Quantifying the Agreement between Observed and Simulated Extratropical Modes of Interannual Variability

-- Routine Evaluation of Various Climate Models based on Big-data Sharing Ecosystem

Jiwoo Lee, Ph. D

(jwlee@llnl.gov)

Lawrence Livermore National Laboratory, California, USA

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Lawrence Livermore National Laboratory

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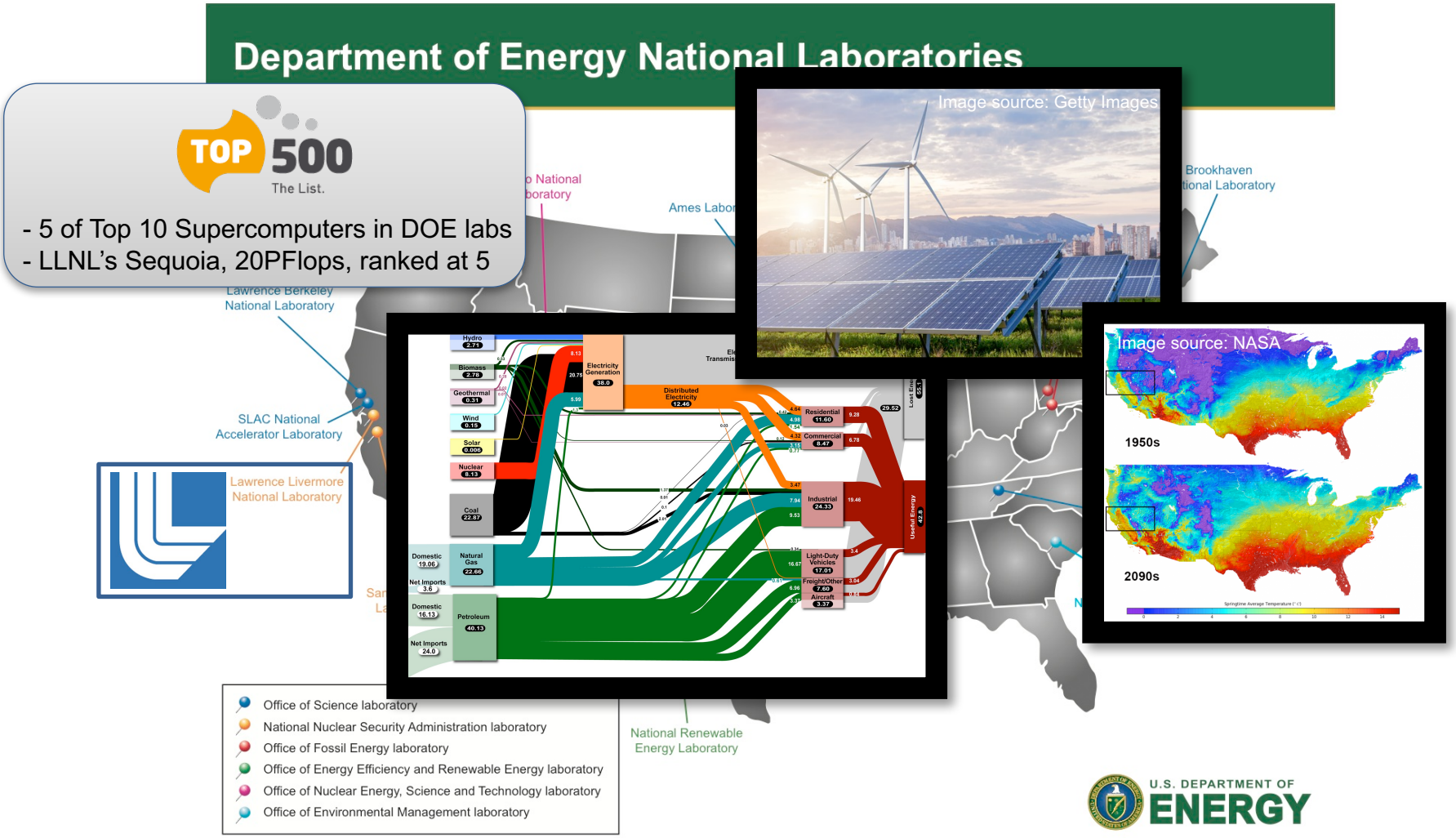


PART 1. Infrastructure Development for Climate Research

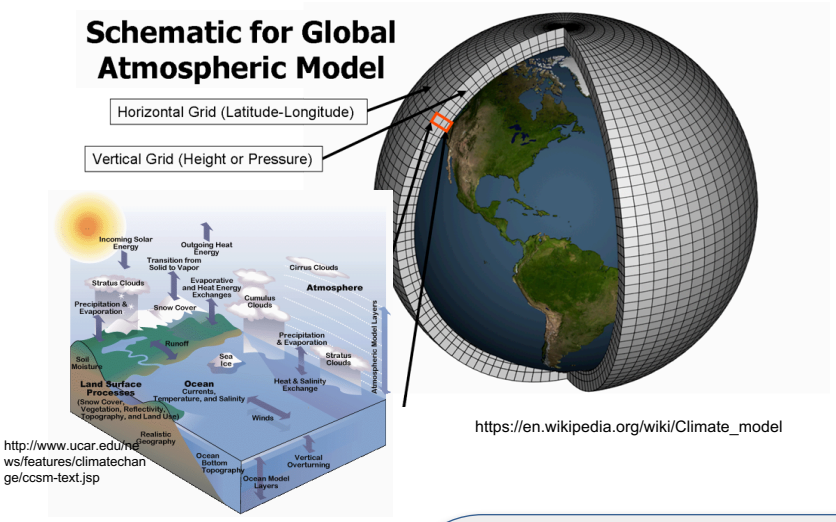
(next 15 slides…)

- ***Climate research as community efforts: CMIP & Obs4MIPs***
- ***Data sharing ecosystem for the community: ESGF***
- ***Advanced tool for climate big data analysis: CDAT***
- ***Help accelerating evolution of climate model: PMP***

Acknowledgements to: **Dean Williams, Charles Doutriaux, Denis Nadeau, et al. (AIMS Group); Peter Gleckler, Karl Taylor, Paul Durack, et al. (PCMDI)**

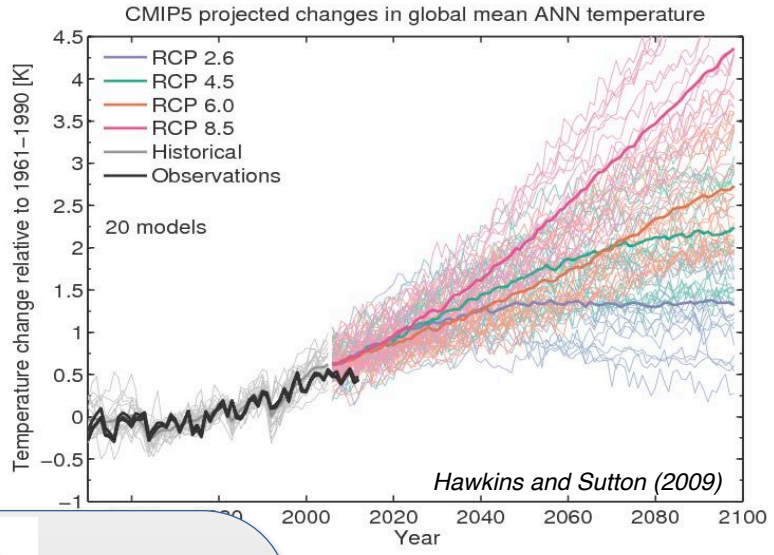
CMIP:

Climate Model Inter-comparison Project

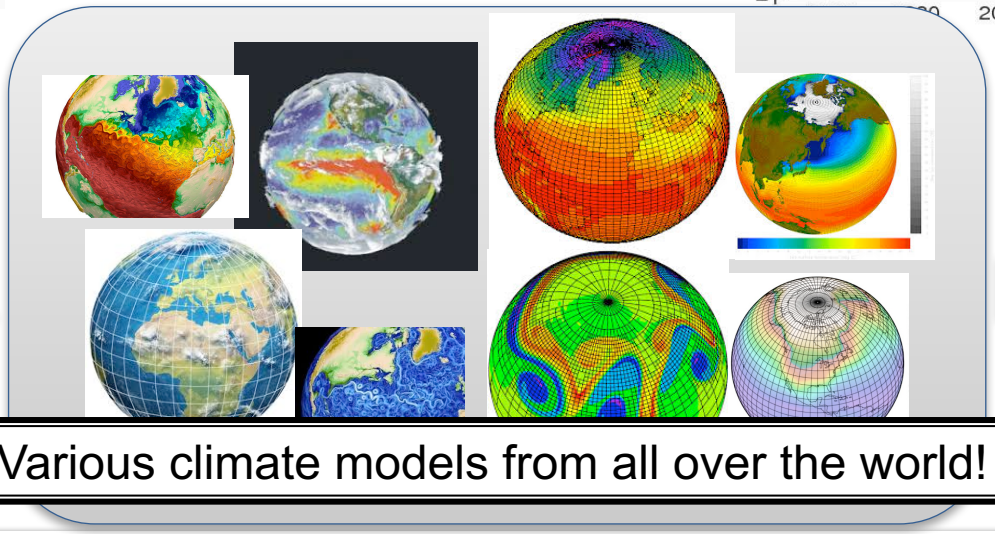


http://www.ucar.edu/news/features/climatechange/ccsm-text.jsp

https://en.wikipedia.org/wiki/Climate_model



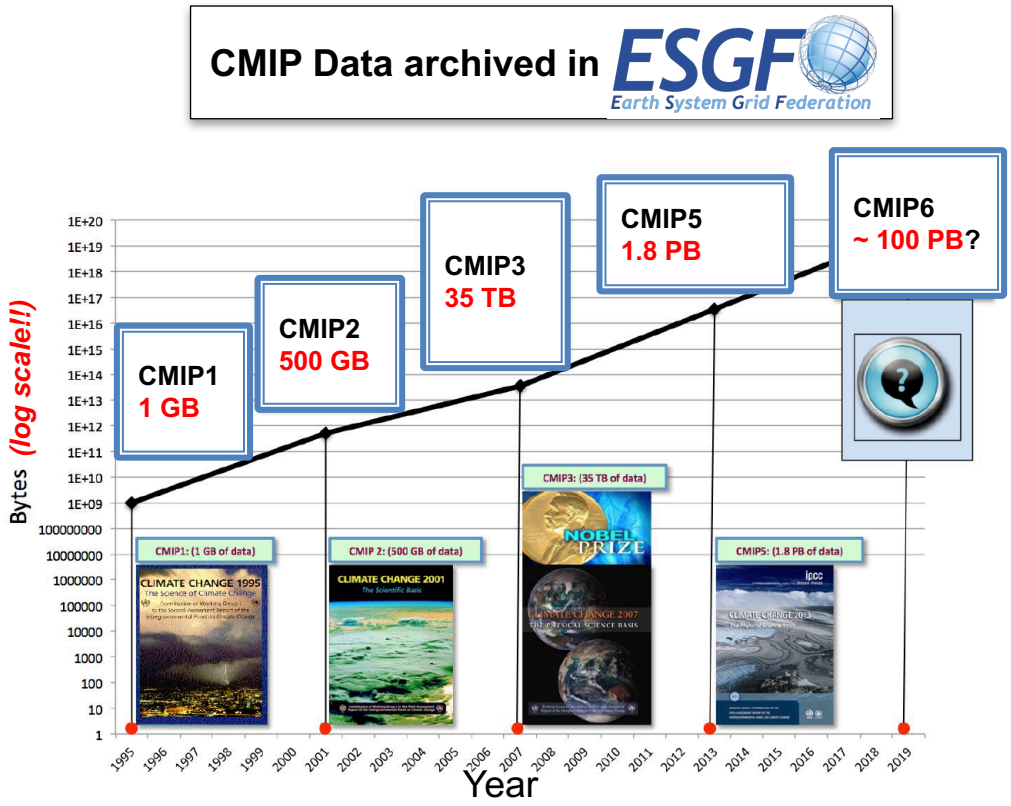
Uncertainties…



Various climate models from all over the world!

Simulate same target using different models!

CMIP:
Climate Model Inter-comparison Project



(Williams et al. 2015, BAMS)

- **CMIP** has collected a massive volume of climate model data
- CMIP research output have significantly contributed to publish **IPCC reports**

IPCC Awards Nobel Prize

PARIS2015
UN CLIMATE CHANGE CONFERENCE
COP21·CMP11

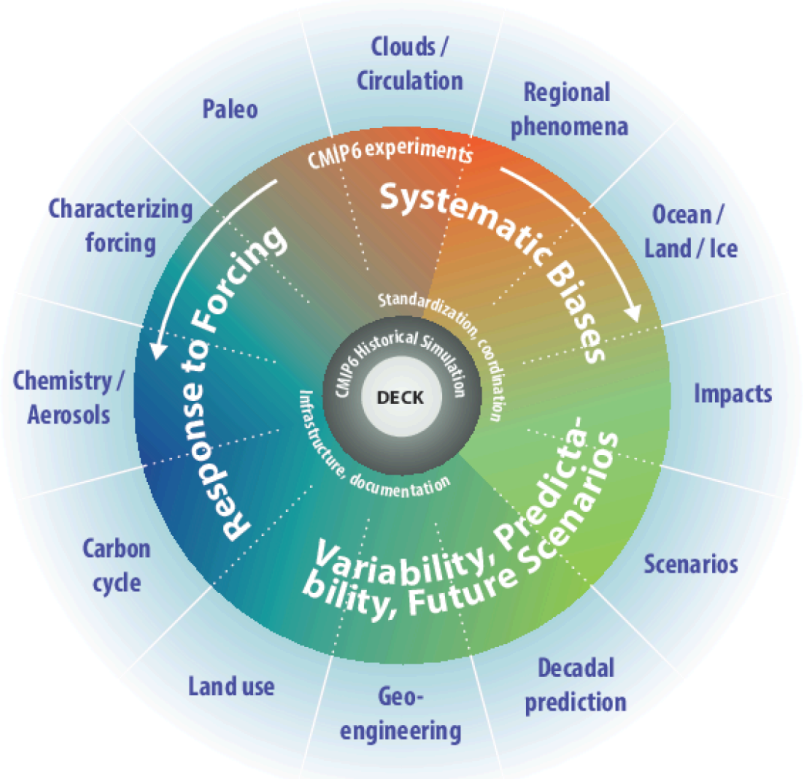
UNITED NATIONS
PARIS CLIMATE AGREEMENT
SIGNING CEREMONY
22 APRIL 2016

Paris Agreement

CMIP:
Climate Model Inter-comparison Project

Scientific Questions of CMIP6:

- How does the Earth system respond to **forcing**?
- What are the origins and consequences of systematic **model biases**?
- How can we assess **future climate changes** given internal climate variability, predictability, and uncertainties in scenarios?



Schematic of the CMIP6 experiment design

(Eyring et al. 2016, GMD)

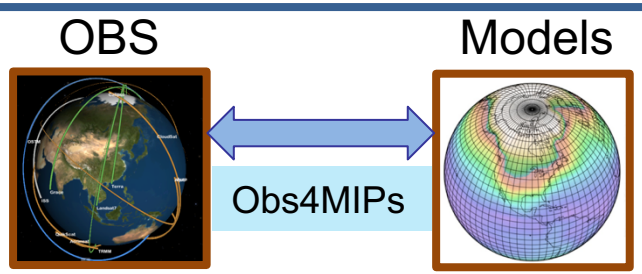
Other MIPs!

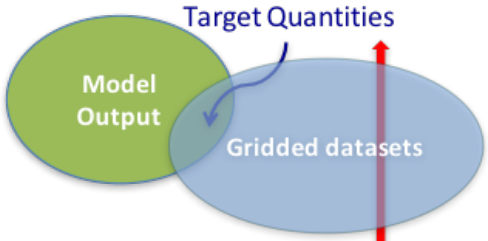
AerChemMIP	Aerosols and Chemistry Model Intercomparison Project
C4MIP	Coupled Climate Carbon Cycle Model Intercomparison Project
CFMIP	Cloud Feedback Model Intercomparison Project
DAMIP	Detection and Attribution Model Intercomparison Project
DCPP	Decadal Climate Prediction Project
FAFMIP	Flux-Anomaly-Forced Model Intercomparison Project
GeoMIP	Geoengineering Model Intercomparison Project
GMMIP	Global Monsoons Model Intercomparison Project
HighResMIP	High-Resolution Model Intercomparison Project
ISMIP6	Ice Sheet Model Intercomparison Project for CMIP6
LS3MIP	Land Surface, Snow and Soil Moisture
LUMIP	Land-Use Model Intercomparison Project
OMIP	Ocean Model Intercomparison Project
PMIP	Palaeoclimate Modelling Intercomparison Project
RFMIP	Radiative Forcing Model Intercomparison Project
ScenarioMIP	Scenario Model Intercomparison Project
VolMIP	Volcanic Forcings Model Intercomparison Project
CORDEX	Coordinated Regional Climate Downscaling Experiment
DynVarMIP	Dynamics and Variability Model Intercomparison Project
SIMIP	Sea Ice Model Intercomparison Project
VIACS AB	Vulnerability, Impacts, Adaptation and Climate Services Advisory Board
:	

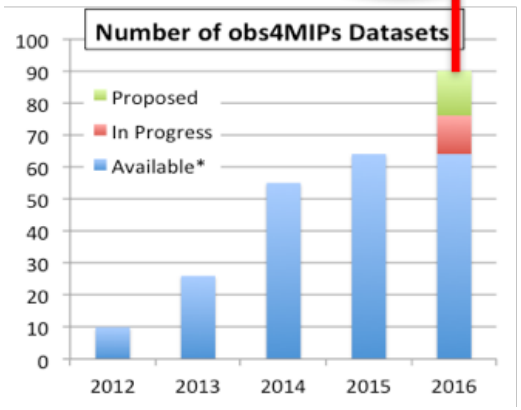
https://www.wcrp-climate.org/wgcm-overview

Obs4MIPs:
Observations for Model Intercomparisons Project

- A Project for identifying, documenting and disseminating observations for climate model evaluation in WCRP model intercomparisons, notably CMIP.
- Data sets accessible on the ESGF alongside CMIP model output, **adhering to the same data conventions**
- Observations to be structured in coordination with the CMIP output (e.g. NetCDF files, CF Convention, common vocabularies)





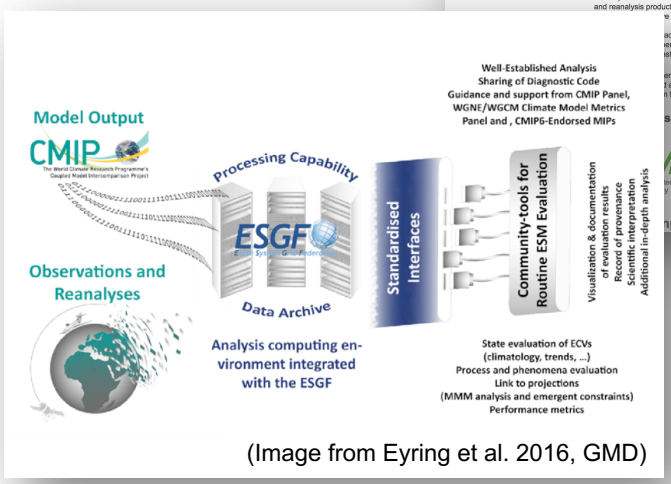


…. and growing!

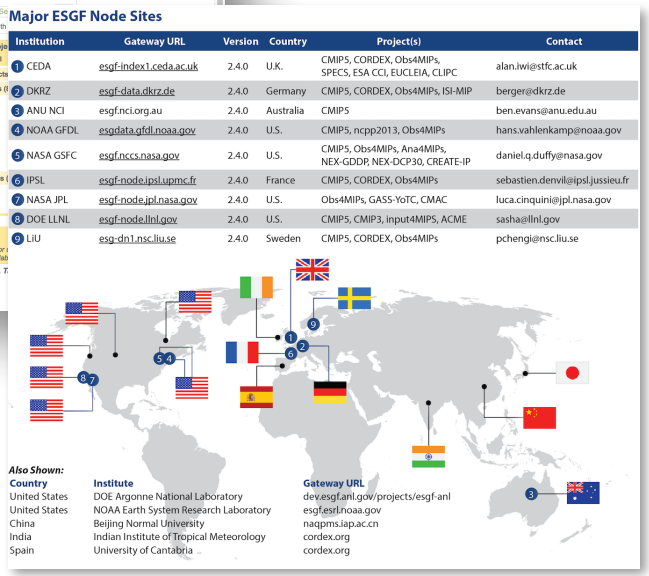
https://www.earthsystemcog.org/projects/obs4mips/

Earth System Grid Federation

The ESGF peer-to-peer (P2P) enterprise system is one of the largest-ever collaborative data efforts in Earth system science



(Image from Eyring et al. 2016, GMD)

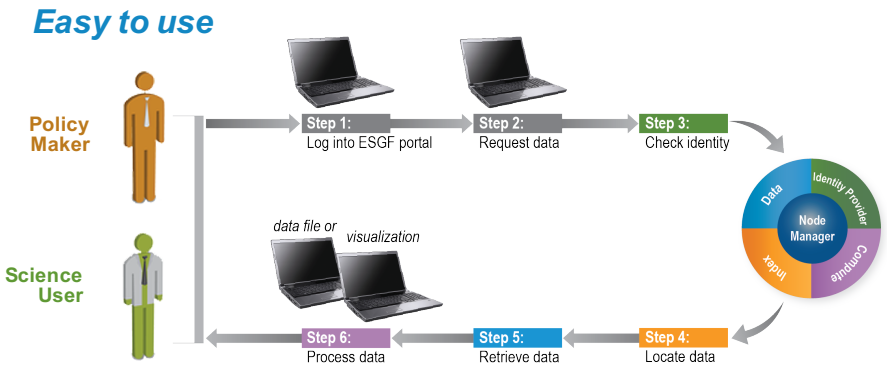


https://esgf-node.llnl.gov/

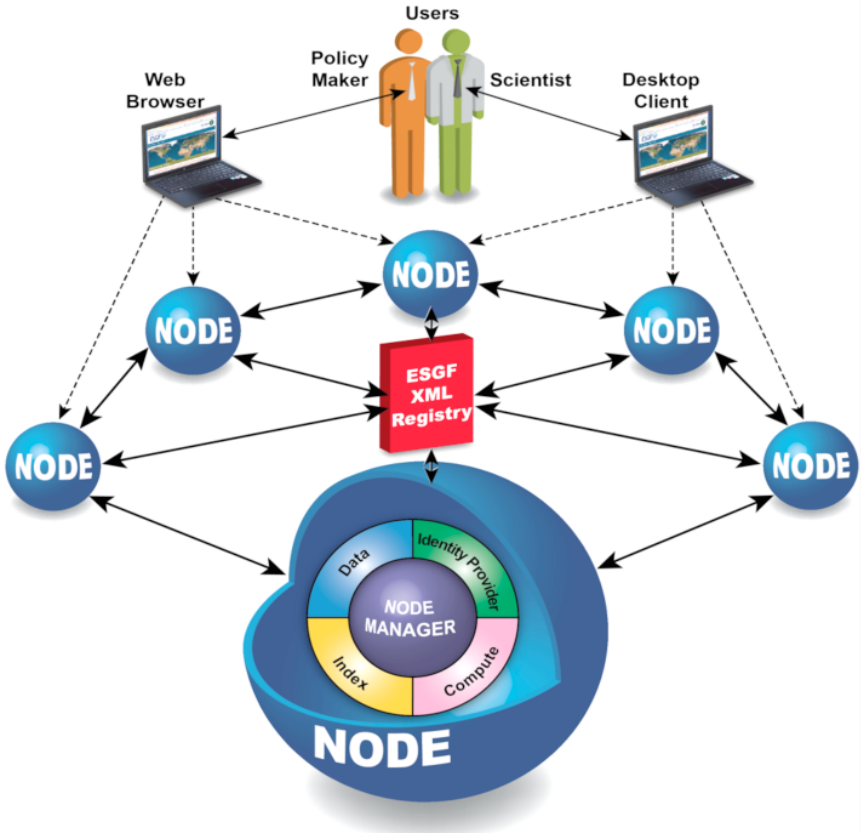
https://esgf.llnl.gov/

Unified virtual data cloud

User's View:



Actual Structure:



Distributed archives

Earth system science supported projects:

- **CMIP3, CMIP5, and CMIP6**—Phases 3, 5, and 6 of the Coupled Model Intercomparison Project
- **CORDEX**—Coordinated Regional climate Downscaling Experiment
- **ACME**—Accelerated Climate Modeling for Energy
- **EUCLEIA**—EUropean Climate and weather Events: Interpretation and Attribution
- **Obs4MIPs**—Observational for Model Intercomparison Project
- **GeoMIP**—Geo-engineering Model Intercomparison Project
- **Ana4MIPs**—Reanalysis for the coupled model intercomparison
- **LUCID**—Land-Use and Climate, Identification of robust impacts
- **ESA CCI**—European Space Agency Climate Change Initiative Earth Observation data
- **TAMIP**—Transpose-Atmospheric Model Intercomparison Project
- **PMIP**—Paleoclimate Modeling Intercomparison Project
- **HIWPP**—High Impact Weather Prediction Project
- **NEMS**—NOAA Environmental Modeling System
- **NEX-DCP30**—NASA NEX Downscaled Climate Projections
- **CREATE-IP**—Collaborative REAnalysis Technical Environment – Intercomparison Project

4,635.828 TB
ESGF total data volume

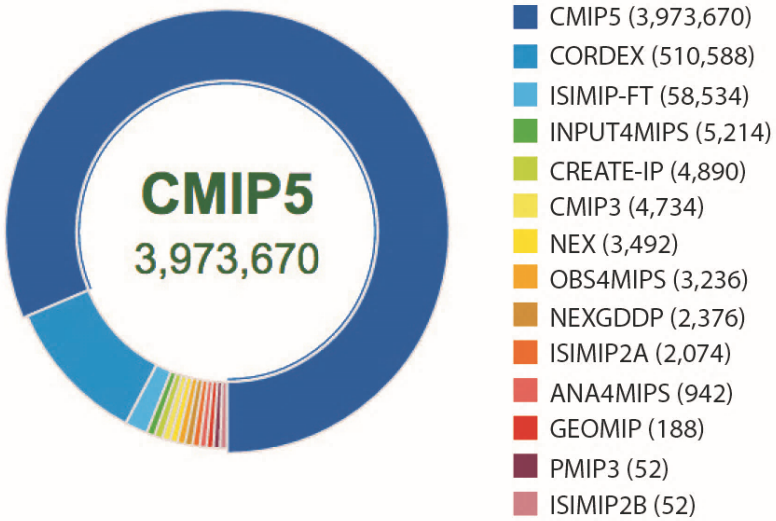
4,261.921 TB
CMIP5 total data volume

59.813 TB
CORDEX total data volume

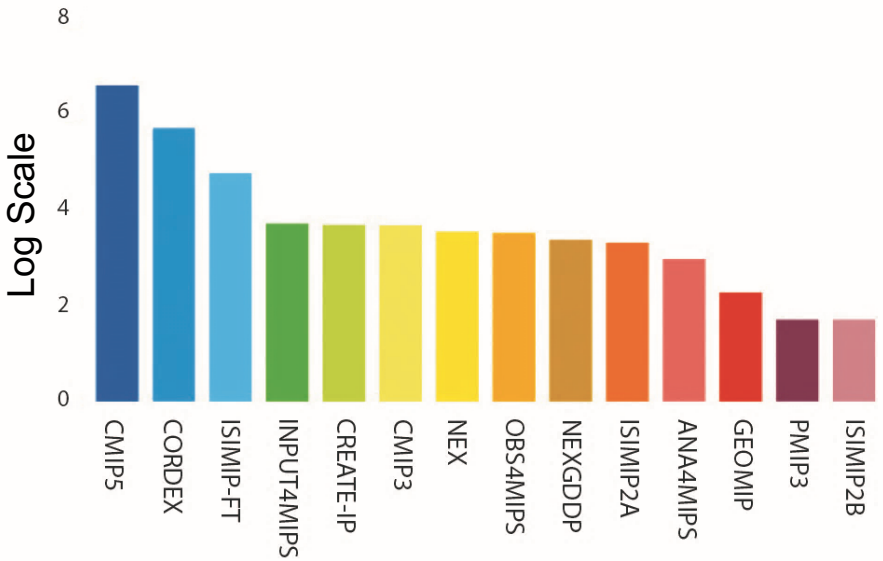
More complete list:
https://esgf-node.llnl.gov/ac/list/

Distributed archives

Number of Downloads Per Project



Number of Downloads Per Project



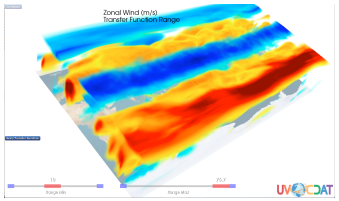
Total number of downloads: ~ 4,500K

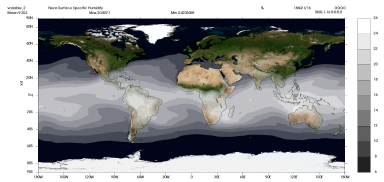
Most downloaded projects:

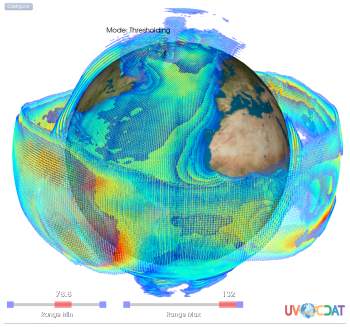
1. **CMIP5**
2. **CORDEX**
   :

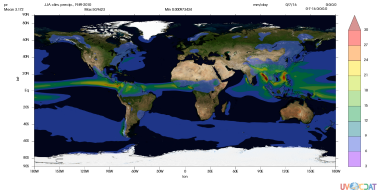
Community Data Analysis Tools

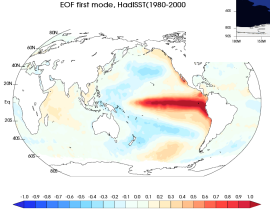
- Python based application (GUI / Command Line)
- CDMS (Climate Data Management System)
  - Handle multi-dimensional climate variables
  - cdutil, genutil: Python library specialized for climate analysis
- VCS Graphics Module

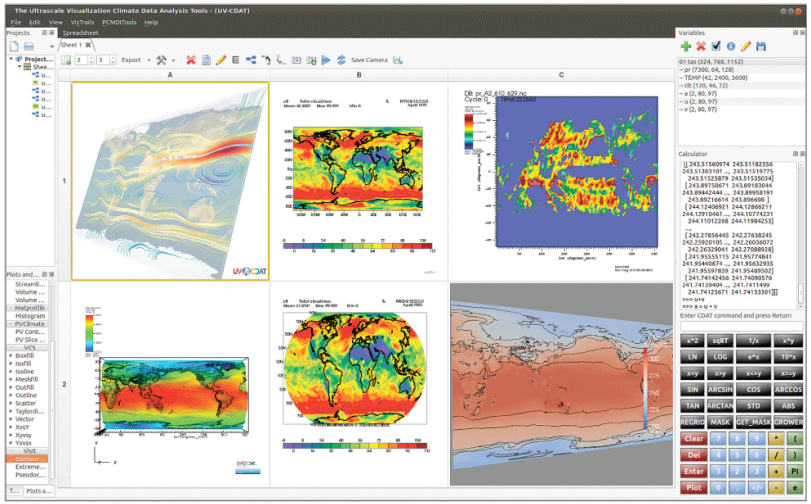






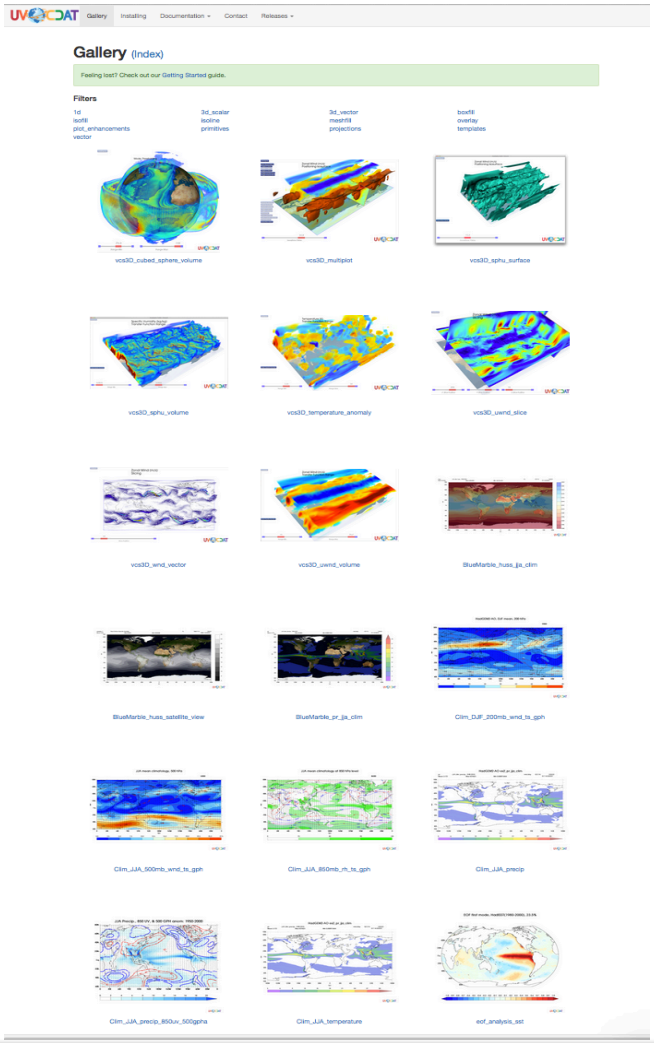






https://uvcdat.llnl.gov/

CDAT analysis examples (1)



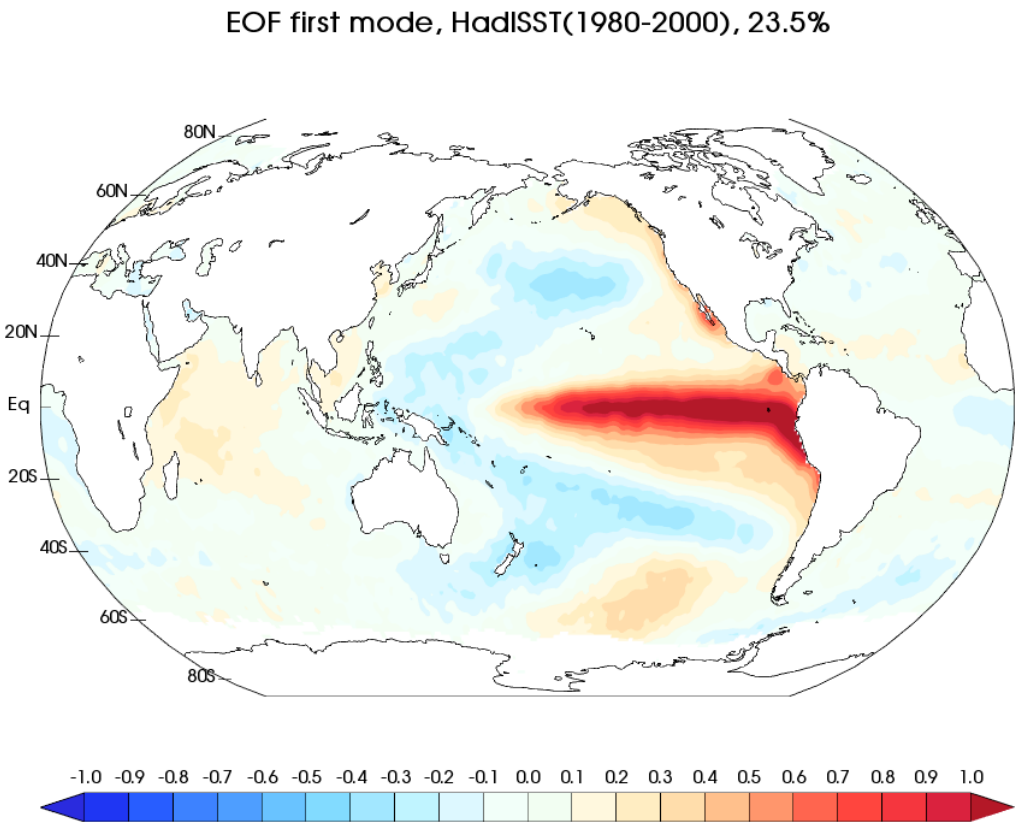
Examples of frequently repeated analyses:

- Seasonal climatology / anomaly
- EOF analysis
- Running average
- Hovmoller & Taylor Diagram
- Multi-model ensemble
- Etc

https://uvcdat.llnl.gov/gallery.html

CDAT analysis examples (2)

Community Data Analysis Tools



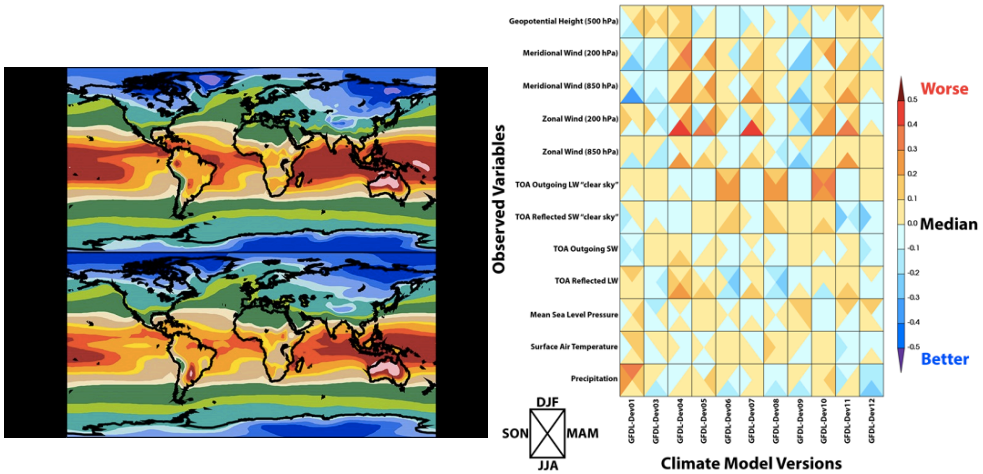
Highlight of the example Python code:

```
import cdms2
from eofs.cdms import Eof

#Open file
:

# Load variable
d = …
:

# EOF (take leading mode)
solver = Eof(d, weights='area')
eof = solver.eofsAsCovariance(neofs=1)

# Plot
:
```

https://uvcdat.llnl.gov/examples/eof_analysis_sst.html

PCMDI Metrics Package (PMP)

- **Emphasizes a diverse suite of relatively robust high level summary statistics objectively comparing models and observations across space and time scales**
- End-to-end provenance to ensure reproducibility
- **Open source Python** publicly available on **GitHub**
- Designed to enable the research community to contribute
- Currently collaborating with 5 modeling groups

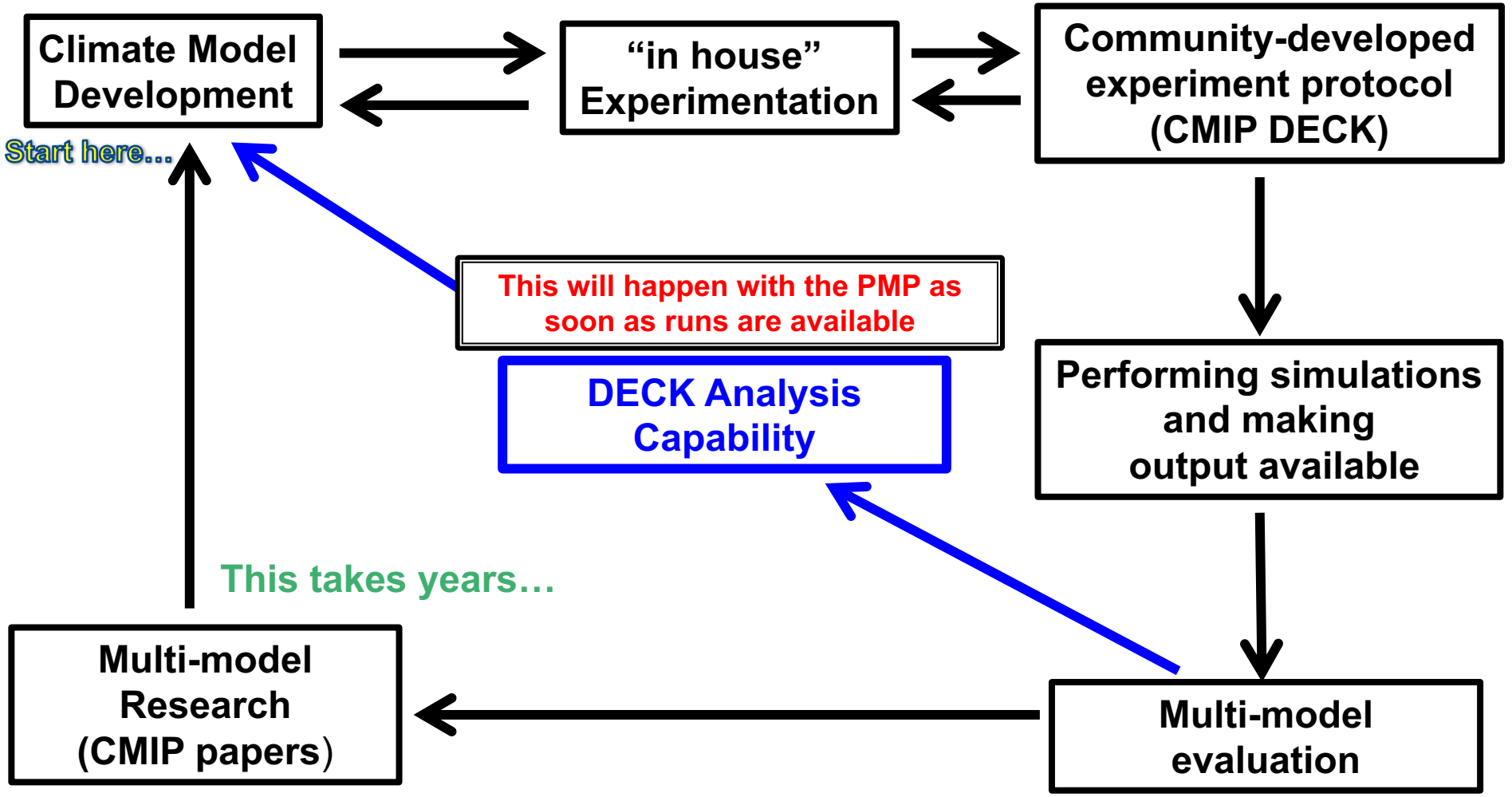


Gleckler, P. J., C. Doutriaux, P. J. Durack, K. E. Taylor, Y. Zhang, D. N. Williams, E. Mason, and J. Servonnat (2016), A more powerful reality test for climate models, Eos, 97, doi:10.1029/2016EO051663. Published on 3 May 2016.

PCMDI
Program for Climate Model Diagnosis and Intercomparison

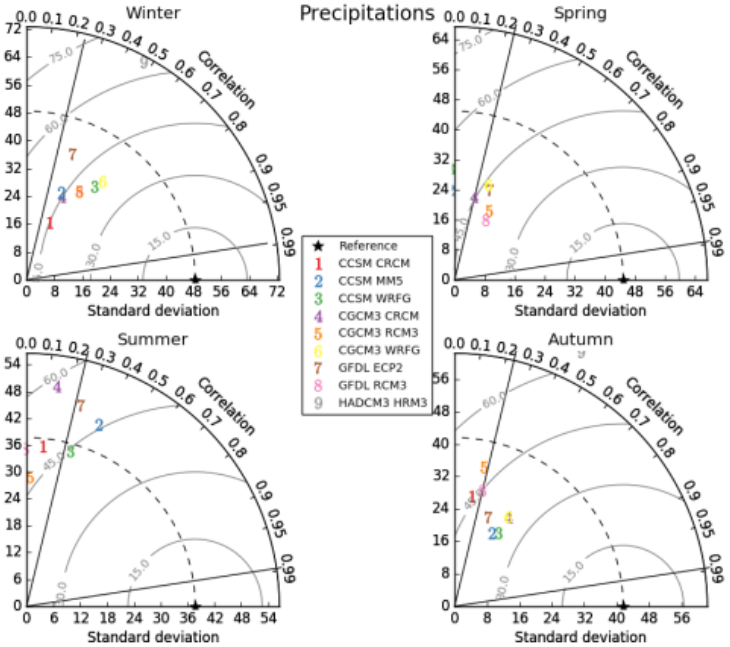
How can CMIP more directly assist model development?

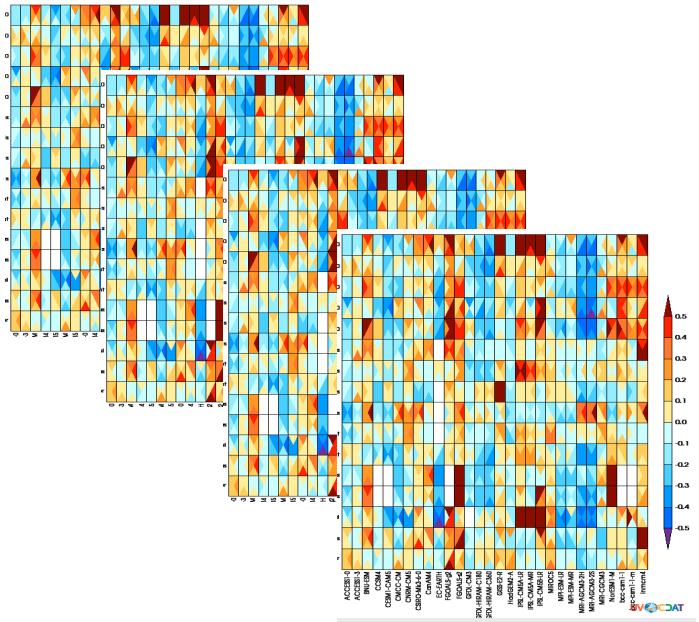
Enable modelers to leverage diverse analysis community expertise



The PCMDI Metrics Package (v1.1x)
Prototyped on climatological summaries

Taylor Diagrams and Portrait Plots:
Orthogonal decompositions of large scale climatological error statistics





PART 2. Evaluation of Various Climate Models

(next 15 slides…)

- ***Scientific study based on the infrastructure, and currently being implemented to PMP***
- ***Specific research title: Quantifying the Agreement Between Observed and Simulated Extratropical Modes of Interannual Variability***

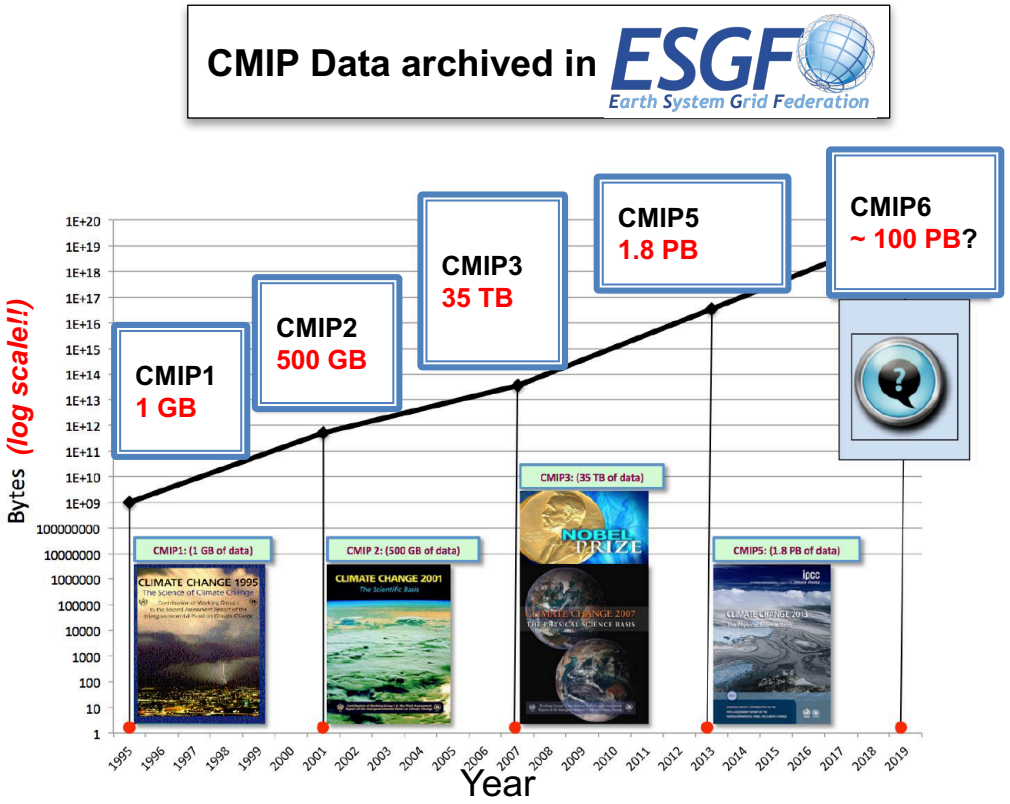
Acknowledgements to: **Kenneth Sperber, Peter Gleckler, Celine Bonfils,** and **Karl Taylor**

Objective: Routine Evaluation of Models

- **CMIP** has collected a massive volume of climate model output

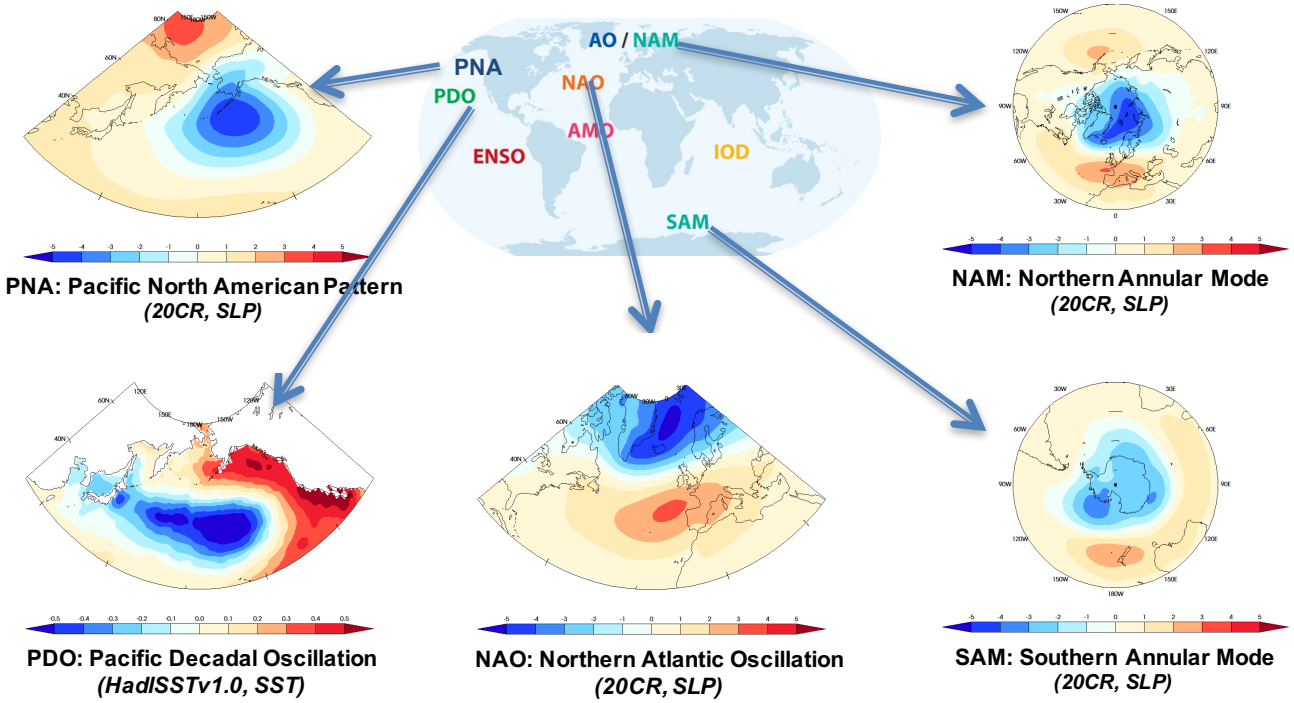
- To have a better understanding of model *uncertainties and performance*, it is important to *evaluate models routinely in a systematic and collective way*

- PCMDI/LLNL is developing a metrics package (the PMP) to more directly contribute to model development (via quick feedback)



(Williams et al. 2015, BAMS)

Background: Modes of Variability



- Generally defined by the **leading EOF mode** in observations
- Represent **long-term large-scale** variance
- Important test for diagnosing model behavior, and detection & attribution

Datasets

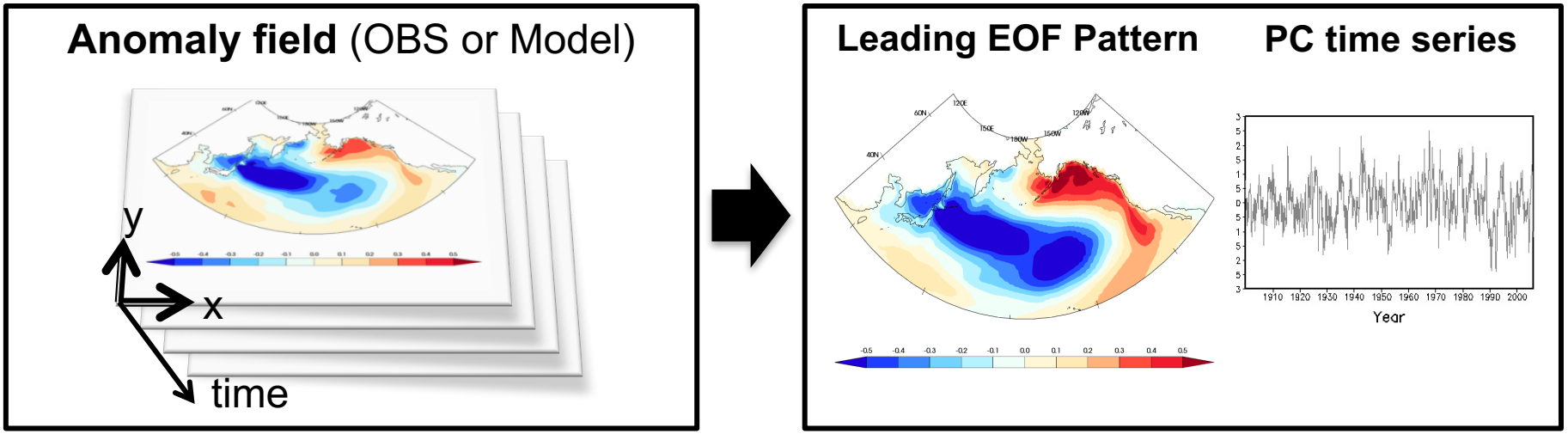
- **CMIP5 Models**
  - Models: **180 historical simulations (45 models with their realizations)**
  - Time window: 1900-2005 (except SAM: 1956-2005)
  - Variables: 1) **Sea level pressure (SLP)**: Seasonal anomalies
    2) **Sea surface temperature (SST)**: Monthly anomalies (for PDO)
  - Area-weighted average over EOF domain was removed at each time step

- **Observation based reference datasets**

	SLP	SST
OBS 1 *(default)*	NOAA CIRES 20CR	HadISST v1.1
OBS 2	ERA 20C	HadISST v2.1
OBS 3	HadSLP	ERSST v3.0

- **Tools**
  - ***PCMDI Metrics Package (PMP)***: Python based open-source tool *(Gleckler et al. 2016, EOS)*
  - ***UV-CDAT***: Python based large-scale data analysis and visualization tool *(Williams 2014, EOS)*
  - ***eofs***: Python library for EOF analysis *(Dawson 2016)*

Conventional EOF Approach



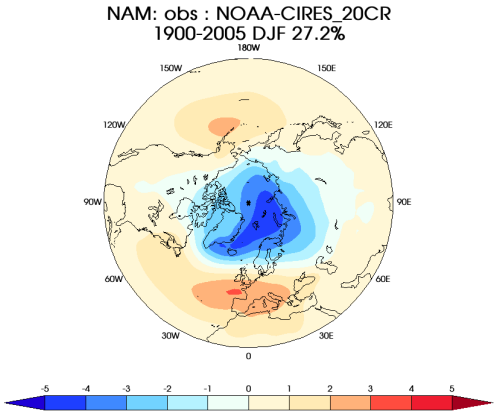
Limitations:

1. **Sign ambiguity**: EOF sign is arbitrary, sometimes it needs to be flipped
2. **EOF mode swapping**: Cases in which leading OBS EOF better corresponds to 2nd or 3rd mode of model

EOF mode swapping (1): Example

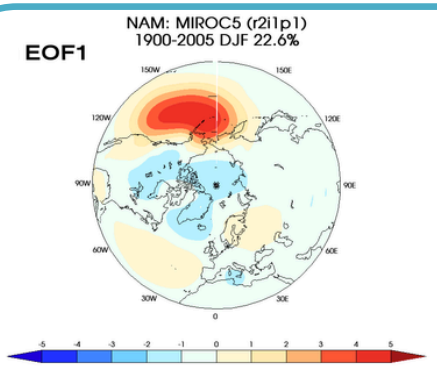
- **NAM (DJF) simulated by MIROC5 (r2i1p1)**

OBS

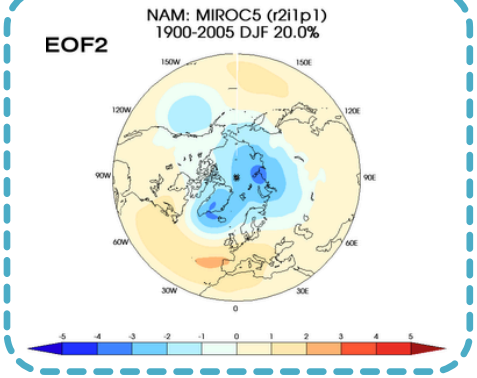


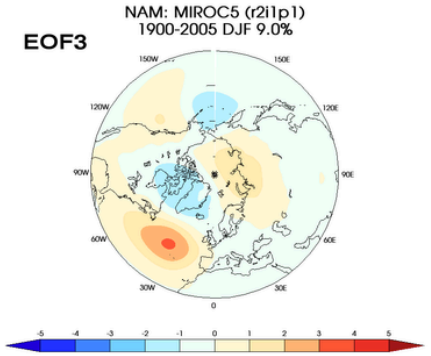
NAM: Northern Annular Mode
(20CR, SLP)

Model



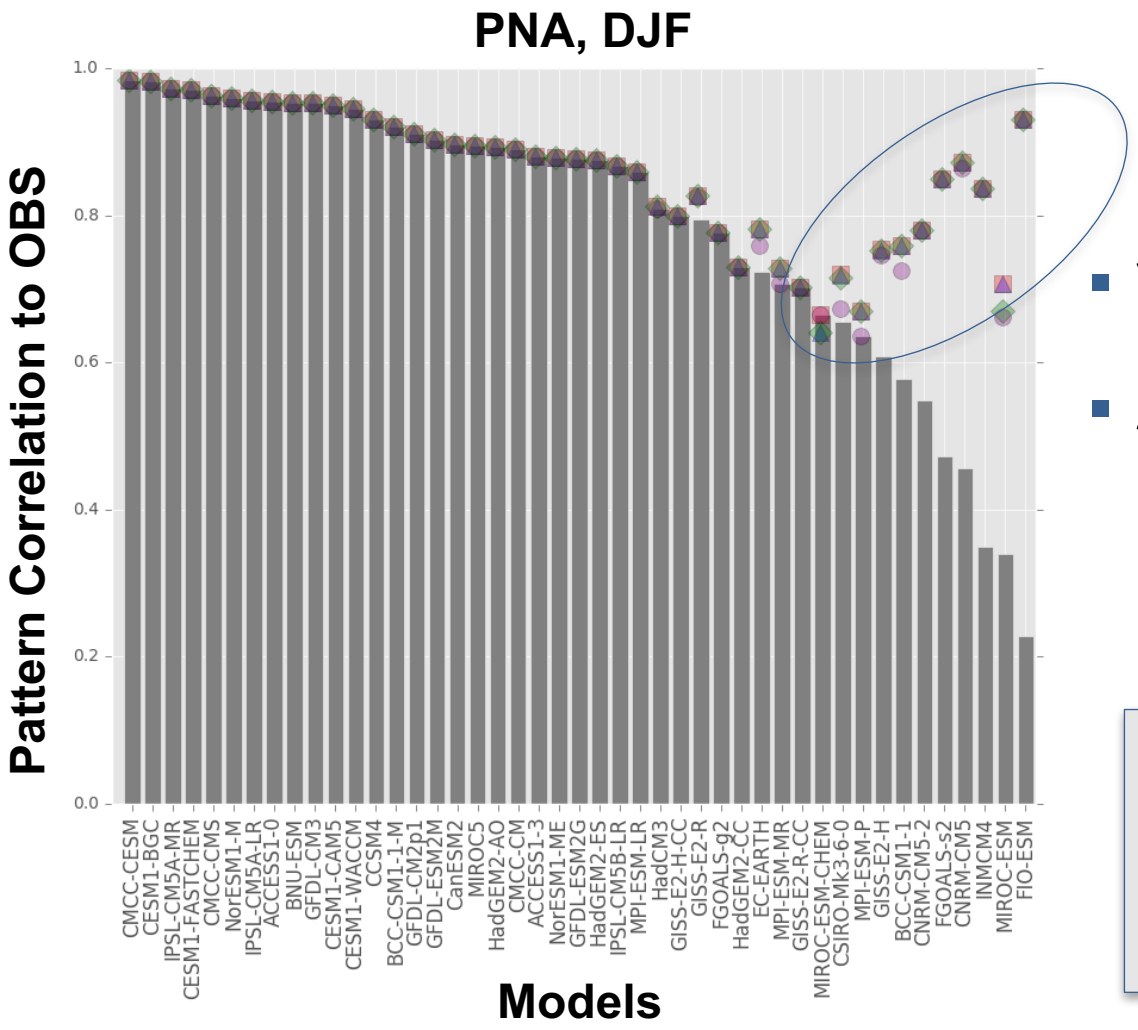
Best matching: EOF2





The leading OBS EOF corresponds best to model's 2nd EOF mode

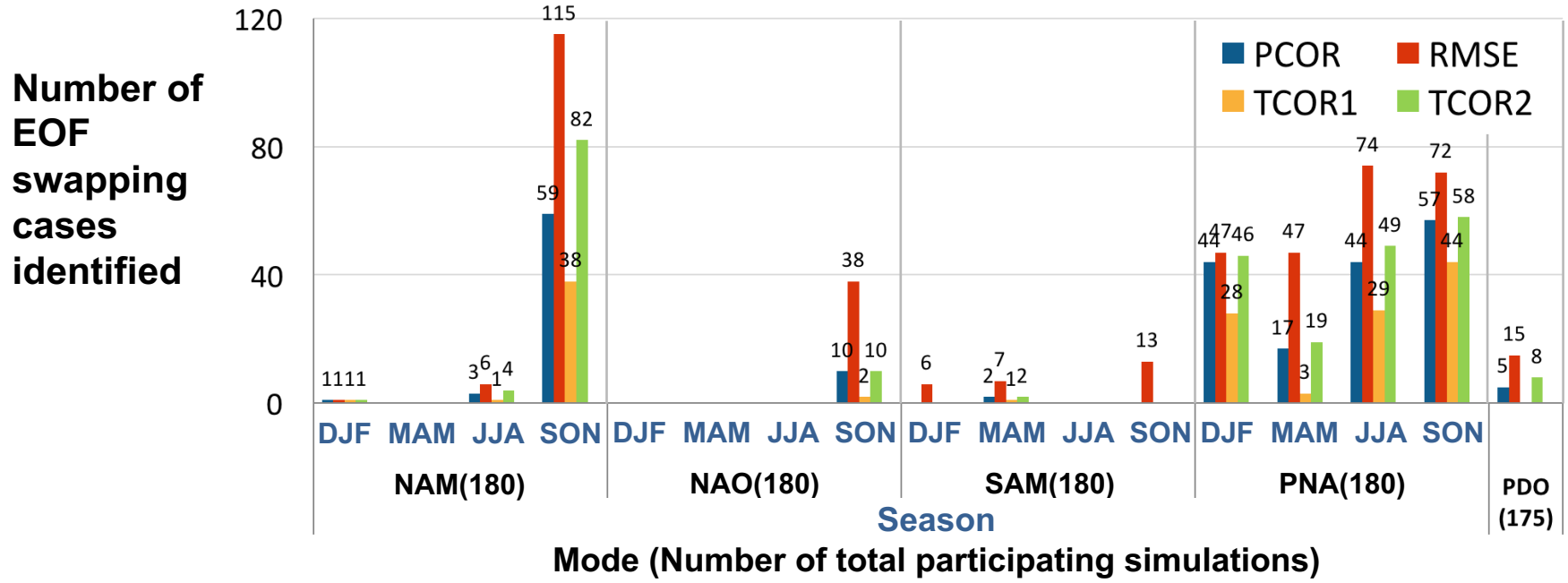
EOF mode swapping (2): Is it significant?



- Yes, it could be!
- Accounting for EOF swapping gives more fair comparison

Conventional EOF1
EOF swapped by ***PCOR***
EOF swapped by ***RMSE***
EOF swapped by ***TCOR1***
EOF swapped by ***TCOR2***

EOF mode swapping (3): How often it happen?



Applied criteria to decide best matching EOF:

Spatial:

- **PCOR**: Pattern correlation
- **RMSE**: Root mean square error

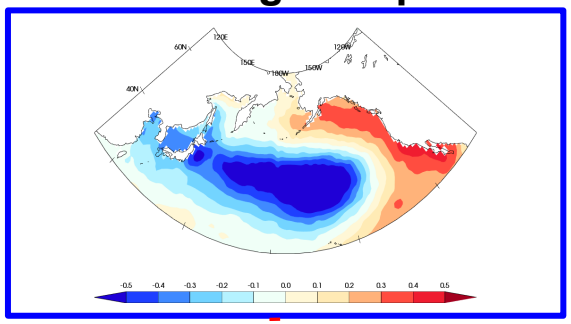
Temporal:

- **TCOR1**: CBF PC vs EOF PCs
- **TCOR2**: OBS PC vs tweaked CBF PCs

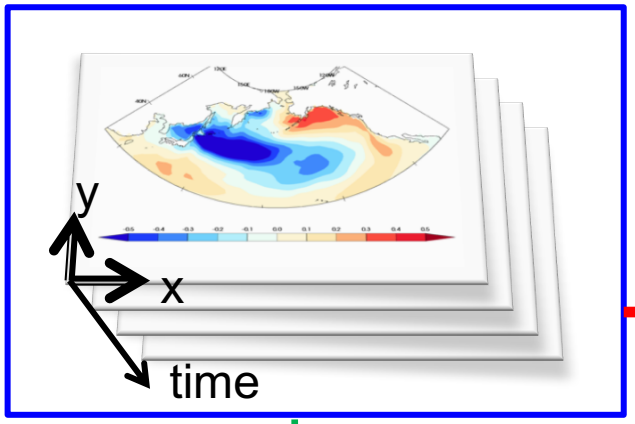
- Significant number of EOF swapping cases are identified
- There is no single best criteria

Common Basis Function (CBF) Approach

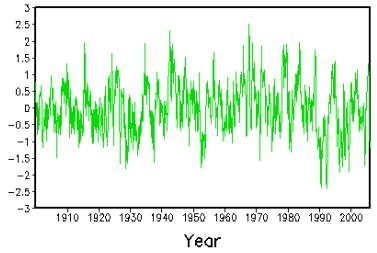
OBS leading EOF pattern



Model's anomaly field



Model's CBF PC time series

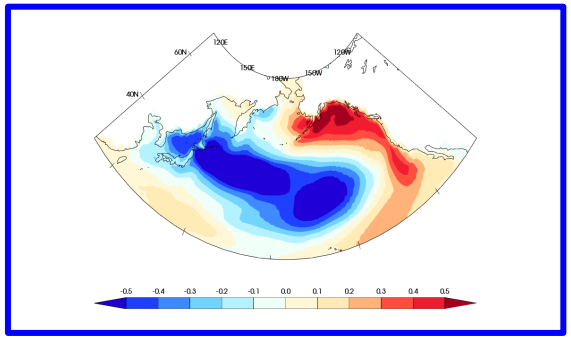


(1) Projection

Get PC time series by projecting OBS pattern into model's anomaly space

(2) Linear Regression

Model's CBF Pattern

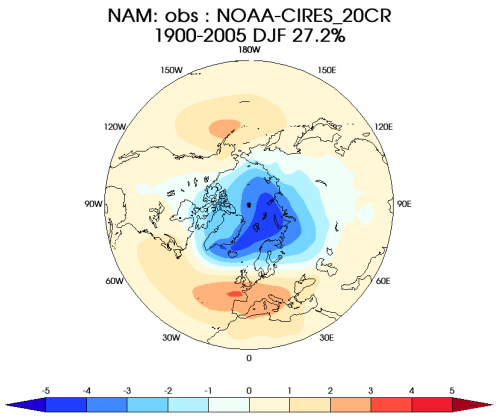


Reconstruct Pattern by linear regression between CBF PC & model field

CBF Result: Example

- **NAM (DJF) simulated by MIROC5 (r2i1p1)**

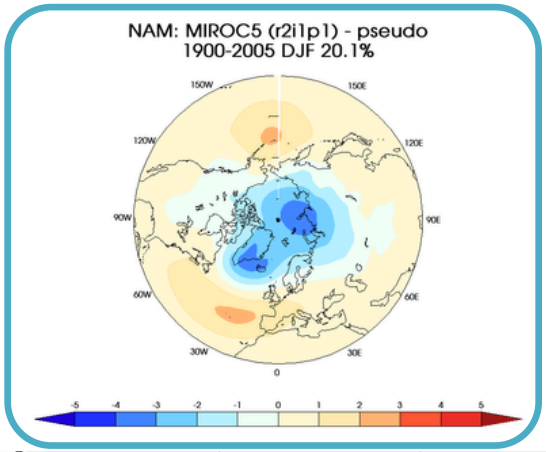
OBS



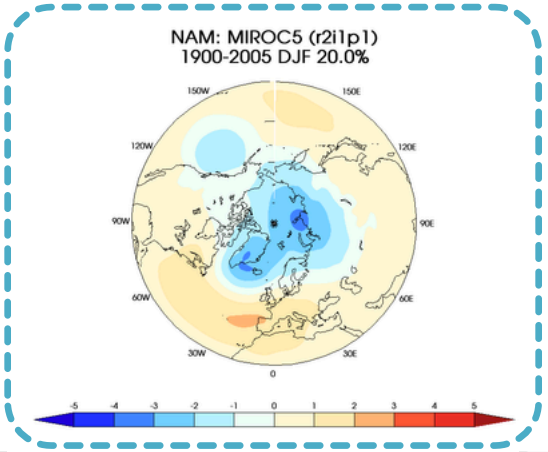
NAM: Northern Annular Mode
(20CR, SLP)

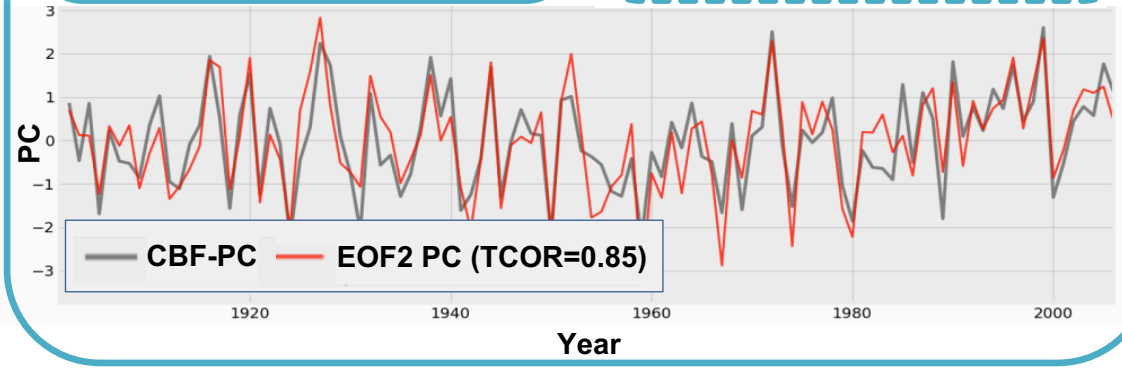
Model

CBF



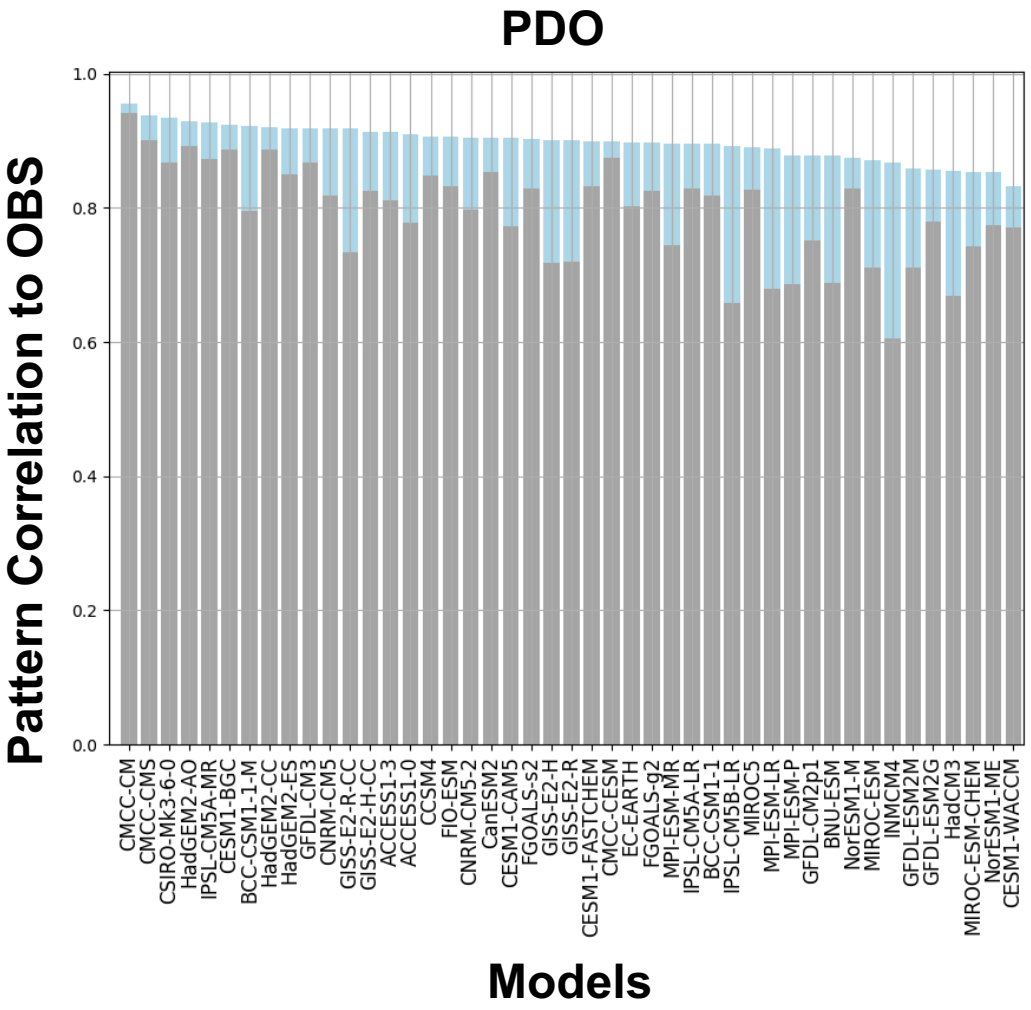
Best matching: EOF2





- CBF pattern better corresponds to OBS than the best-matching EOF mode
- CBF PC corresponds to PC of best-matching EOF mode

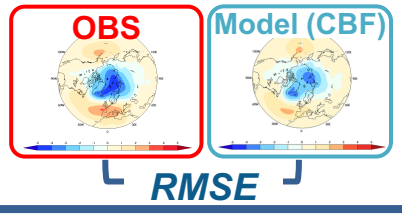
CBF vs. EOF swapping

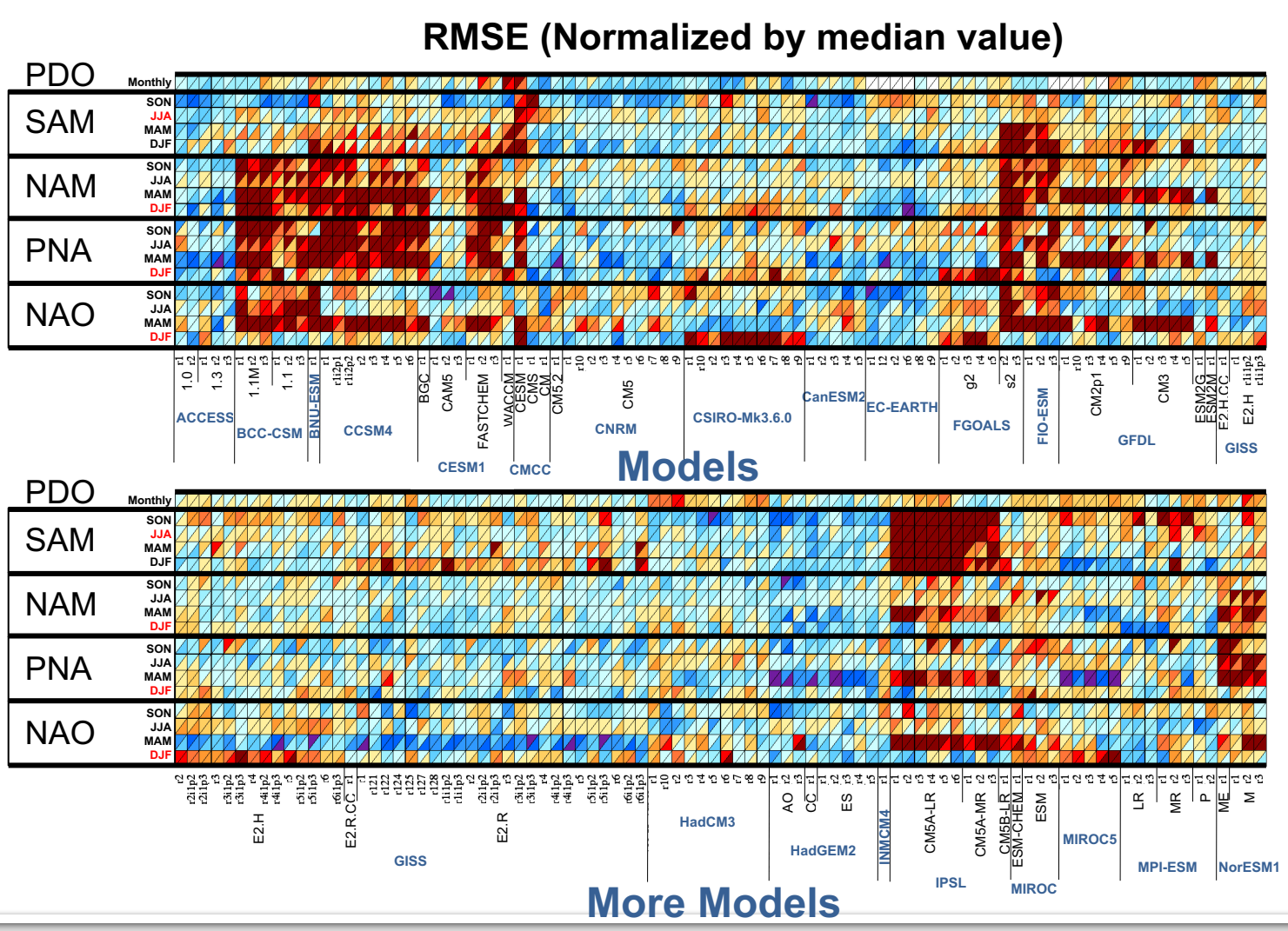


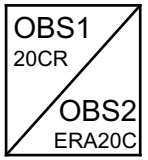
CBF
EOF swapped
Averaged across realizations

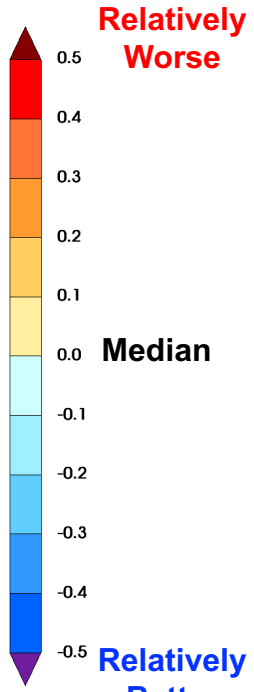
- The CBF provides a **more fair comparison with observations** than the conventional EOF
- The CBF reveals that **model skill is better** than indicated by conventional EOF analysis

Performance Diagnostics (1): Pattern + Amplitude

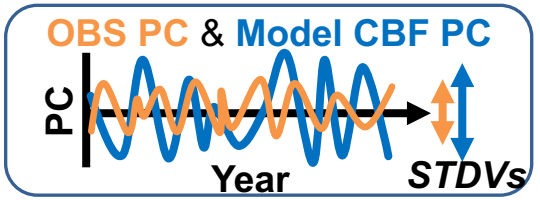




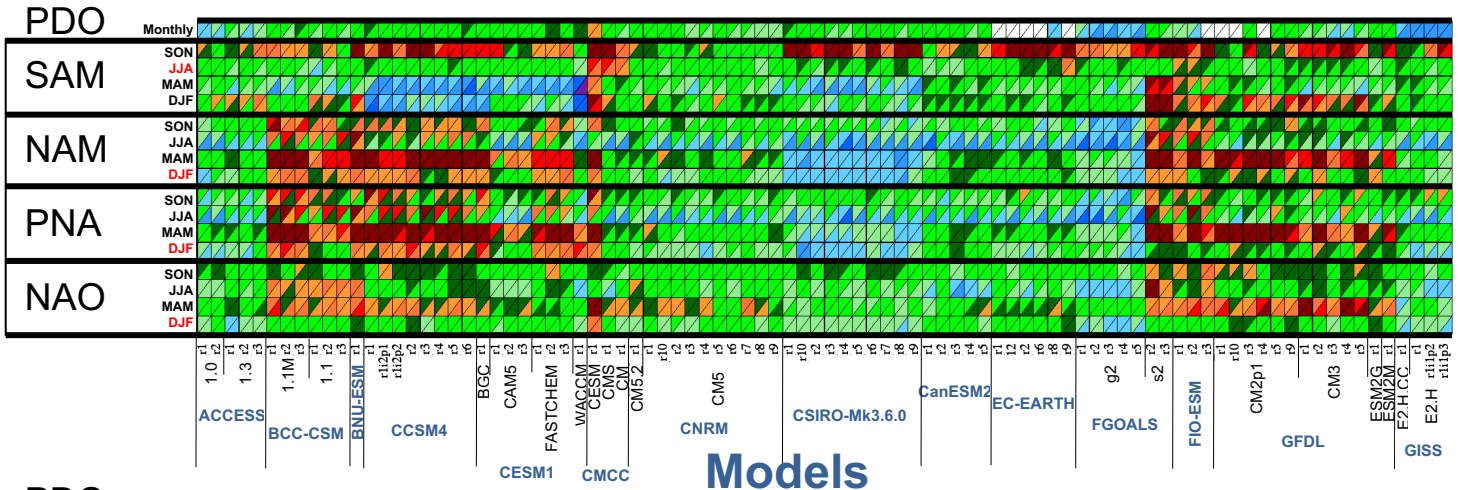


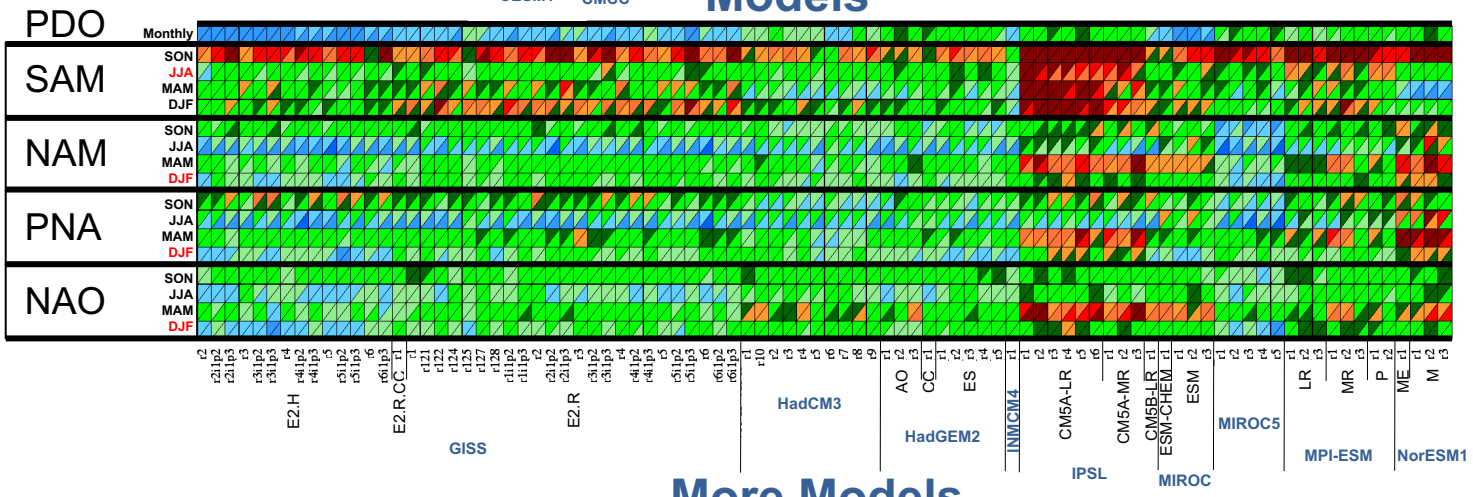


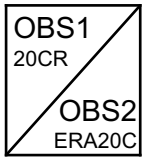
Performance Diagnostics (2): Amplitude

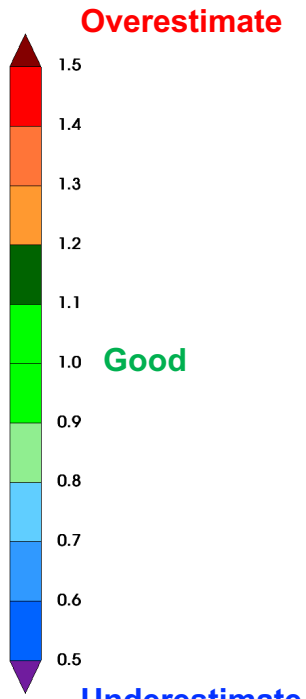


Ratio of PC STDVs: Model/OBS

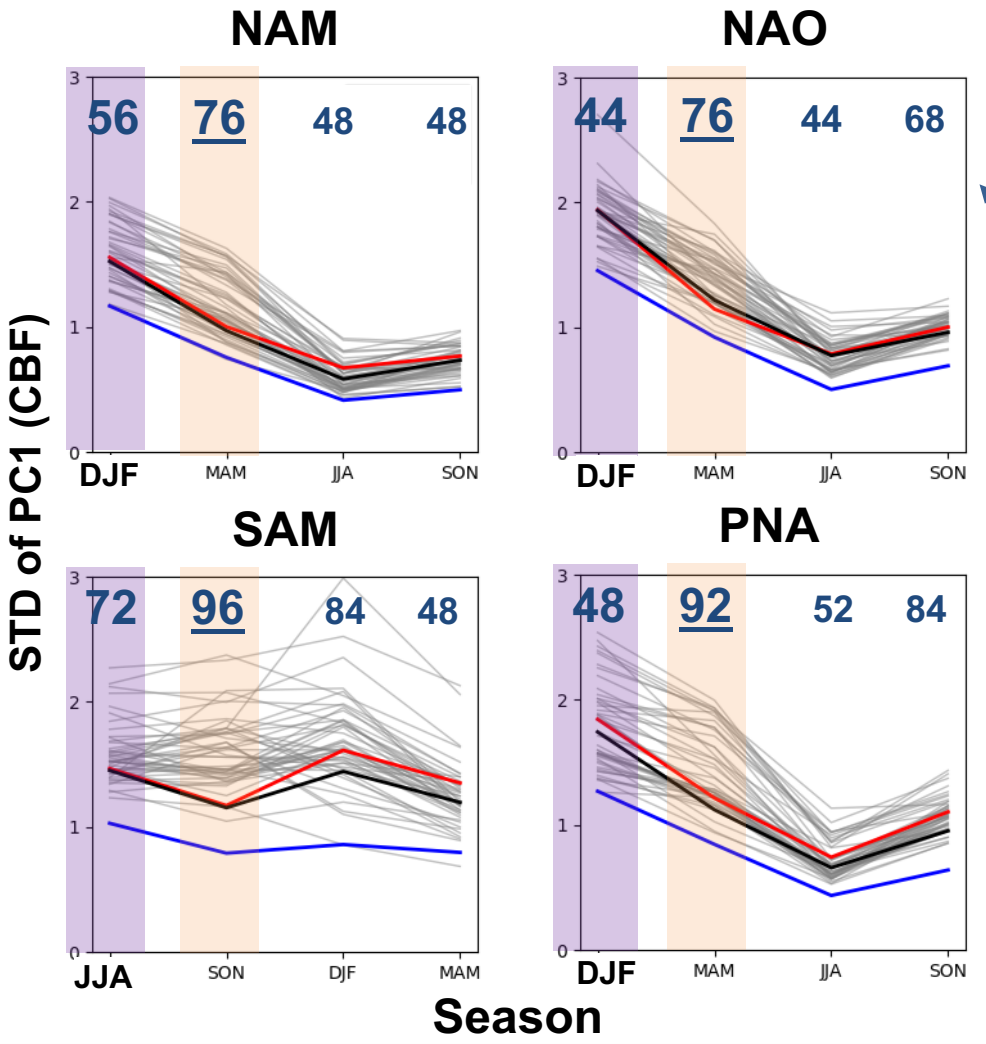








Seasonal Variation



Dominant Season *(Winter)*

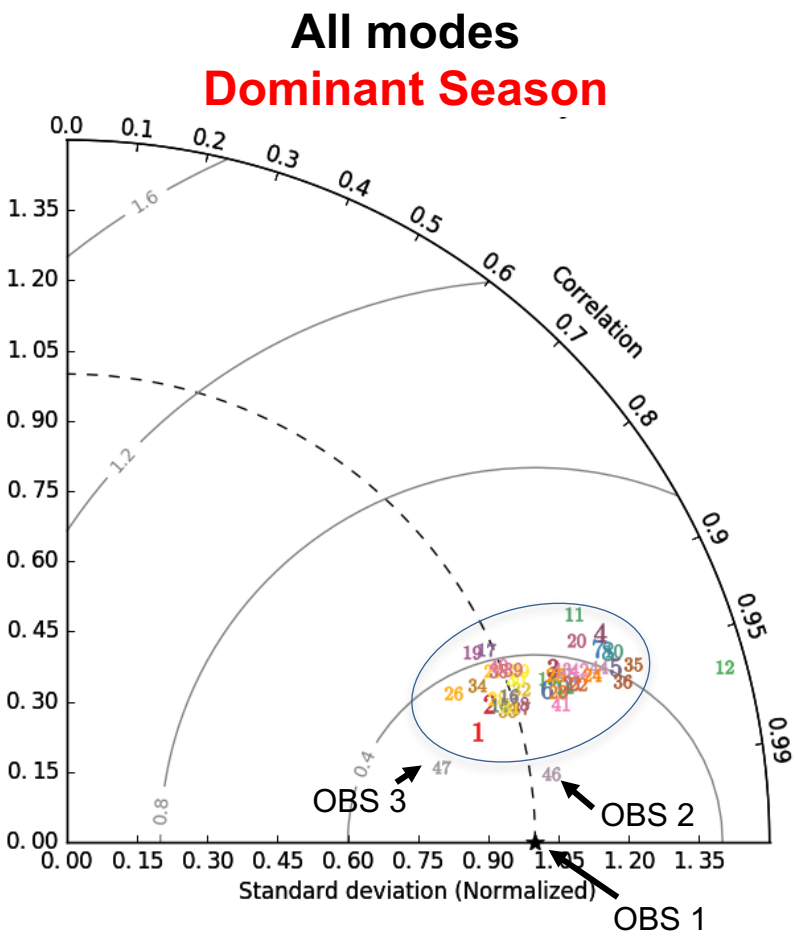
Post-dominant Season *(Spring)*

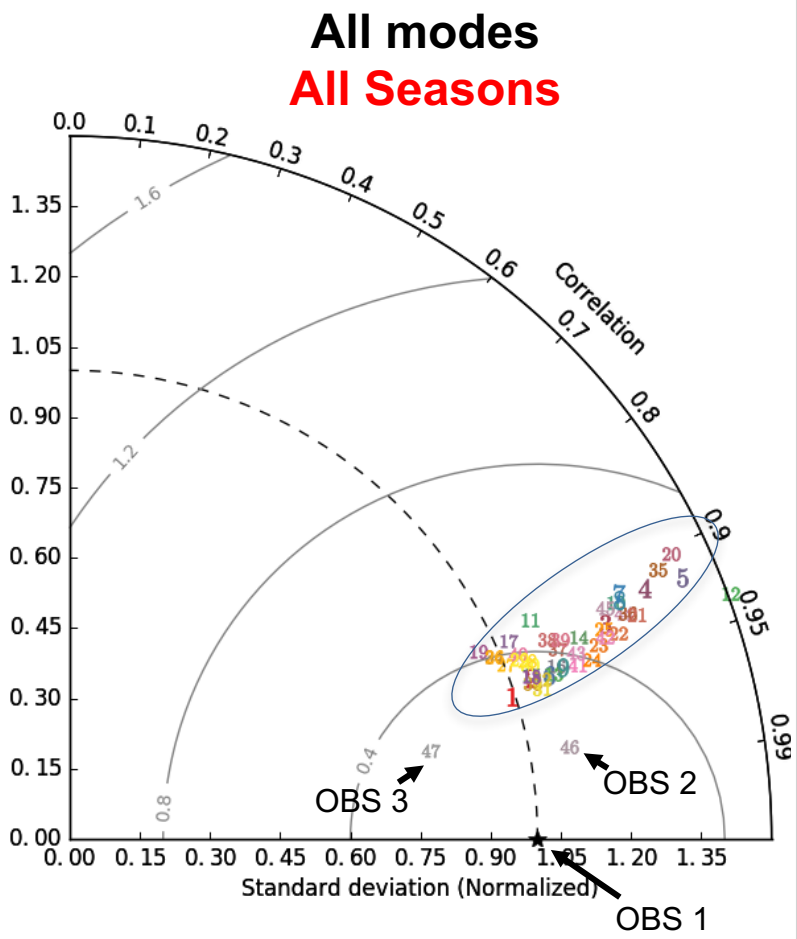
OBS1 (20CR)
OBS2 (ERA20C)
OBS3 (HadSLP2)
Models (averaged across realizations)

Percentage [%] of overestimating models

- Some models dramatically overestimate variability immediately following dominant season
- More attention is needed for evaluating the *seasonality* of these modes, not just the dominant season

Taylor Diagrams





★ OBS 1
1 ACCESS1-0
2 ACCESS1-3
3 BCC-CSM1-1
4 BCC-CSM1-1-M
5 BNU-ESM
6 CanESM2
7 CCSM4
8 CESM1-BGC
9 CESM1-CAM5
10 CESM1-FASTCHEM
11 CESM1-WACCM
12 CMCC-CESM
13 CMCC-CM
14 CMCC-CMS
15 CNRM-CM5
16 CNRM-CM5-2
17 CSIRO-Mk3-6-0
18 EC-EARTH
19 FGOALS-g2
20 FGOALS-s2
21 FIO-ESM
22 GFDL-CM2p1
23 GFDL-CM3
24 GFDL-ESM2G
25 GFDL-ESM2M
26 GISS-E2-H
27 GISS-E2-H-CC
28 GISS-E2-R
29 GISS-E2-R-CC
30 HadCM3
31 HadGEM2-AO
32 HadGEM2-CC
33 HadGEM2-ES
34 INMCM4
35 IPSL-CM5A-LR
36 IPSL-CM5A-MR
37 IPSL-CM5B-LR
38 MIROC-ESM
39 MIROC-ESM-CHEM
40 MIROC5
41 MPI-ESM-LR
42 MPI-ESM-MR
43 MPI-ESM-P
44 NorESM1-M
45 NorESM1-ME
46 OBS 2
47 OBS 3

Post-dominant season (Spring) is the major contributor to the overestimation

Summary

Further detail:
J. Lee, K. R. Sperber, P. J. Gleckler, C. W. Bonfils, and K. E. Taylor (2017) Quantifying the Agreement Between Observed and Simulated Extratropical Modes of Interannual Variability. Climate Dynamics (in review)

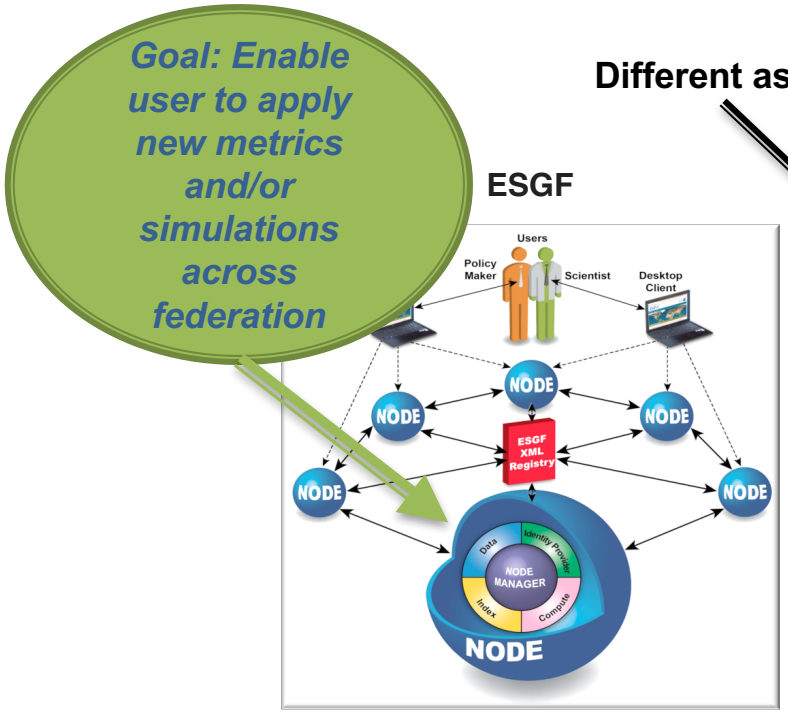
- We have developed **evaluation metrics** for extra-tropical **modes of variability** using **CBF approach** – *projecting model anomalies onto the observational leading EOF*
- The CBF method leads to a more **consistent** approach for evaluation, overcoming limitations of conventional EOF
- The **amplitude error** is the dominant contributor to systematic error in many models
- Models generally agree **better in the dominant season** of each mode, while many models systematically **overestimate** the variability in **post-dominant season**
  ➔ ***More attention needs to be devoted to evaluating the seasonality of modes***

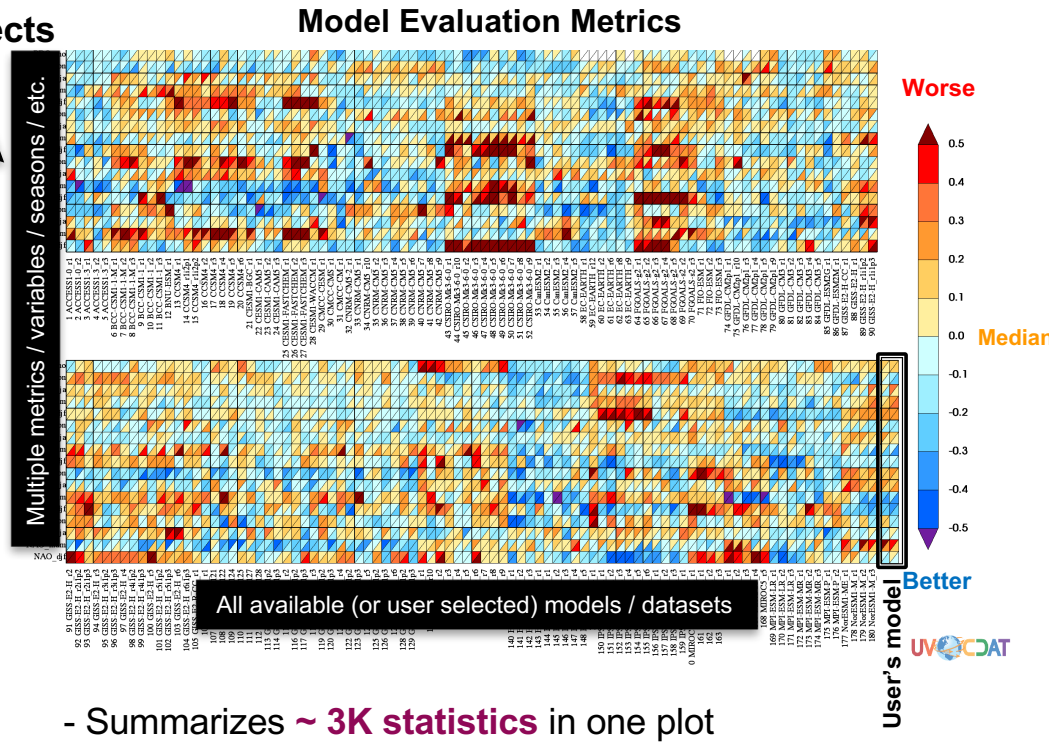
Further Works

(only 3 slides left!)

On-going further works (1): *Server-side analysis*

- Server-side calculation of metrics



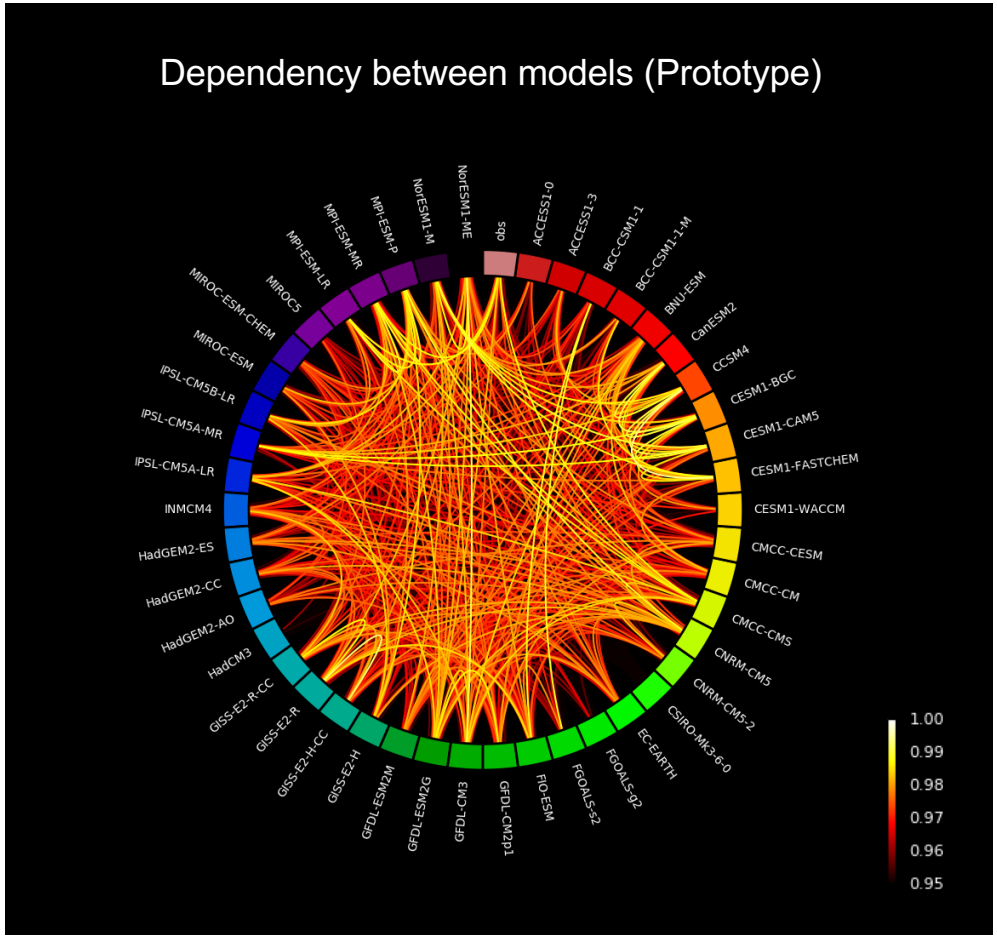


- Summarizes **~ 3K statistics** in one plot

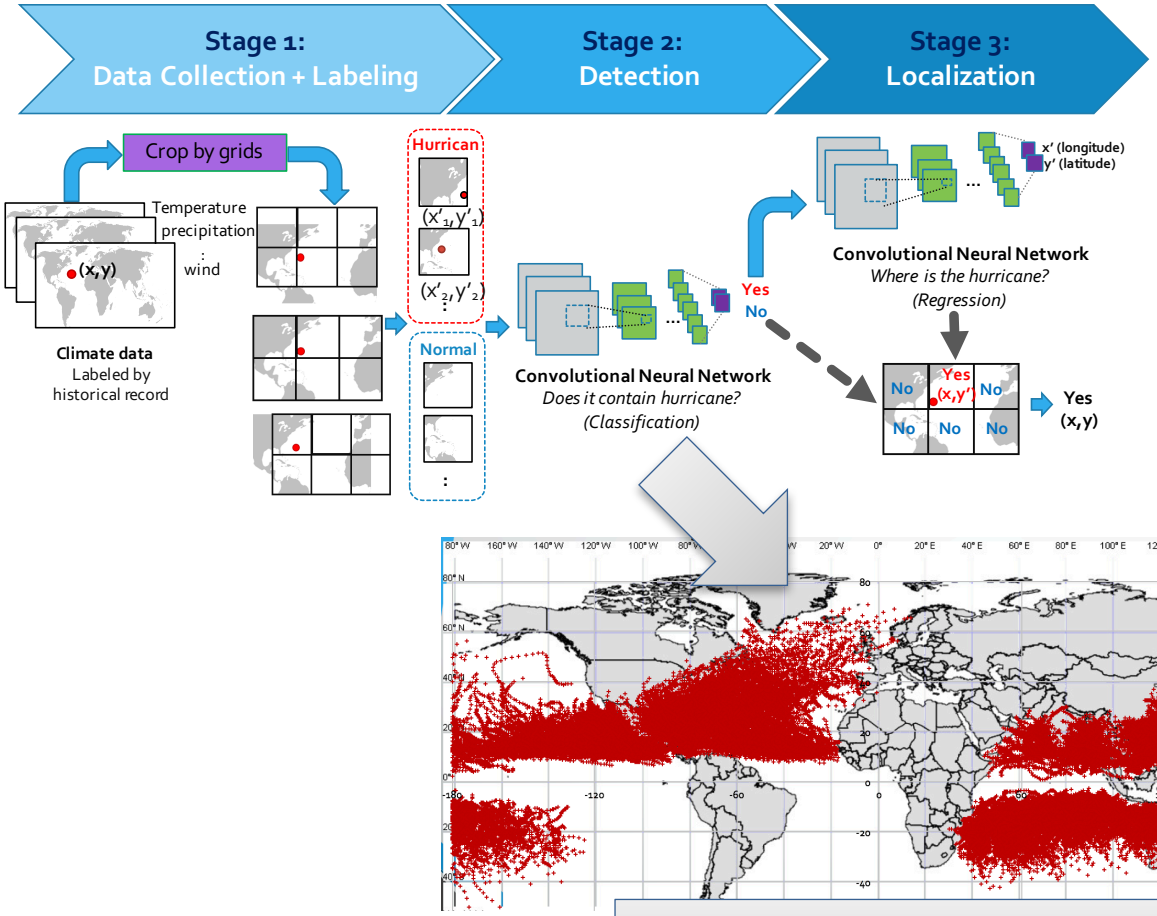
On-going further works (2): *Big-data visualization*

Developing alternative way of big-data visualization:

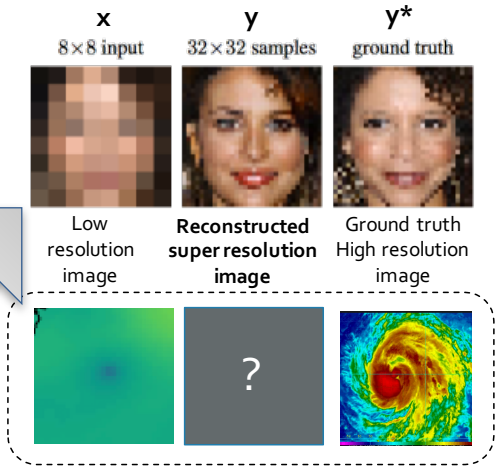
- Example plot enables identifying dependency between models
- Originally designed for bio-medical applications to identify connectivity between genes or cells
- Summarizes relationship between **more than 30K statistics** in one plot
- Open doors to ***Climate model genealogy***



On-going further works (3): *Machine Learning*



Dahl, Ryan, Mohammad Norouzi, and Jonathon Shlens. "Pixel recursive super resolution." *arXiv preprint arXiv:1702.00783* (2017)



Courtesy of Dr. Soo Kyung Kim

Further detail:
S. K. Kim, S. Ames, **J. Lee**, C. Zhang, A. C. Wilson, D. Williams (2017) Massive Scale Deep Learning For Detecting Extreme Climate Events. *Climatic Informatics* (in review)

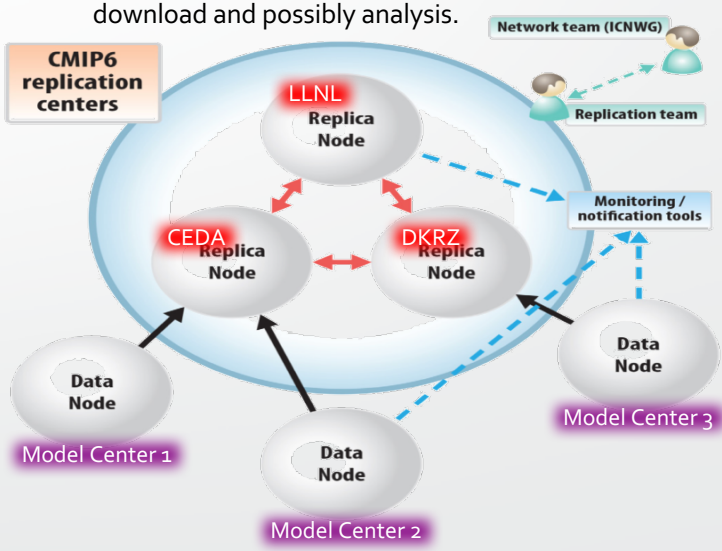
Thank you, Questions?

Extra Back-up Slides

ESGF Tier 1 and Tier 2 node site requirements for CMIP6

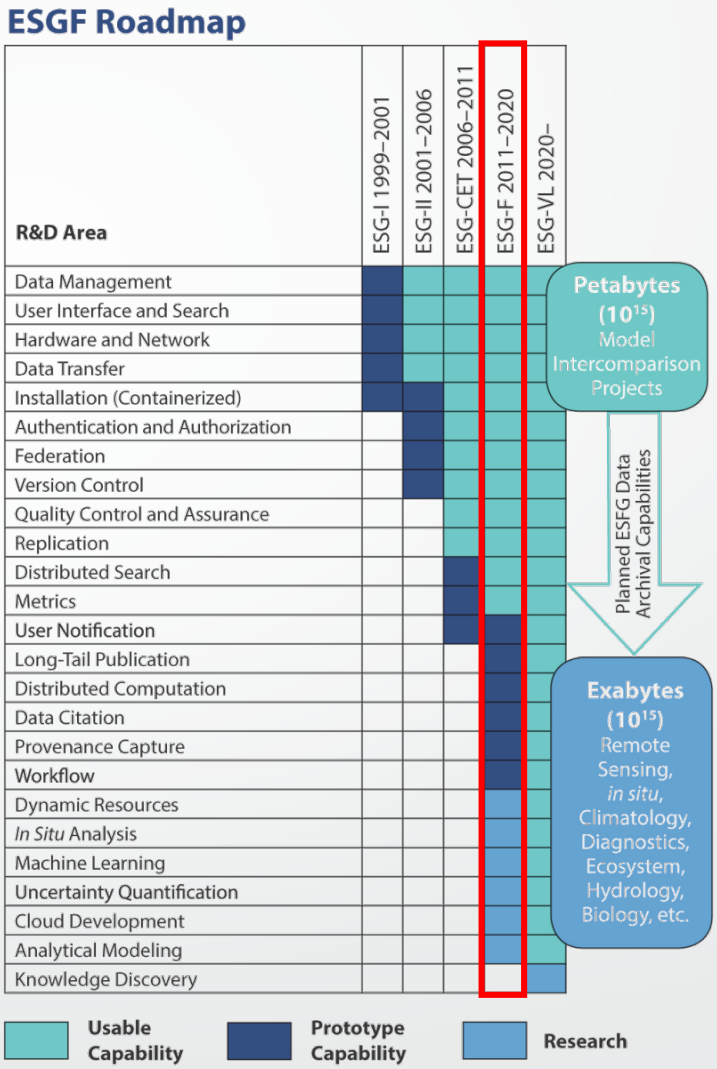
- **Tier 1 sites requirements**
  - Tier 1 sites are expected to **run the full suite of ESGF services** for data and user management, which can be used to support their own activities and those of Tier 2 sites
  - Have an **uptime (>98%)**
  - Have **10 petabytes of spinning disk** storage space
  - Have at least a **10 gigabits per second connection** to their wide-area network provider with plans to upgrade beyond 10Gbps by 2017
  - Run a 10 gigabits per second **perfSONAR host** (preferably on a physical server),
  - Deploy at least four 10 gigabits per second **Data Transfer Nodes (DTNs)** in a "Science DMZ" environment with plans to run production ESGF data services on the DTNs by 2017
  - Deploy sufficient high-performance storage to allow the DTNs to effectively serve CMIP6 data at high performance levels
  - Publish data **using GridFTP and Globus URLs** in addition to wget URLs,
  - Configure the DTNs to use Globus as well as GridFTP and wget, and
  - Use **Synda for data replication** between Tier 1 sites.
  - **Core monitoring services**
    - Unnoticed downtime by system administrator should not happen
    - Certificates end of validity monitoring
  - Quality of Service (TBD)

- **Tier 2 sites requirements**
  - Centers that typically have fewer physical or staff resources available for ESGF interactions but that still need to distribute a certain (possibly significant) amount of data to the scientific community.
  - Tier 2 sites are **encouraged to leverage some of the services supported by Tier 1 sites,** such as a Metadata Index and Identity Provider, and focus instead on supporting local services for data download and possibly analysis.

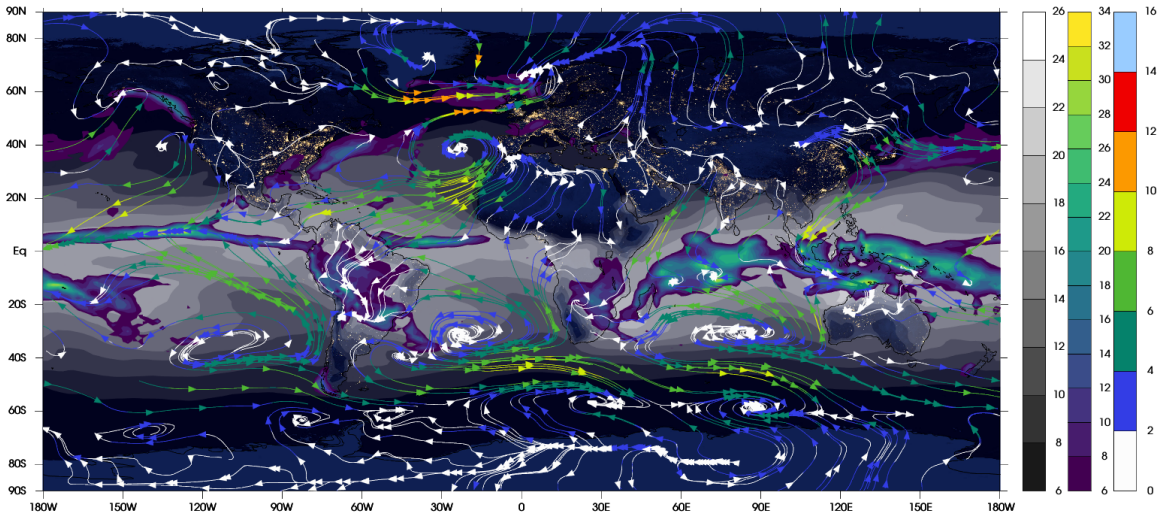


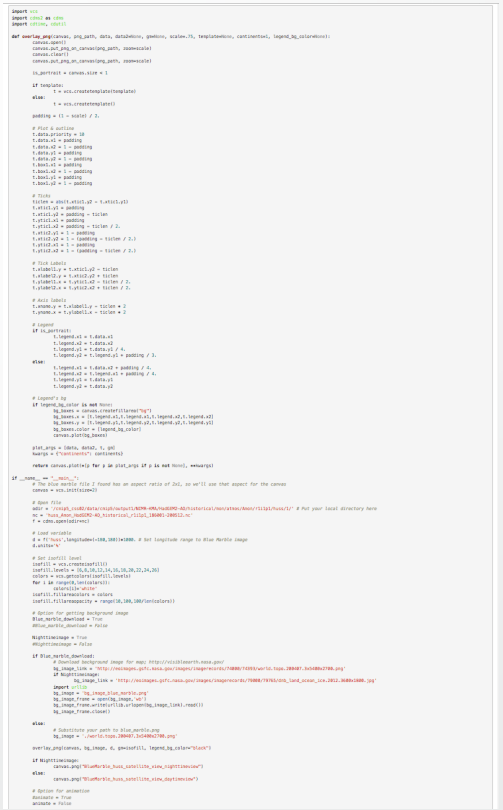
Future work on the horizon

- **Dynamic resources:** Manage and enhance user accessibility.
- ***In situ* analysis:** Enable users to obtain real-time computational results by performing calculations at the site where data resides.
- **Machine learning:** Find patterns and features in exabyte-scale data, providing users with new insights based on the vast wealth of available data.
- **Uncertainty quantification:** Connect uncertainty in underlying data with the reliability of conclusions.
- **Cloud development:** Enable easy setup of ESGF nodes and services on the cloud, either for permanent management or for transitional computational tasks.
- **Analytical Modeling:** Gauge how long calculations will take on various platforms, so that users can optimize their use of worldwide computational resources.



CDAT: analysis examples (2)





Users can have self-describing Python source code and easily apply it to their analysis

Previous studies

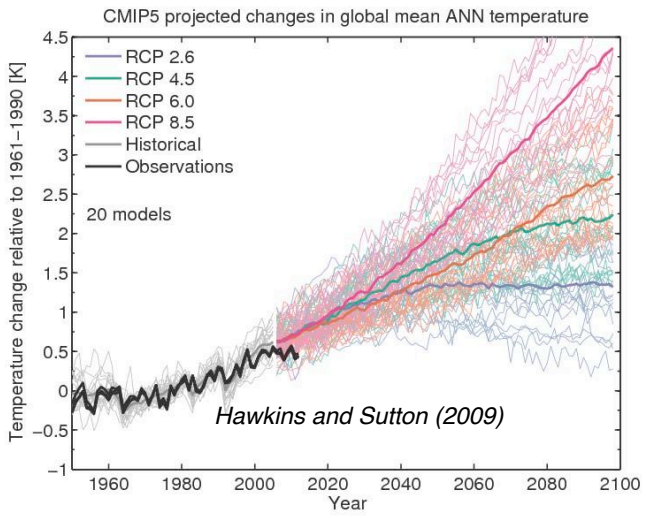
- **The majority of previous studies have focused on one or two modes of variability**

- **A few studies have conducted systematic evaluation for a variety of modes, e.g.:**
  - *Stoner et al. (2009)* focused on the CMIP3 simulations
  - *Phillips et al. (2014)* has developed diagnostic package (NCAR CVDP) and released a repository for evaluating simulated modes in CMIP5

- **We expand these studies to develop *metrics* with an emphasis on how to:**
  - Objectively compare the models with observations, including seasonality
  - Test the skill sensitivity to: 1) multiple realizations from individual models
    2) choice of observations
    3) methodological consideration
  - Ascertain the role of pattern error versus amplitude error in assessing the fidelity of the simulations using ***skill metrics***

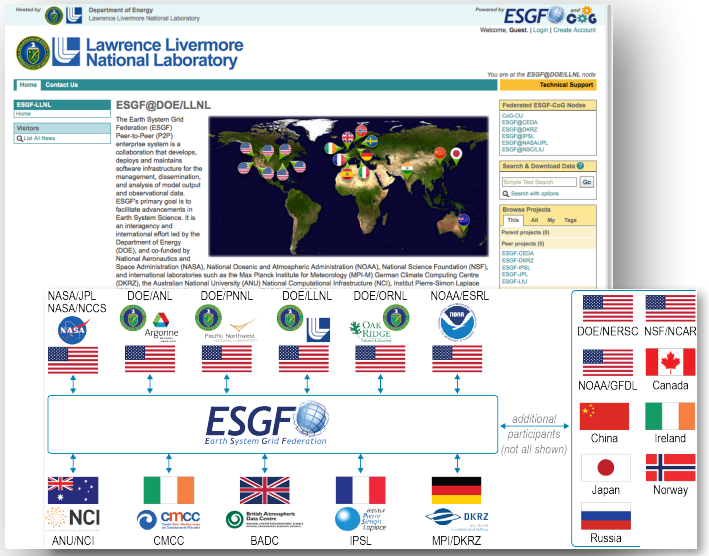
Climate Research as Community Effort: CMIP and ESGF

Coupled Model Intercomparison Project (CMIP)



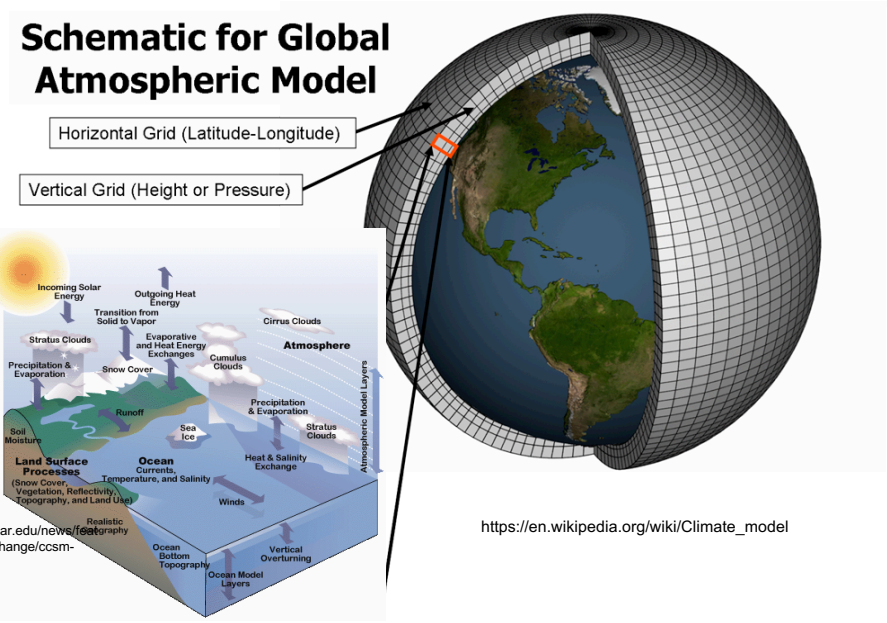
Future projections simulated by CMIP participating models

ESGF



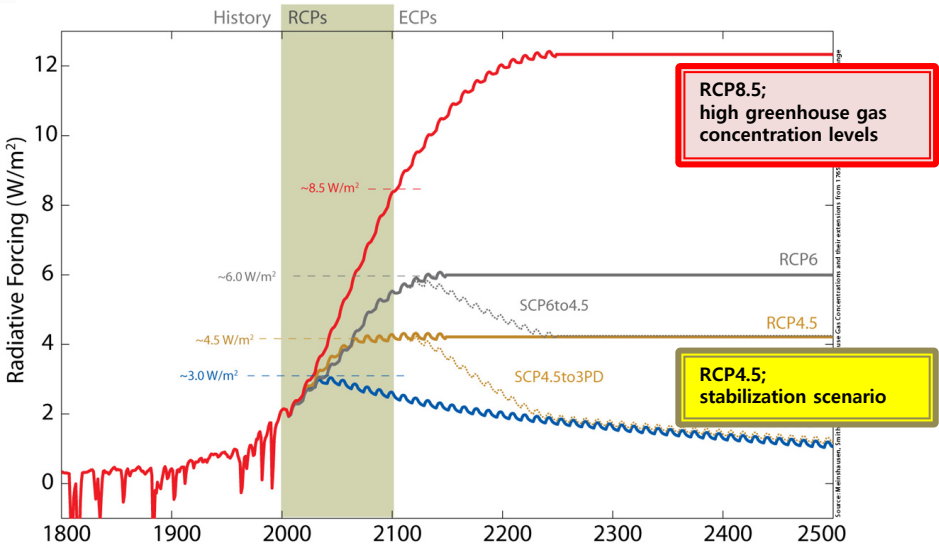
ESGF data nodes and its web access

Modeling Climate Under Future Possible Change Scenarios



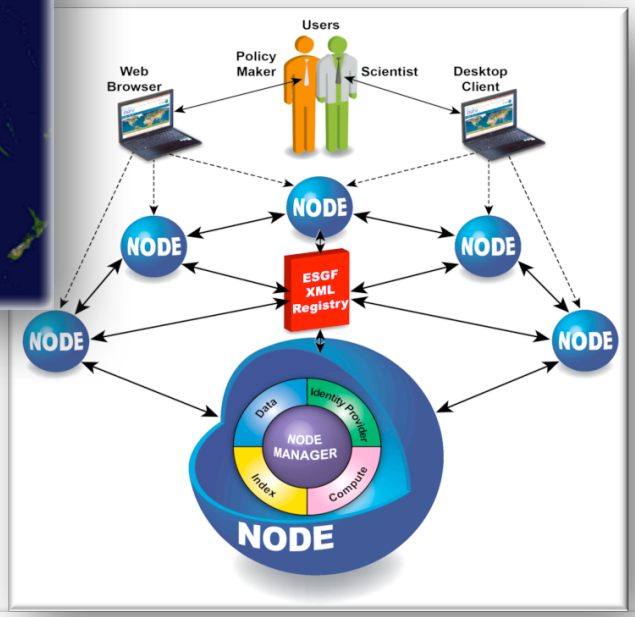
http://www.ucar.edu/news/features/climatechange/ccsm-text.jsp

https://en.wikipedia.org/wiki/Climate_model



(Meinshausen et al. 2011)

World-wide Climate Data Archive



+ Data standardization, which open door to

Climate Model Inter-comparison

Modes of variability: NAO

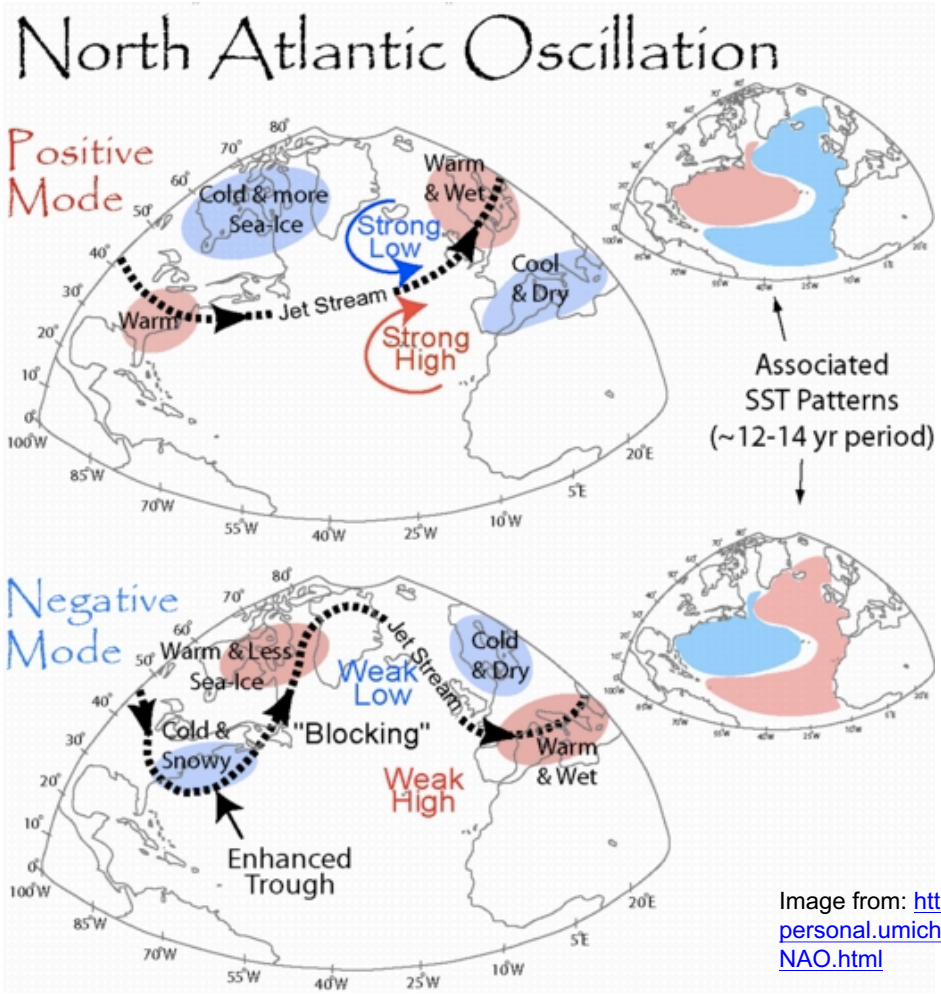
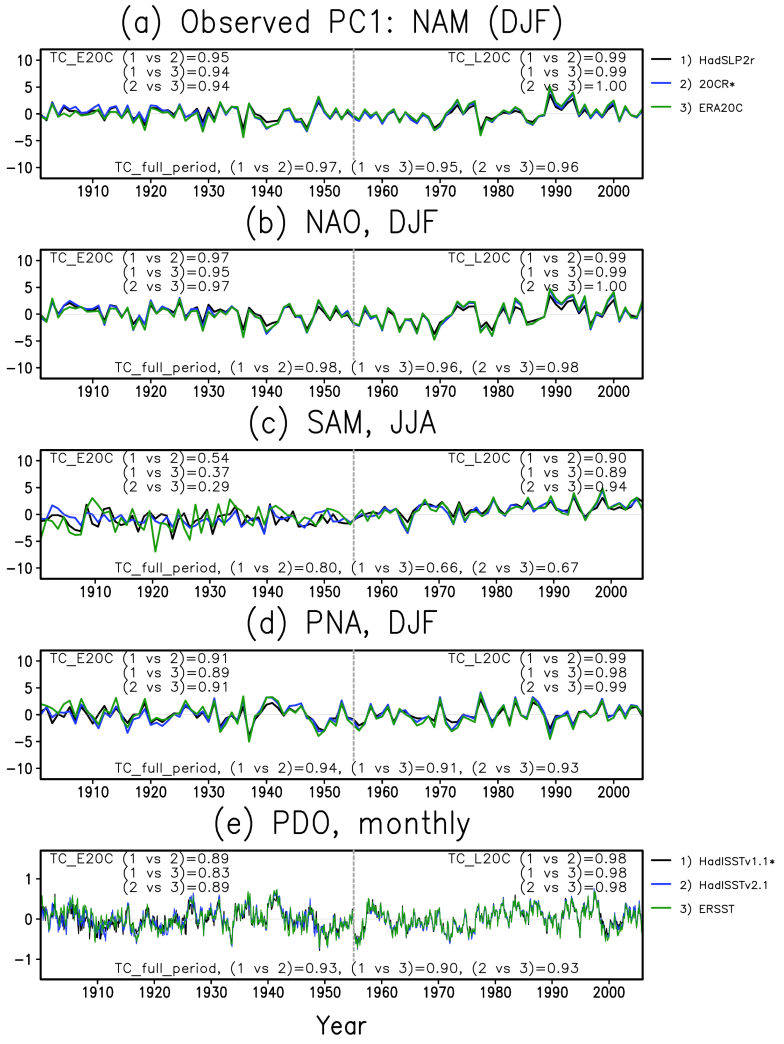
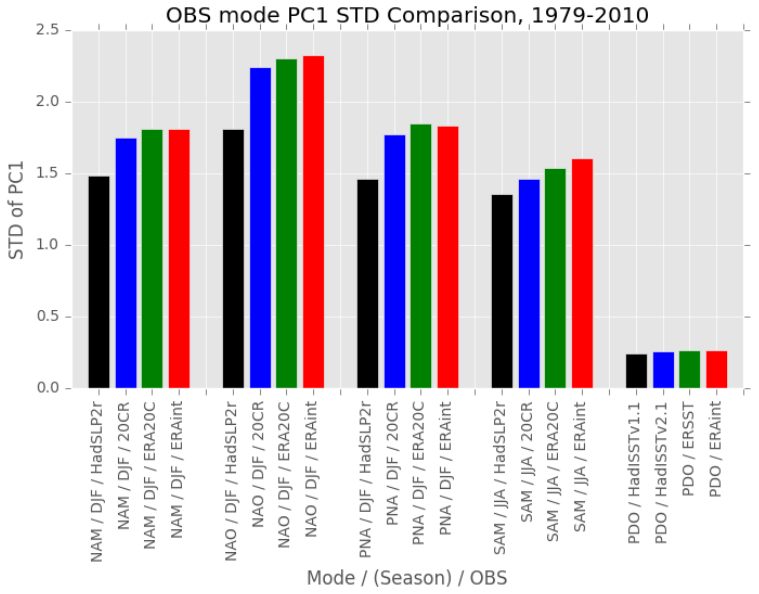


Image from: http://www-personal.umich.edu/~auraell/precipitation/pages/NAO.html

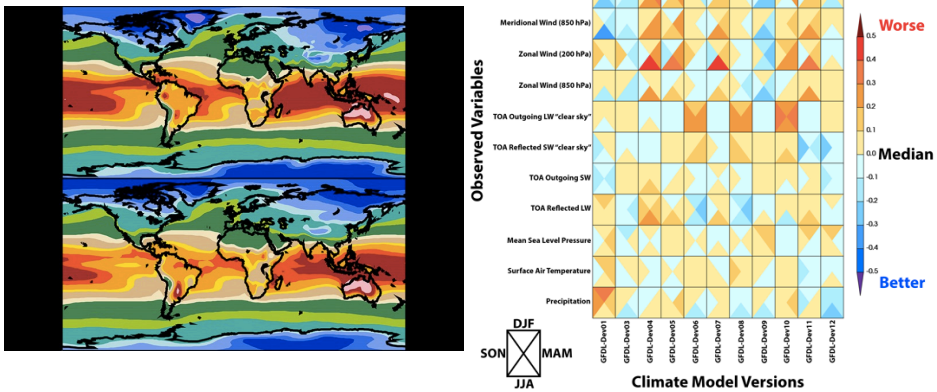
Observation





Software Development

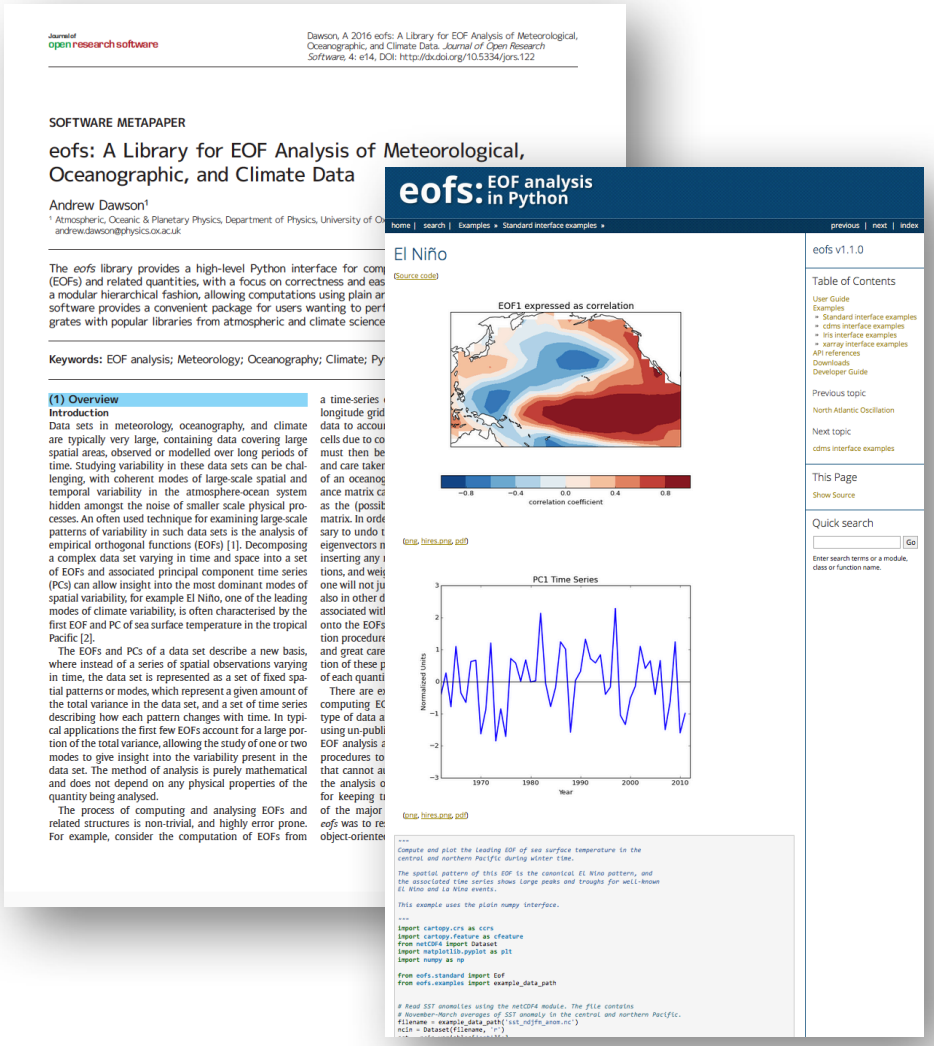
- **Python** (free of H/W System dependency)
- **Built over:**
  - **PCMDI Metrics Package (PMP)**
  - **UV-CDAT**
  - **EOFs** (Dawson 2016)
- **Open source (Github)**
- **Reusable code**
  - user friendly designed
  - self-describing documentation



Gleckler, P. J., C. Doutriaux, P. J. Durack, K. E. Taylor, Y. Zhang, D. N. Williams, E. Mason, and J. Servonnat (2016), A more powerful reality test for climate models, Eos, 97, doi:10.1029/2016EO051663. Published on 3 May 2016.

Python EOFs Library

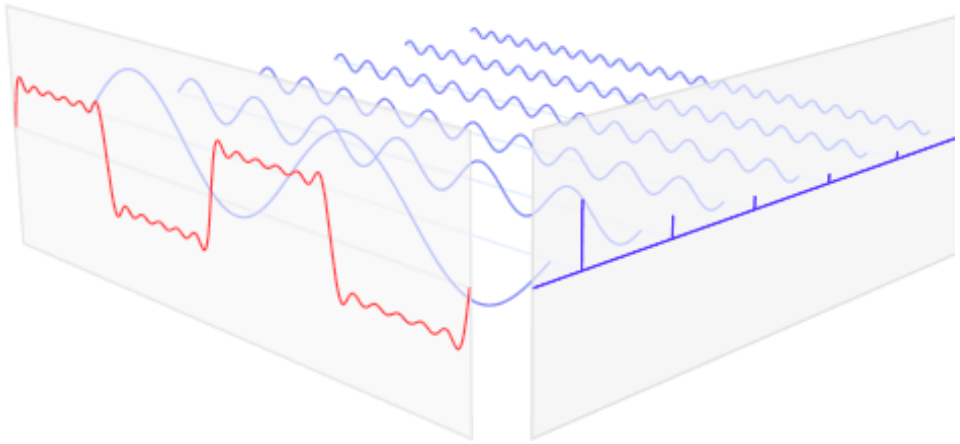
- High-level interface for computing empirical orthogonal functions (EOFs) and related quantities



Dawson, A., (2016). eofs: A Library for EOF Analysis of Meteorological, Oceanographic, and Climate Data. Journal of Open Research Software. 4(1), p.e14. DOI: http://doi.org/10.5334/jors.122

Empirical Orthogonal Function (EOF) analysis

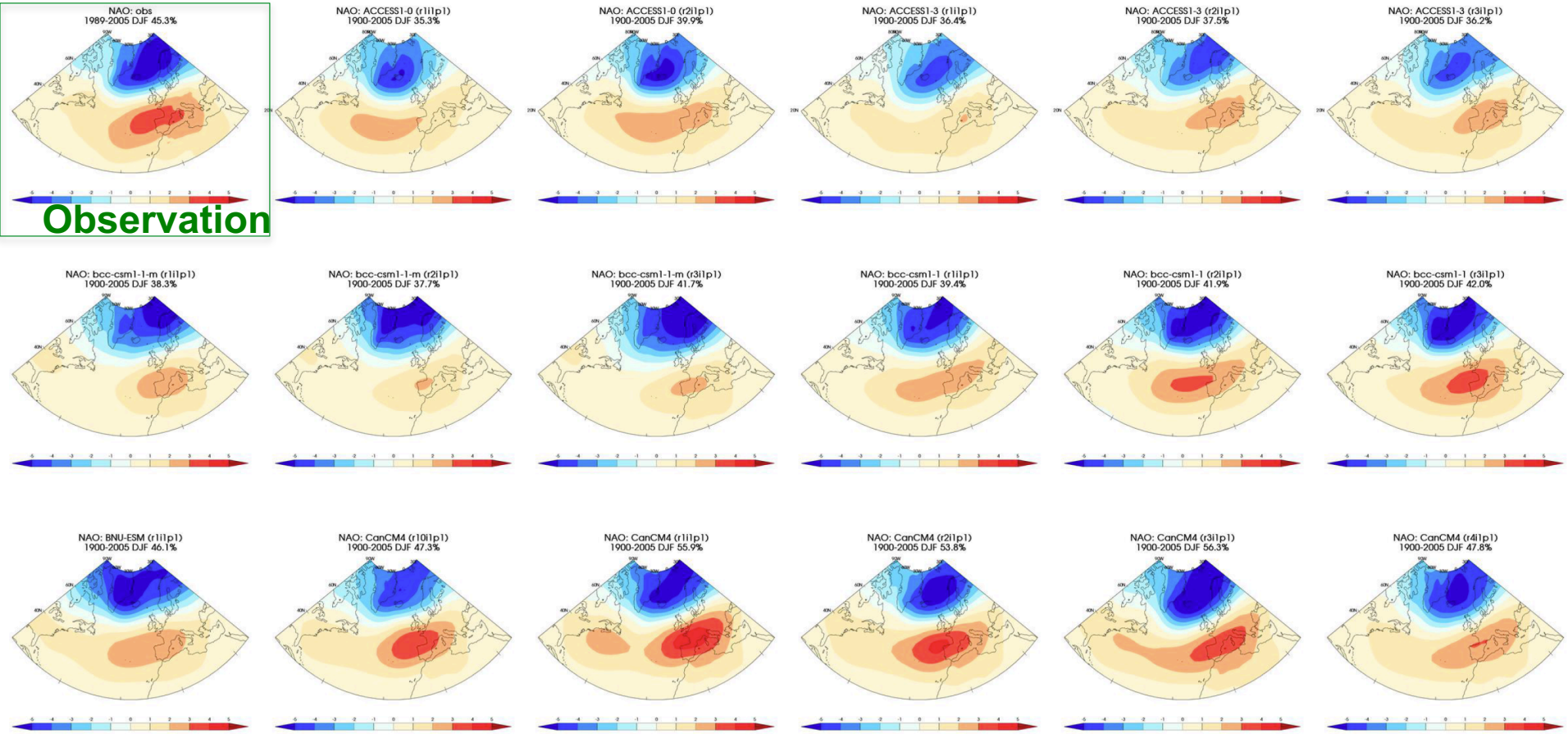
- **Fourier Transform:**



http://tex.stackexchange.com/questions/127375/replicate-the-fourier-transform-time-frequency-domains-correspondence-illustrati

- **EOF:**
  - **Similar concept to FT, but separates modes based on orthogonality**
  - **It is more useful when time series has “jumps” in it**

Loop through all CMIP5 simulations.. (e.g. NAO)



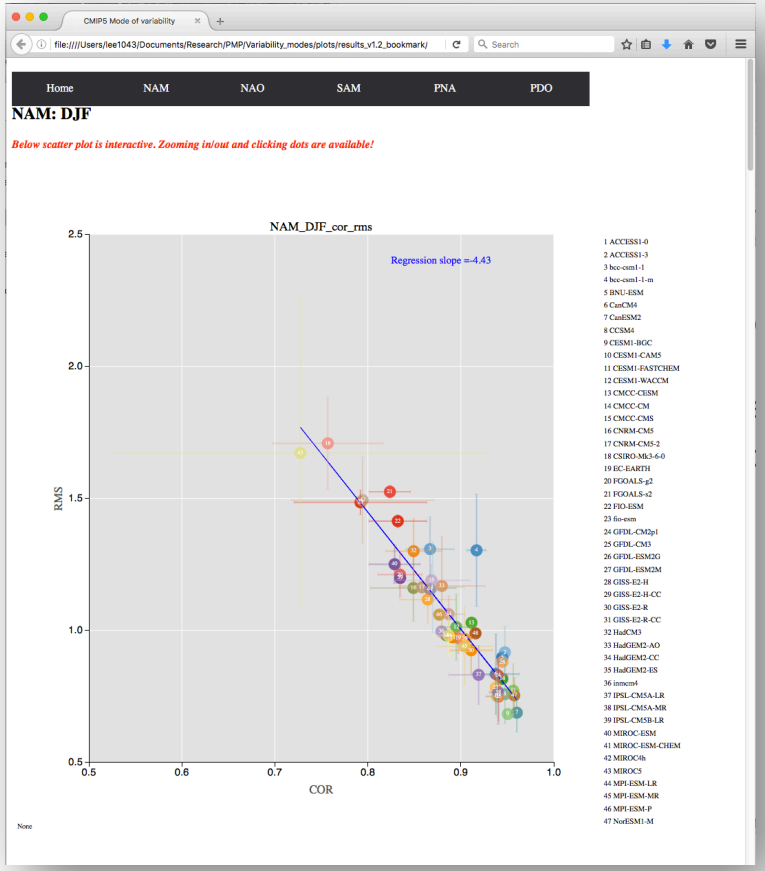
5 modes, 4 seasons, about 45 models with all available realizations (1~25 per model), various type of plots;
≈ 13,000 images at the end…

Database Construction

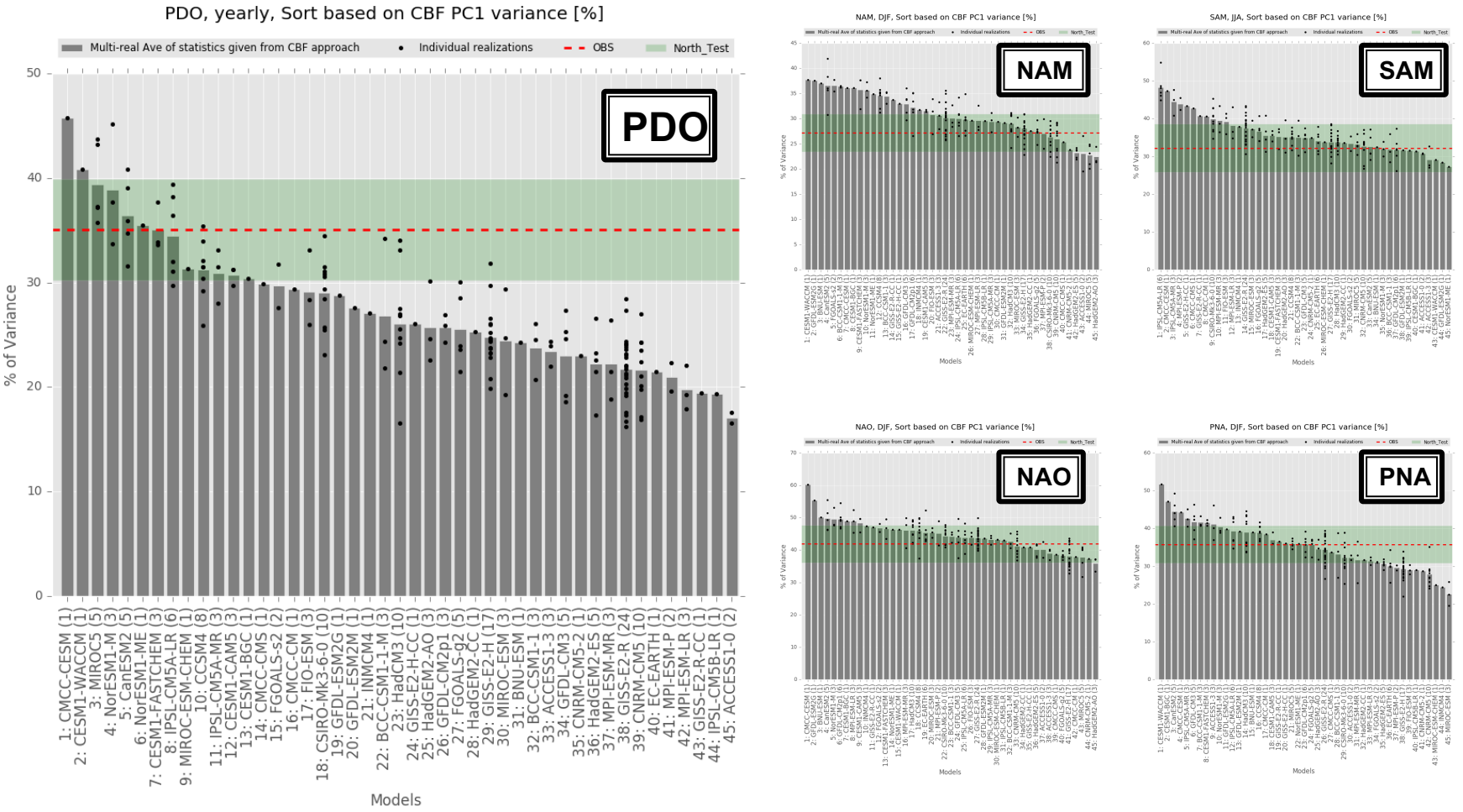
- Browsing available
  web-like navigation

- Statistics based Interactive plots
  (mpld3 Library)

- Starting version for PCMDI web service

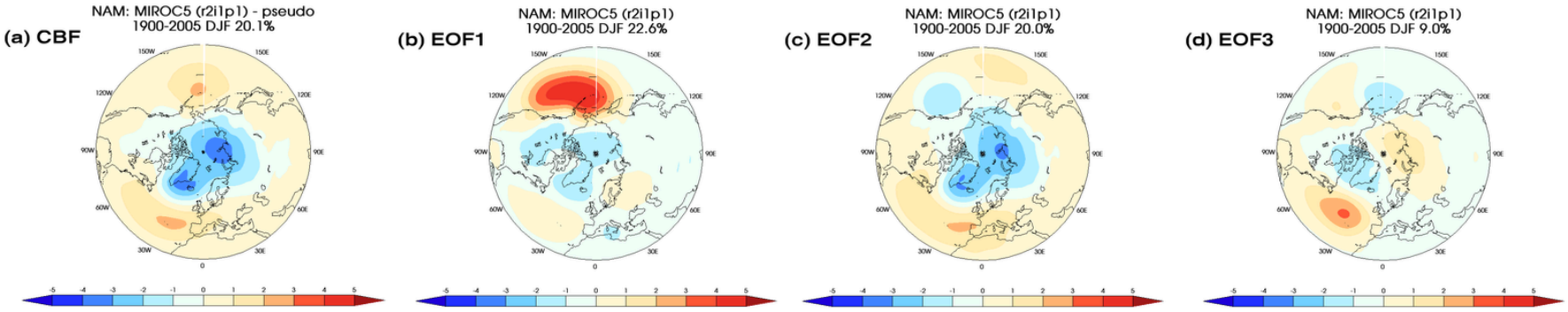


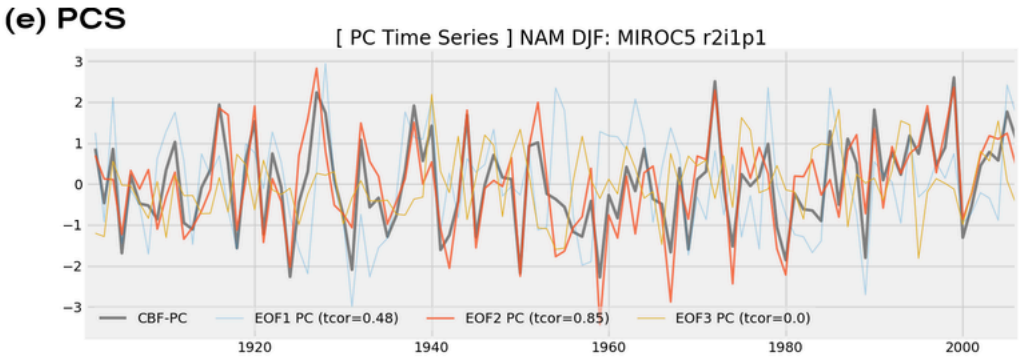
PDO and others - Variance in time



EOF mode swapping: NAM, DJF

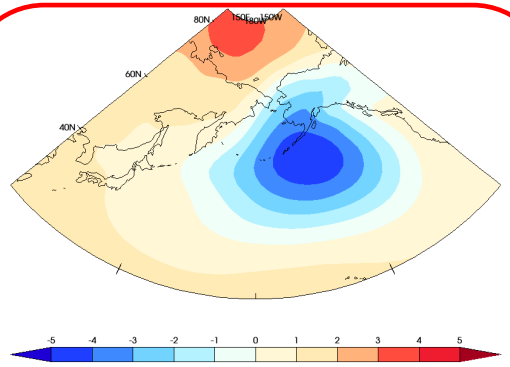
- NAM in MIROC5 (r2i1p1)



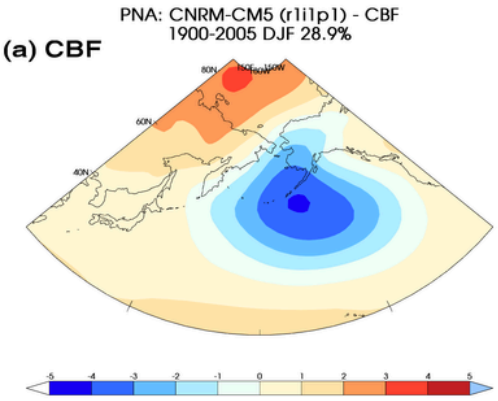


EOF mode swapping and CBF: PNA Example

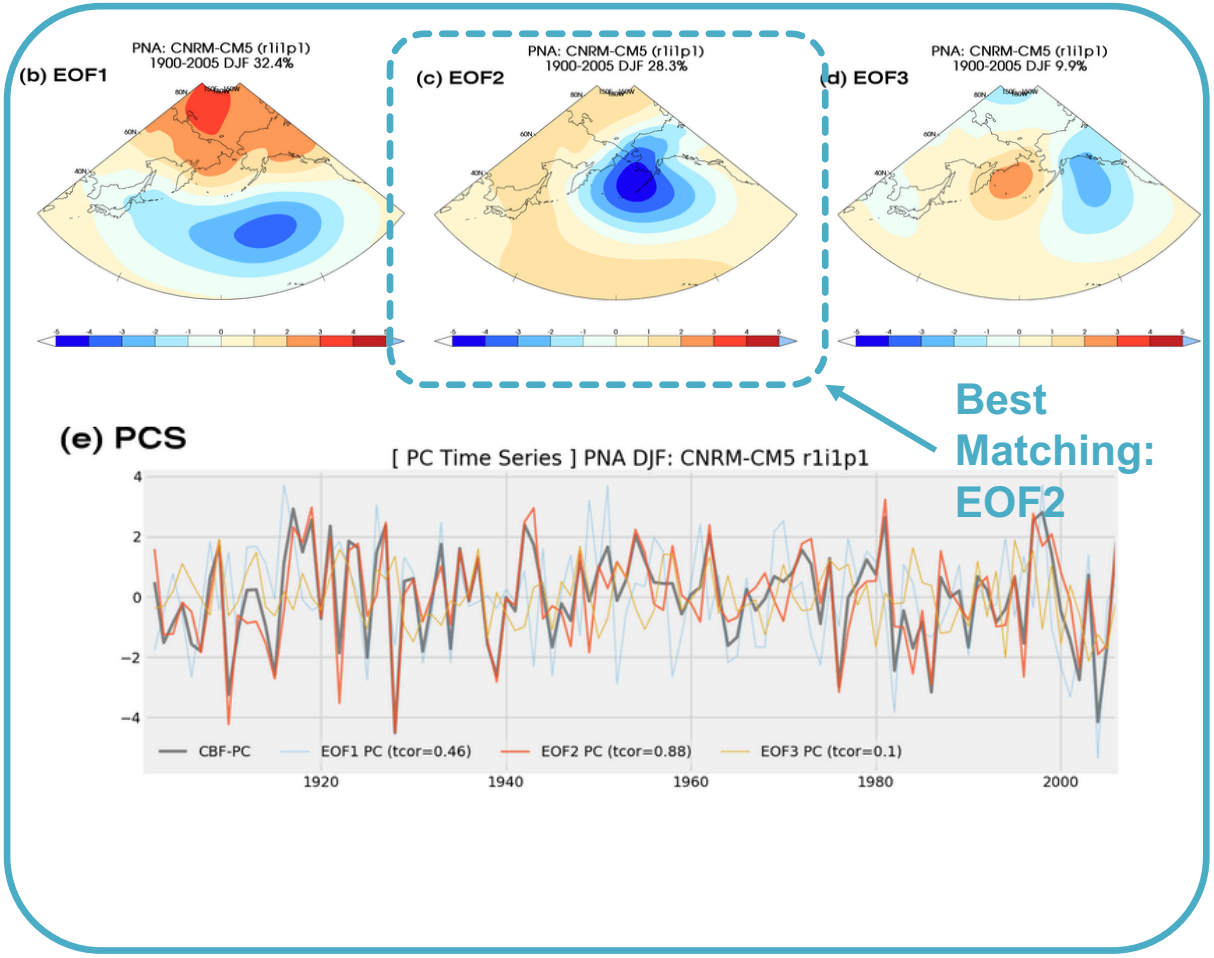
OBS



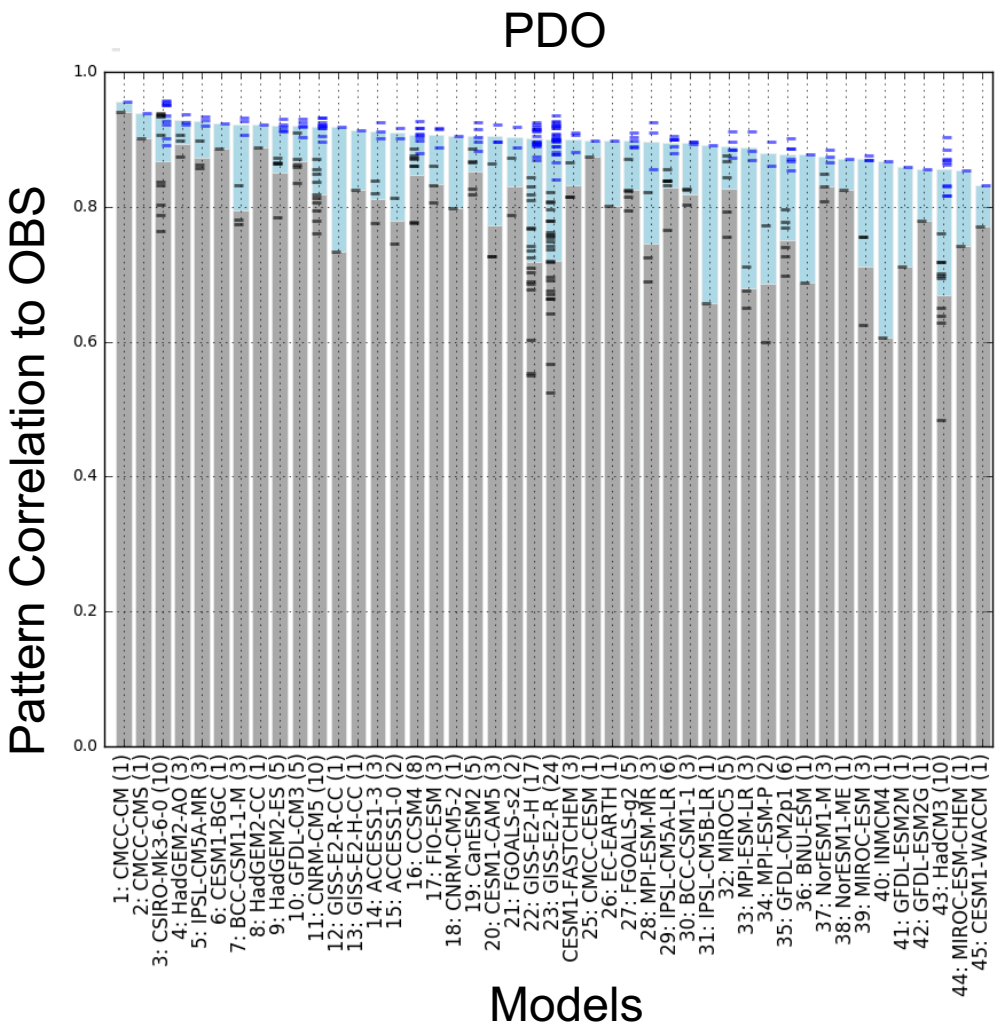
PNA: Pacific North American Pattern
(20CR, SLP)



Model

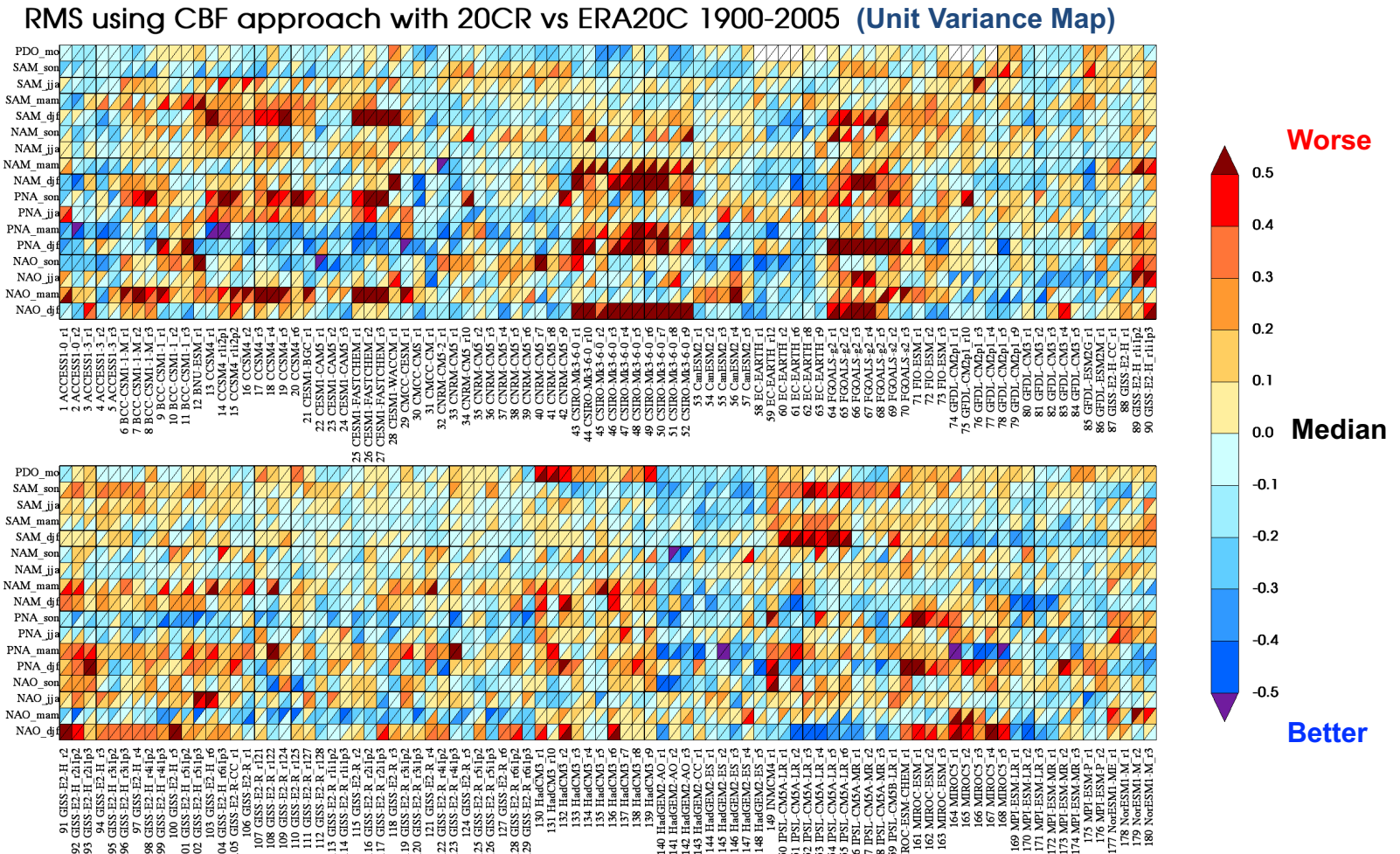


CBF vs. EOF swapping



- CBF has better performance than EOF swapping
- CBF brings models to space of more fair comparison

Performance Diagnostics: Pattern (RMSE) – Unit variance map



Amplitude comparison for CBF