Evaluating Climate Variability in Models: Challenges and Tools

Clara Deser
Climate Analysis Section, NCAR

CESM Tutorial, 13 July 2023

Evaluating Climate Variability in Models: Challenges and Tools

Biggest challenges (in my view)

- Limited sampling due to short data records.
- Removal of the evolving forced climate change signal.

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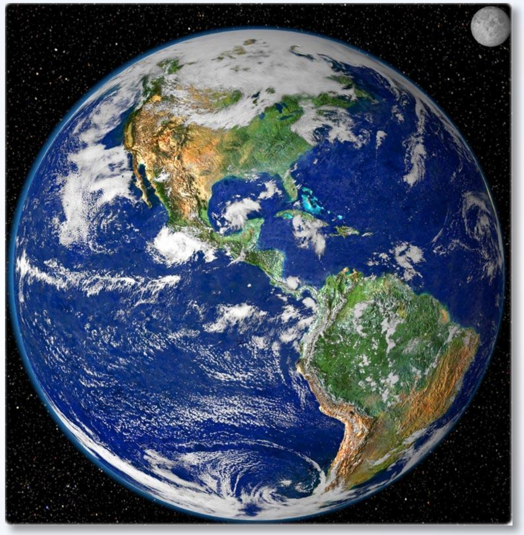
New Tools

- Large Ensembles of simulations with a given model and forcing protocol.
- NCAR Climate Variability Diagnostics Package for Large Ensembles.

Single Model Initial-condition Large Ensembles (SMILES)

CMIP 5/6 Models

Global, Coupled



Spatial resolution
~ 1-2° latitude/longitude

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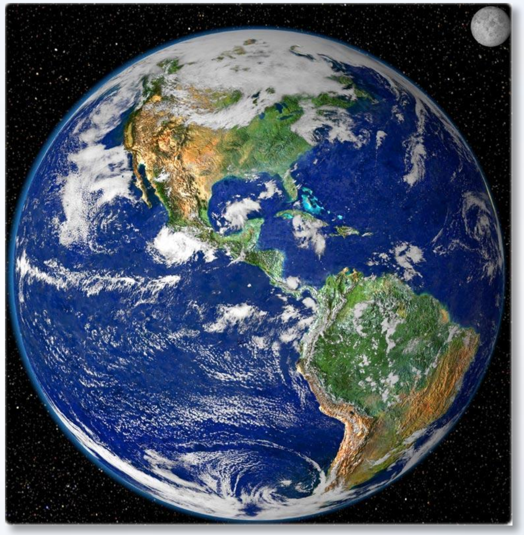

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Free-running or partially constrained
(e.g. “Pacemaker” protocol)

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Salient Features

- **Large** ensemble size (30-100 simulations).
- **Different** initial conditions for each simulation.
- **Same** forcing protocol for each simulation
  (e.g., emissions scenario or Pacemaker constraint).

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 Each simulation follows a **different random sequence of internally-generated variability**, superimposed upon a **common forced response** (after memory of the initial conditions is lost).

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Forced response (*t*) ≈ ensemble mean (*t*)

Internal variability (*t*) in each simulation ≈ deviation from ensemble mean (*t*)

Single Model Initial-condition Large Ensembles (SMILES)

CMIP 5/6 Models
Global, Coupled

Spatial resolution
~ 1-2° latitude/longitude

Free-running or
partially constrained
(e.g. "Pacemaker" protocol)

Lots of samples of internal variability for robust estimation of the evolving characteristics of the forced response on local and regional scales in a given model.

Forced response:

1) Background climate change;
2) Changes in variability and extremes.

Forced response (*t*) ≈ ensemble mean (*t*)

Internal variability (*t*) in each simulation ≈ deviation from ensemble mean (*t*)

Single Model Initial-condition Large Ensembles (SMILES)

US CLIVAR Working Group on Large Ensembles

nature climate change

30 March 2020

Deser et al.

PERSPECTIVE

https://doi.org/10.1038/s41558-020-0731-2

Check for updates

Insights from Earth system model initial-condition large ensembles and future prospects

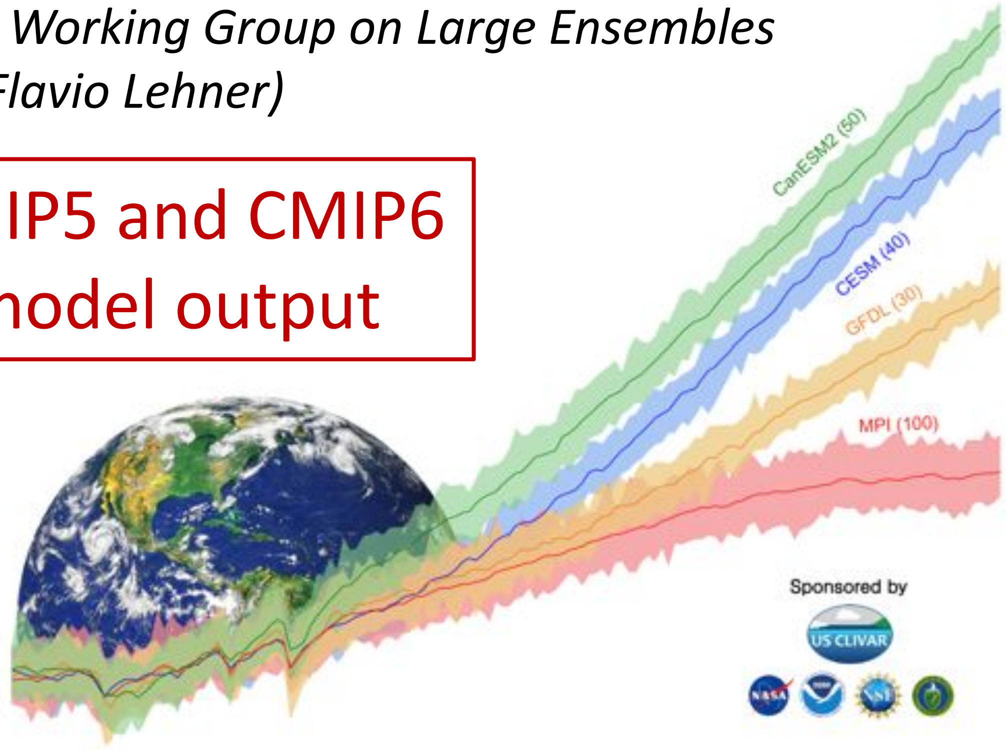
C. Deser[1,2] ✉, F. Lehner[1,2], K. B. Rodgers[2,3,4], T. Ault[2,5], T. L. Delworth[2,6], P. N. DiNezio[2,7], A. Fiore[2,8], C. Frankignoul[2,9], J. C. Fyfe[2,10], D. E. Horton[2,11], J. E. Kay[2,12,13], R. Knutti[2,14], N. S. Lovenduski[2,12,15], J. Marotzke[2,16], K. A. McKinnon[2,17], S. Minobe[2,18], J. Randerson[2,19], J. A. Screen[2,20], I. R. Simpson[1,2] and M. Ting[2,8]

What are they? Why are they useful?
How large do they need to be?
How are they best designed?
Emerging applications and future directions?

MULTI-MODEL LARGE ENSEMBLE ARCHIVE

US CLIVAR Working Group on Large Ensembles (credit to Flavio Lehner)

CMIP5 and CMIP6 model output



https://www.cesm.ucar.edu/community-projects/mmlea

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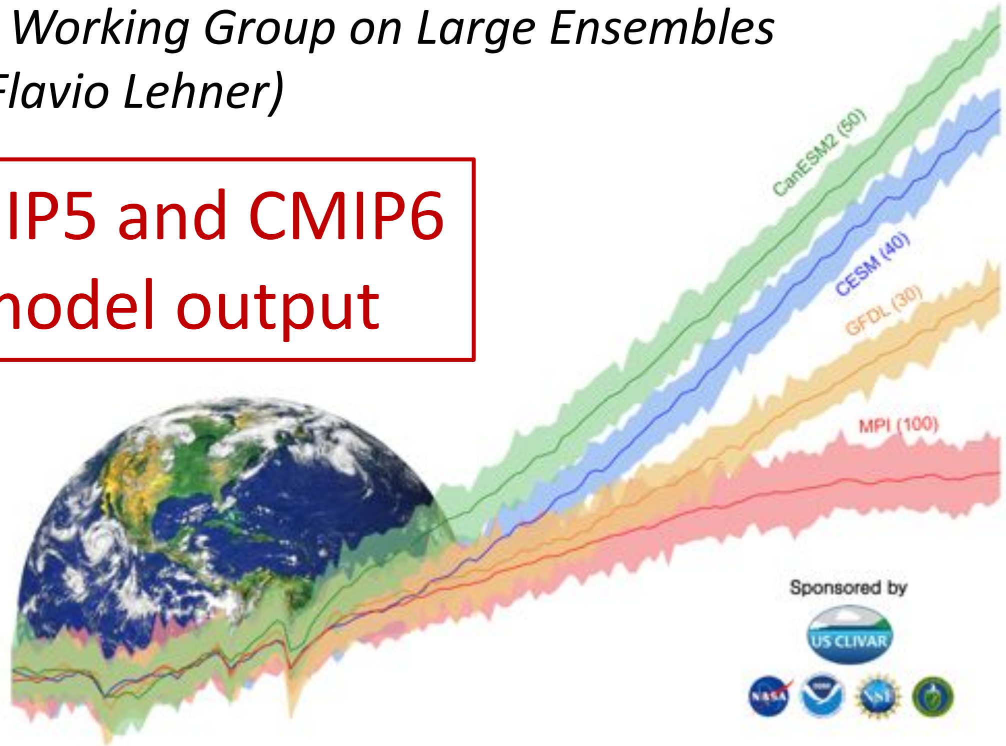

Sponsored by

Expansion to 16 models and 11 variables coming soon!
(credit to Nicola Maher)

https://www.cesm.ucar.edu/community-projects/mmlea

Two Examples

ENSO Teleconnections

NAO

Two Examples

ENSO Teleconnections

"How well do we know them and
how do we evaluate models accordingly?"

Deser et al. 2017 and 2018, *Journal of Climate*.

Two Examples

ENSO Teleconnections

CESM1 "Tropical Pacific Pacemaker" Ensemble

(Run by the CESM Climate Variability and Change Working Group)

10 realizations for 1920-2013 under historical radiative forcing;
SST anomalies in the Tropical Pacific nudged to the observed evolution.

CESM1 “Tropical Pacific Pacemaker” Ensemble

DJF SLP
Composite

18 El Nino
minus
14 La Nina
events
(1920-2013)

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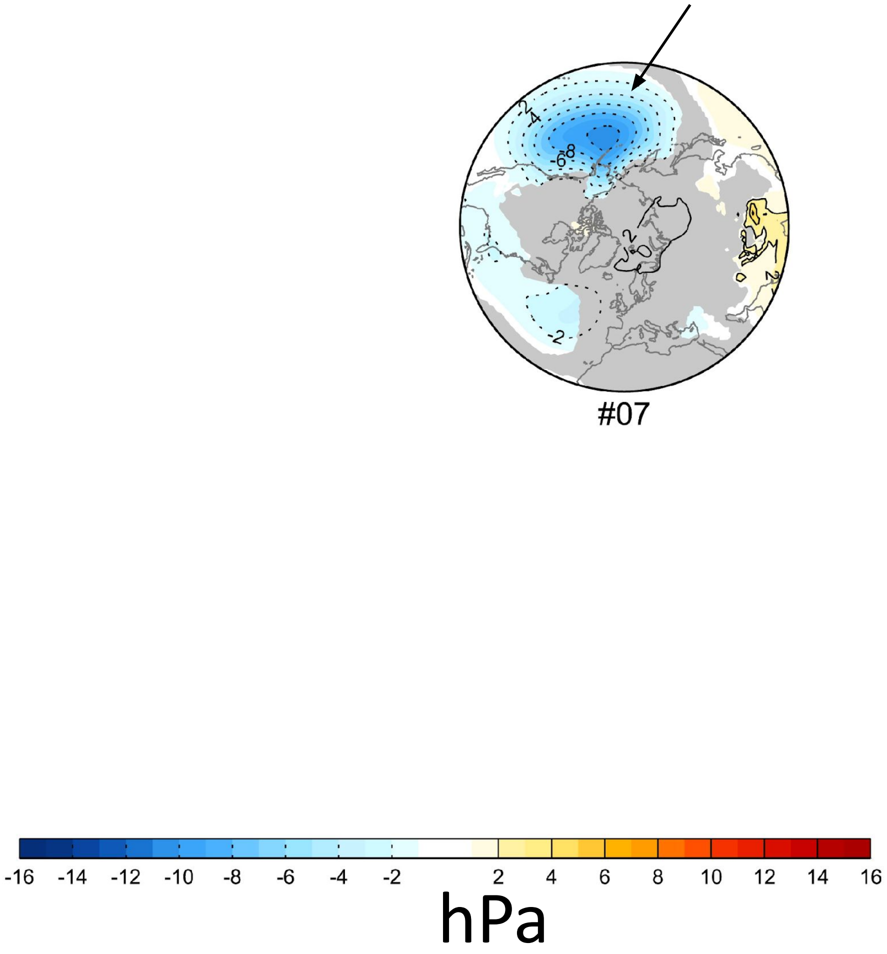
Deepening of the
Aleutian Low



gray:
insignificant
(t-test, 10%)

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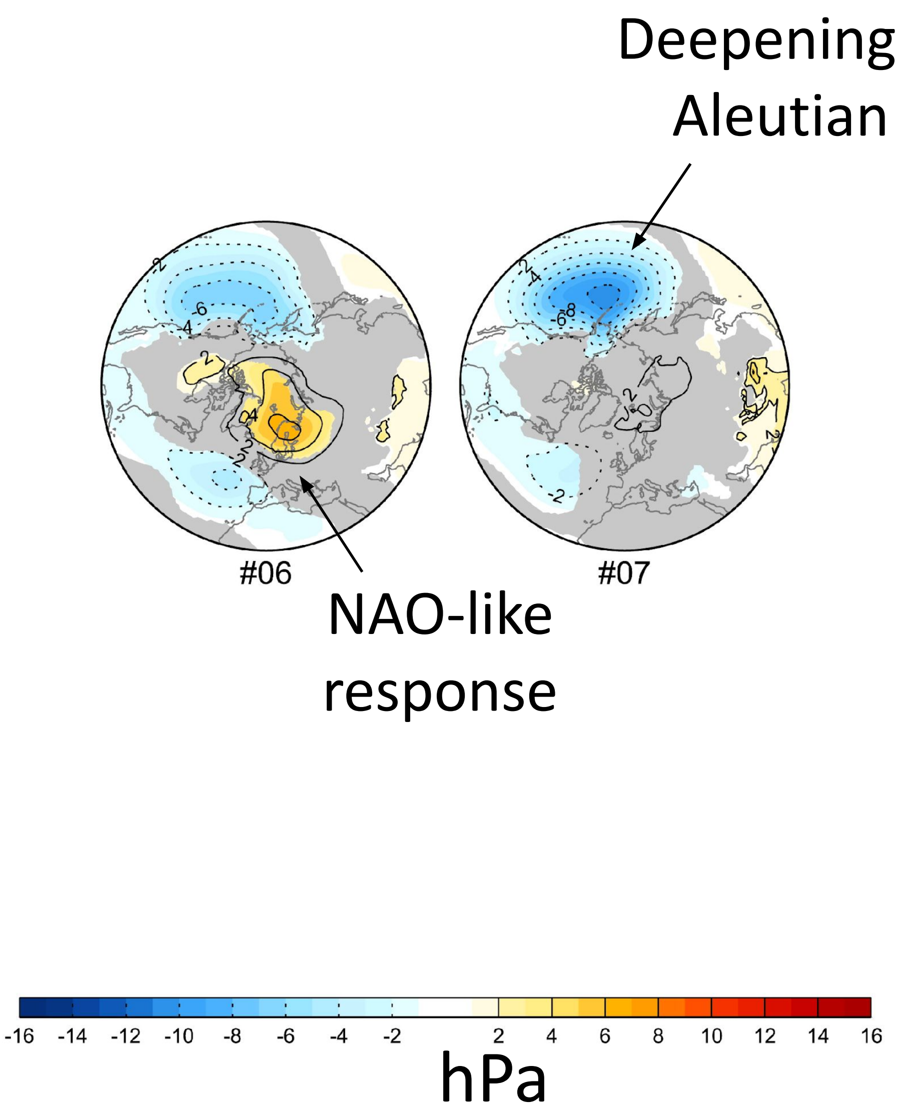

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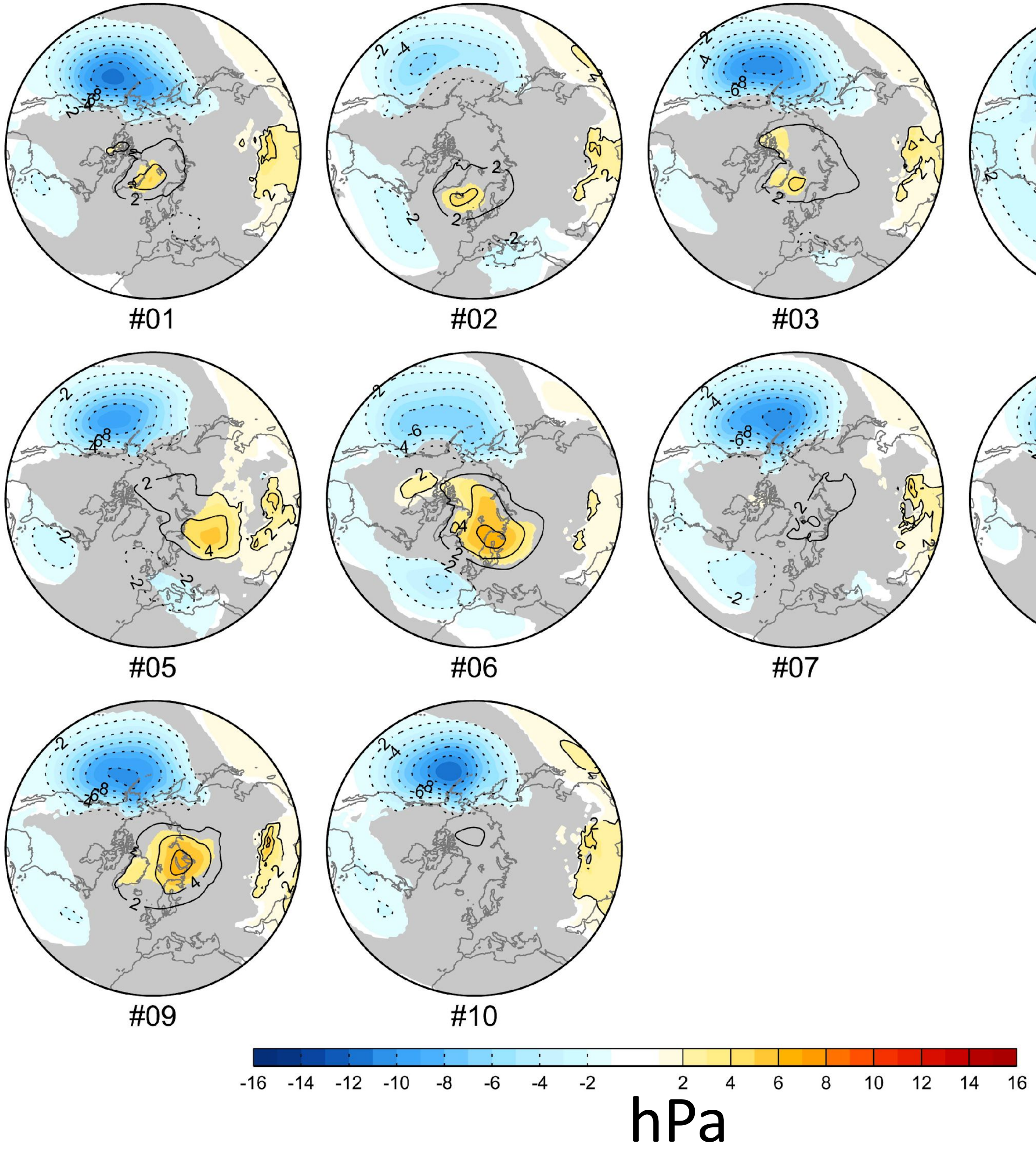

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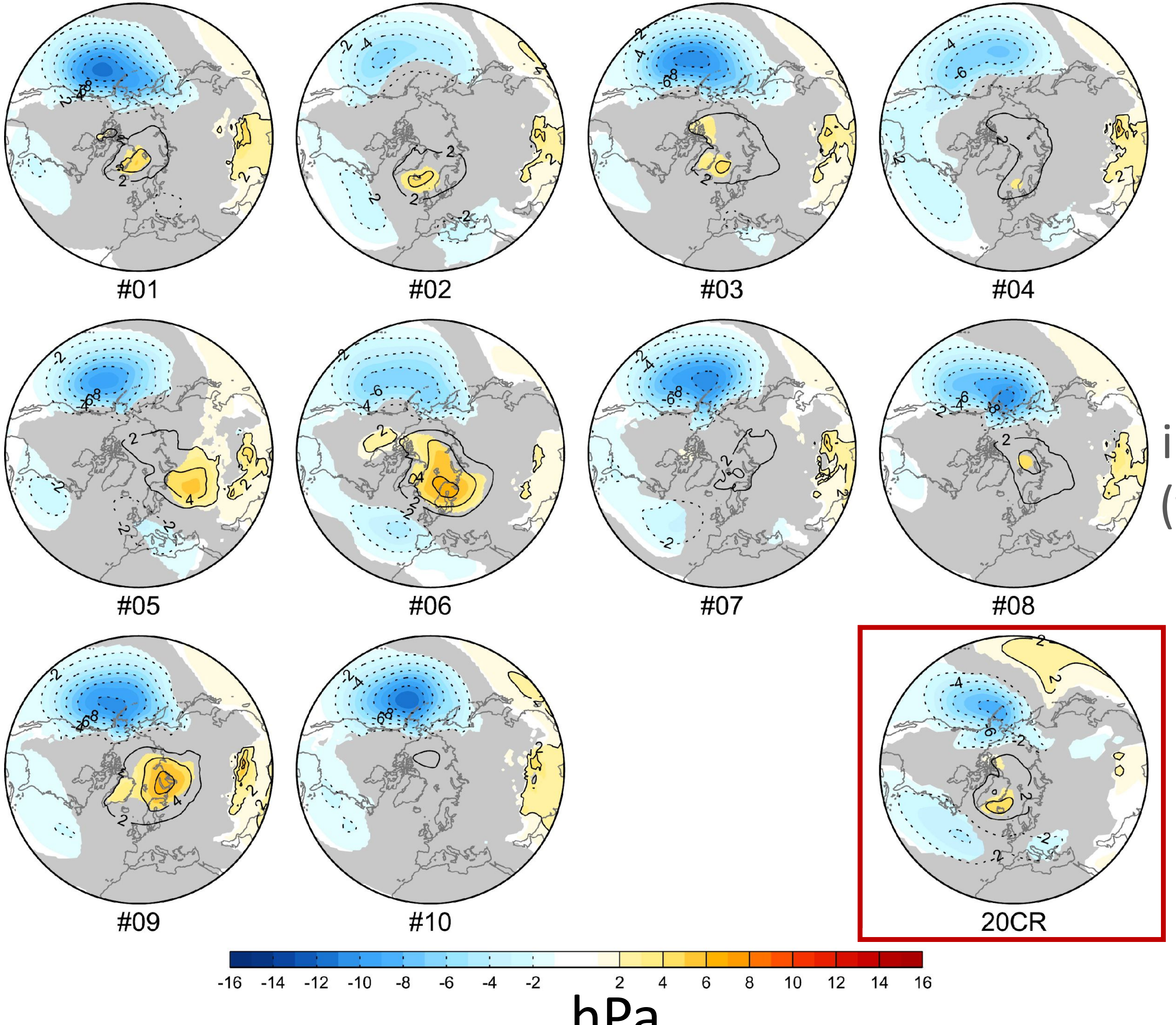

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OBS

CESM1 “Tropical Pacific Pacemaker” Ensemble

1. How well do we know the observed composite?

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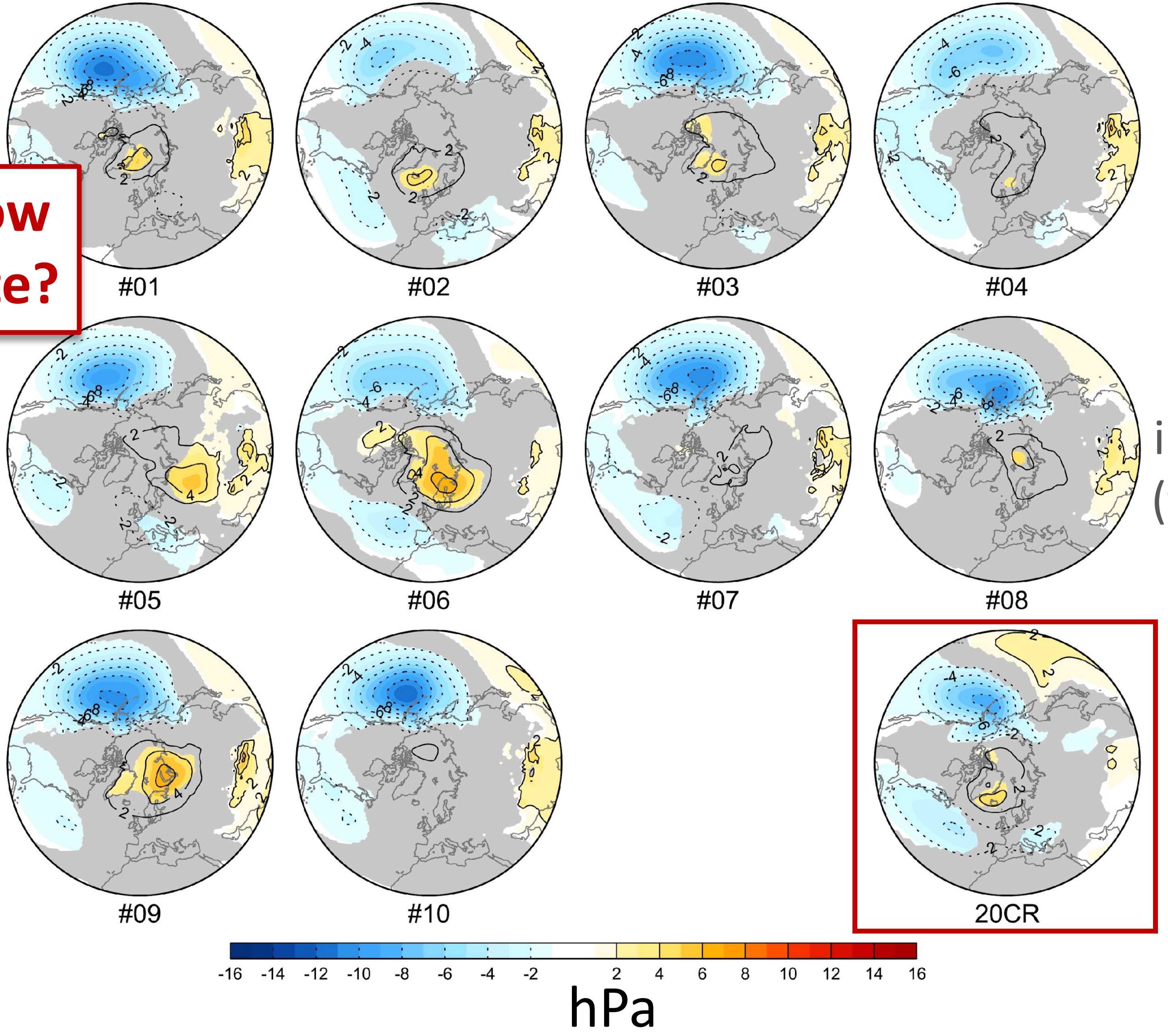

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OBS

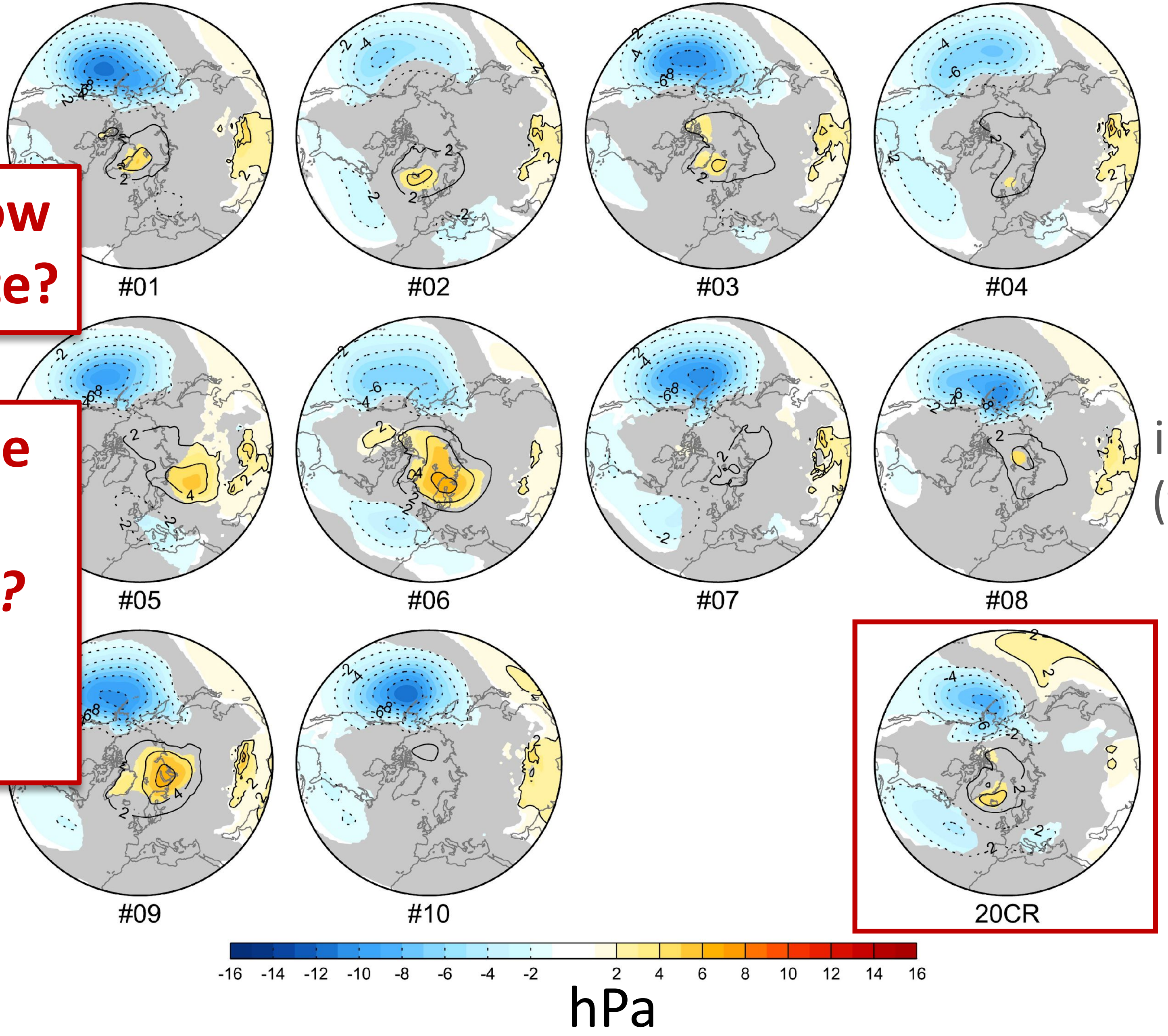
CESM1 "Tropical Pacific Pacemaker" Ensemble

1. How well do we know the observed composite?

2. How do we evaluate the model?

Is the spread realistic?

Is the true response realistic?



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OBS

Two Examples

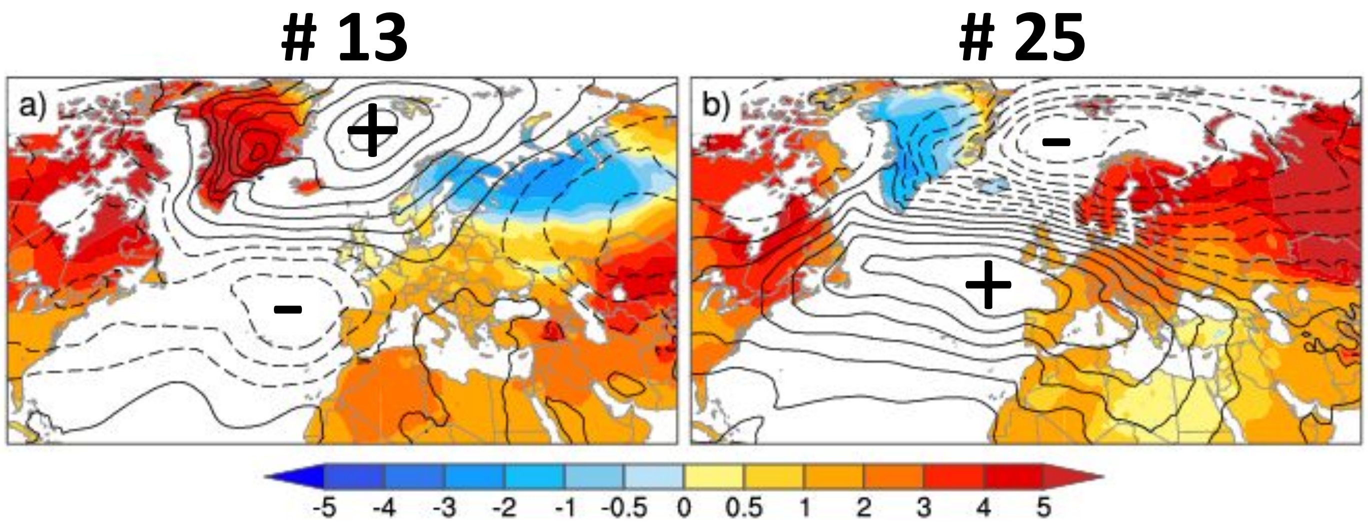
NAO

"The Role of the North Atlantic Oscillation in European Climate Projections"

Deser et al. 2017, *Climate Dynamics.*

CESM1 Large Ensemble (Kay, Deser et al. 2015)
40 members, 1920-2100 historical + RCP8.5 forcing

CESM1 Projected Trends over the next 30 years



SLP and Air Temperature

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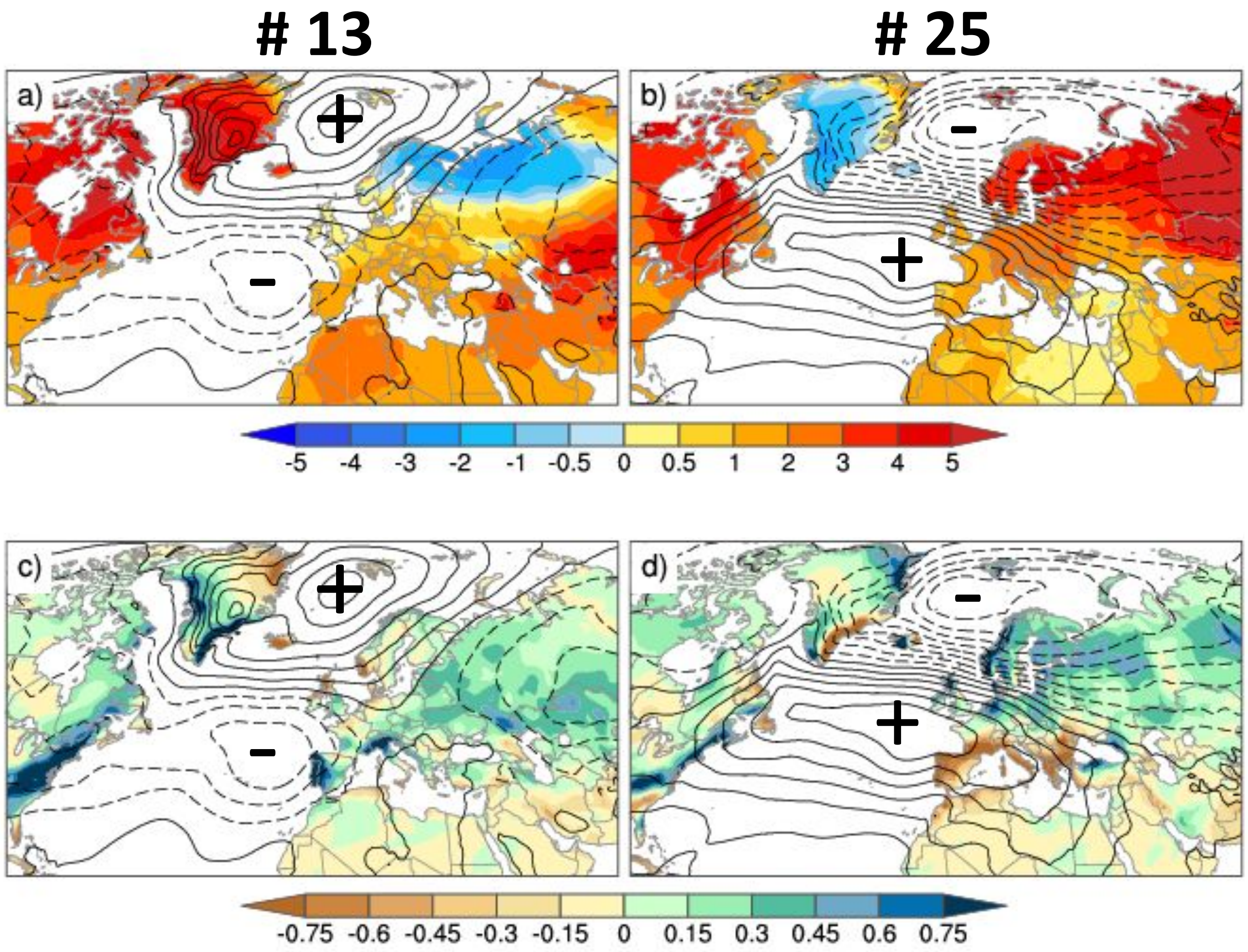

SLP and Air Temperature

SLP and Precipitation

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CGD's Climate Analysis Section

Climate Variability Diagnostics Package

for Large Ensembles

https://www.cesm.ucar.edu/projects/cvdp-le

An automated analysis tool and data repository for exploring forced and internal components of climate variability and change.

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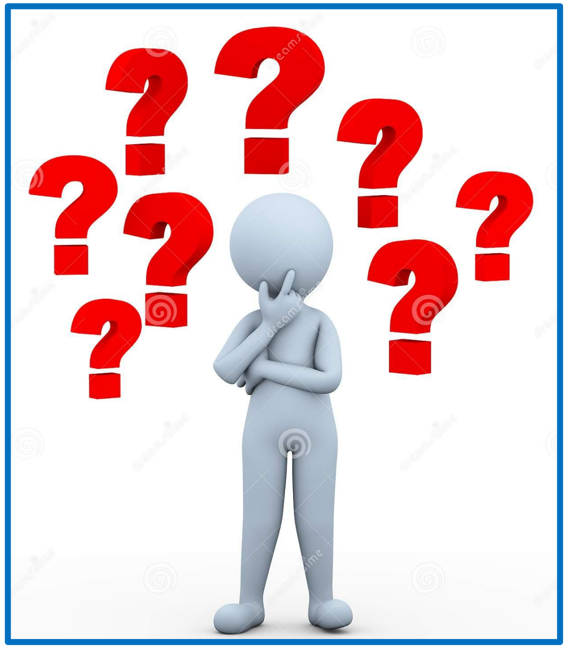
- **How well does a given model simulate the mean state, long-term trends, and modes of variability such as ENSO, NAO, AMV, PDV?**
- **How do models compare with each other? Are there true structural differences?**
- **How does climate change affect internal variability?**
- **What are the relative contributions of internal variability and forced climate change to long-term trends?**



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Climate Variability Diagnostics Package *for Large Ensembles*

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Null hypothesis for any apparent *model bias, model difference,* and *model-projected change in variability* should be "sampling fluctuations" (i.e., inadequate sampling).

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CGD's Climate Analysis Section

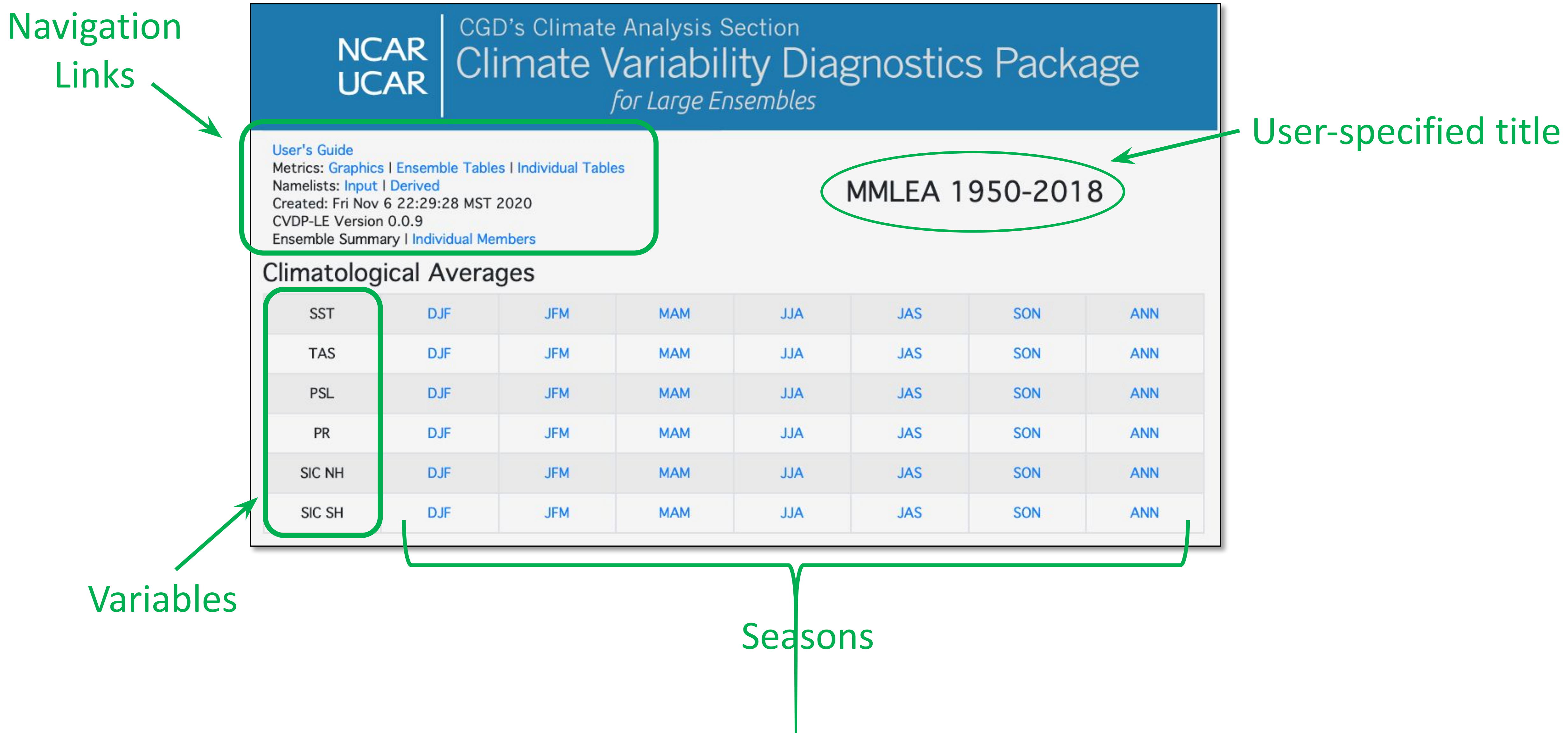
Climate Variability Diagnostics Package

for Large Ensembles

https://www.cesm.ucar.edu/projects/cvdp-le

- **Computes modes of variability, trends, and climate indices.**
- **Provides ensemble-mean and ensemble-spread metrics for each model.**
- **Quantitative comparison to observations (*via* rank metrics).**
- **Comprehensive User's Guide.**
- **User specifies the data sets and time periods (models & observations).**
- **All output saved to a data repository for later use.**

Diagnostics Overview



CGD's Climate Analysis Section
NCAR UCAR
Climate Variability Diagnostics Package
for Large Ensembles

User's Guide
Metrics: Graphics | Ensemble Tables | Individual Tables
Namelists: Input | Derived
Created: Fri Nov 6 22:29:28 MST 2020
CVDP-LE Version 0.0.9
Ensemble Summary | Individual Members

MMLEA 1950-2018

Climatological Averages

SST	DJF	JFM	MAM	JJA	JAS	SON	ANN
TAS	DJF	JFM	MAM	JJA	JAS	SON	ANN
PSL	DJF	JFM	MAM	JJA	JAS	SON	ANN
PR	DJF	JFM	MAM	JJA	JAS	SON	ANN
SIC NH	DJF	JFM	MAM	JJA	JAS	SON	ANN
SIC SH	DJF	JFM	MAM	JJA	JAS	SON	ANN

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SIC NH	DJF	JFM	MAM	JJA	JAS	SON	ANN
SIC SH	DJF	JFM	MAM	JJA	JAS	SON	ANN

Standard Deviations

SST	DJF	JFM	MAM	JJA	JAS	SON	ANN
TAS	DJF	JFM	MAM	JJA	JAS	SON	ANN
PSL	DJF	JFM	MAM	JJA	JAS	SON	ANN
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SIC NH	DJF	JFM	MAM	JJA	JAS	SON	ANN
SIC SH	DJF	JFM	MAM	JJA	JAS	SON	ANN

Global Trend Maps

SST	DJF	JFM	MAM	JJA	JAS	SON	ANN
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Global Trend Maps

SST	DJF	JFM
TAS	DJF	JFM
PSL	DJF	JFM
PR	DJF	JFM
SIC NH	DJF	JFM
SIC SH	DJF	JFM

Coupled Modes of Variability

ENSO	Spatial Composites	El Niño - La Niña SST/TAS/PSL JJA^0 SON^0 DJF^1 MAM^1	El Niño - La Niña PR JJA^0 SON^0 DJF^1 MAM^1
		El Niño SST/TAS/PSL JJA^0 SON^0 DJF^1 MAM^1	El Niño PR JJA^0 SON^0 DJF^1 MAM^1
		La Niña SST/TAS/PSL JJA^0 SON^0 DJF^1 MAM^1	La Niña PR JJA^0 SON^0 DJF^1 MAM^1
		El Niño Hovmöller	La Niña Hovmöller
	Niño3.4	Timeseries	Monthly Std. Dev.
		Power Spectra	Wavelet
		Autocorrelation	Running Standard Deviation
AMV	Regr: SST TAS PR	Timeseries	Power Spectra
	Regr LP: SST TAS PR	Timeseries	
AMV'	Regr: SST TAS PR	Timeseries	Power Spectra
	Regr LP: SST TAS PR	Timeseries	
PDV	Regr: SST TAS PR	Timeseries	Power Spectra
PDV'	Regr: SST TAS PR	Timeseries	Power Spectra
AMOC	Means	Standard Deviations	Patterns
	Timeseries	SST/TAS Regressions	
	Spectra	AMV/AMOC Lag Correlations	

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SIC SH	DJF	JF

Standard Deviations

SST	DJF	JF
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PSL	DJF	JF
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Global Trend Maps

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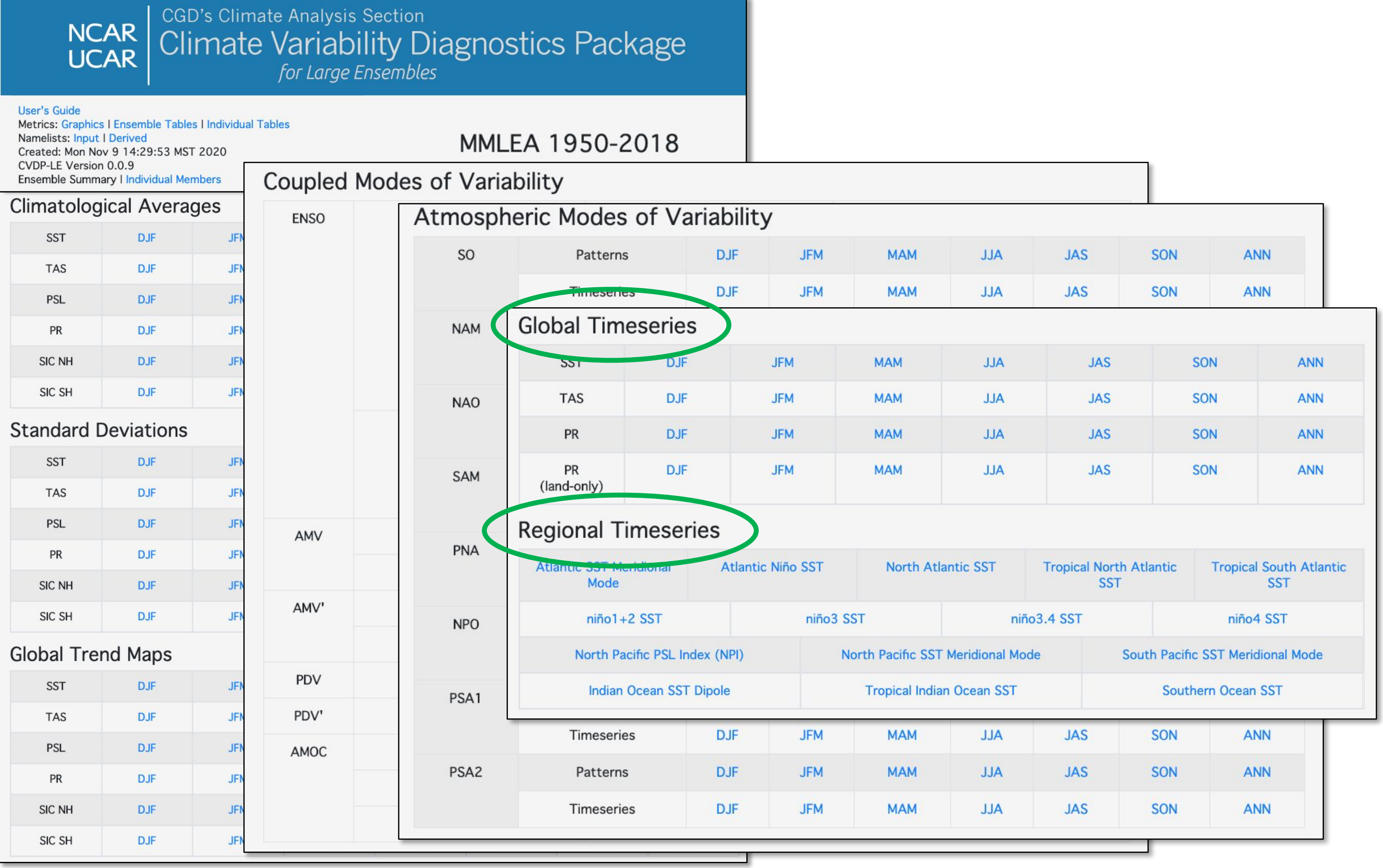
Coupled Modes of Variability

ENSO
AMV
AMV'
PDV
PDV'
AMOC

Atmospheric Modes of Variability

SO	Patterns	DJF	JFM	MAM	JJA	JAS	SON	ANN
	Timeseries	DJF	JFM	MAM	JJA	JAS	SON	ANN
NAM	Patterns	DJF	JFM	MAM	JJA	JAS	SON	ANN
	Timeseries	DJF	JFM	MAM	JJA	JAS	SON	ANN
NAO	Patterns	DJF	JFM	MAM	JJA	JAS	SON	ANN
	Timeseries	DJF	JFM	MAM	JJA	JAS	SON	ANN
SAM	Patterns	DJF	JFM	MAM	JJA	JAS	SON	ANN
	Timeseries	DJF	JFM	MAM	JJA	JAS	SON	ANN
PNA	Patterns	DJF	JFM	MAM	JJA	JAS	SON	ANN
	Timeseries	DJF	JFM	MAM	JJA	JAS	SON	ANN
NPO	Patterns	DJF	JFM	MAM	JJA	JAS	SON	ANN
	Timeseries	DJF	JFM	MAM	JJA	JAS	SON	ANN
PSA1	Patterns	DJF	JFM	MAM	JJA	JAS	SON	ANN
	Timeseries	DJF	JFM	MAM	JJA	JAS	SON	ANN
PSA2	Patterns	DJF	JFM	MAM	JJA	JAS	SON	ANN
	Timeseries	DJF	JFM	MAM	JJA	JAS	SON	ANN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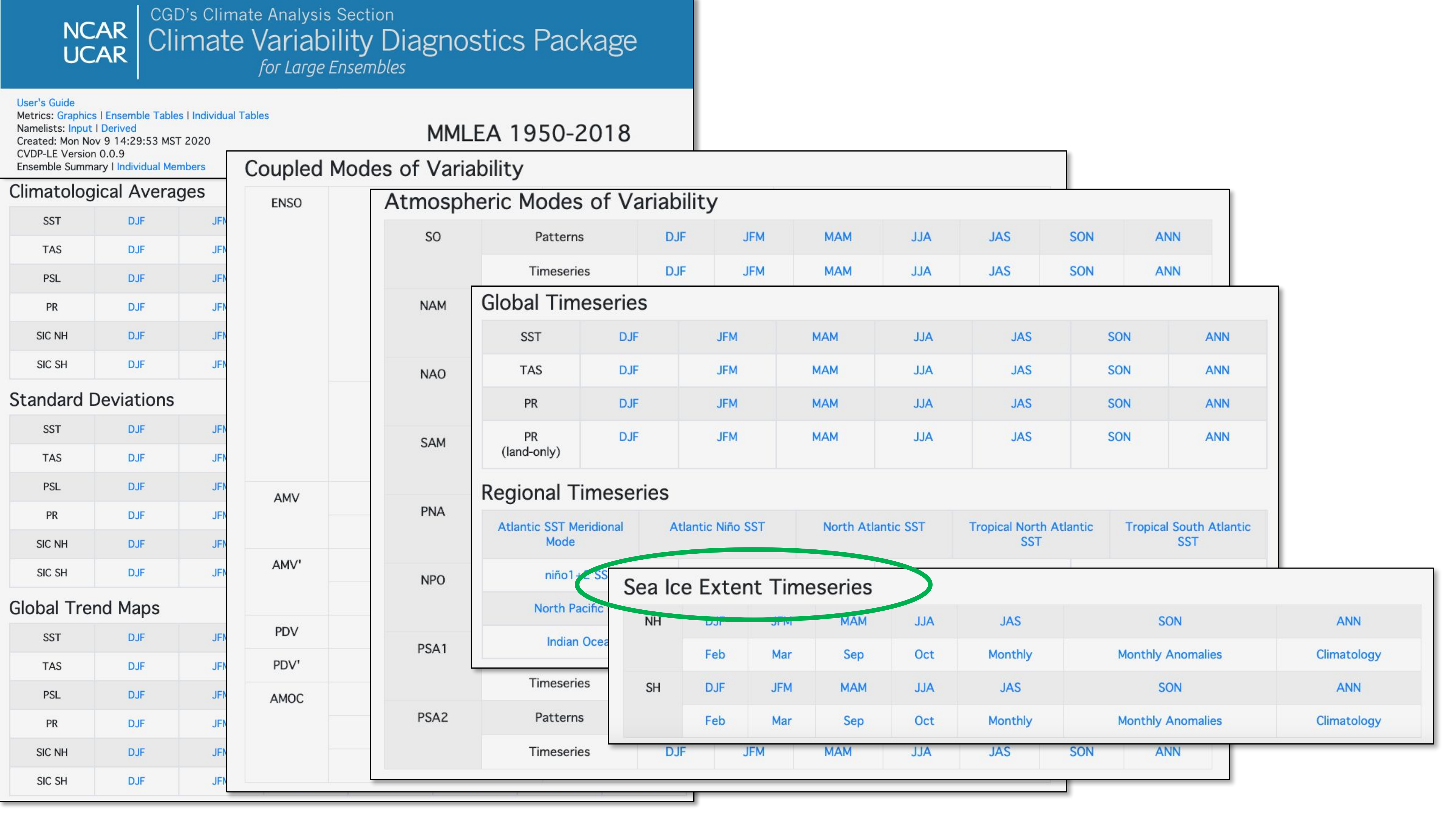
PR DJF JFM MAM JJA JAS SON ANN
PR (land-only) DJF JFM MAM JJA JAS SON ANN
Regional Timeseries
Atlantic SST Meridional Mode
Atlantic Niño SST
North Atlantic SST
Tropical North Atlantic SST
Tropical South Atlantic SST
niño1+2 SST
niño3 SST
niño3.4 SST
niño4 SST
North Pacific PSL Index (NPI)
North Pacific SST Meridional Mode
South Pacific SST Meridional Mode
Indian Ocean SST Dipole
Tropical Indian Ocean SST
Southern Ocean SST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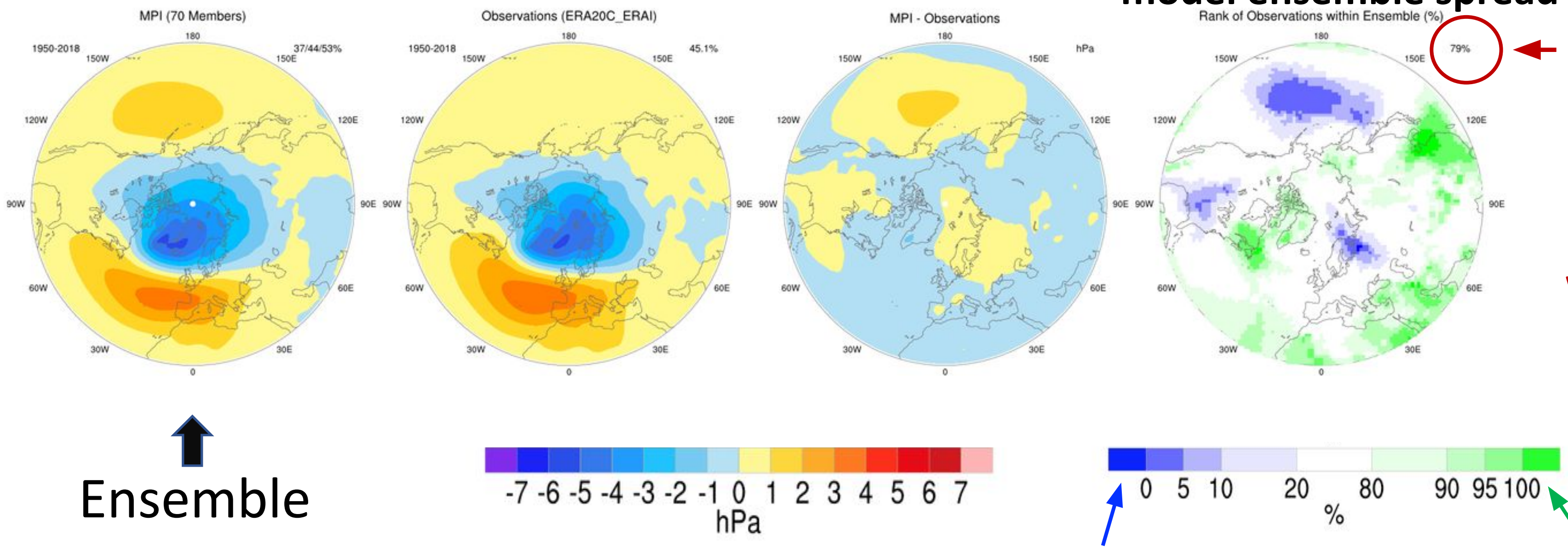
Tropical South Atlantic SST
North Pacific
Indian Ocea
Sea Ice Extent Timeseries
NH MAM JJA JAS SON ANN
Feb Mar Sep Oct Monthly Monthly Anomalies Climatology
SH DJF JFM MAM JJA JAS SON ANN
Feb Mar Sep Oct Monthly Monthly Anomalies Climatology

Ensemble Summary: NAO Pattern (DJF)

1950-2018

MPI
70 members

Model | **Observations** | **Difference** | **Rank of Obs within model ensemble spread**



Ensemble Average

Fractional area between 10-90%

***White areas:* Observations lie within 20-80% of model ensemble spread.**

Obs < any member

Obs > any member

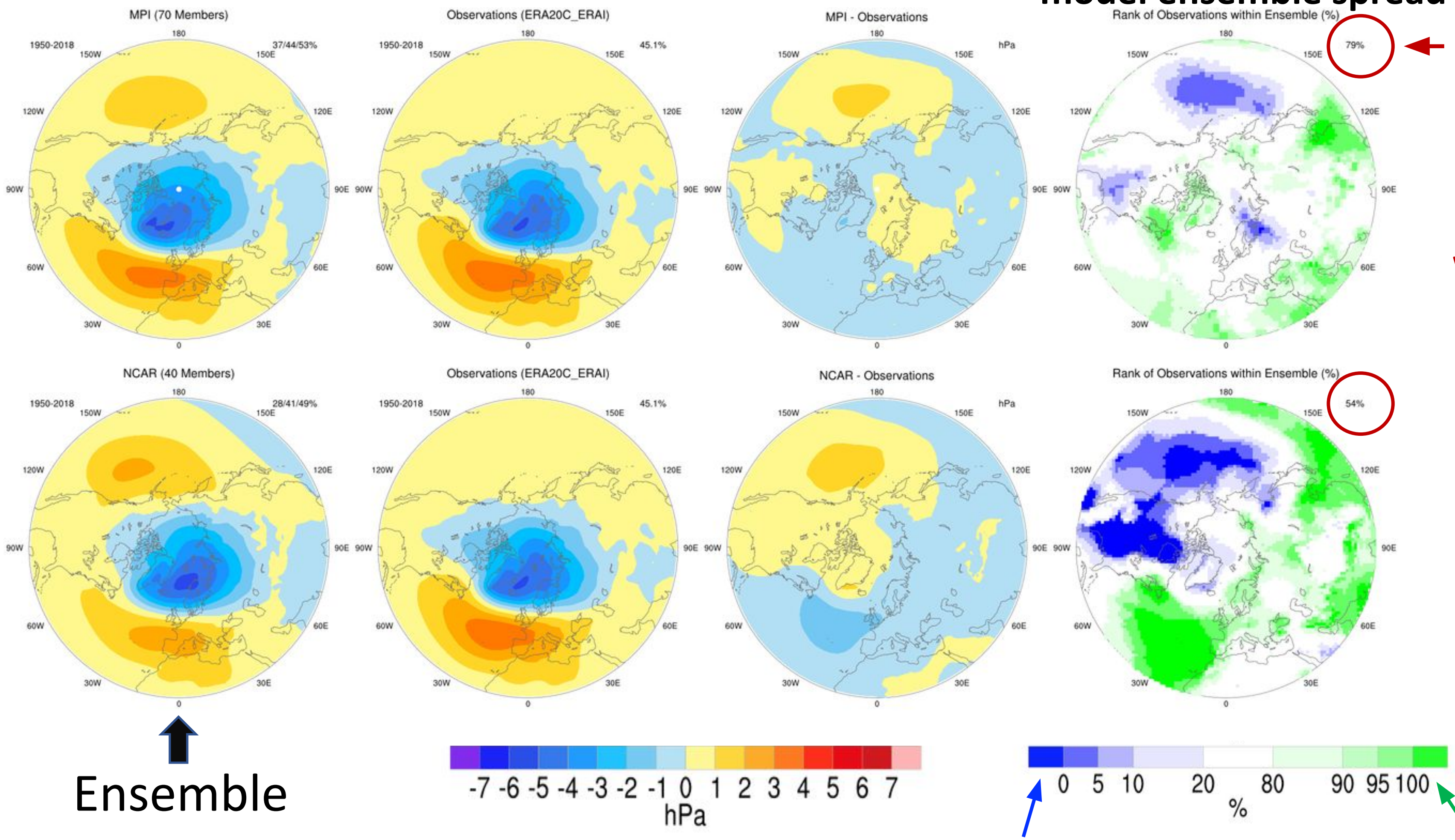
Ensemble Summary: NAO Pattern (DJF)

1950-2018

Model | **Observations** | **Difference** | **Rank of Obs within model ensemble spread**

MPI
70 members

CESM1
40 members



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Ensemble Average

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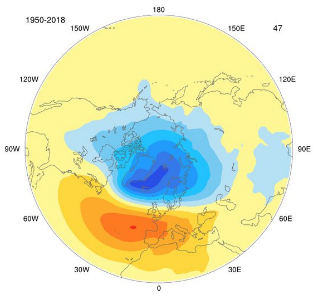
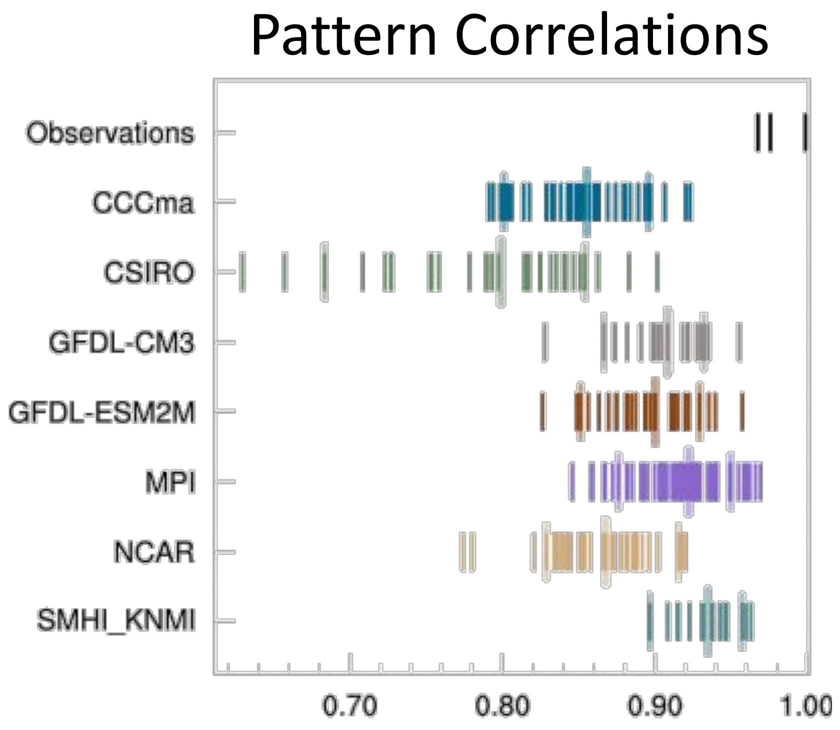
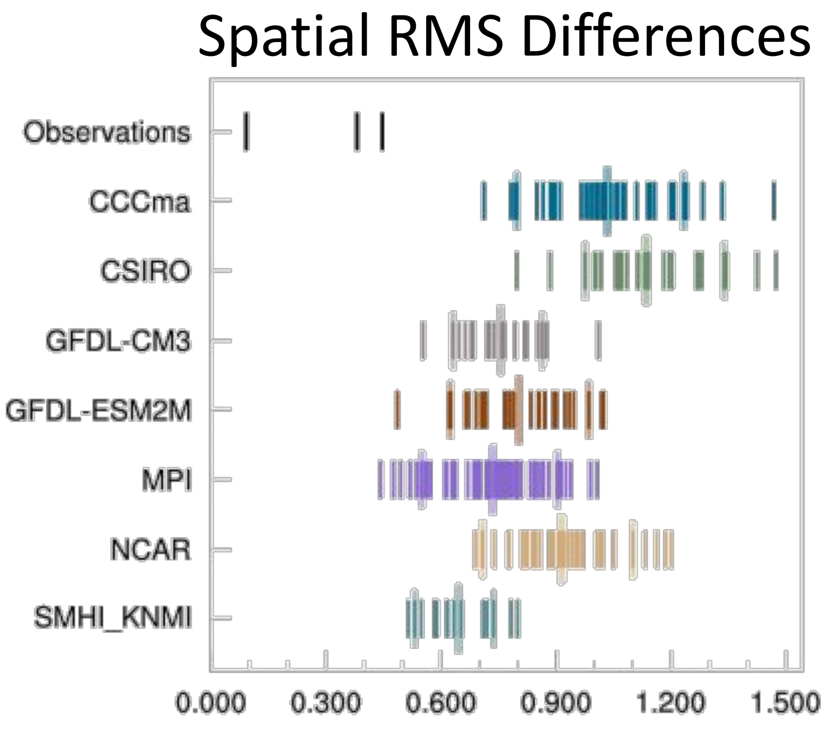
Obs > any member

CMIP5 Multi-Model Large Ensemble Archive



Winter NAO (Model *vs.* ERA-20C, 1950-2018)





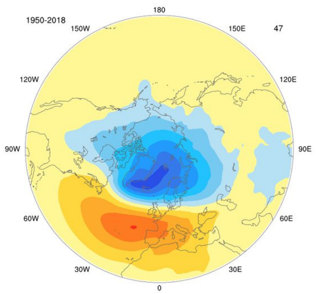
Longer bars: 10th / 50th / 90th percentiles

All graphics, data and metrics saved to a repository.

Observational Uncertainty

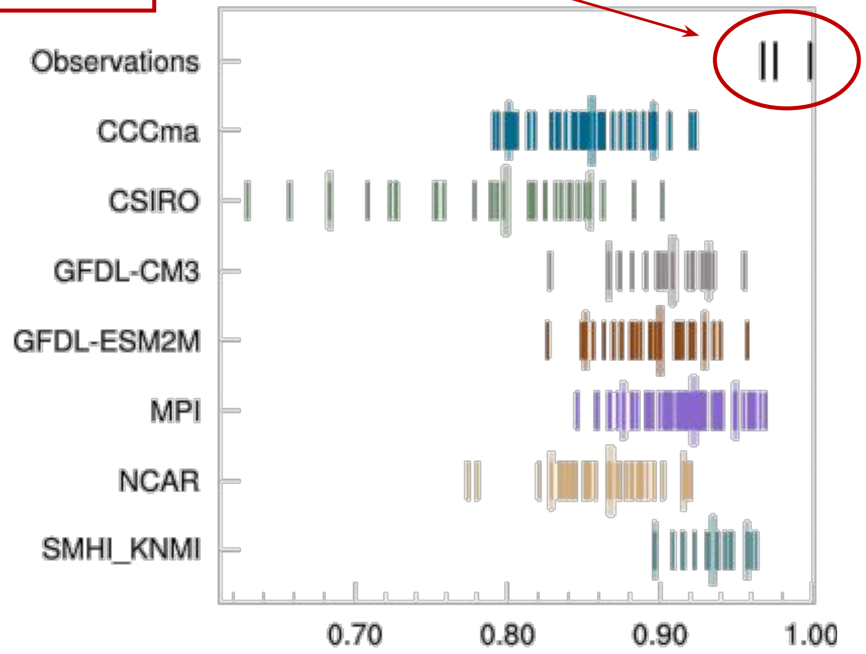
CERA20C (1950-2018)
ERA-I (1979-2018)
MERRA2 (1980-2017)

CMIP5 Multi-Model Large Ensemble Archive

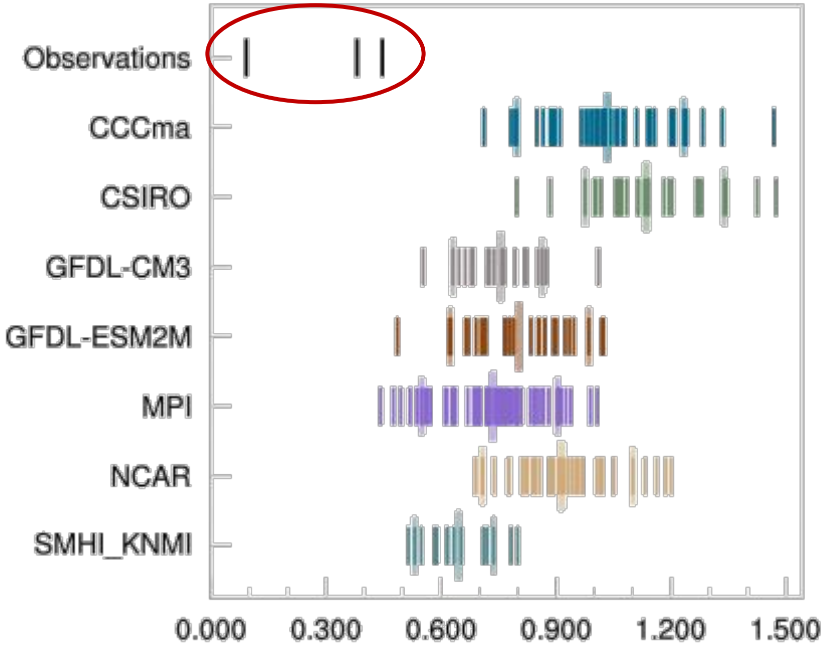


Winter NAO (Model *vs.* ERA-20C, 1950-2018)

Pattern Correlations



Spatial RMS Differences



Longer bars: 10th / 50th / 90th percentiles

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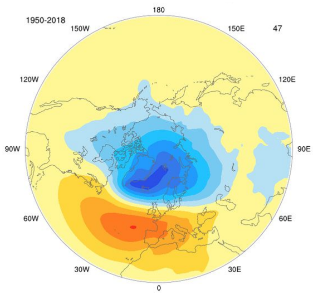
CMIP5 Multi-Model Large Ensemble Archive



Winter NAO (Model *vs.* ERA-20C, 1950-2018)

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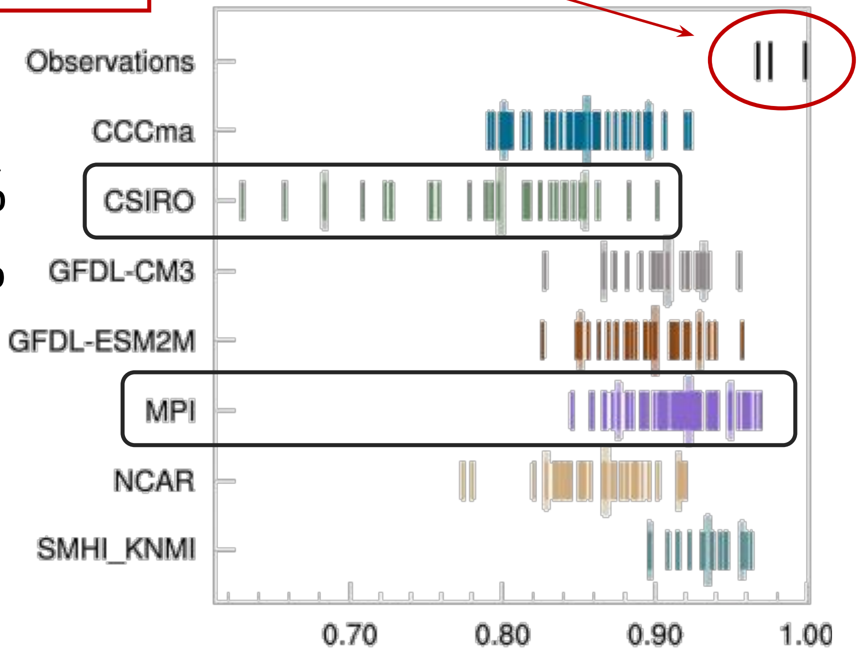
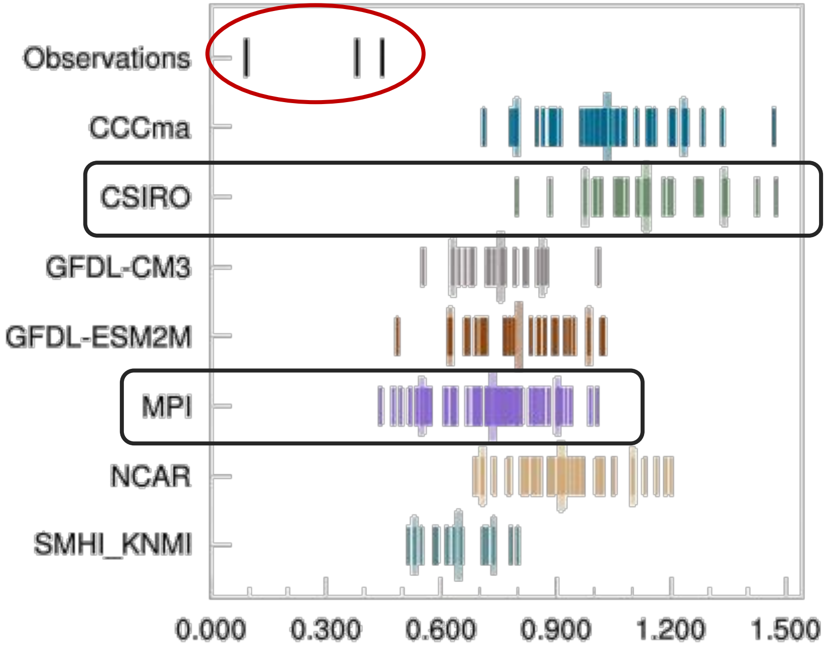


Spatial RMS Differences



CSIRO 90th %
< MPI 10th %

Models are structurally different.

Longer bars: 10th / 50th / 90th percentiles

See also Fasullo et al. (2020)

All graphics, data and metrics saved to a repository.

CMIP6
Large Ensembles

Observations

Model
Ensemble Mean

Ensemble Spread

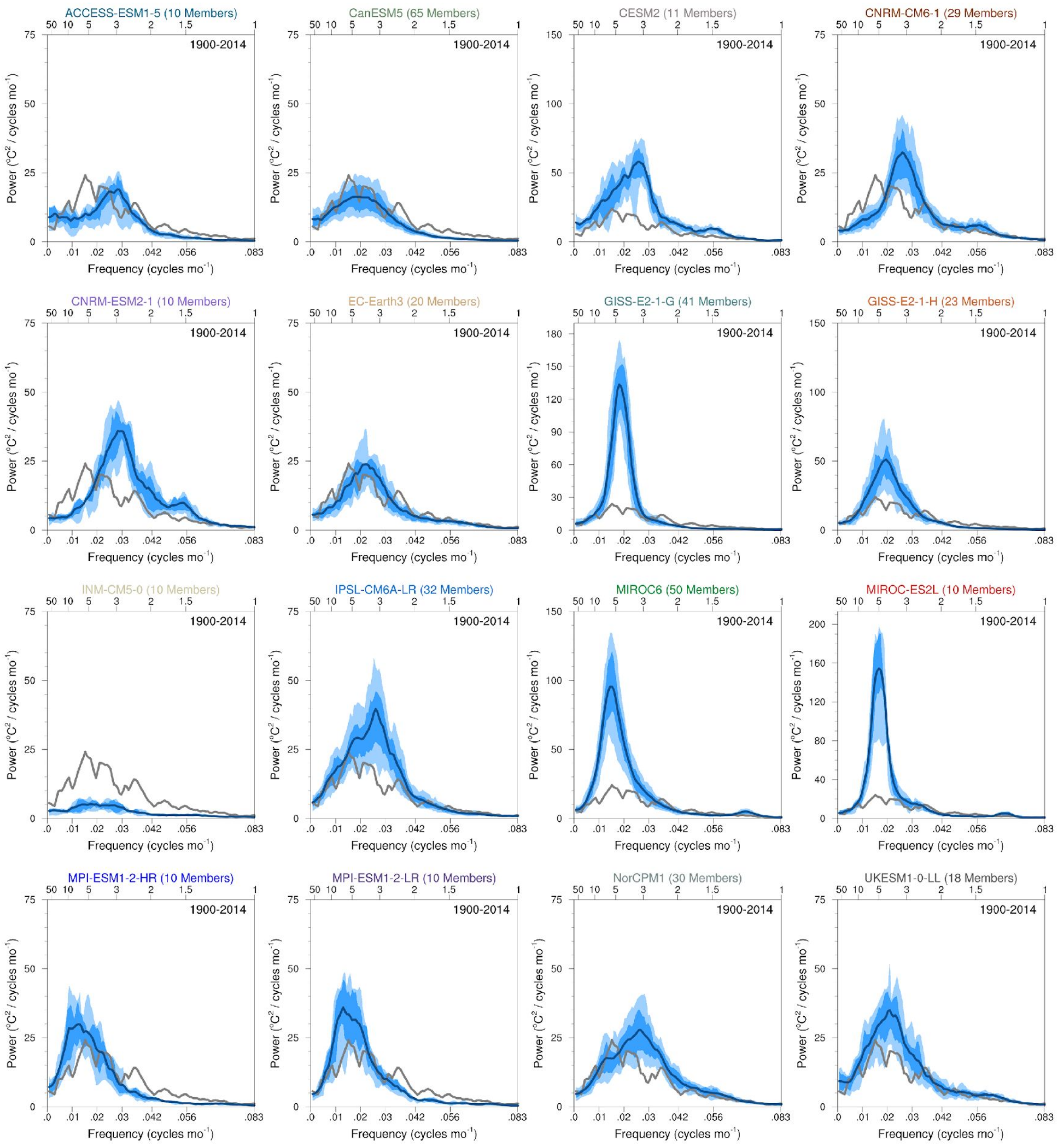
25-75%

10-
90
%

All graphics, data and metrics saved to a repository.

Ensemble Summary: Niño3.4 SST Power Spectra (Monthly)

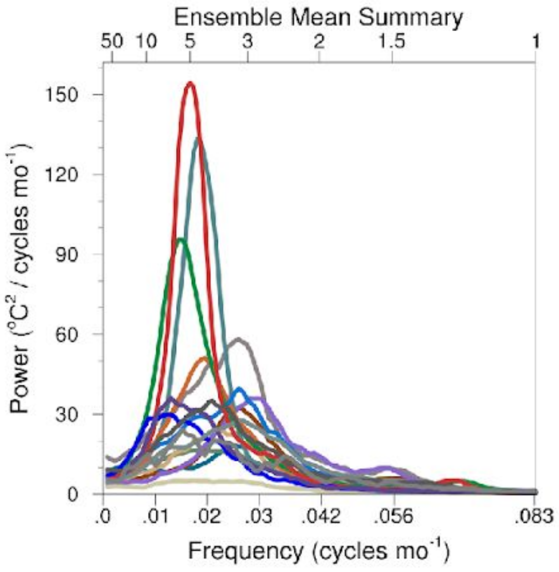
ERSST v5 1900-2014

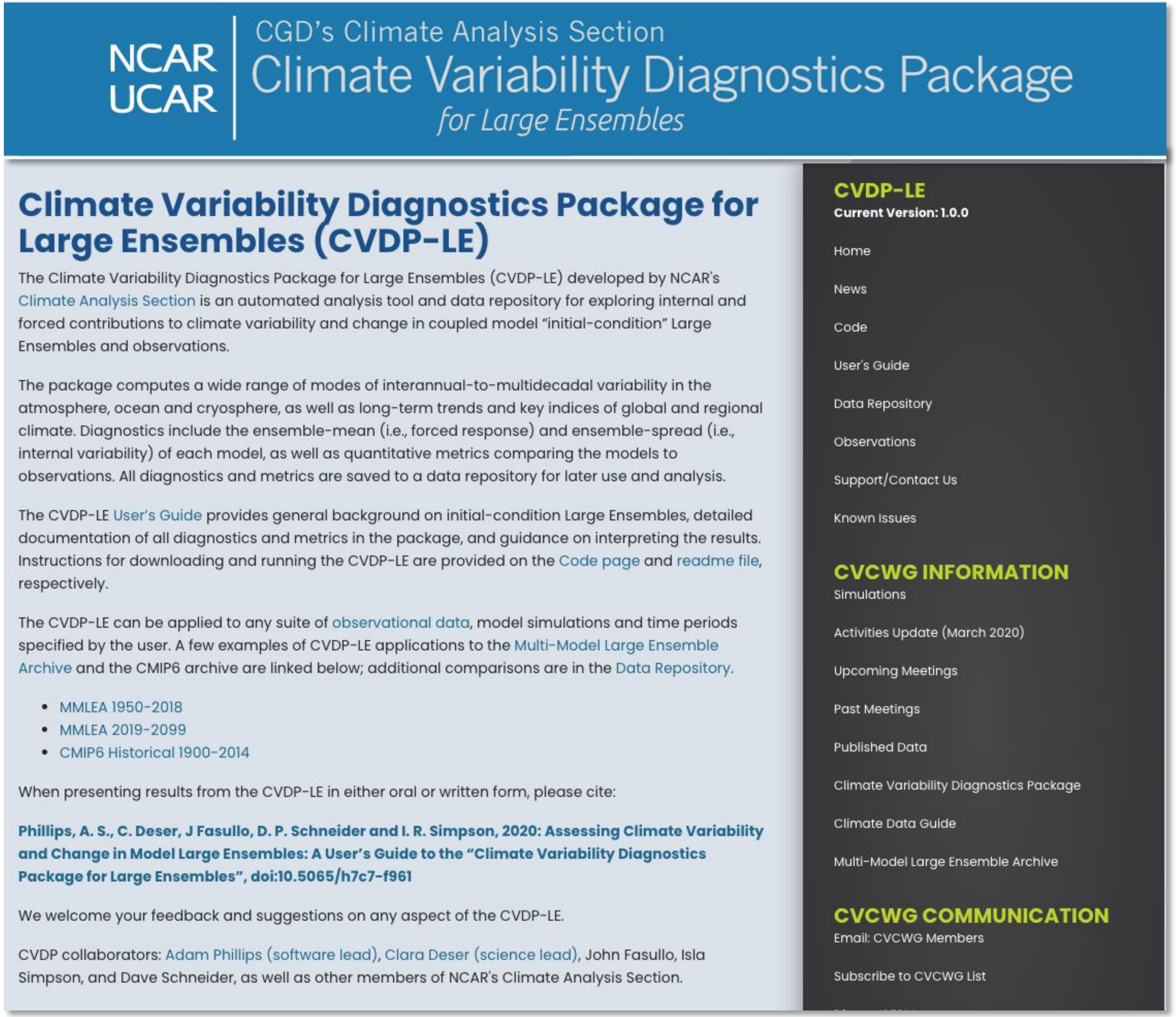


1900-2014

Power Spectra

Niño3.4 SST Index (detrended)





NCAR UCAR

CGD's Climate Analysis Section

Climate Variability Diagnostics Package

for Large Ensembles

Climate Variability Diagnostics Package for Large Ensembles (CVDP-LE)

The Climate Variability Diagnostics Package for Large Ensembles (CVDP-LE) developed by NCAR's Climate Analysis Section is an automated analysis tool and data repository for exploring internal and forced contributions to climate variability and change in coupled model "initial-condition" Large Ensembles and observations.

The package computes a wide range of modes of interannual-to-multidecadal variability in the atmosphere, ocean and cryosphere, as well as long-term trends and key indices of global and regional climate. Diagnostics include the ensemble-mean (i.e., forced response) and ensemble-spread (i.e., internal variability) of each model, as well as quantitative metrics comparing the models to observations. All diagnostics and metrics are saved to a data repository for later use and analysis.

The CVDP-LE User's Guide provides general background on initial-condition Large Ensembles, detailed documentation of all diagnostics and metrics in the package, and guidance on interpreting the results. Instructions for downloading and running the CVDP-LE are provided on the Code page and readme file, respectively.

The CVDP-LE can be applied to any suite of observational data, model simulations and time periods specified by the user. A few examples of CVDP-LE applications to the Multi-Model Large Ensemble Archive and the CMIP6 archive are linked below; additional comparisons are in the Data Repository.

- MMLEA 1950-2018
- MMLEA 2019-2099
- CMIP6 Historical 1900-2014

When presenting results from the CVDP-LE in either oral or written form, please cite:

Phillips, A. S., C. Deser, J Fasullo, D. P. Schneider and I. R. Simpson, 2020: Assessing Climate Variability and Change in Model Large Ensembles: A User's Guide to the "Climate Variability Diagnostics Package for Large Ensembles", doi:10.5065/h7c7-f961

We welcome your feedback and suggestions on any aspect of the CVDP-LE.

CVDP collaborators: Adam Phillips (software lead), Clara Deser (science lead), John Fasullo, Isla Simpson, and Dave Schneider, as well as other members of NCAR's Climate Analysis Section.

CVDP-LE
Current Version: 1.0.0

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Known Issues

CVCWG INFORMATION
Simulations
Activities Update (March 2020)
Upcoming Meetings
Past Meetings
Published Data
Climate Variability Diagnostics Package
Climate Data Guide
Multi-Model Large Ensemble Archive

CVCWG COMMUNICATION
Email: CVCWG Members
Subscribe to CVCWG List

Some Application Ideas
(User's Guide)

- Multiple time periods to see if modes of variability change with time.
- Subsets of ensemble members to assess robustness.
- Filter the data to investigate dependence on time scale.
- Use an "ensemble" of shorter segments from a control simulation.

Resources for Studying Climate variability and Change

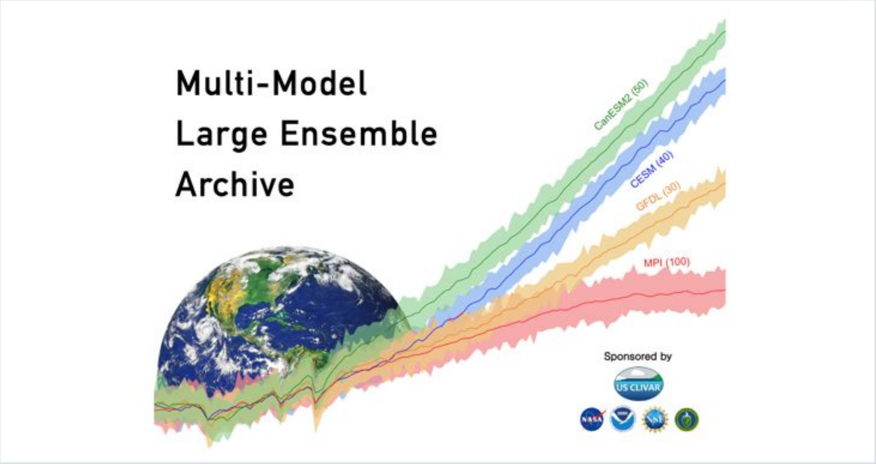
NCAR UCAR ClimateDataGuide *inform • compare • discover*

CLIMATE DATA | ANALYSIS TOOLS | MODEL EVALUATION | EXPERT CONTRIBUTORS | ABOUT | Site-wide Search >>

Concise and reliable expert guidance on the strengths, limitations and applications of climate data…

https://climatedataguide.ucar.edu/

MULTI-MODEL LARGE ENSEMBLE ARCHIVE



NCAR UCAR CGD's Climate Analysis Section

Climate Variability Diagnostics Package *for Large Ensembles*

https://www.cesm.ucar.edu/projects/cvdp-le

https://www.cesm.ucar.edu/community-projects/mmlea

Extra Slides

NCAR UCAR

CGD's Climate Analysis Section

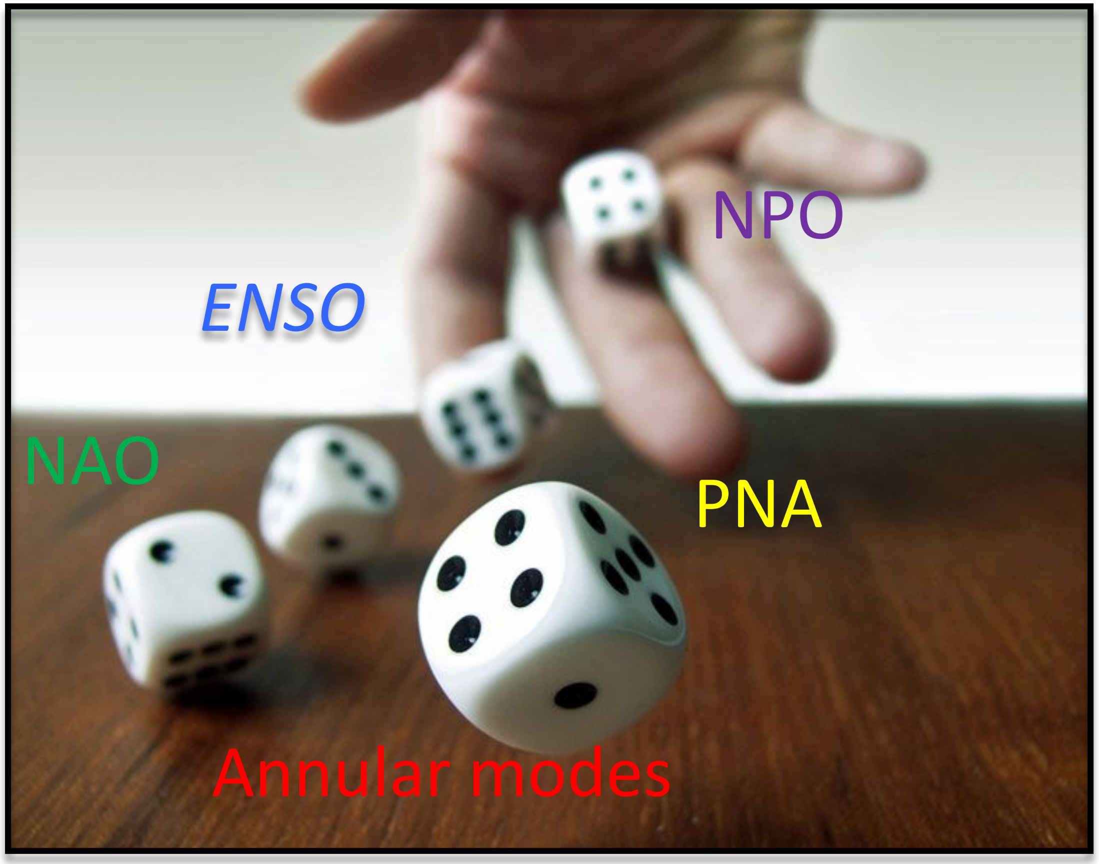
Climate Variability Diagnostics Package

for Large Ensembles

Tutorial and teaching resource

User's Guide (35 pages)

- Background on internal climate variability
- Utility of Large Ensembles
- Diagnostics and metrics (fully referenced)
- Treatment of observational uncertainty
- Two views: *Ensemble Summary* vs. *Individual Members*
- Interpretation of plots and metrics
- Best practices and tips for applying the package



Lots of random variability, which means it is essential to have a large number of samples for robust assessment.

Null hypothesis for any apparent *model bias in variability* and any apparent *change in variability* due to radiative forcing (e.g.,solar, GHG, volcanoes …) should be "sampling fluctuations".