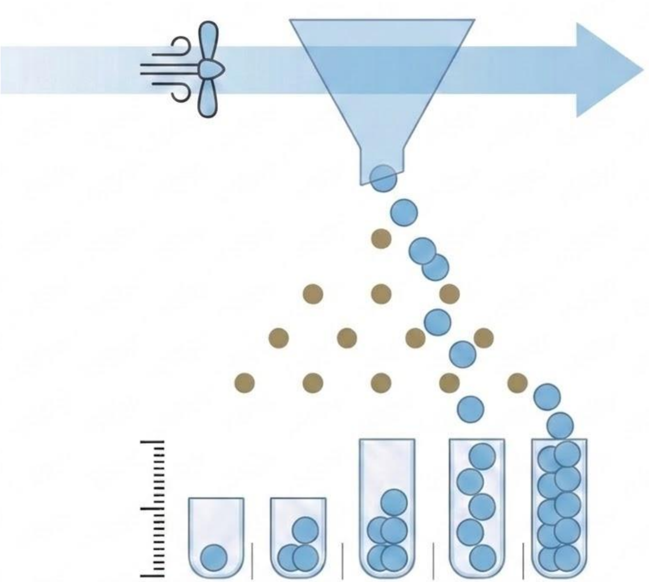
Goal of climate prediction is to anticipate changes in climate (i.e. future weather ***statistics***, not future weather events).

Volcanic Eruptions

Emissions

ENSO Cycles

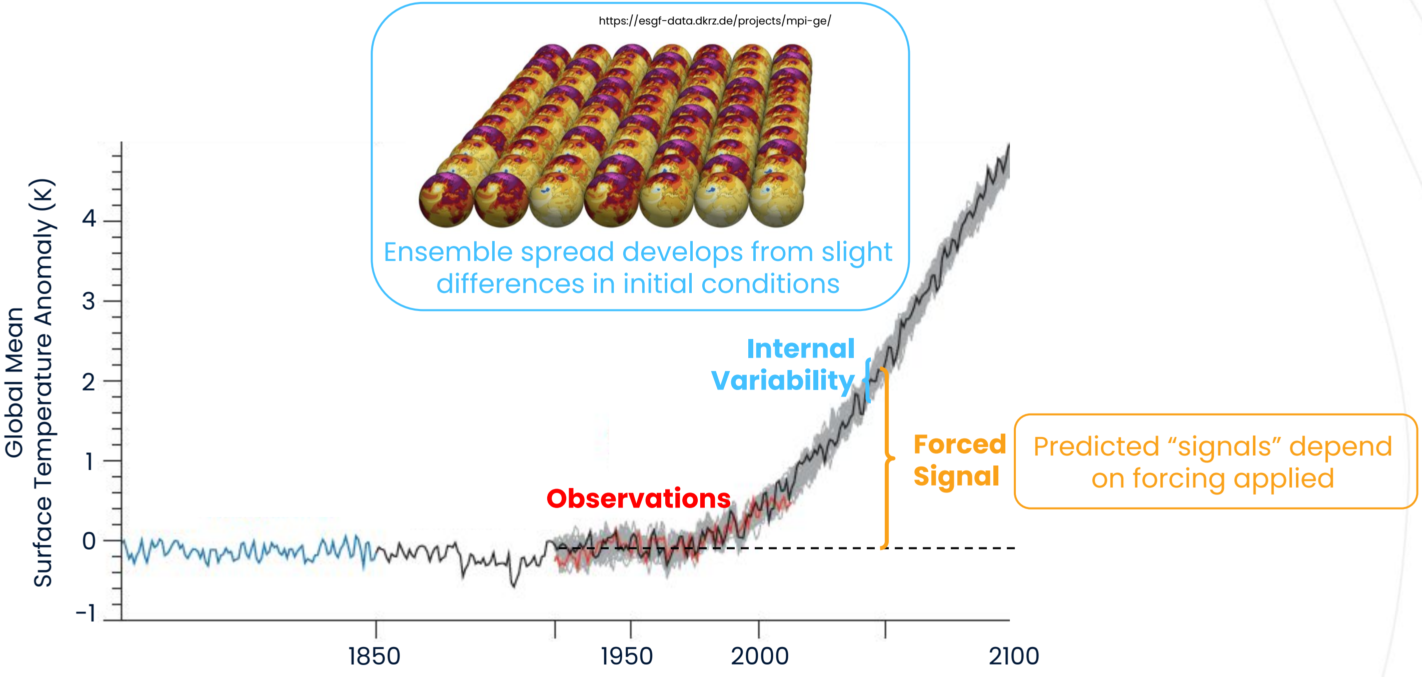




more extreme weather events

Climate Projection with Large Ensembles

Large ensembles permit decomposition into forced vs. internal variability



Modified figure from Kay et al. (2015, 10.1175/BAMS-D-13-00255.1)

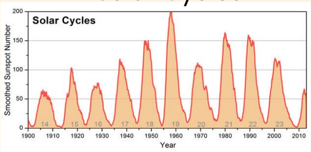
Forced vs Internal Variability

Forced Variability & Change

Greenhouse Gases

Biomass Emissions

Solar Cycles



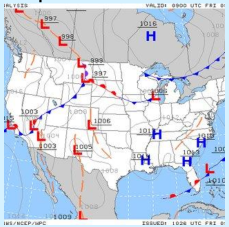
Volcanic Eruptions

Ensemble mean (signal)

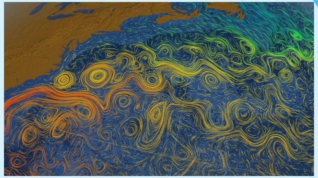
Environmental Change

Internal Variability

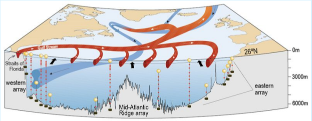
Atmospheric Turbulence



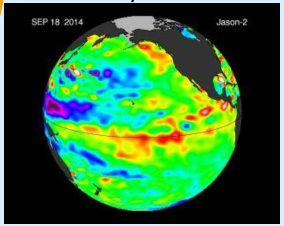
Oceanic Turbulence



AMOC

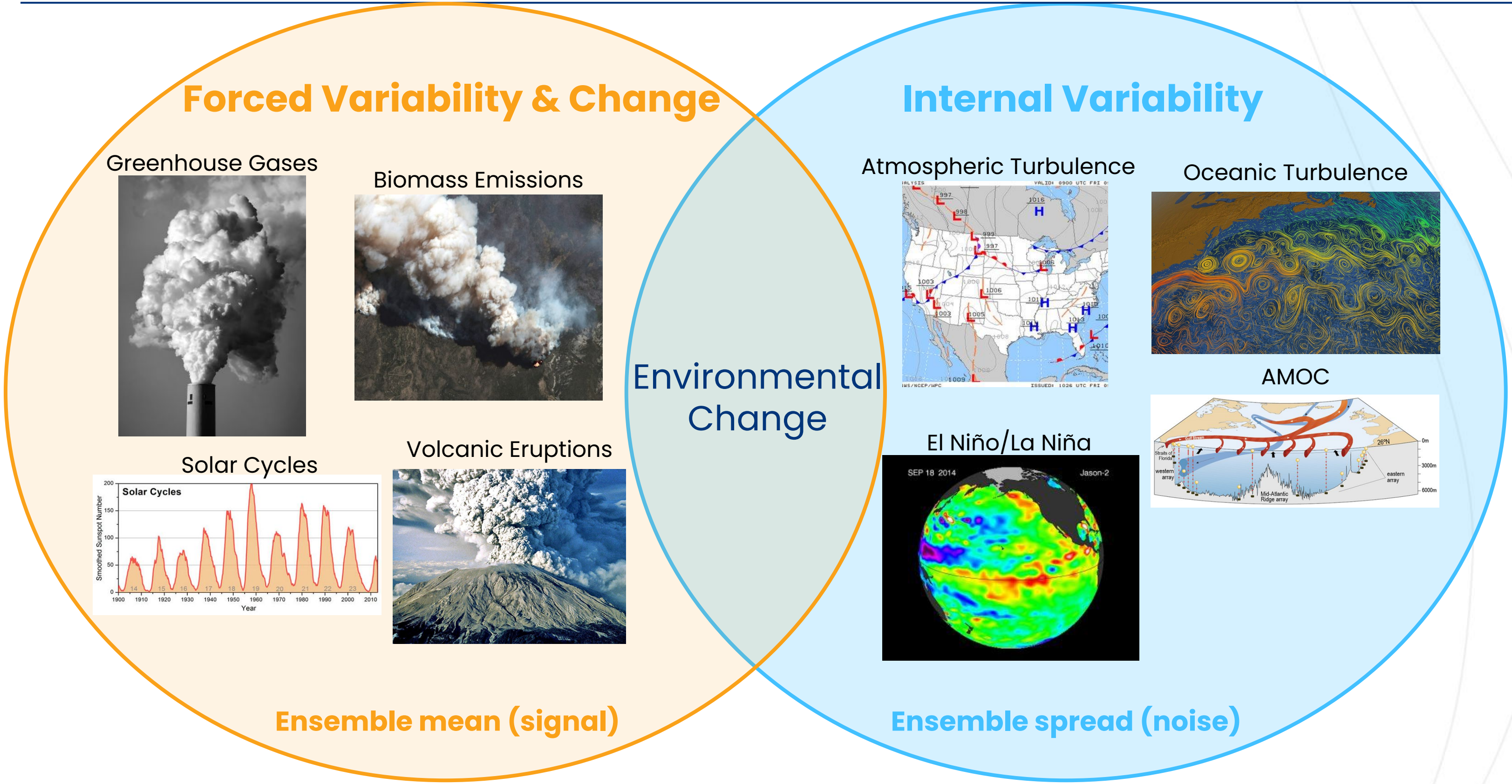


El Niño/La Niña



Ensemble spread (noise)

Forced vs Internal Variability

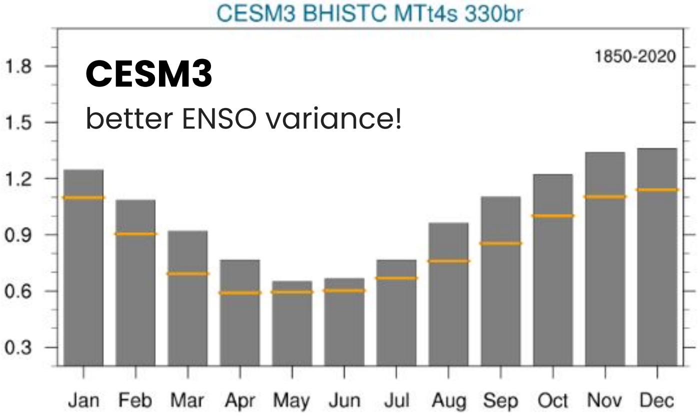


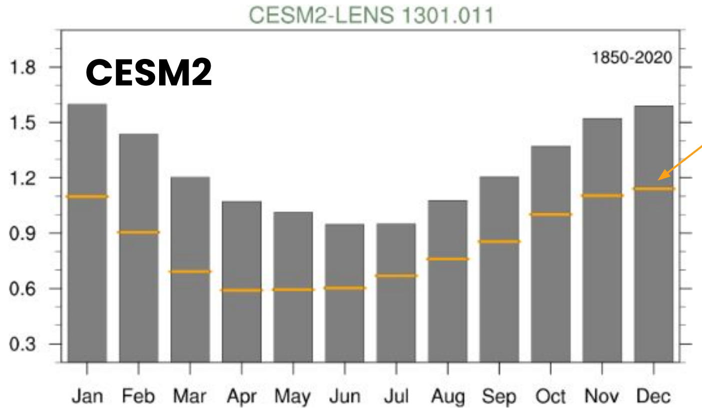
 | **Projection Large Ensembles ("uninitialized")**: skill = forced + predictable internal variability

Uninitialized: CESM3 (preliminary)

Uninitialized: ENSO in CESM3 (preliminary)

Monthly Nino3.4 standard deviation





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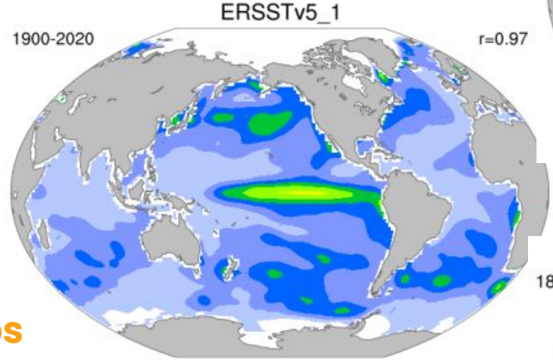
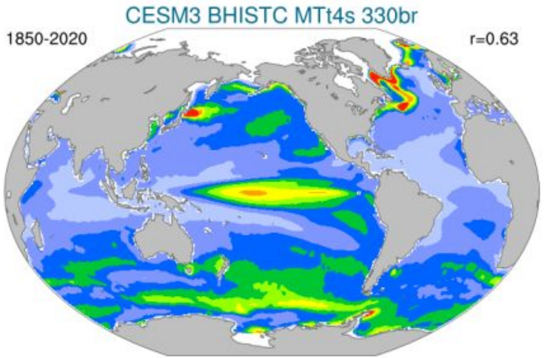
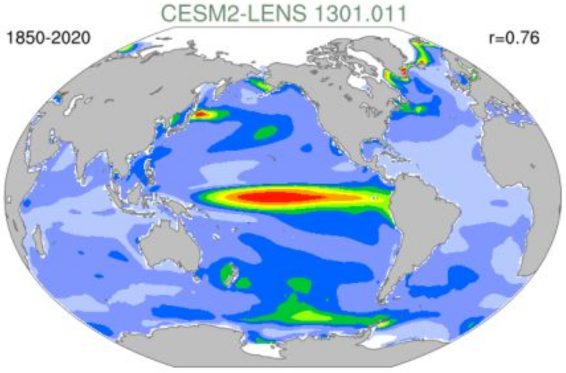




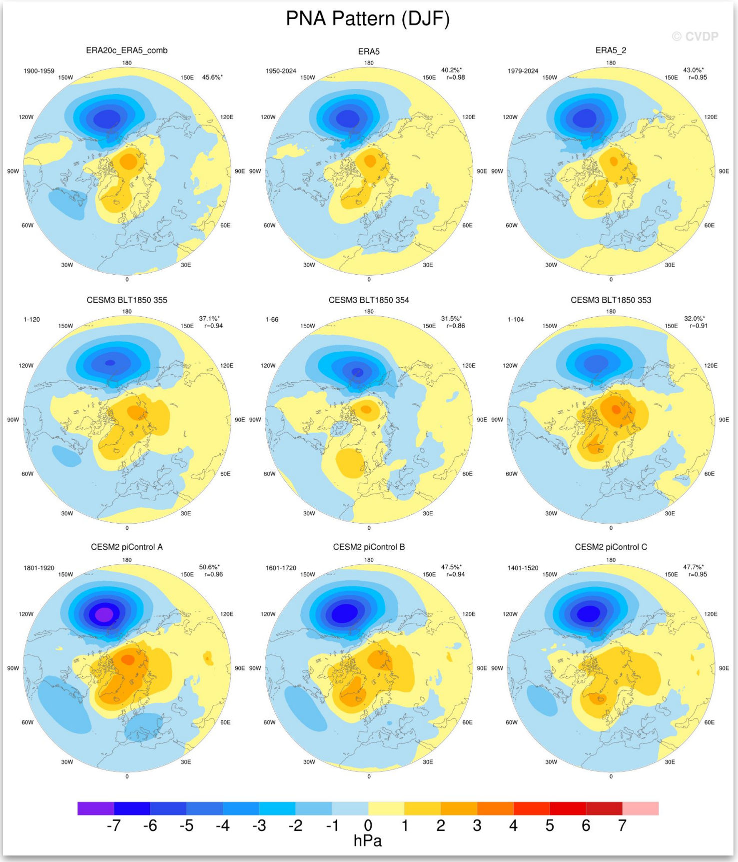


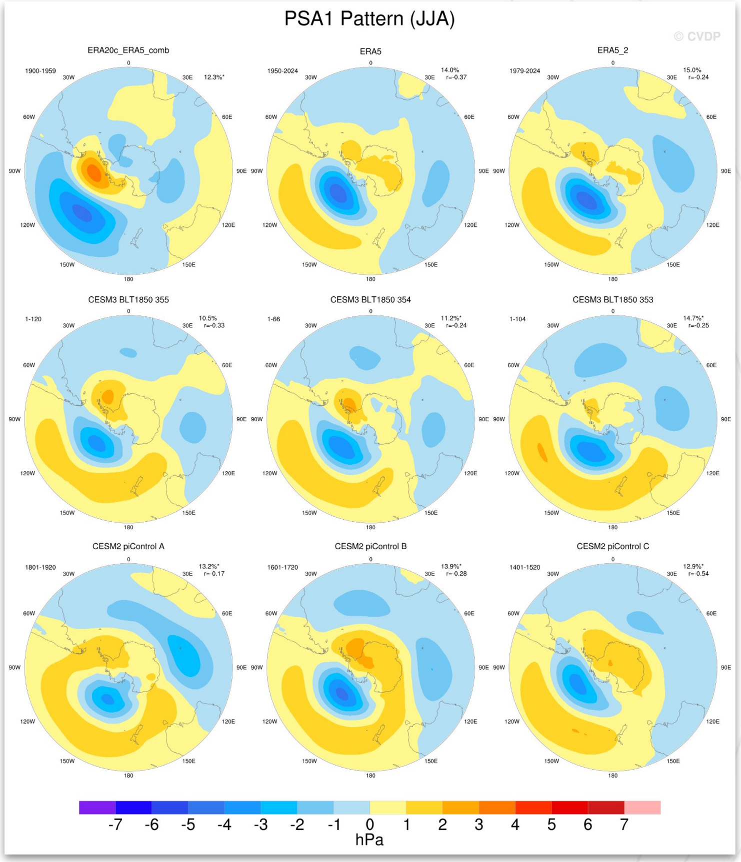
Uninitialized: MOVs in CESM3 (preliminary)

ERA20c

CESM3

CESM2





Outstanding Questions

- **How/where can we increase Earth System prediction skill?**
  - Machine Learning (emulation, post-processing)
  - Resolution
  - Initialization
  - Physics

- **What are the coupled mechanisms at work in initialized ensemble prediction simulations? What explains skillful (or unskillful) S2S2D predictions?**
  - E.g. what role does the land play in S2S prediction?

- **How can we enhance connections with potential end-users?**

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Interested? Get Involved!

- Analyze ESPWG datasets
- Propose new experiments that can utilize ESPWG compute allocation
- Share your work at future meetings

Website: https://www.cesm.ucar.edu/working-groups/earth-system/

Model Drift & Drift Correction

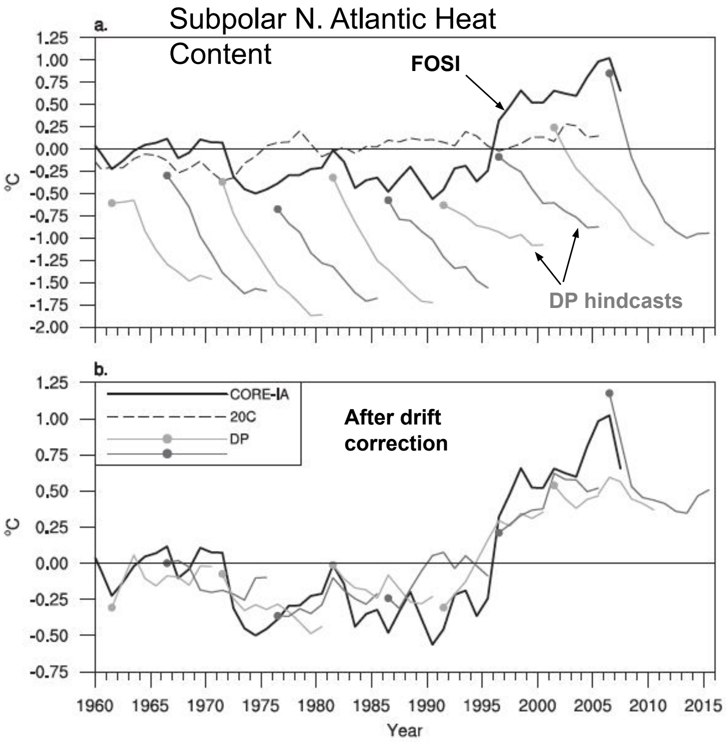
- Biased models initialized from realistic states “drift” back towards model attractor
- Standard post-processing to remove hindcast drift:

$$f'_{i\tau} = f_{i\tau} - \overline{f_\tau} = f_{i\tau} - \frac{1}{N}\sum_{1}^{N} f_{i\tau}$$

for hindcast samples $i = 1 \ldots N$ and forecast lead time τ

- Other more sophisticated methods have been explored:

Kharin et al. (2012, *GRL*, https://doi.org/10.1029/2012GL052647)
Meehl et al. (2022, *CLI DYN*, https://doi.org/10.1007/s00382-022-06272-7)



Yeager et al. (2012, https://doi.org/10.1175/JCLI-D-11-00595.1)