27th Annual CESM Workshop
June 13, 2022

A Decade of Decadal Prediction Research

Advancing CESM near-term prediction capabilities in the face of drift, shock, and noise

Stephen Yeager

National Center for Atmospheric Research (NCAR), Boulder, CO

This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

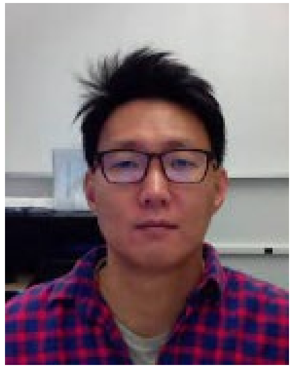


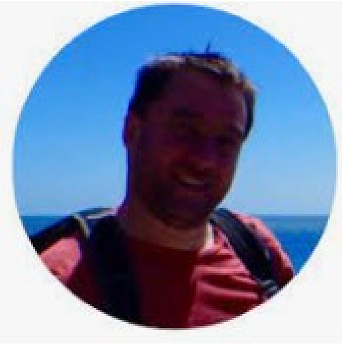
















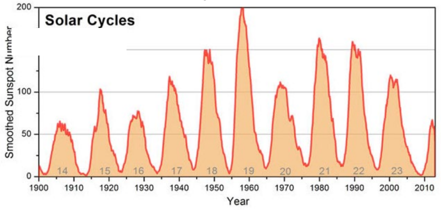
Forced Variability & Change

Greenhouse Gases

Biomass Emissions

Volcanic Eruptions

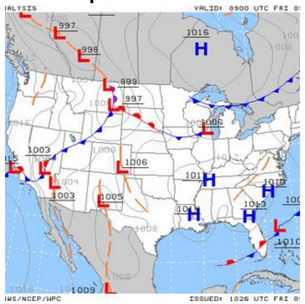
Solar Cycles



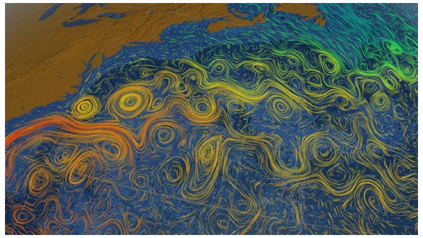
Regional Environmental Change

Internal Variability

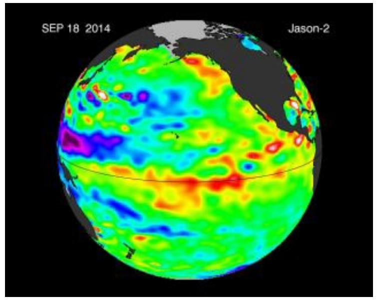
Atmospheric Turbulence



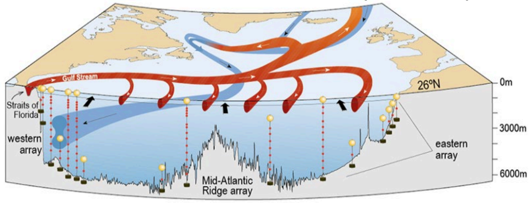
Oceanic Turbulence



El Niño/La Niña



Atlantic Meridional Overturning Circulation (AMOC)



Forced Variability & Change

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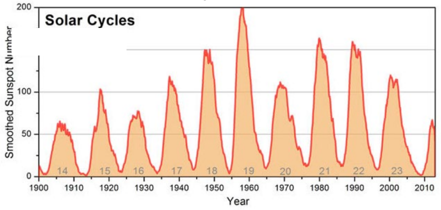


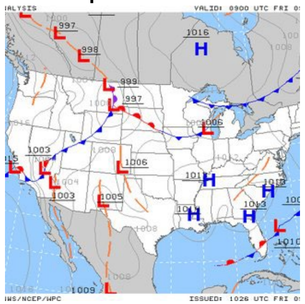
Ensemble mean (signal) = forced variability/change

Regional Environmental Change

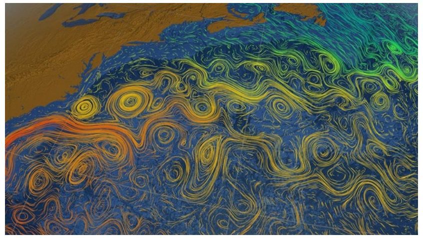
SMILEs (Single Model Initial-condition Large Ensembles)

Internal Variability

Atmospheric Turbulence



Oceanic Turbulence



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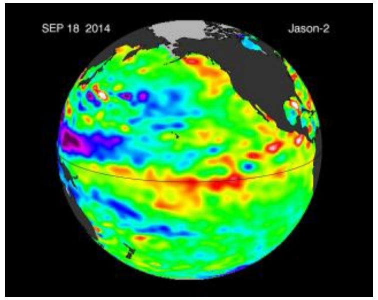

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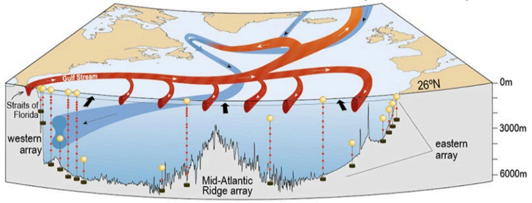


Ensemble spread (noise) = internal variability ("irreducible uncertainty")

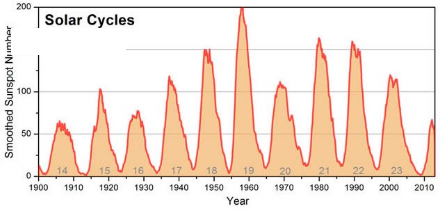
Forced Variability & Change

Greenhouse Gases

Biomass Emissions

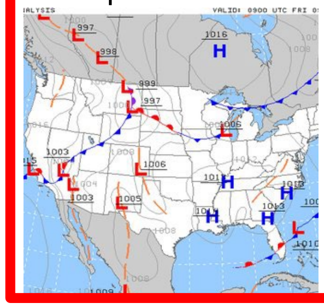
Volcanic Eruptions

Solar Cycles



Internal Variability

Atmospheric Turbulence



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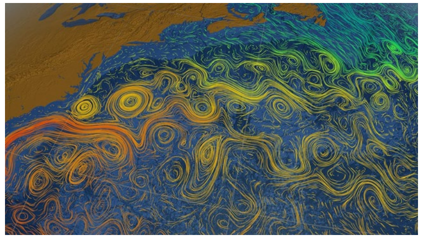

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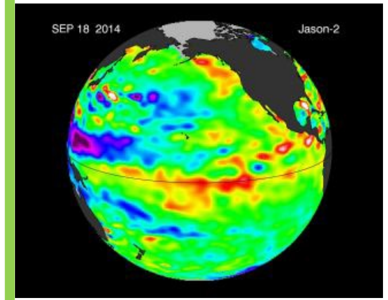

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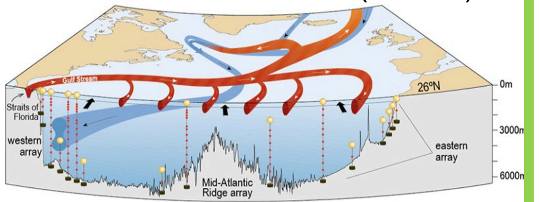


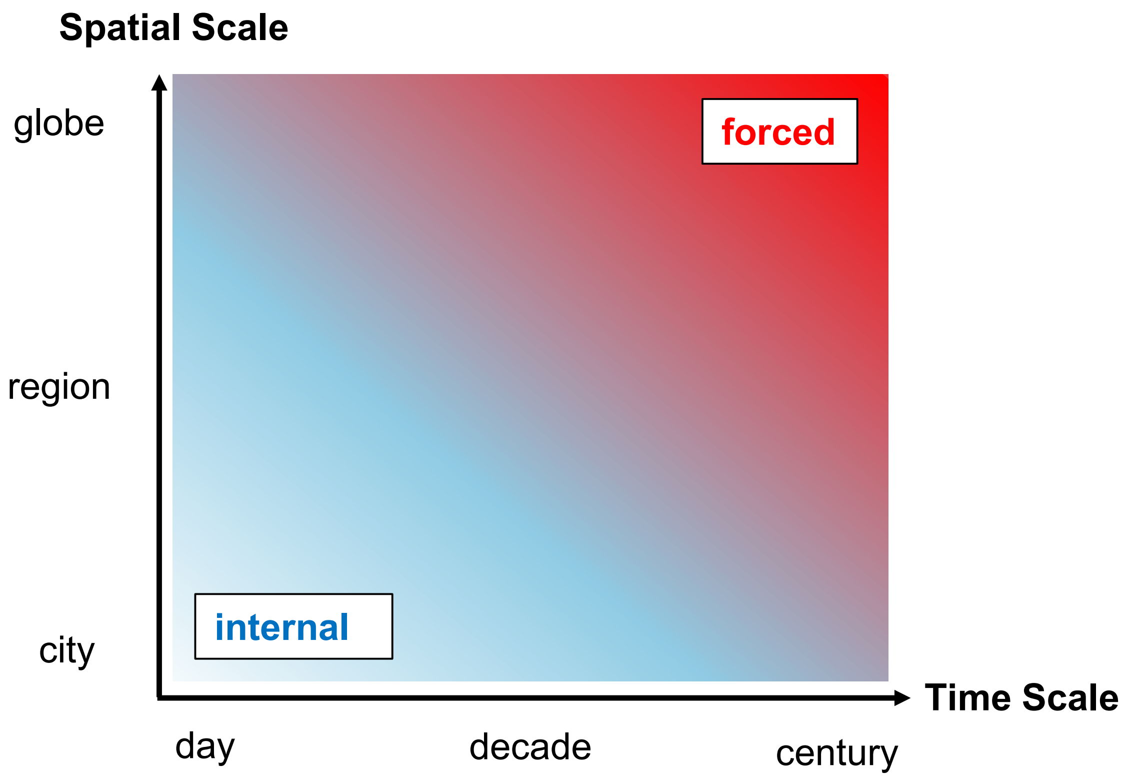
Regional Environmental Change

Initialized Decadal Prediction Ensembles

Ensemble mean (signal) = forced variability/change + predictable internal variability

Ensemble spread (noise) = unpredictable internal variability

Which matters more for Earth system prediction: internal variability or forced climate change?



- Depends on spatiotemporal scale
- Accurate decadal prediction of regional environmental change requires constraining the internal component of variability in climate models (in addition to the forced component)
- As in NWP, constraining internal variability can be accomplished through initialization

Science, 1997

REPORTS

Predictability of North Atlantic Multidecadal Climate Variability

Stephen M. Griffies* and Kirk Bryan

Science, 2007

Improved Surface Temperature Prediction for the Coming Decade from a Global Climate Model

Doug M. Smith,* Stephen Cusack, Andrew W. Colman, Chris K. Folland, Glen R. Harris, James M. Murphy

Nature, 2008

Advancing decadal-scale climate prediction in the North Atlantic sector

N. S. Keenlyside[1], M. Latif[1], J. Jungclaus[2], L. Kornblueh[2] & E. Roeckner[2]

J. Climate, 2010

Decadal Prediction in the Pacific Region

GERALD A. MEEHL AND AIXUE HU

National Center for Atmospheric Research, Boulder, Colorado*

CLAUDIA TEBALDI+

National Center for Atmospheric Research, Boulder, Colorado, and Climate Central, Princeton, New Jersey*

BAMS, 2009

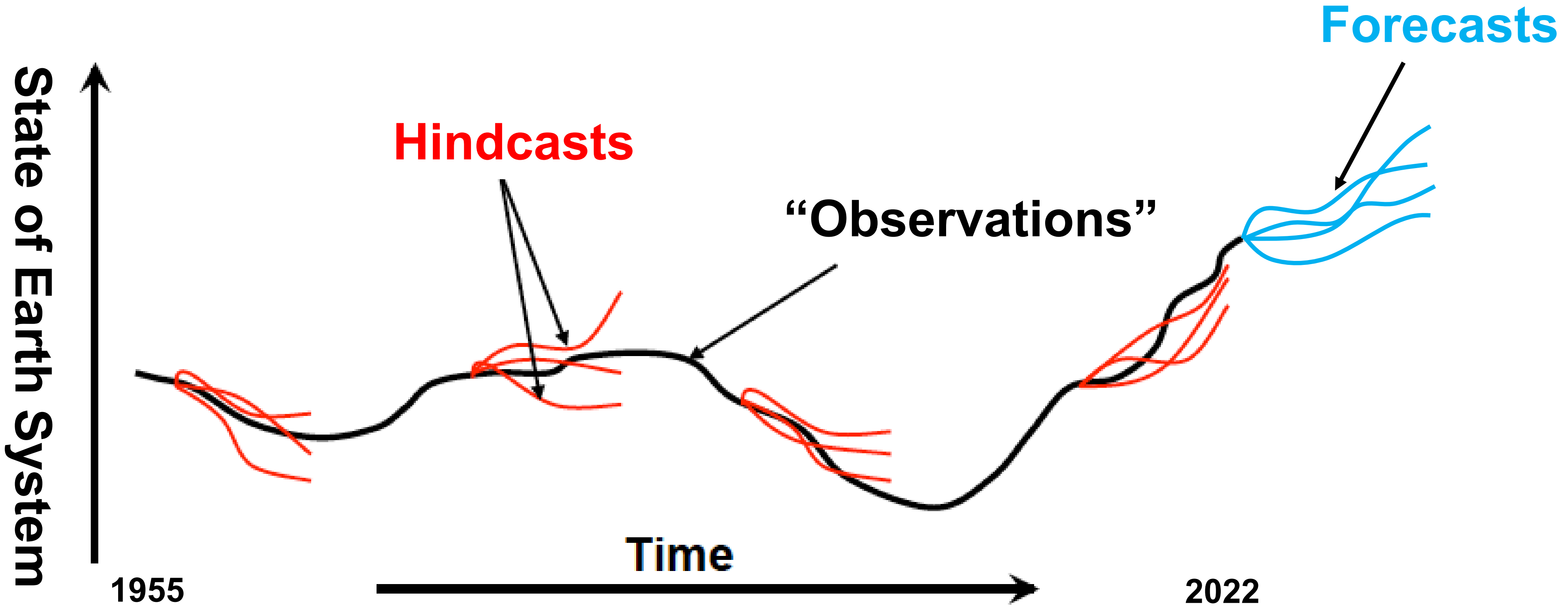
DECADAL PREDICTION

Can It Be Skillful?

BY GERALD A. MEEHL, LISA GODDARD, JAMES MURPHY, RONALD J. STOUFFER, GEORGE BOER, GOKHAN DANABASOGLU, KEITH DIXON, MARCO A. GIORGETTA, ARTHUR M. GREENE, ED HAWKINS, GABRIELE HEGERL, DAVID KAROLY, NOEL KEENLYSIDE, MASAHIDE KIMOTO, BEN KIRTMAN, ANTONIO NAVARRA, ROGER PULWARTY, DOUG SMITH, DETLEF STAMMER, AND TIMOTHY STOCKDALE

← Laid out the scientific rationale for a decadal prediction protocol for CMIP5

Decadal Prediction Experiment Design

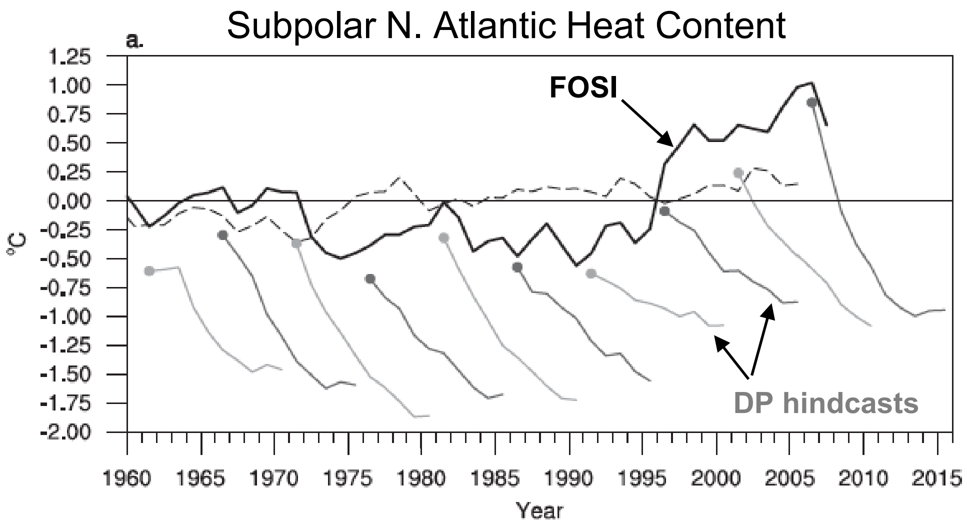


J. Climate, 2012

SPECIAL
Community Climate System Model CCSM4
COLLECTION

A Decadal Prediction Case Study: Late Twentieth-Century North Atlantic Ocean Heat Content

STEPHEN YEAGER, ALICIA KARSPECK, GOKHAN DANABASOGLU, JOE TRIBBIA, AND HAIYAN TENG
National Center for Atmospheric Research, Boulder, Colorado



- 10-member CCSM4-DP initialized each Jan. 1st 1961,1966,…,2006 (N=10) from a forced ocean—sea-ice (**FOSI**) simulation constrained by historical atmospheric observations.

J. Climate, 2012

SPECIAL
Community Climate System Model CCSM4
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A Decadal Prediction Case Study: Late Twentieth-Century North Atlantic Ocean Heat Content

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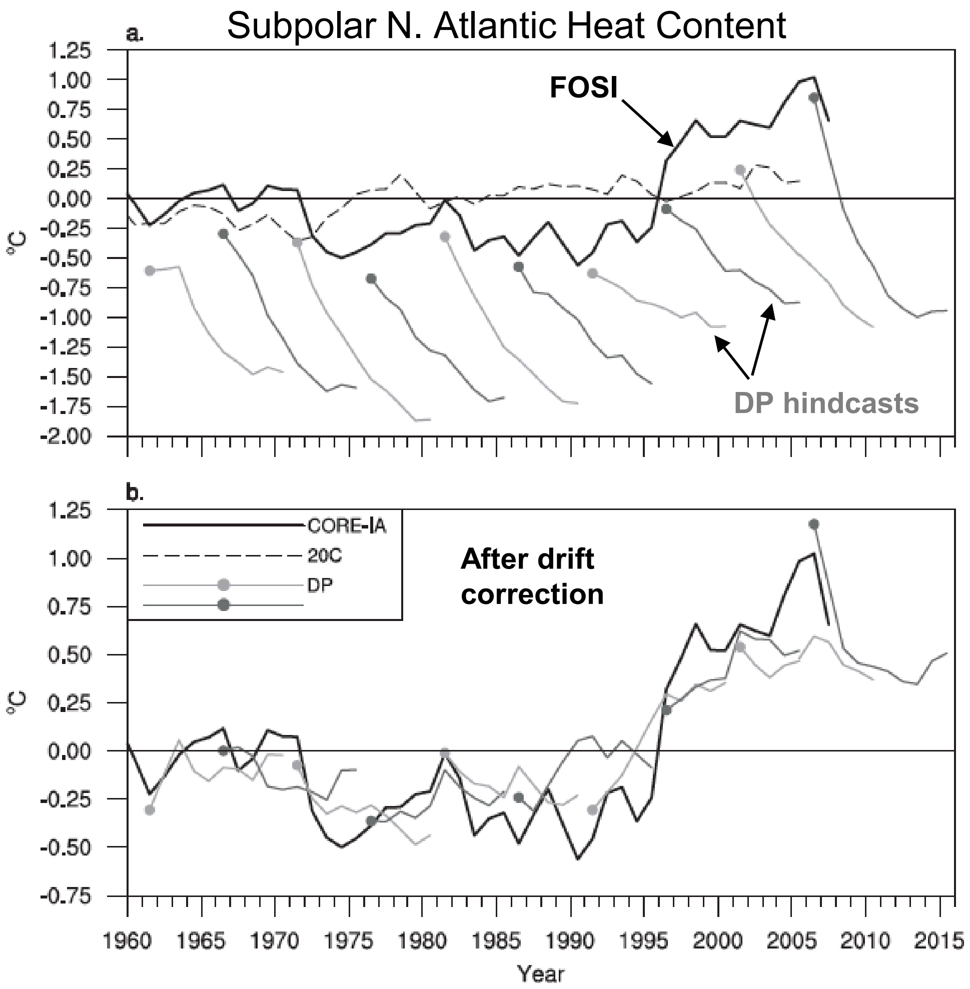
- First demonstration of decadal prediction skill of CCSM hindcasts initialized from observation-based states
- Heat budget analysis showed that skill derives from predictable ocean advective heat convergence (as had been hypothesized, but not shown)



Clim. Dyn., 2014

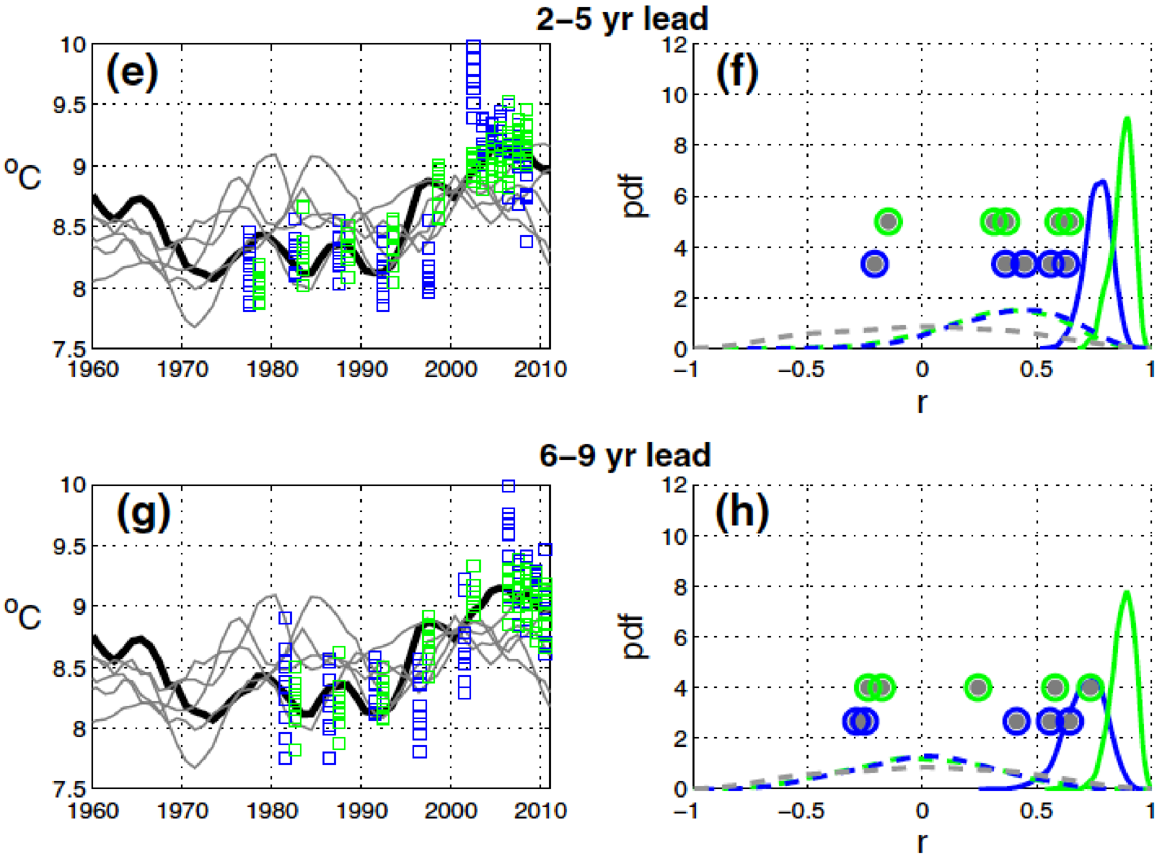
An evaluation of experimental decadal predictions using CCSM4

A. Karspeck · S. Yeager · G. Danabasoglu · H. Teng

- Analysis of CCSM4-DP, including extra start dates and a companion set initialized from ocean data assimilation historical “snapshots”.

- In the primary region where initialization impacts are large (SPNA), **hindcast initialization** method yields higher skill than **data assimilation** initialization method.

Subpolar N. Atlantic SST



1975-2006 forecast starts

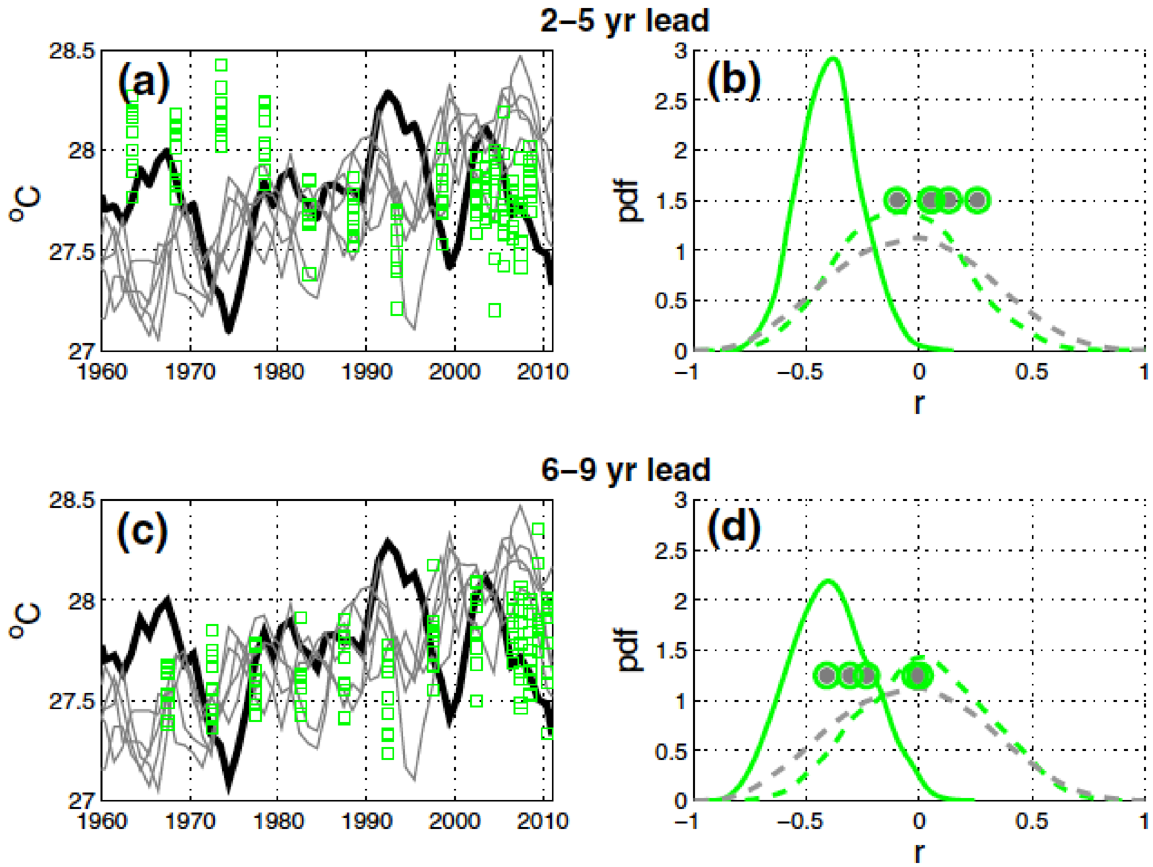
Clim. Dyn., 2014

An evaluation of experimental decadal predictions using CCSM4

A. Karspeck · S. Yeager · G. Danabasoglu ·
H. Teng

- Poor skill in the tropical Pacific using FOSI initialization.

Equatorial Pacific SST



1961-2006 forecast starts

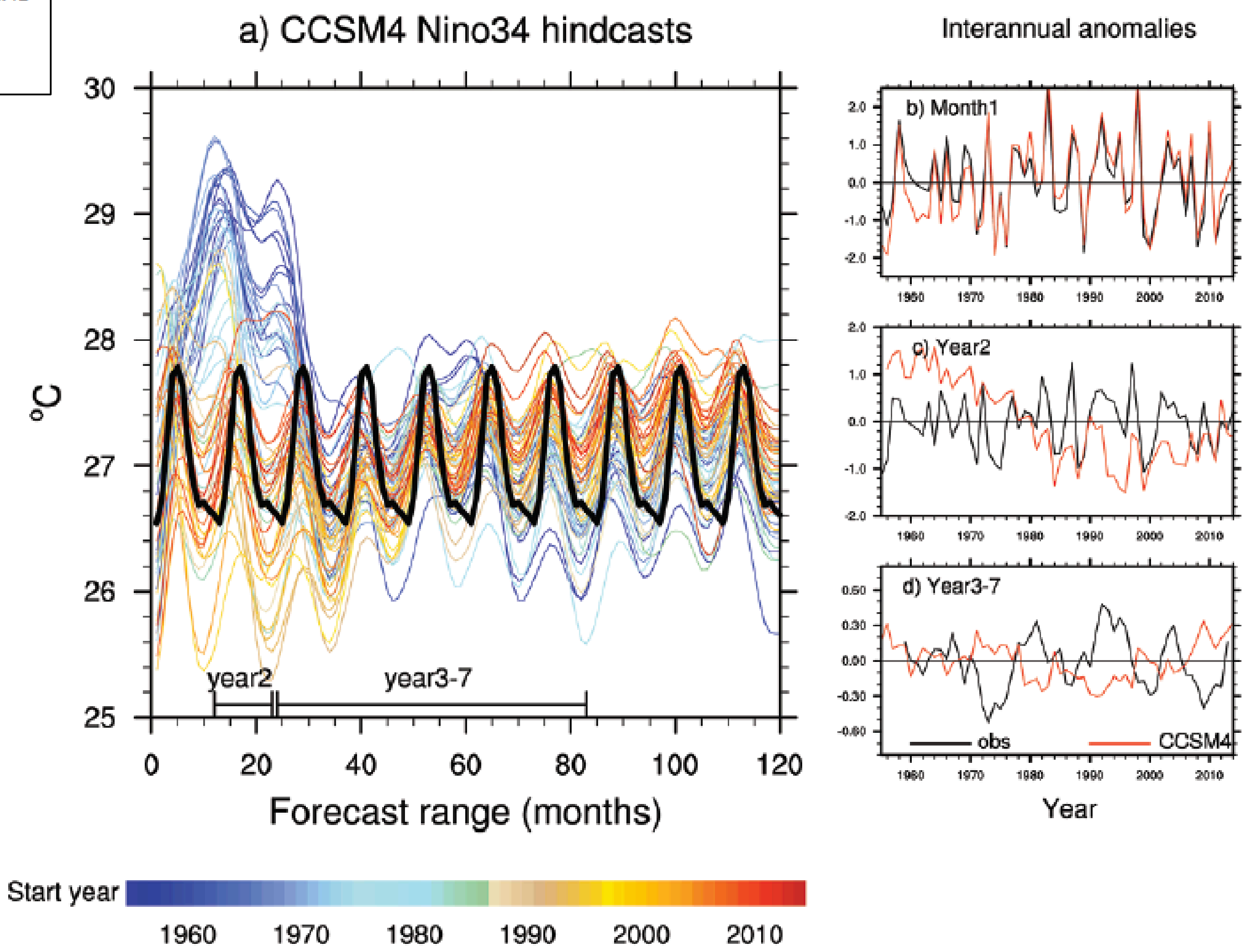
CLIVAR Exchanges, 2017

Initialization Shock in CCSM4 Decadal Prediction Experiments

doi: 10.22498/pages.25.1.41

Haiyan Teng, Gerald A. Meehl, Grant Branstator, Stephen Yeager, Alicia Karspeck

- Large initialization shock in CCSM4-DP, was later traced to a (correctable) bias in zonal tropical SST gradients in FOSI



GRL, 2015

Geophysical Research Letters

RESEARCH LETTER
10.1002/2015GL065364

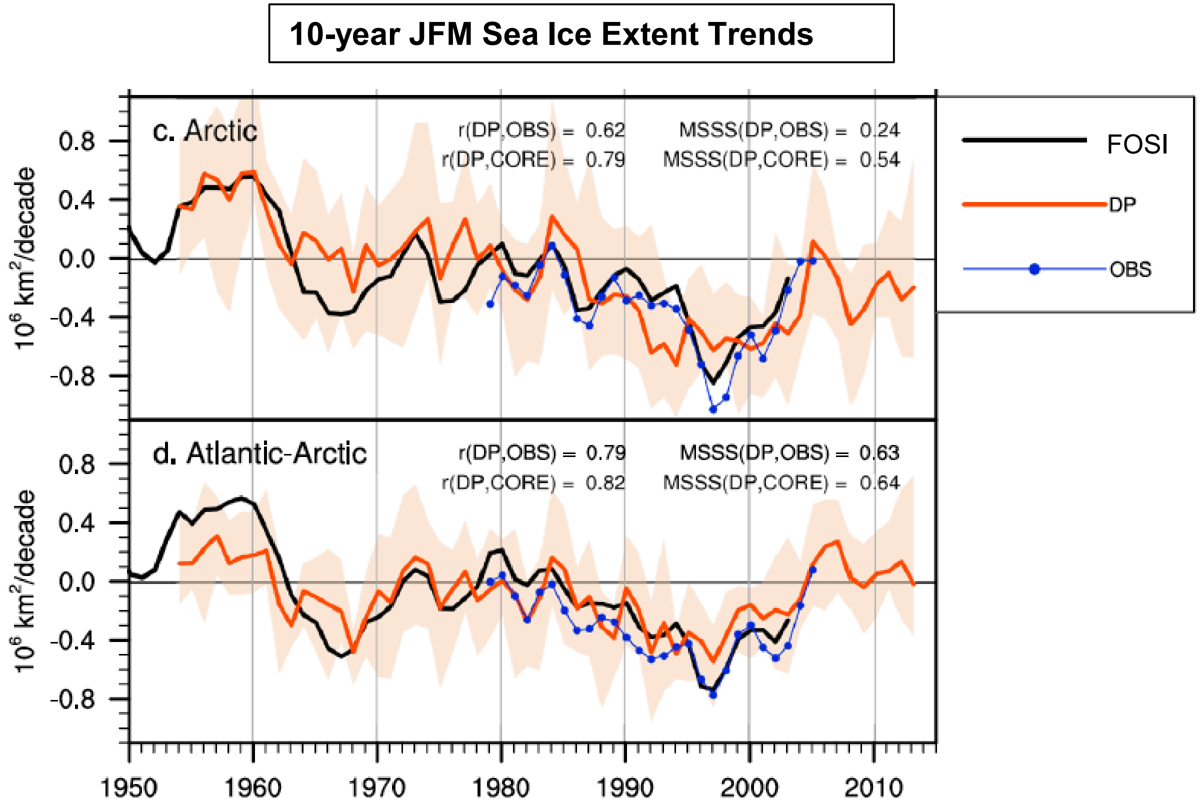
Predicted slowdown in the rate of Atlantic sea ice loss

Stephen G. Yeager[1], Alicia R. Karspeck[1], and Gokhan Danabasoglu[1]

[1]Climate and Global Dynamics Laboratory, National Center for Atmospheric Research, Boulder, Colorado, USA

Key Points:
- Ocean thermohaline circulation

- 10-member CESM1-DP initialized from FOSI each Jan. 1st 1955-2014 (N=60)
- Parallel work examining N. Atlantic mechanisms in FOSI
- Predictable decadal changes in N. Atlantic ocean thermohaline circulation (THC) strength & northward heat transport (related to low-frequency NAO buoyancy forcing) translates into predictable changes in the rate of Arctic winter sea ice decline.
- Rapid sea ice decline in 1990s was associated with THC spinup, & ongoing and future THC spindown (weak NAO forcing after 1997) will result in a slowdown in the rate of Arctic winter sea ice loss.



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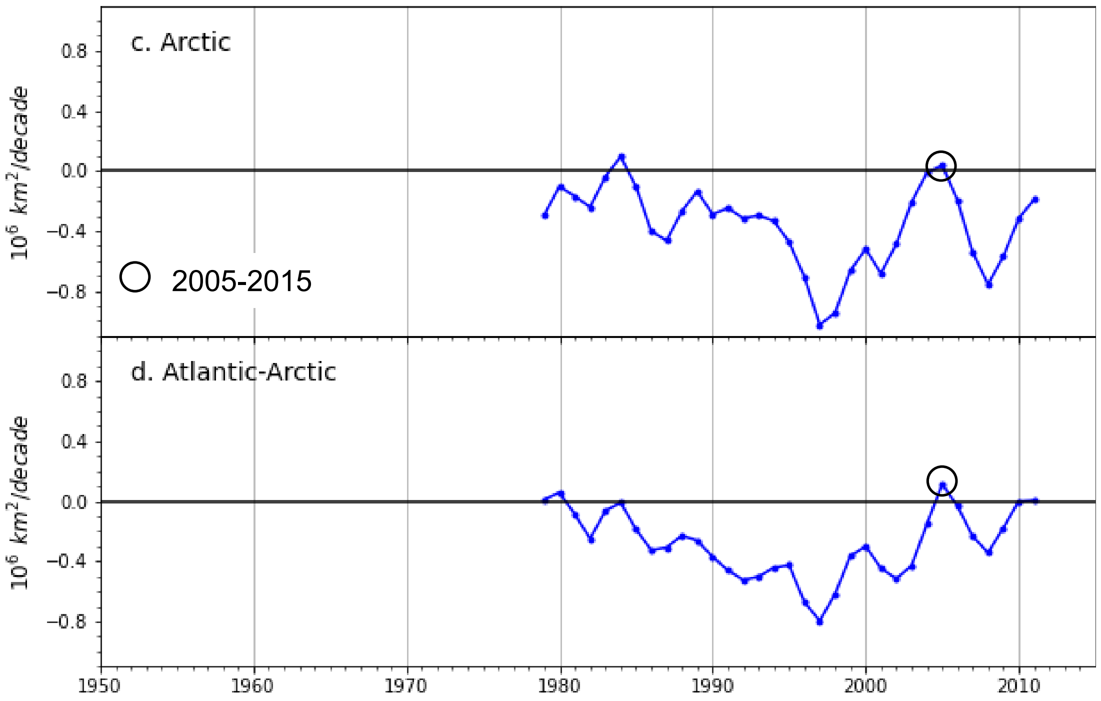
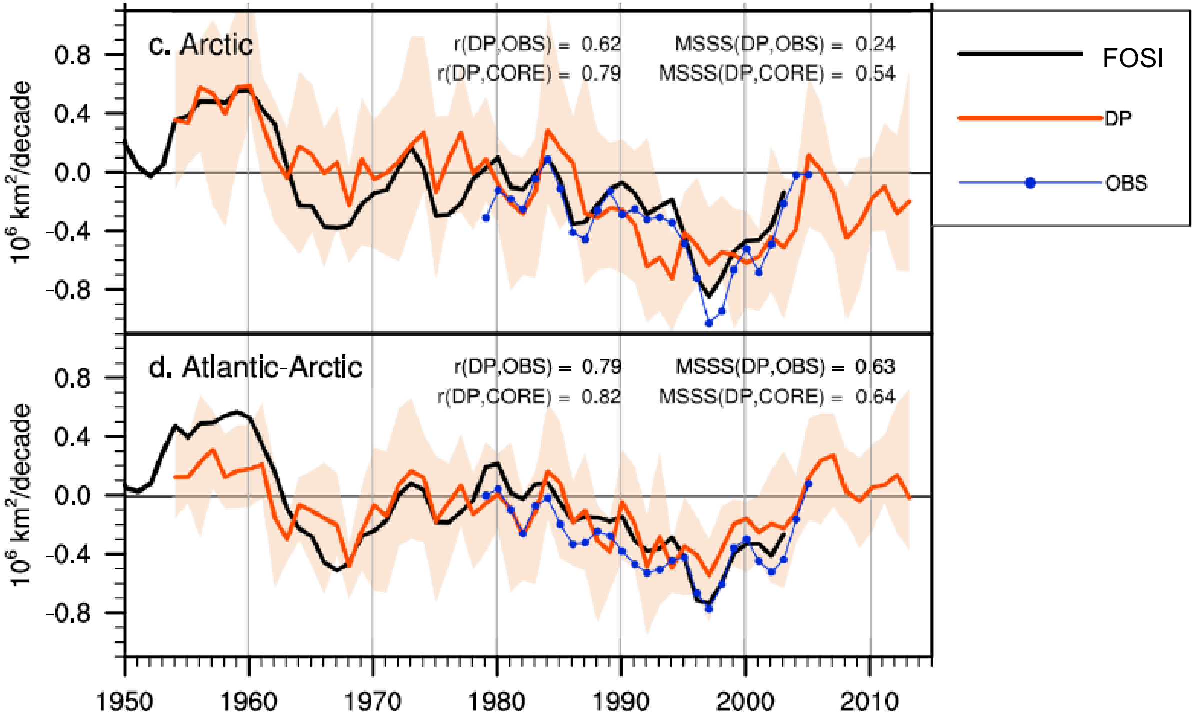
10-year Observed Trends extended through 2011-2021



10-year JFM Sea Ice Extent Trends



- S2D prediction systems exhibit deficient signal variability (too much noise)

GRL, 2014

RESEARCH LETTER
10.1002/2014GL059637

Key Points:
- The winter NAO can be skilfully predicted months ahead
- The signal-to-noise ratio of the predictable signal is anomalously low
- Predictions of the risk of regional winter extremes are possible

Skillful long-range prediction of European and North American winters

A. A. Scaife[1], A. Arribas[1], E. Blockley[1], A. Brookshaw[1], R. T. Clark[1], N. Dunstone[1], R. Eade[1], D. Fereday[1], C. K. Folland[1,2], M. Gordon[1], L. Hermanson[1,3], J. R. Knight[1], D. J. Lea[1], C. MacLachlan[1], A. Maidens[1], M. Martin[1], A. K. Peterson[1], D. Smith[1], M. Vellinga[1], E. Wallace[1], J. Waters[1], and A. Williams[1]

[1]Met Office Hadley Centre, Exeter, UK, [2]Department of Earth Sciences, University of Gothenburg, Gothenburg, Sweden, [3]Willis Research Network

GRL, 2014

RESEARCH LETTER
10.1002/2014GL061146

Key Points:
- Model members can be too noisy and not potential realizations of the real world
- Predictability may be underestimated by idealized experiments and skill measures
- Can achieve skilful and reliable forecasts using large ensembles to reduce noise

Do seasonal-to-decadal climate predictions underestimate the predictability of the real world?

Rosie Eade[1], Doug Smith[1], Adam Scaife[1], Emily Wallace[1], Nick Dunstone[1], Leon Hermanson[1], and Niall Robinson[1]

[1]Met Office Hadley Centre, Exeter, UK

Nat. Geosci., 2016

Skilful predictions of the winter North Atlantic Oscillation one year ahead

Nick Dunstone*, Doug Smith, Adam Scaife, Leon Hermanson, Rosie Eade, Niall Robinson, Martin Andrews and Jeff Knight

npj Clim. Atm. Sci., 2018

REVIEW ARTICLE OPEN

A signal-to-noise paradox in climate science

Adam A. Scaife[1,2] and Doug Smith[1]

The signal-to-noise paradox (in a nutshell)

- The inherent predictability of Earth's climate ($\sigma_{sig}/\sigma_{tot}$) is not known.
- However, initialized forecasts verified against observations provide a lower bound estimate of real-world predictability limits (ACC <= $\sigma_{sig}/\sigma_{tot}$).
- The inherent predictability of model climate can be quantified from forecast ensembles ($\sigma^f_{sig}/\sigma^f_{tot}$).
- Large ensemble climate forecast systems show that model-world predictability is often significantly lower than real-world predictability.

$$Ratio\ of\ Predictable\ Components\ (RPC) = \frac{ACC}{\sigma^f_{sig}/\sigma^f_{tot}} = \frac{ACC}{S2T}$$

Signal-to-noise paradox when RPC > 1 (model predicts real-world better than it predicts itself)

➔ Large ensembles needed to achieve skill (beat down excessive model noise)

➔ Significant potential to improve/extend predictions by improving coupled model fidelity

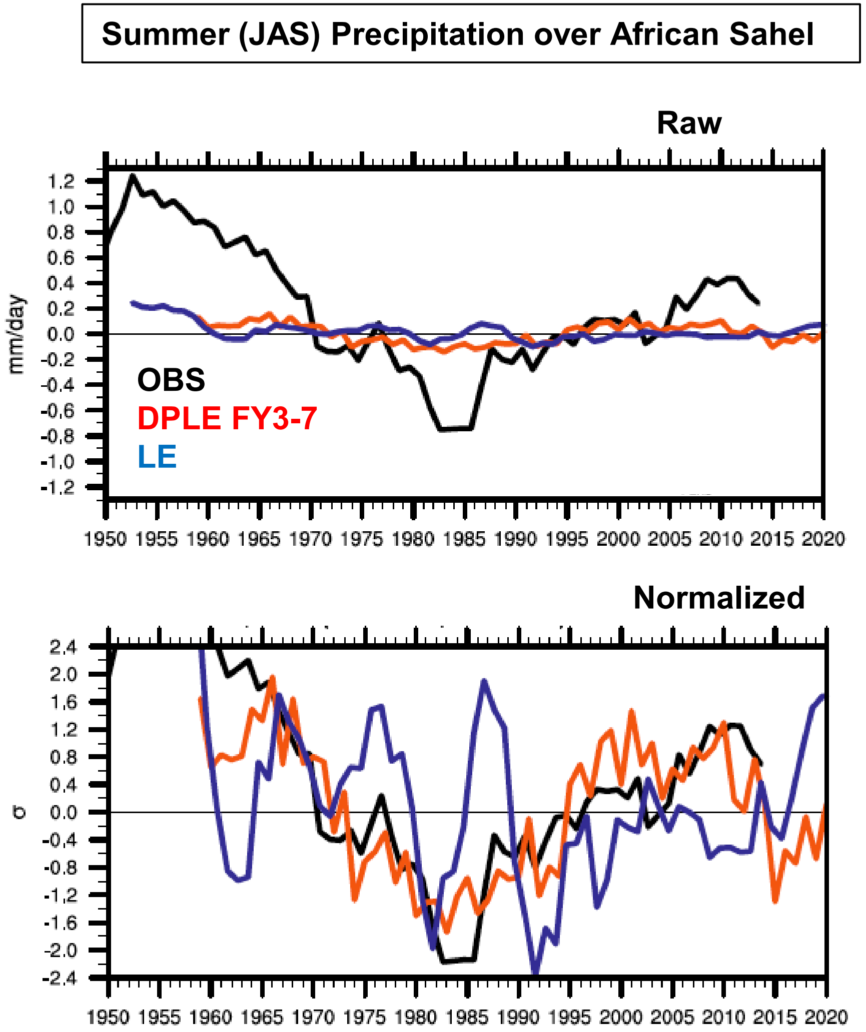
BAMS, 2018

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

- 40-member CESM1.1-DPLE initialized each Nov. 1st 1954-2017 (N=64)
- ~26,000 sim-year experiment (CISL ASD award on Cheyenne)
- Pacific shock greatly ameliorated through improved FOSI initialization
- Direct comparison with 40-member CESM1-LE revealed widespread skill improvement associated with initialization (e.g., Sahel precipitation ➔)
- Large ensemble generally improves skill and also enhances confidence in differentiating DPLE from LE
- One of the first DP systems to include ocean biogeochemistry
- Evidence of signal-to-noise paradox



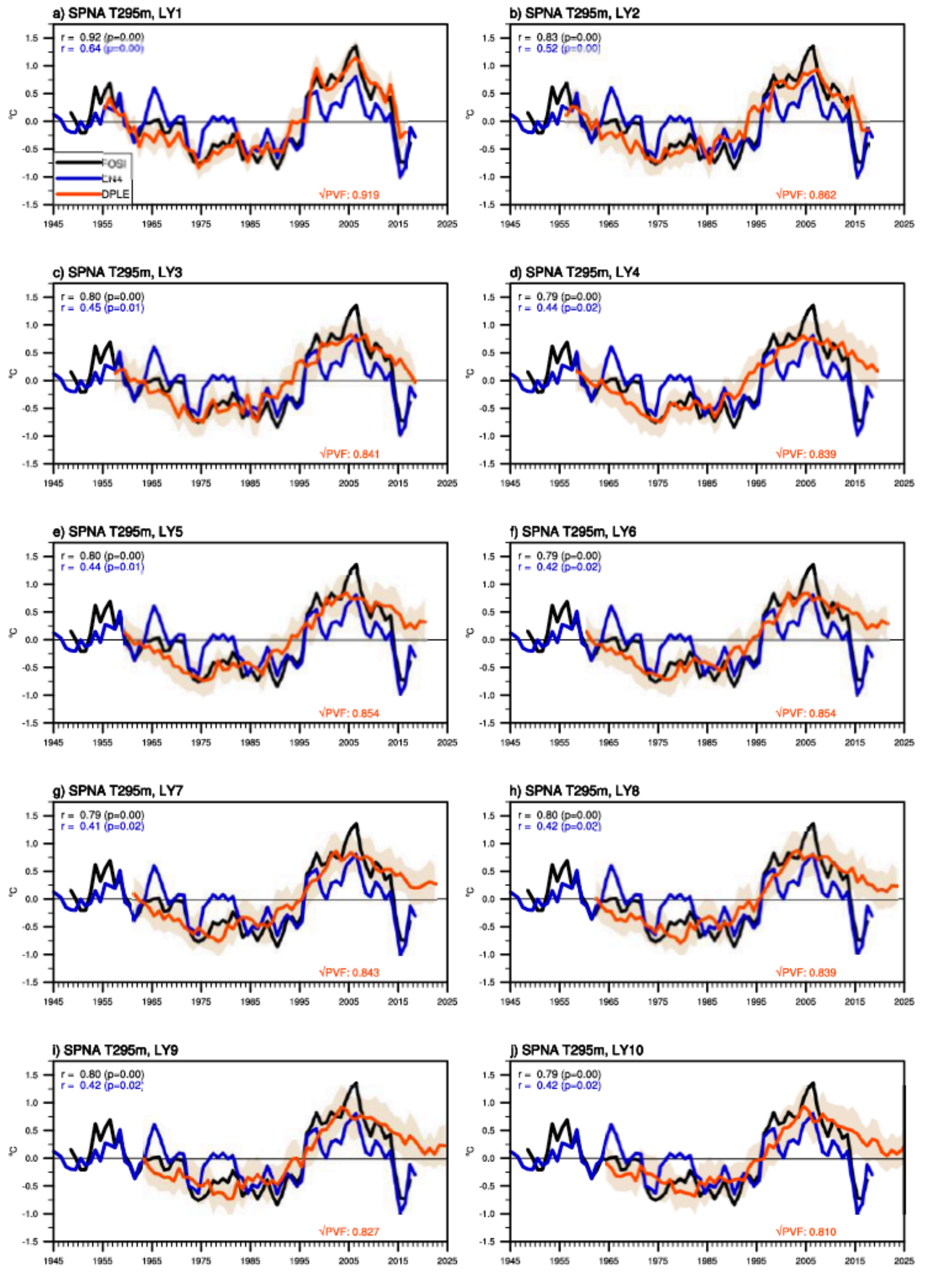
RPC ~ 2

Clim. Dyn., 2020

The abyssal origins of North Atlantic decadal predictability

Stephen Yeager[1]

- Remarkably high and long-lasting ocean prediction skill in SPNA region made DPLE a good system for exploring the mechanisms underlying Atlantic skill.
- Conventional explanation: "AMOC"

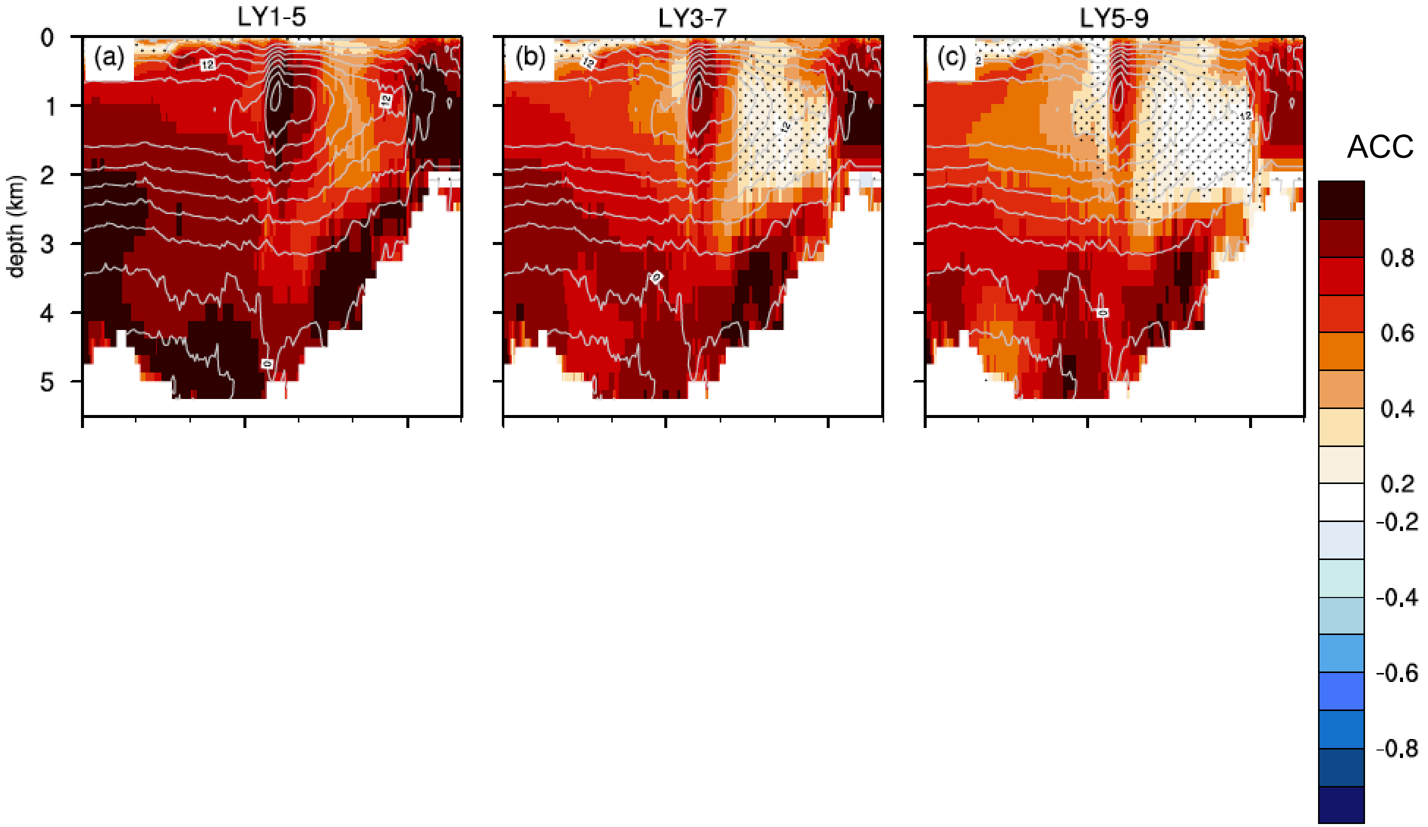


DPLE
FOSI

Clim. Dyn., 2020

The abyssal origins of North Atlantic decadal predictability

Stephen Yeager[1]

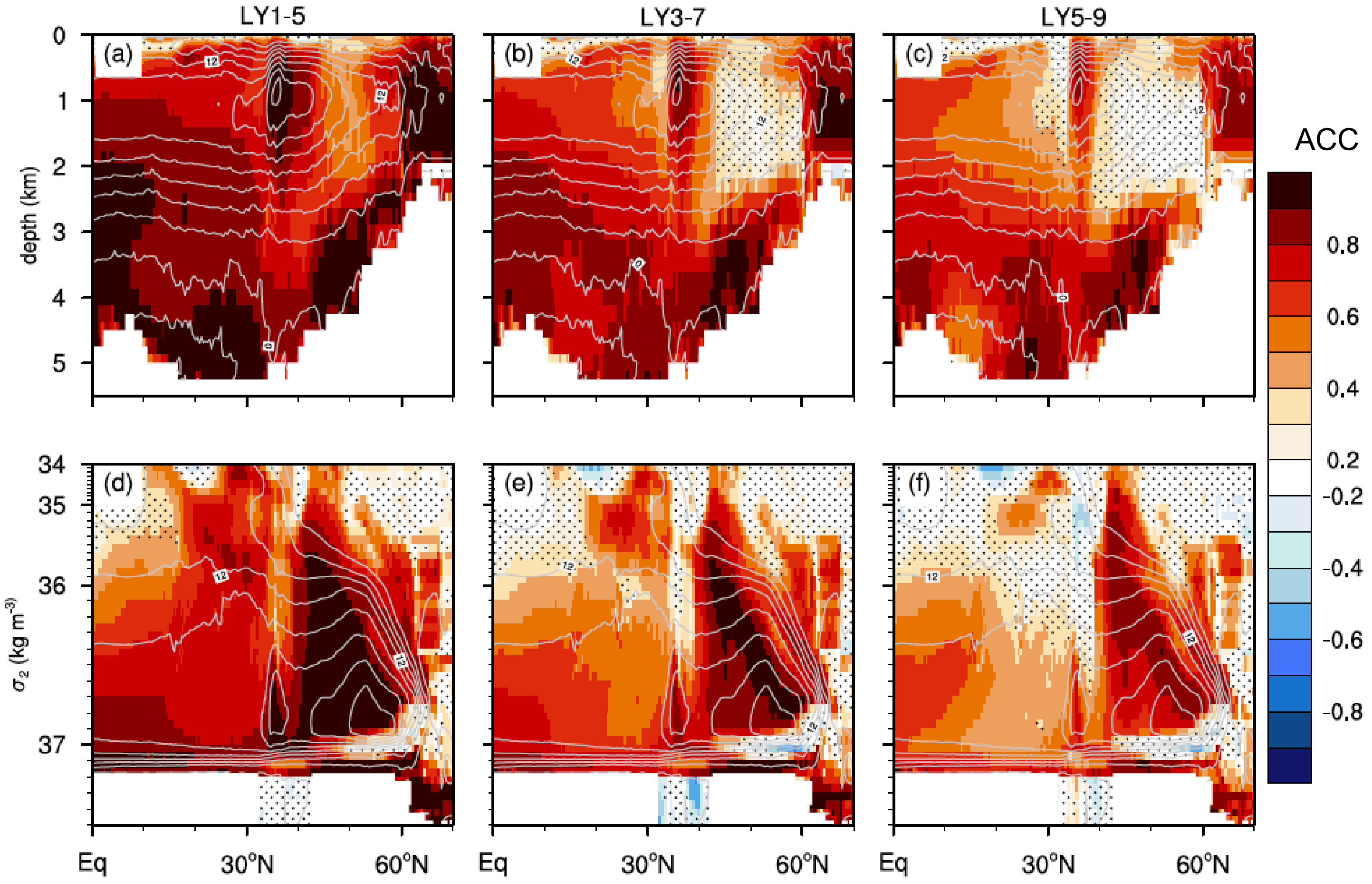


- But skill for AMOC strength declines rapidly after a few years

Clim. Dyn., 2020

The abyssal origins of North Atlantic decadal predictability

Stephen Yeager[1]



- But skill for AMOC strength declines rapidly after a few years
- AMOC(σ) is a more relevant quantity for understanding decadal predictability in the N. Atlantic
- Time-lagged coupling of AMOC lower/upper limbs as a key decadal predictability mechanism
- Core of ocean memory resides in deep (>2 km) Labrador Sea Water thickness anomalies

➔ Lack of deep ocean observations poses a challenge for decadal prediction initialization *npj Clim. Atm. Sci.*, 2020

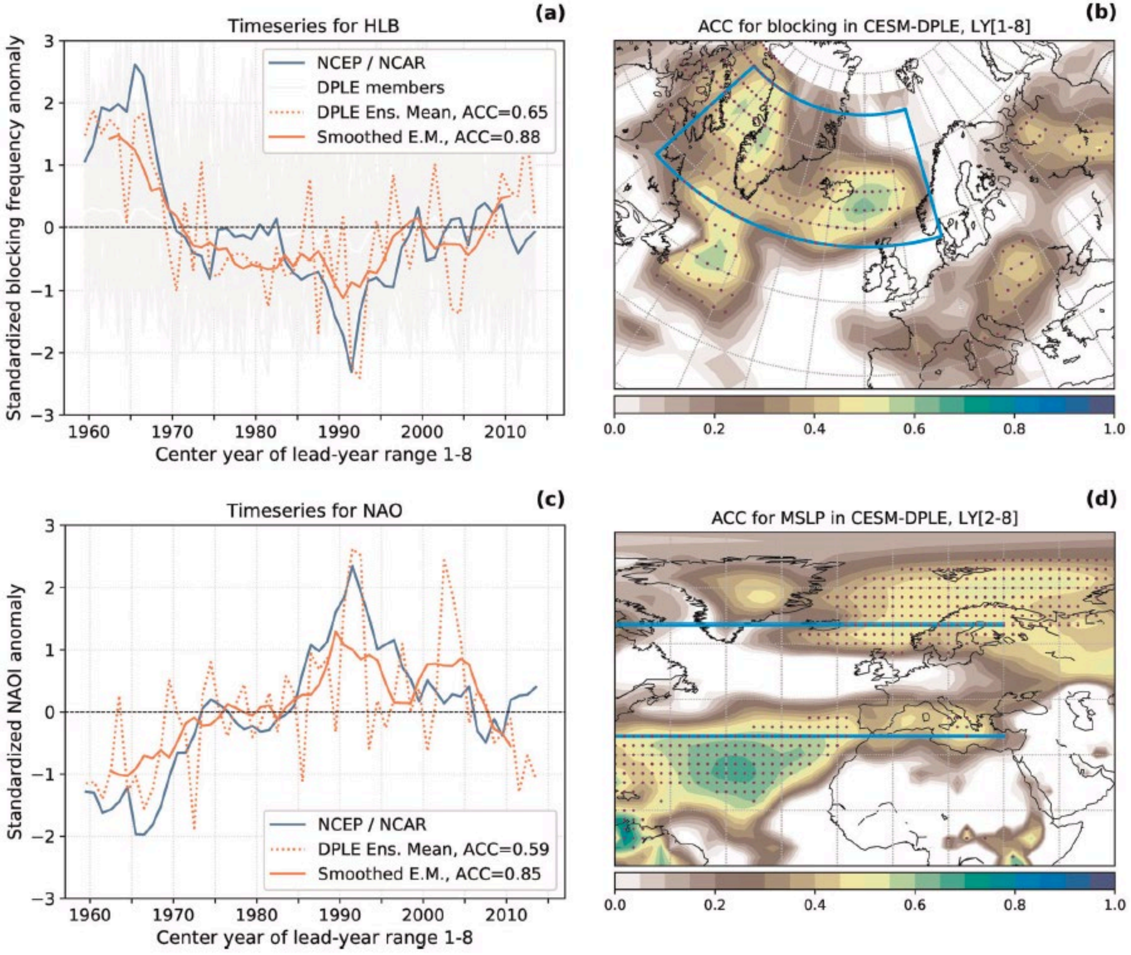
ARTICLE OPEN

Check for updates

Decadal predictability of North Atlantic blocking and the NAO

Panos J. Athanasiadis[1] ✉, Stephen Yeager[2], Young-Oh Kwon[3], Alessio Bellucci[1], David W. Smith[4] and Stefano Tibaldi[1]

- 40-member CESM1.1-DPLE
- First study to demonstrate skillful decadal prediction of winter NAO & blocking frequency
- Some evidence that *weak* decadal atmospheric signal was related to strong decadal ocean signal
- Skill is perceptible, but does not saturate, with a 40-member ensemble



RPC ~ 6

submitted, 2022

Enhanced Skill and Signal-to-Noise in an Eddy-Resolving Decadal Prediction System

Stephen G. Yeager*[1], Ping Chang[2], Gokhan Danabasoglu[1], Lixin Wu[3], Nan Rosenbloom[1], Qiuying Zhang[2], Fred S. Castruccio[1], Abishek Gopal[2], M. Cameron Rencurrel[2]

Texas Advanced Computing Center

- iHESP has completed a 10-member set of DP hindcasts using high-resolution CESM1.3
- Can be directly compared to DPLE to isolate the impact of model horizontal resolution on prediction system performance

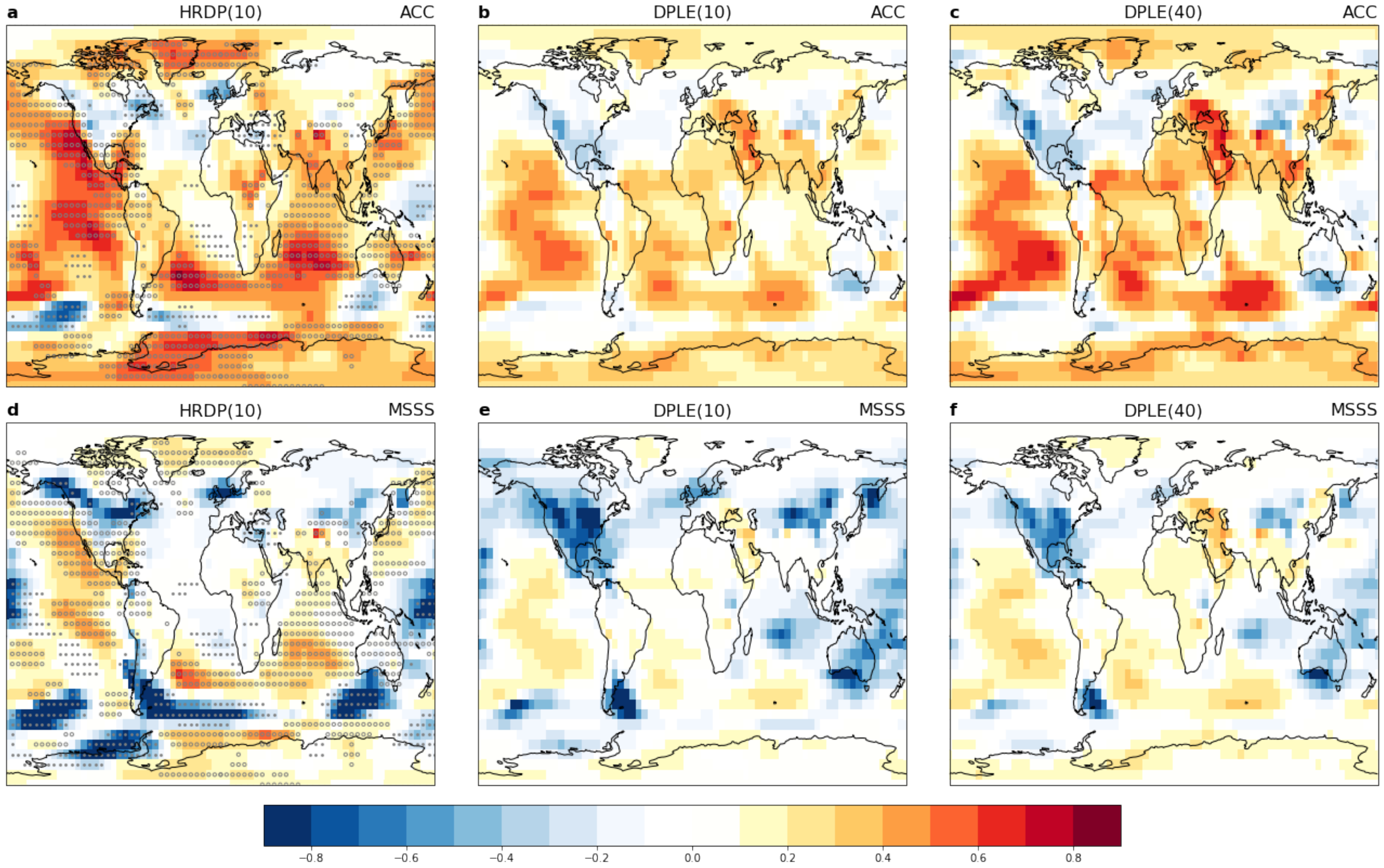
	HRDP	DPLE
Model ocean atmosphere land sea ice	CESM1.3 POP2 (0.1°, 62L) CAM5-SE (0.25°, 30L) CLM4 (0.25°) CICE4 (0.1°)	CESM1.1 POP2 (1°, 60L) CAM5-FV (1°, 30L) CLM4 (1°) CICE4 (1°)
Forcing scenario	CMIP5 RCP8.5	CMIP5 RCP8.5
Initialization ocean atmosphere land sea ice	Full field FOSI (0.1°, OMIP2) JRA55 reanalysis HighResMIP Tier 1 FOSI (0.1°, OMIP2)	Full field FOSI (1°, OMIP1*) N/A N/A FOSI (1°, OMIP1*)
Hindcasts start date start year simulation length	N=18 November 1st 1982, 1984, .., 2016 62 months	N=64 November 1st 1954-2017 122 months
Ensemble Size	10	40
Total Simulation Years	930	~26,000

submitted, 2022

Enhanced Skill and Signal-to-Noise in an Eddy-Resolving Decadal Prediction System

Stephen G. Yeager*[1], Ping Chang[2], Gokhan Danabasoglu[1], Lixin Wu[3], Nan Rosenbloom[1], Qiuying Zhang[2], Fred S. Castruccio[1], Abishek Gopal[2], M. Cameron Rencurrel[2]

FY1-5 DFJM Sea Level Pressure (SLP) Skill Maps



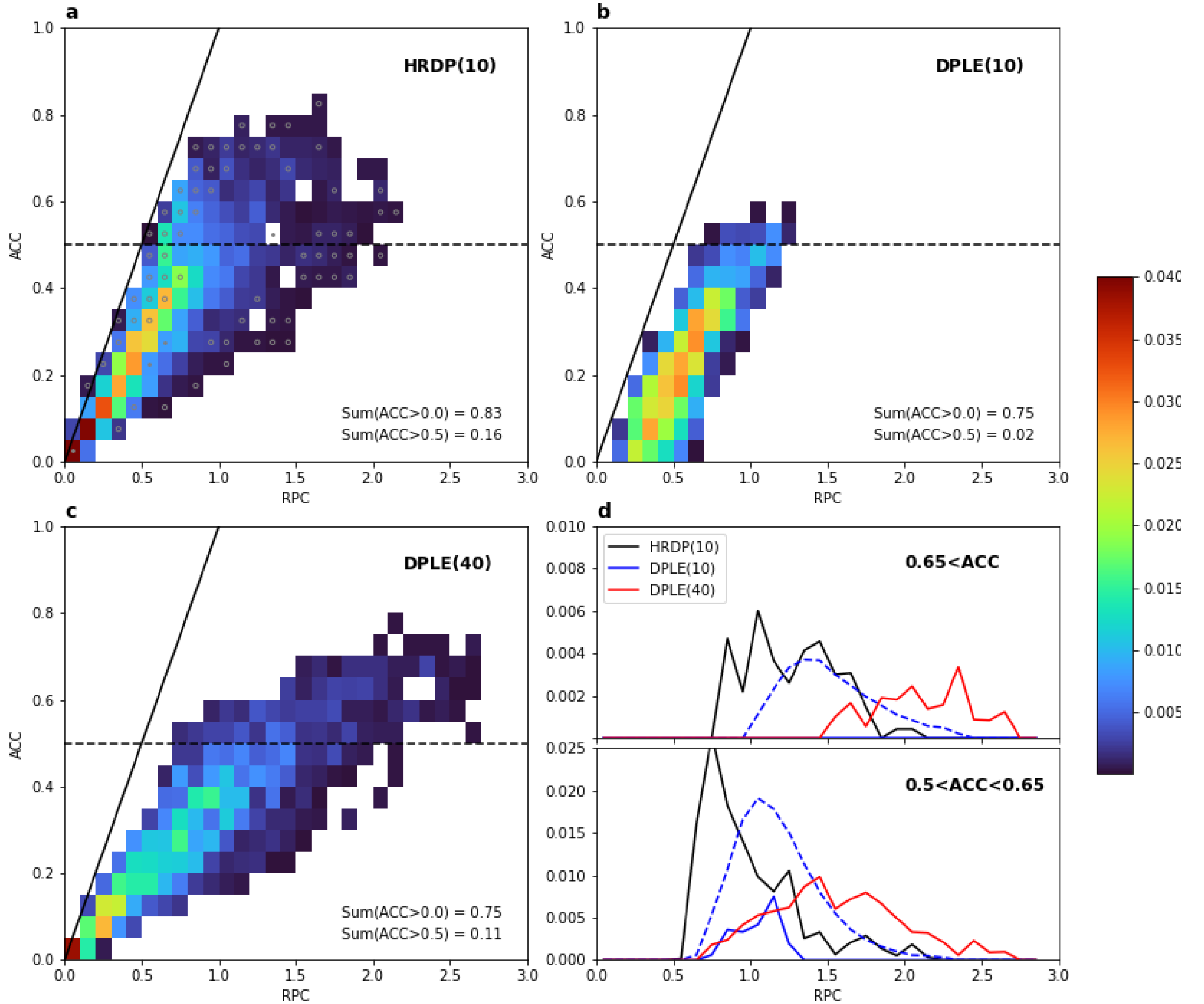
- Statistically significant skill <u>improvement</u> in HRDP(10) vs. DPLE(10)
  - ACC: 33% of globe
  - MSSS: 33% of globe
- Statistically significant skill <u>degradation</u> in HRDP(10) vs. DPLE(10)
  - ACC: 9% of globe
  - MSSS: 15% of globe

submitted, 2022

Enhanced Skill and Signal-to-Noise in an Eddy-Resolving Decadal Prediction System

Stephen G. Yeager*[1], Ping Chang[2], Gokhan Danabasoglu[1], Lixin Wu[3], Nan Rosenbloom[1], Qiuying Zhang[2], Fred S. Castruccio[1], Abishek Gopal[2], M. Cameron Rencurrel[2]

Histograms of FY1-5 DFJM SLP Skill Metrics



- Relative occurrence in units of fraction of global surface area of paired ACC/RPC values (note that slope gives S2T)
- Overall higher skill in HRDP
- Signal-to-noise paradox, clearly evident in DPLE(40), is significantly ameliorated in HRDP due to higher S2T in regions where ACC is high

$$RPC = \frac{ACC}{S2T}, \quad S2T = \frac{ACC}{RPC}$$

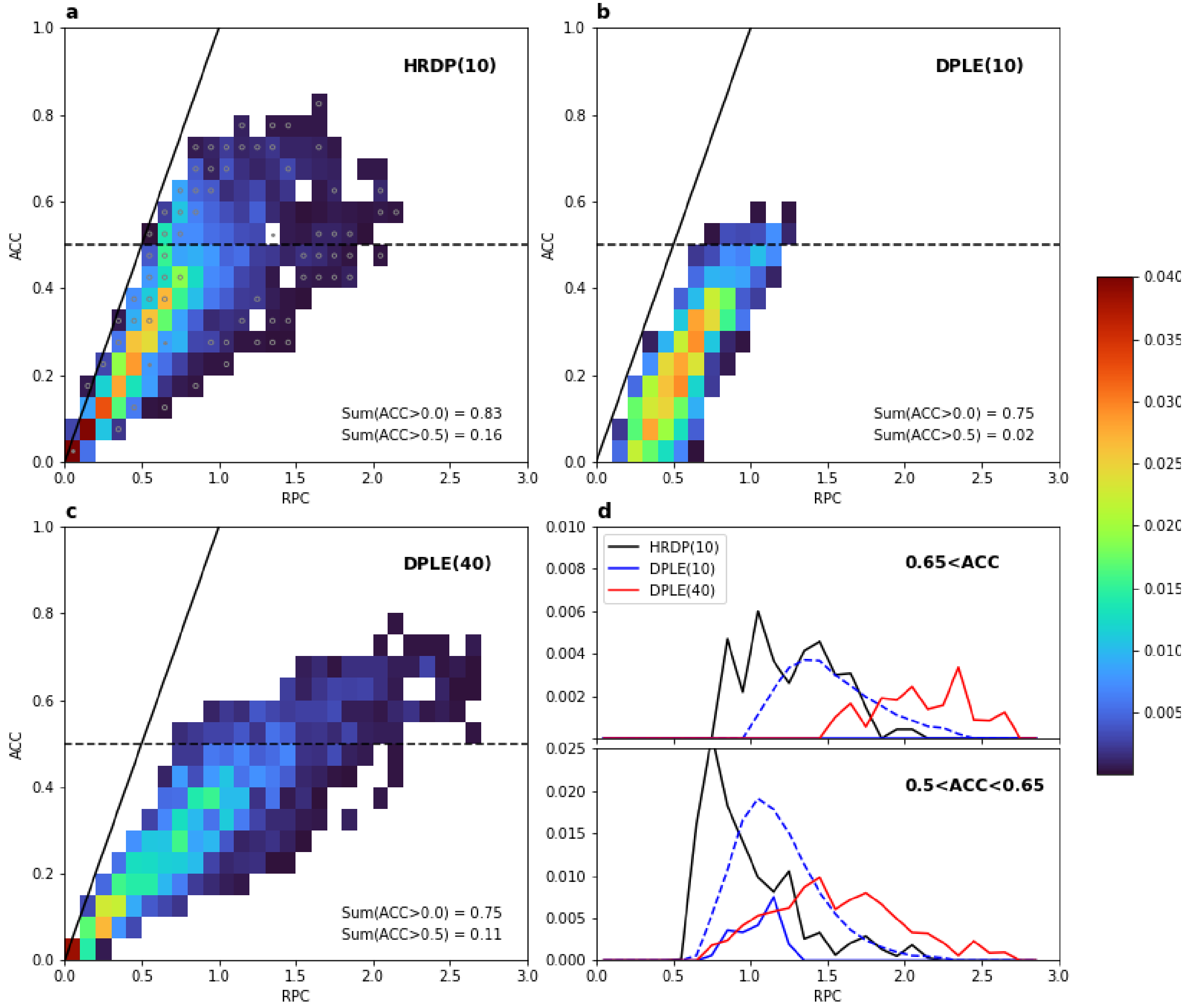
submitted, 2022

Enhanced Skill and Signal-to-Noise in an Eddy-Resolving Decadal Prediction System

Stephen G. Yeager*[1], Ping Chang[2], Gokhan Danabasoglu[1], Lixin Wu[3], Nan Rosenbloom[1], Qiuying Zhang[2], Fred S. Castruccio[1], Abishek Gopal[2], M. Cameron Rencurrel[2]

- ➔ Current estimates of climate predictability based on coarse resolution models may be overly pessimistic.
- ➔ Higher horizontal resolution improves coupled model fidelity (it improves prediction skill and helps to resolve the signal-to-noise paradox).
- ➔ Mesoscale air-sea interaction (present in HRDP but absent in DPLE) is a key mechanism involved in the transmission of predictable signals from the ocean to the atmosphere.
- ➔ Inclusion of ocean "noise" in a prediction system has the net effect of increasing signal more than noise in the atmosphere.

Histograms of FY1-5 DFJM SLP Skill Metrics



Summary Thoughts

- We've come a long way in the past ~10 years. DP research has delivered more than most would have anticipated back in the late 2000s in terms of refining our understanding of and capacity to predict regional environmental change years in advance.

- CESM DP efforts have been at the forefront of many recent advances in the field (large ensembles, sensitivity to initialization, carbon cycle prediction, mechanistic understanding, high resolution), in large part due to collaborative group efforts that have built bridges between disciplines, CGD sections, funding streams, NCAR Laboratories, and between NCAR and the broader university community.

- CGD/NCAR is well-positioned to continue serving as a community hub for DP research (e.g., CESM ESPWG).

- Advancements in DP system design have led to reappraisals of our estimation of the inherent limits of Earth system predictability on climate timescales. Indications are that we have not yet reached the true limits. More research is clearly warranted to explore the many outstanding questions (how to minimize drift & shock; methods to improve initialization; sensitivity to resolution; predictability mechanisms; etc.) and to push the frontiers of actionable Earth system prediction science.

Thank You