Representation of Modes of Variability (MoV) in 6 U.S. Climate Models

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Background

- One of several outcomes of the 2019 US Climate Modeling Summit was funding from NASA MAP, DOE and NOAA to support a comprehensive assessment of the current representation of key modes of atmospheric and oceanic variability among models developed at six U.S. climate modeling centers.

- Thanks to that support, our team performed an extensive evaluation of several modes of variability (MoV) among current (CMIP6) U.S. climate models, focusing not only on key tropical modes of variability like the El-Nino Southern Oscillation (ENSO) and the Madden-Julian Oscillation (MJO), but also on extratropical tropospheric modes (e.g. Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO)) and on the (stratospheric) Quasi-Biennial Oscillation (QBO).

Background

- The timing was opportune (i.e. IPCC AR6 WG1 deadlines) and the project unique in that it combined the efforts of scientists across multiple U.S. agencies and presented an analysis of variability unprecedented in scope.
- 12 team members representing multiple agencies (right) presented an evaluation that focused primarily on climate models but also, when possible, extended to short-term (sub-seasonal) forecasts (i.e. GEOS and GEFS S2S).

Modeling Group	Model
Department of Energy (DOE)	E3SMv1
NOAA Geophysical Fluid Dynamics Laboratory (GFDL)	CM(3,4)
NASA Goddard Institute for Space Studies (GISS)	GISS E2-R, E2.1-G/H, E2.2-G
NASA Global Modeling and Assimilation Office (GMAO)	GEOS-5
National Center for Atmospheric Research (NCAR)	CESM(1,2)(CAM/WACCM(5,6))
NOAA National Center for Environmental Prediction (NCEP)	CFS v2

Project Outcomes

Practically, over the course of several months of bi-weekly telecons we completed an analysis consisting uniquely of:

- *Expertise spanning multiple modes*: ENSO (Fasullo), NAM/SAM (Gleckler), QBO (Orbe), MJO (Adams)
- *Several model analysis measures* for assessing the robustness of model fidelity
- *Incorporation of "Intermediary" model versions* between CMIP5 and CMIP6, which afforded a lens into why certain development changes improved model performance.

This effort culminated in the submission of the following manuscript (on 12/19/19):

Orbe, C., L. Van Roekel, Á. Adames, A. Dezfuli, J. Fasullo, P.J. Gleckler, J. Lee, W. Li, L. Nazarenko, G.A. Schmidt, K. Sperber, and M. Zhao, 2019: Representation of modes of variability in 6 U.S. climate models, *J. Climate*, Under Review.

Models

- The models considered in the MoV analysis represented a reasonably broad range across model top, vertical resolution, horizontal resolution and convective and gravity wave drag parameterizations.

Model	Vertical Layers (Total/Trop/Strat+Mes)	Model Top (hPa)	Horizontal Resolution	Convection Scheme	Gravity Wave Drag
NCAR-CESM1 (CAM5)	32/24/8	3.6	1 degree	Zhang and McFarlane (1995) Park and Bretherton (2009)	McFarlane (1987) Richter et al. (2010)
NCAR-CESM1 (WACCM5)	70/24/28	6×10^{-6}	1 degree	Zhang and McFarlane (1995) Park and Bretherton (2009)	McFarlane (1987) Richter et al. (2010)
NCAR-CESM2 (CAM6)	32/22/10	3.6	1 degree	Updated ZM95 Golaz et al. (2002)	Scinocca and McFarlane (2000) Richter et al. (2010)
NCAR - CESM2 (WACCM6)	70/24/28	6×10^{-6}	1 degree	Updated ZM95 Golaz et al. (2002)	Scinocca and McFarlane (2000) Richter et al. (2010)
DOE-E3SM1	72/47/25	0.01	1 degree	Xie et al. (2018) Golaz et al. (2002)	McFarlane (1987) Richter et al. (2010)
GFDL-CM3	48/23/25	0.01	2 degree	Bretherton et al. (2004) Donner et al. (2001)	Stern and Pierrehumbert (1988) Alexander and Dunkerton (1999)
GFDL-CM4	33/24/9	1	1 degree	Zhao et al. (2018a)	Garner (2005) Alexander and Dunkerton (1999)
GFDL-ESM4	49/24/25	0.01	1 degree	Zhao et al. (2018a)	Garner (2005) Alexander and Dunkerton (1999)
GISS - E2	40/25/15	0.1	2.5 degrees	Del Genio et al. (2007)	Schmidt et al. (2014)
GISS-E2.1	40/25/15	0.1	2.5 degrees	Kim et al. (2013) Del Genio et al. (2015)	Schmidt et al. (2014)
GISS - E2.2	102/58/44	0.002	2.5 degrees	Kim et al. (2013) Del Genio et al. (2015)	Rind et al. (2014) Rind et al. (2020)
GEOS-M2AMIP	72/35/37	0.01	50 km	Moorthi and Suarez (1992)	McFarlane (1987) Garcia and Boville (1994)
GEOS-S2S	72/35/37	0.01	0.5 degrees	Moorthi and Suarez (1992)	McFarlane (1987) Garcia and Boville (1994)
NCEP GEFS	64/43/21	0.2	T574/T384	Saha et al. (2014)	Chun and Baik (1998)

Model Experiments: CMIP6 DECK Historical

- The main focus of our analysis was on evaluating variability as represented in the DECK Historical simulations that were contributed to CMIP6 (*Eyring et al. (2016)*).

Modeling Center	Version	Type	Ensemble Size	AMIP/Coupled
NCAR	CCSM4	Historical	6	Coupled
	CESM1 (CAM5)	Historical	3	Coupled
	CESM1 (BGC)	Historical	1	Coupled
	CESM1 (WACCM5)	Historical	7	Coupled
	CESM2 (CAM6)	Historical	6	Coupled
		Intermediary	2	Coupled
	CESM2 (WACCM6)	Historical	6	Coupled
GISS	E2-R	Historical	18	Coupled
	E2-R-CC	Historical	1	Coupled
		Intermediary	1	Coupled
	E2-H	Historical	18	Coupled
	E2-H-CC	Historical	1	Coupled
	E2.1-G	Historical	20	Coupled
	E2.1-H	Historical	20	Coupled
	E2.2-G	AMIP	5	Atm.
		Historical	3	Coupled
GEOS	M2AMIP	Historical	10	Atm.
	S2S-v2	45-day Forecasts	4	Coupled
DOE	E3SMv1	Historical	5	Coupled
		AMIP	1	Atm.
	E3SMv1-MODGWD	Intermediary	1	Atm.
			1	Coupled
GFDL	CM2.1	Historical	10	Coupled
	CM3	Historical	5	Coupled
	ESM2G	Historical	1	Coupled
	ESM2M	Historical	1	Coupled
	CM4	Historical	3	Coupled
	ESM4	Historical	3	Coupled
NOAA	GEFS	35-day Forecasts	11	Atm.

Model Experiments: Intermediary

- At the same time, the (unique) incorporation of "intermediary" model versions between CMIP5 and CMIP6 was important for identifying the specific changes in model development that impacted model performance.

Modeling Center	Version	Type	Ensemble Size	AMIP/Coupled
NCAR	CCSM4	Historical	6	Coupled
	CESM1 (CAM5)	Historical	3	Coupled
	CESM1 (BGC)	Historical	1	Coupled
	CESM1 (WACCM5)	Historical	7	Coupled
	CESM2 (CAM6)	Historical	6	Coupled
		Intermediary	2	Coupled
	CESM2 (WACCM6)	Historical	6	Coupled
GISS	E2-R	Historical	18	Coupled
	E2-R-CC	Historical	1	Coupled
		Intermediary	1	Coupled
	E2-H	Historical	18	Coupled
	E2-H-CC	Historical	1	Coupled
	E2.1-G	Historical	20	Coupled
	E2.1-H	Historical	20	Coupled
	E2.2-G	AMIP	5	Atm.
		Historical	3	Coupled
GEOS	M2AMIP	Historical	10	Atm.
	S2S-v2	45-day Forecasts	4	Coupled
DOE	E3SMv1	Historical	5	Coupled
		AMIP	1	Atm.
	E3SMv1-MODGWD	Intermediary	1	Atm.
			1	Coupled
GFDL	CM2.1	Historical	10	Coupled
	CM3	Historical	5	Coupled
	ESM2G	Historical	1	Coupled
	ESM2M	Historical	1	Coupled
	CM4	Historical	3	Coupled
	ESM4	Historical	3	Coupled
NOAA	GEFS	35-day Forecasts	11	Atm.

Model Experiments: Subseasonal Forecasts

- Effort was also placed toward understanding how improved model performance in climate simulations affects performance on (sub) seasonal timescales.

Modeling Center	Version	Type	Ensemble Size	AMIP/Coupled
NCAR	CCSM4	Historical	6	Coupled
	CESM1 (CAM5)	Historical	3	Coupled
	CESM1 (BGC)	Historical	1	Coupled
	CESM1 (WACCM5)	Historical	7	Coupled
	CESM2 (CAM6)	Historical	6	Coupled
		Intermediary	2	Coupled
	CESM2 (WACCM6)	Historical	6	Coupled
GISS	E2-R	Historical	18	Coupled
	E2-R-CC	Historical	1	Coupled
		Intermediary	1	Coupled
	E2-H	Historical	18	Coupled
	E2-H-CC	Historical	1	Coupled
	E2.1-G	Historical	20	Coupled
	E2.1-H	Historical	20	Coupled
	E2.2-G	AMIP	5	Atm.
		Historical	3	Coupled
GEOS	M2AMIP	Historical	10	Atm.
	S2S-v2	45-day Forecasts	4	Coupled
DOE	E3SMv1	Historical	5	Coupled
		AMIP	1	Atm.
	E3SMv1-MODGWD	Intermediary	1	Atm.
			1	Coupled
GFDL	CM2.1	Historical	10	Coupled
	CM3	Historical	5	Coupled
	ESM2G	Historical	1	Coupled
	ESM2M	Historical	1	Coupled
	CM4	Historical	3	Coupled
	ESM4	Historical	3	Coupled
NOAA	GEFS	35-day Forecasts	11	Atm.

Model Validation with Observations and Reanalyses

- Monthly and daily fields from multiple reanalysis and observational products were used for model evaluation, depending on the mode.

Mode	Observation Product	Years	Output for Analysis
MJO	TRMM, ERA5	1998-2014	daily precipitation, daily zonal winds (U) at 850 hPa
QBO	MERRA-2	1980-2016	monthly zonal winds (U) (10-100 hPa)
ENSO and PDO	ERSSTv5, HadISST,	1920-present	monthly sea level pressure (slp)
	ERA20C*/ERAI, BEST, 20CR**		and surface temperature (ts)
SAM, NAM, NAO	NOAA 20CR**	1900-2005***	monthly sea level pressure (slp)

Metrics of Model Performance

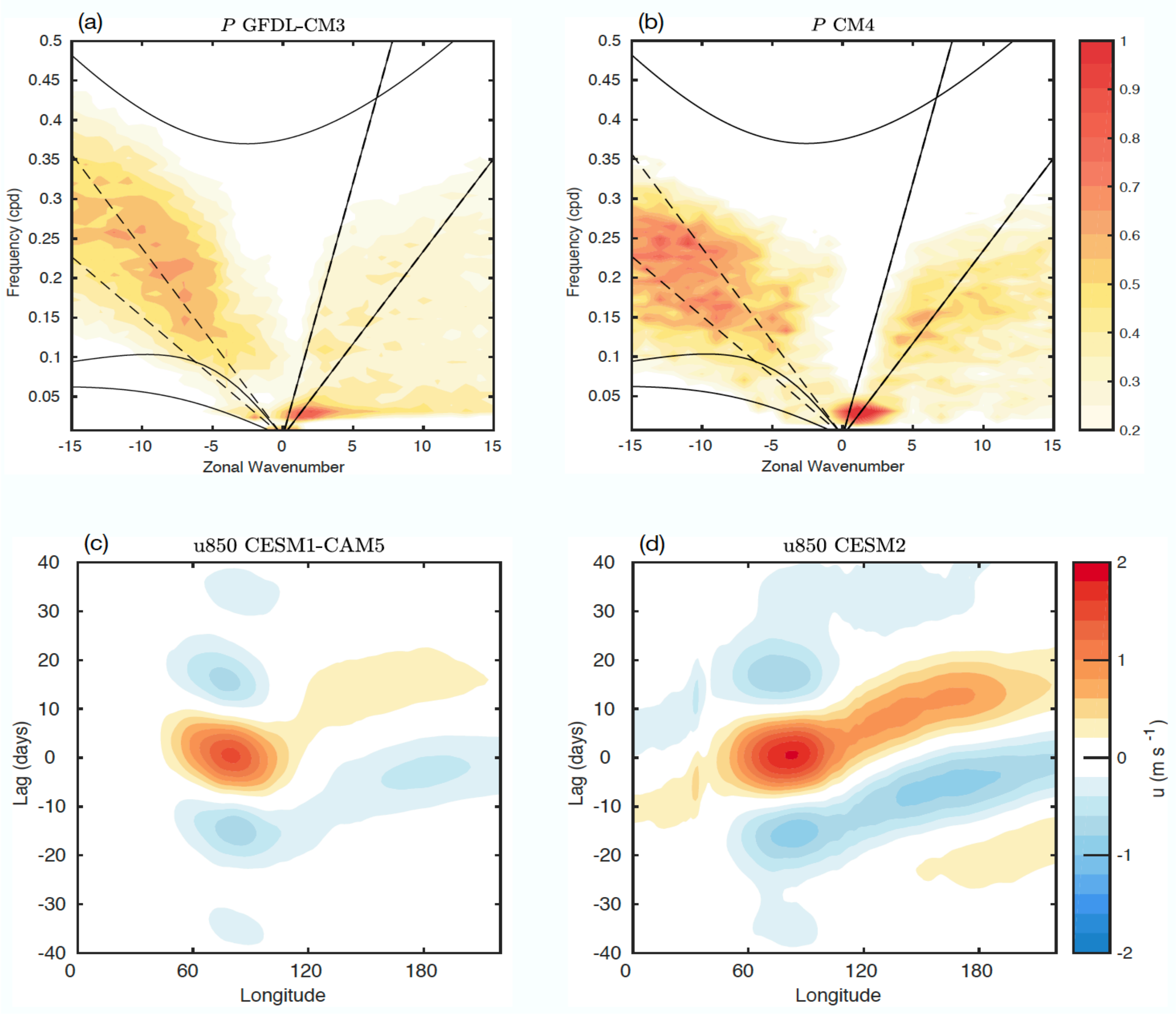
A broad range of model evaluation metrics were used, optimized for each mode:

- Extratropical Coupled Atmosphere-Ocean Modes (PDO, NAO, NAM, SAM):
  - -PCMDI Metrics Package (PMP, *Gleckler et al. (2016)*)
  - -Comparison of observed and modeled EOFs
  - -Illustration of model skill using Taylor Diagrams (*Taylor (2001)*)
- Tropical Coupled Variability (ENSO, MJO):
  - -Climate Variability Diagnostics Package (CVDP, *Phillips et al. (2014))*
  - -MJO global model evaluation measures (*Jiang et al. (2015))*
- Stratospheric Variability (QBO):
  - -Metrics from *Scherzinger et al. (2017)* as applied in the recent SPARC QBO Initiative (QBOi) (*Butchart et al. (2018)*)

Main Findings: Overall Performance

- For some modes (i.e. MJO, QBO) there is unequivocal improvement moving from CMIP5 to CMIP6.
- For other modes (e.g., NAM) improvement in model performance is more clear when conditioning on season, measure, etc. Thus, robust improvements in the representation of these modes will remain important challenges for future model development.
- The incorporation of intermediary (not publicly available) model versions helped in identifying which changes in model development (e.g. increased vertical resolution, convective parameterization changes) impact performance *consistently* across models.

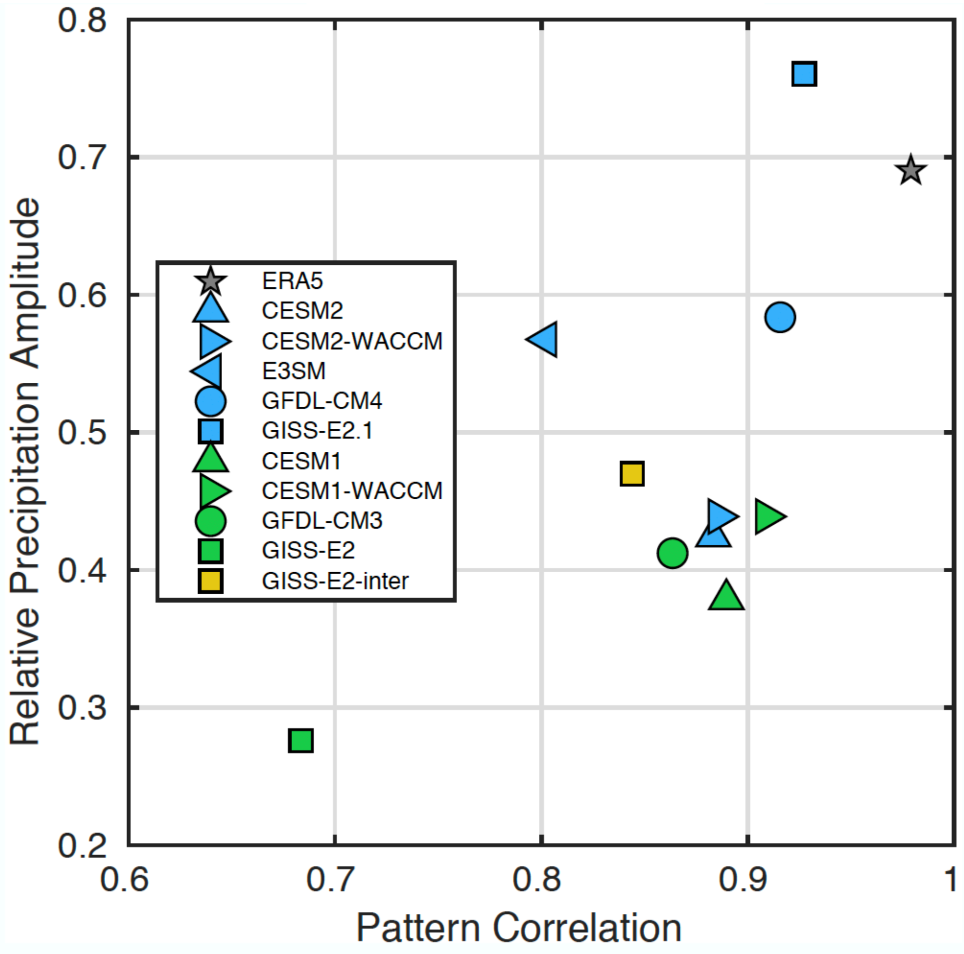
Main Findings: Madden-Julian Oscillation



- The evaluation of the MJO centered around an analysis of the signal strength of precipitation and the coherence of eastward propagating zonal (wind) wavenumbers 1-5 associated with timescales ranging from 20-100 days.

Main Findings: Madden-Julian Oscillation

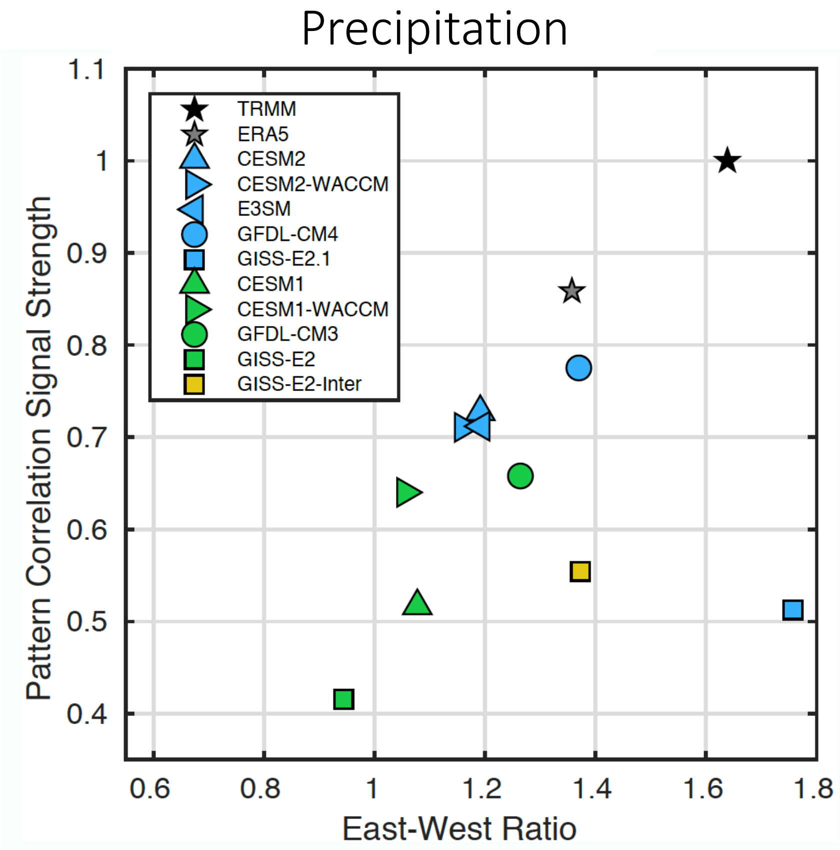
Precipitation

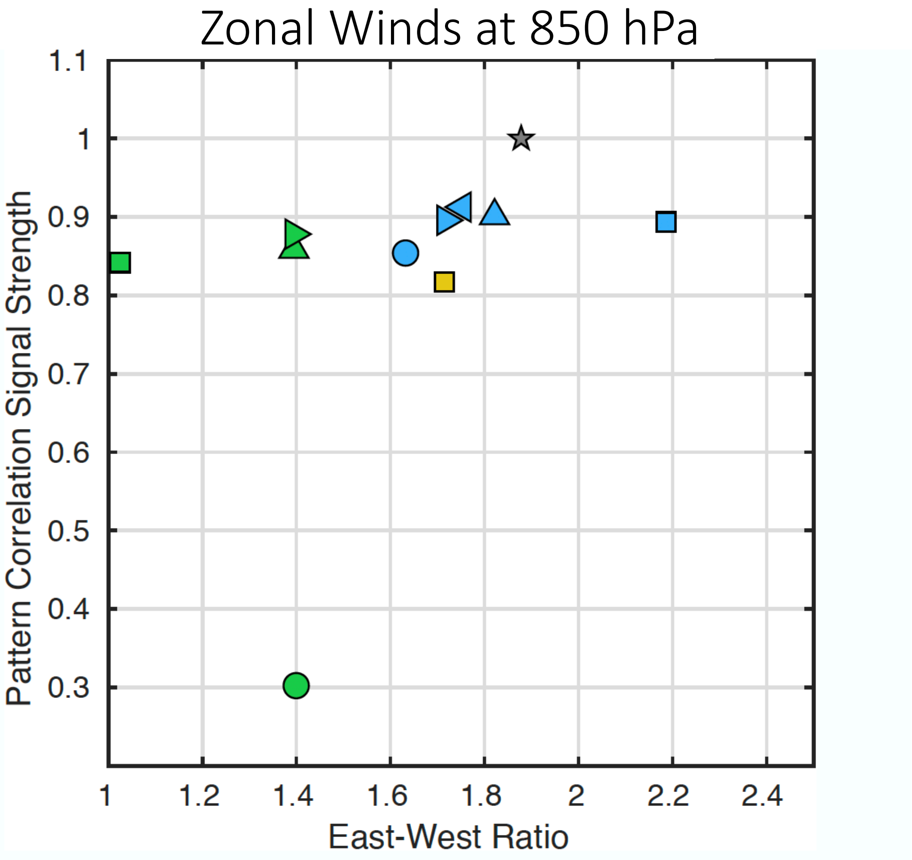


- Clear improvement in MJO performance moving from CMIP5 to CMIP6. This is evident in pattern correlations of precipitation from the MoV models versus TRMM v3b42 (left). Correlations based on other measures (e.g. zonal winds at 850 mb) show a similar story.

Main Findings: Madden-Julian Oscillation

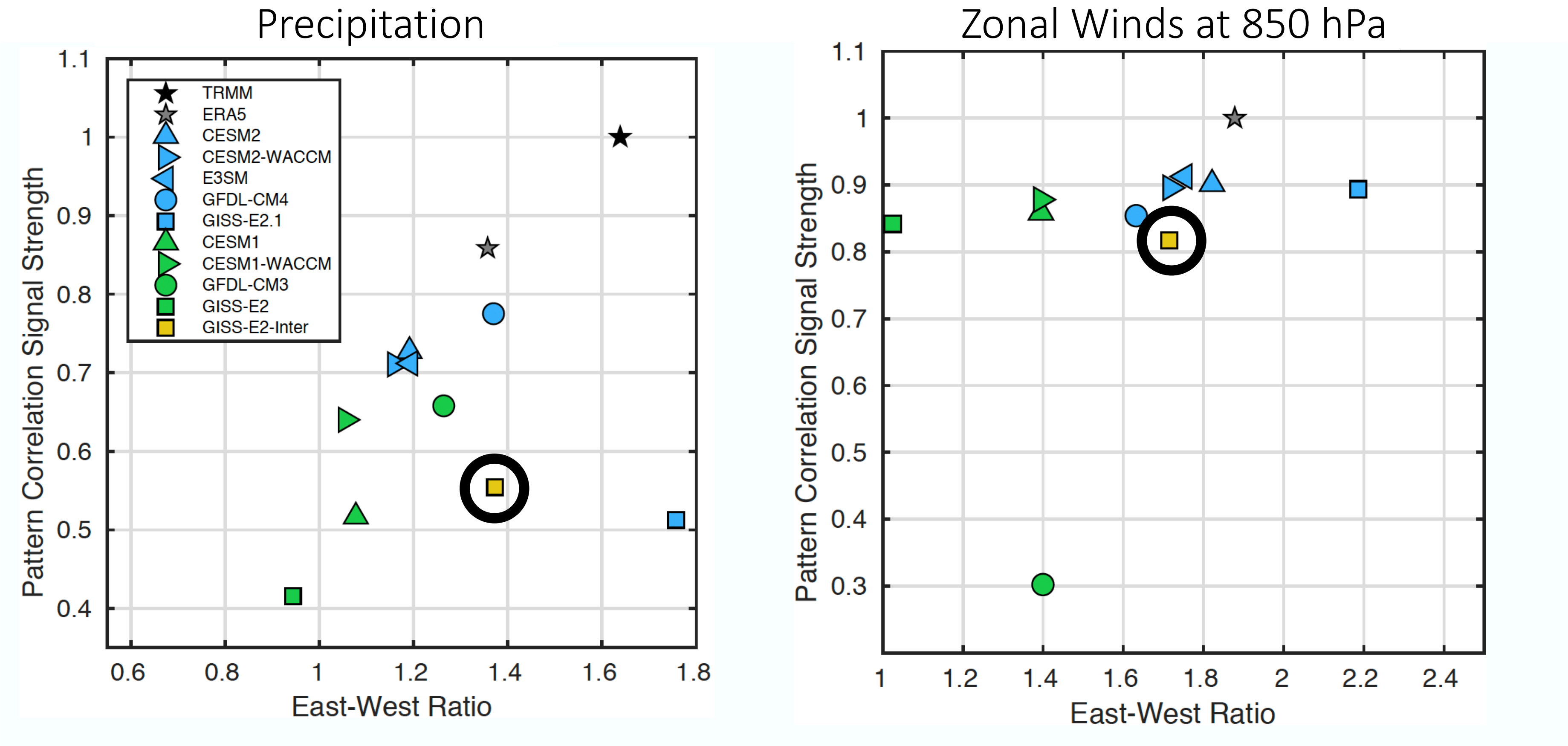
- Evaluation of higher order (more "process-based") measures indicate a similar story reinforcing improved representation of the MJO in CMIP6 model versions.





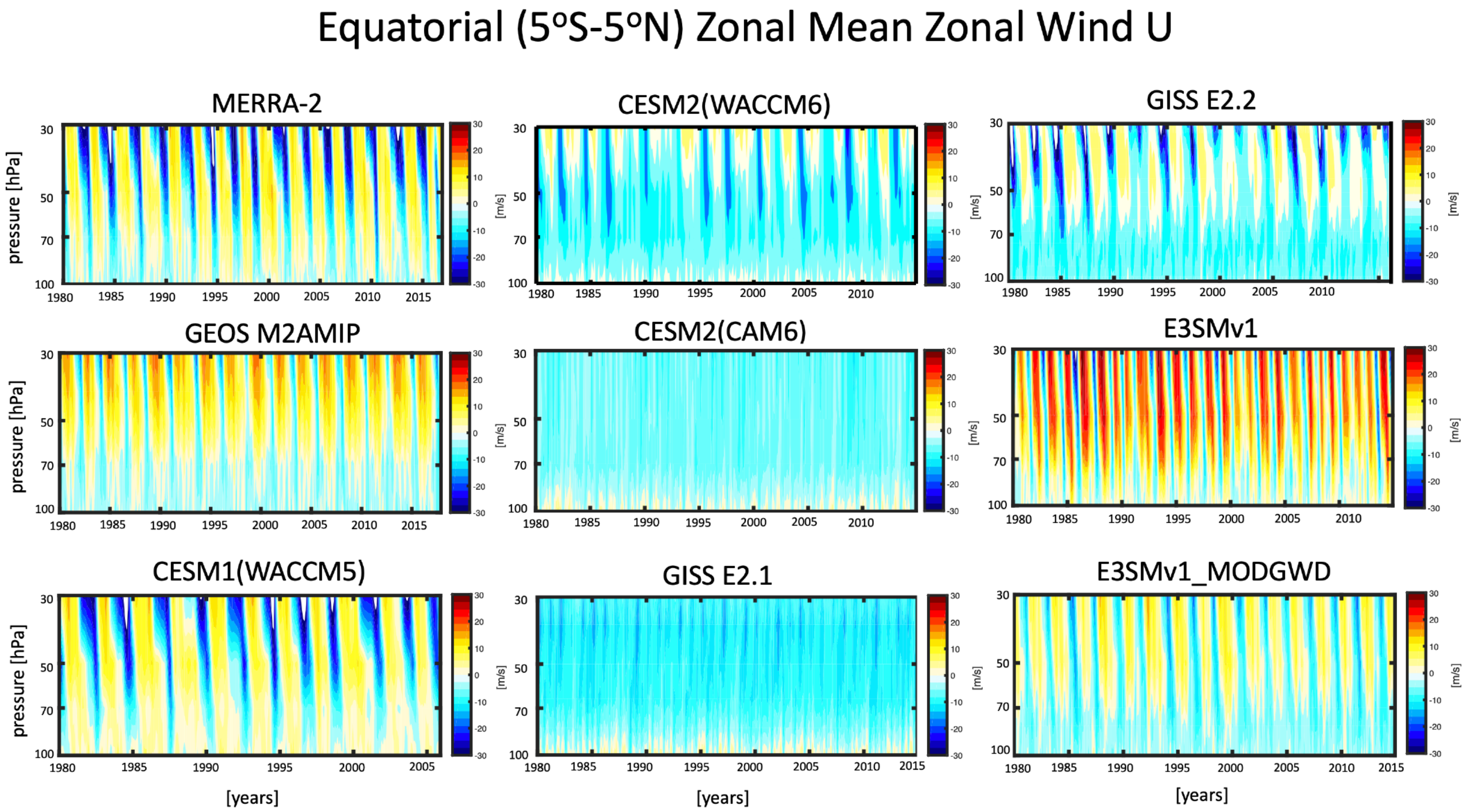
Main Findings: Madden-Julian Oscillation

- Analysis of intermediary experiments from GISS ModelE isolate the role that changes to the sensitivity of parameterized convection to environmental relative humidity have on MJO performance (*Kim et al. (2012), Del Genio et al. (2012)*).



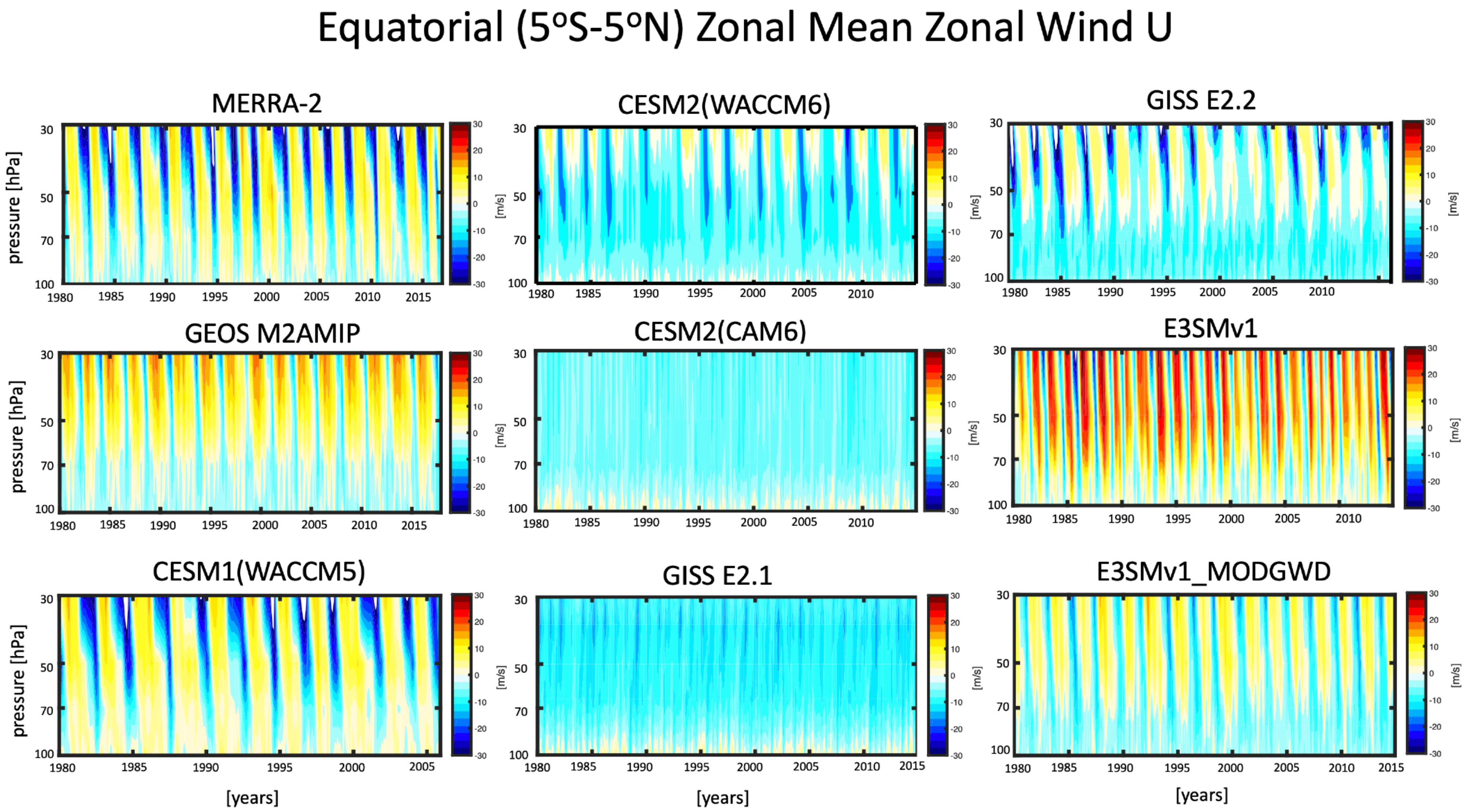
Main Findings: Quasi-Biennial Oscillation

- The MoV team analysis also suggests a substantial leap in QBO representation in current CMIP6 models, with all but three MoV models exhibiting a QBO. This is compared to ***only 5 models*** in CMIP5 (*Butchart et al. 2018*).



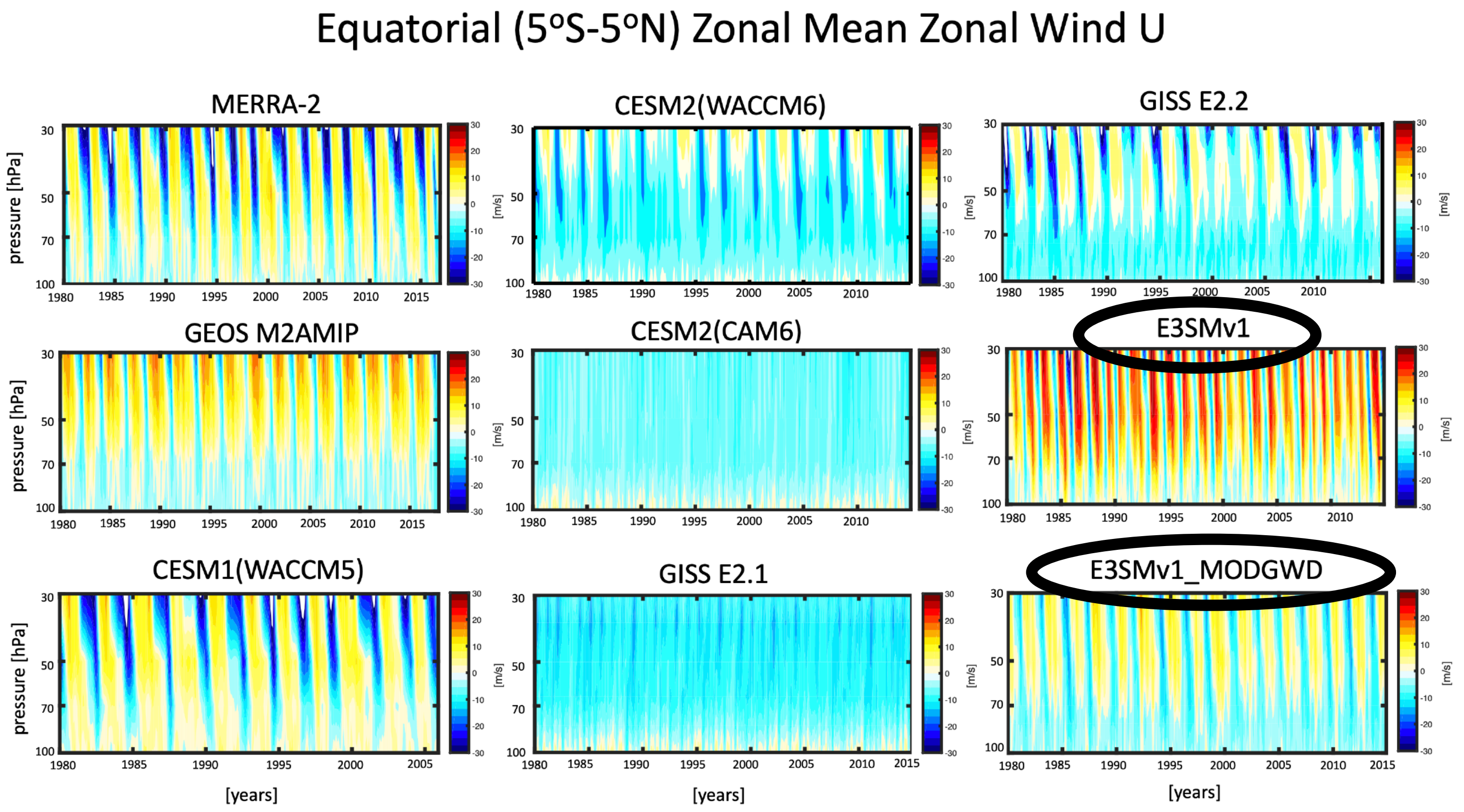
Main Findings: Quasi-Biennial Oscillation

- Overall, the improvement in QBO representation is consistent with increases in vertical resolution and more models incorporating source-based non-orographic gravity wave drag parameterizations.



Main Findings: Quasi-Biennial Oscillation

- In particular, comparison of the intermediary version “E3SMv1_MODGWD” with E3SMv1 unambiguously demonstrates the improvement in QBO period in response to changes to the efficiency with which (parameterized) convection contributes to non-orographic gravity wave momentum flux (*Richter et al. (2019)*).

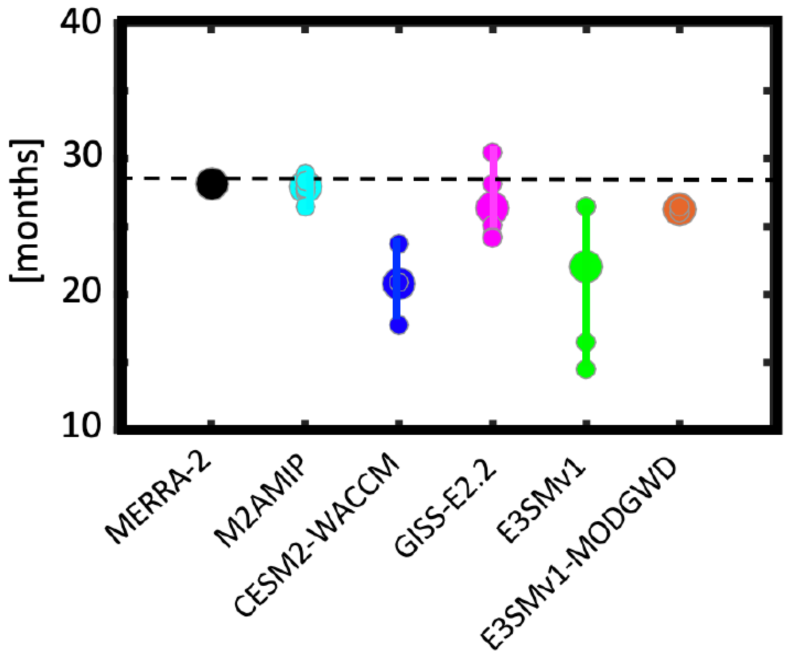


Main Findings: Quasi-Biennial Oscillation

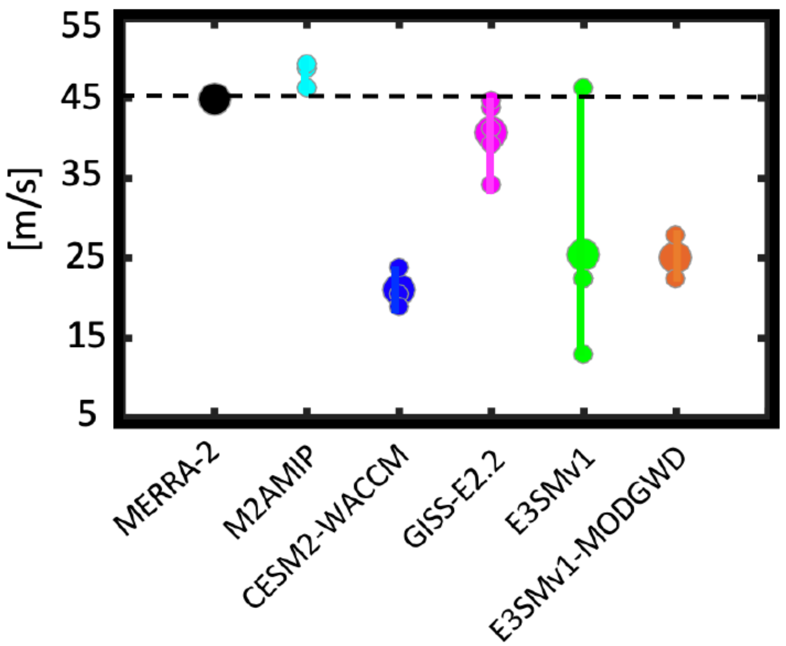
- Nonetheless, key challenges in QBO modeling exist, particularly as the QBO period is often explicitly tuned in models, unlike other aspects of the QBO.

- In particular, the MoV models consistently underestimate the amplitude of the QBO, a bias more broadly exhibited in the QBOi models as well (*Richter et al. 2019*).

Mean QBO Period

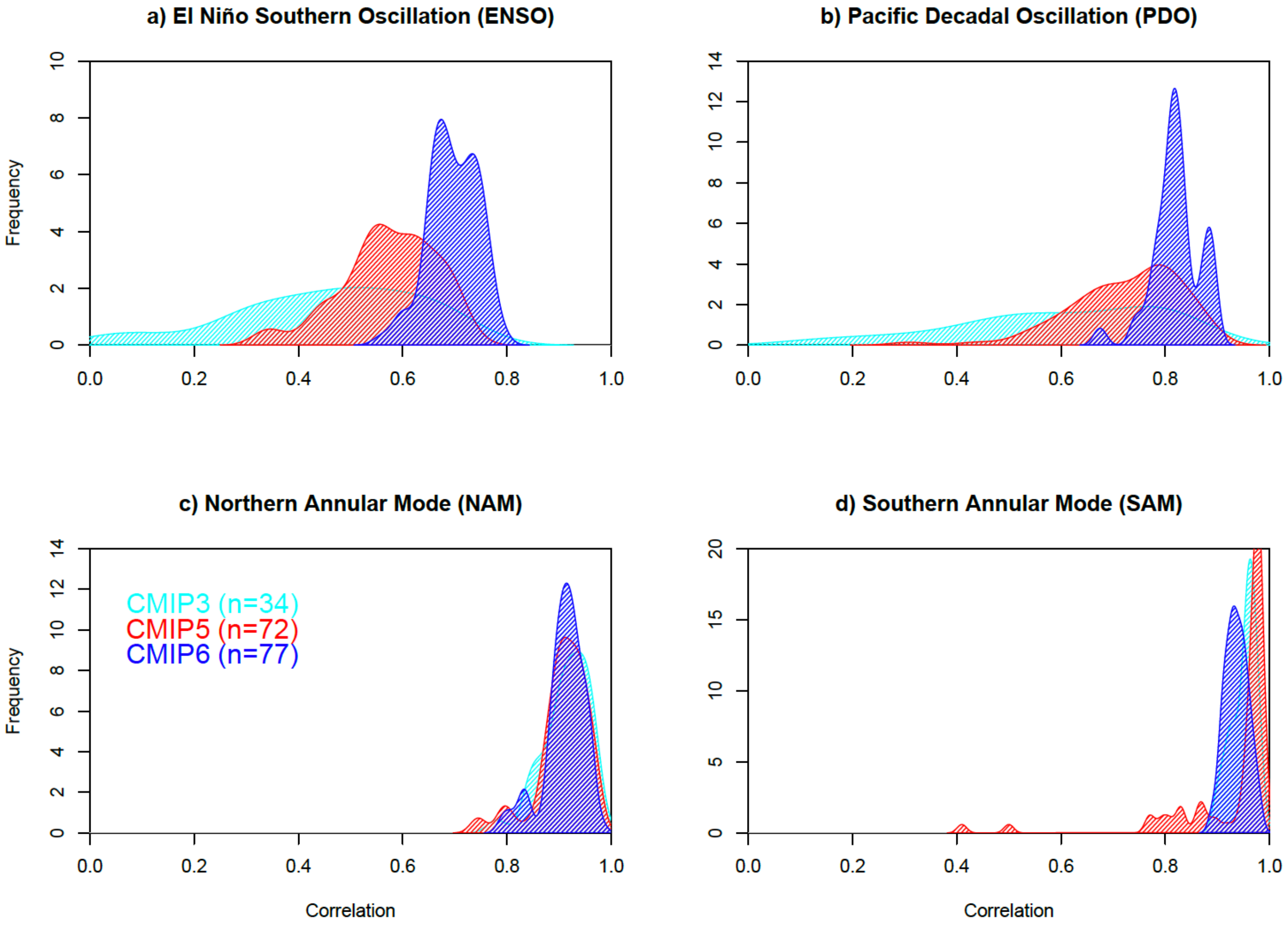


Mean QBO Amplitude



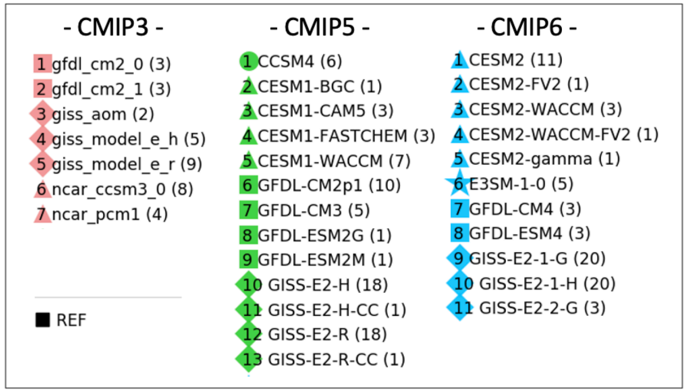
Extratropical Coupled Modes of Tropospheric Variability

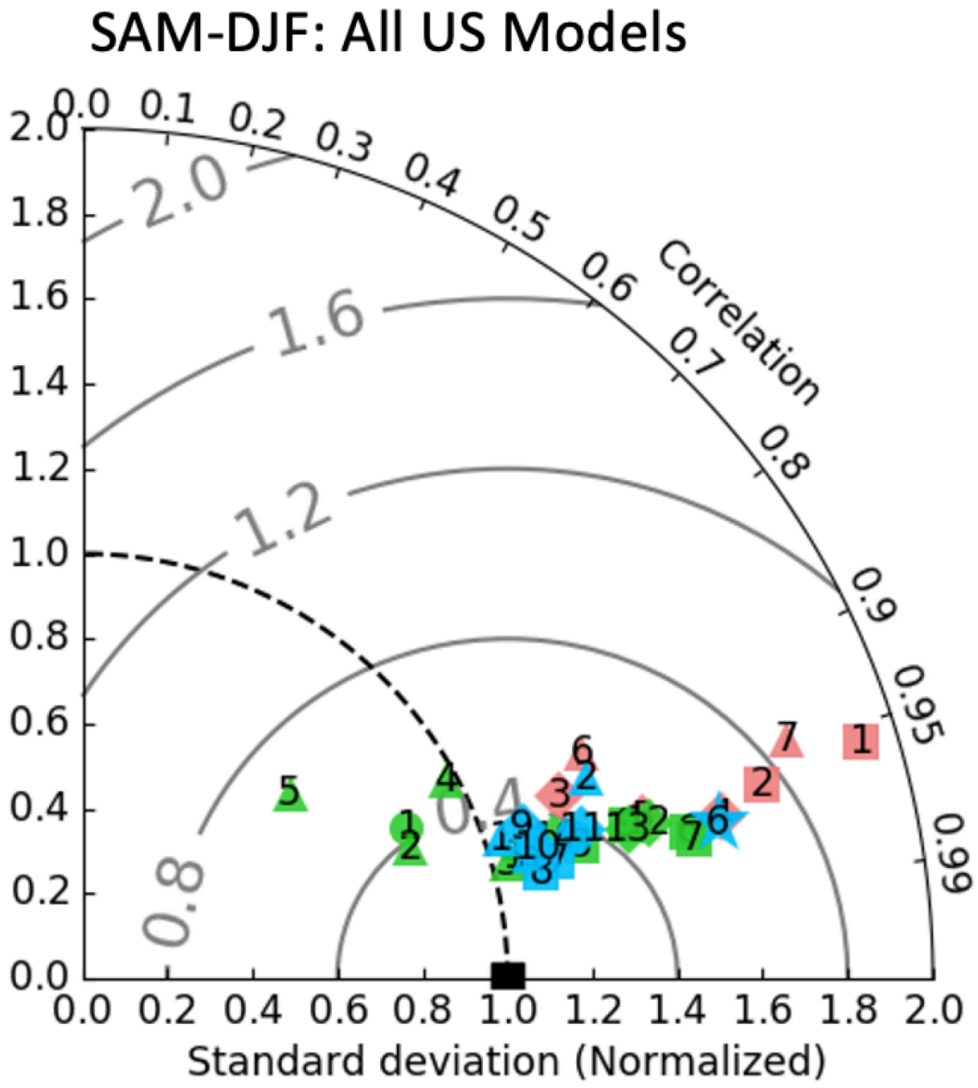
- Overall, CMIP6 models exhibit an improvement in the representation of both tropospheric tropical and extratropical coupled atmosphere-ocean modes of variability (NAM, ENSO, PDO, SAM), compared to previous versions.



Extratropical Coupled Modes of Tropospheric Variability

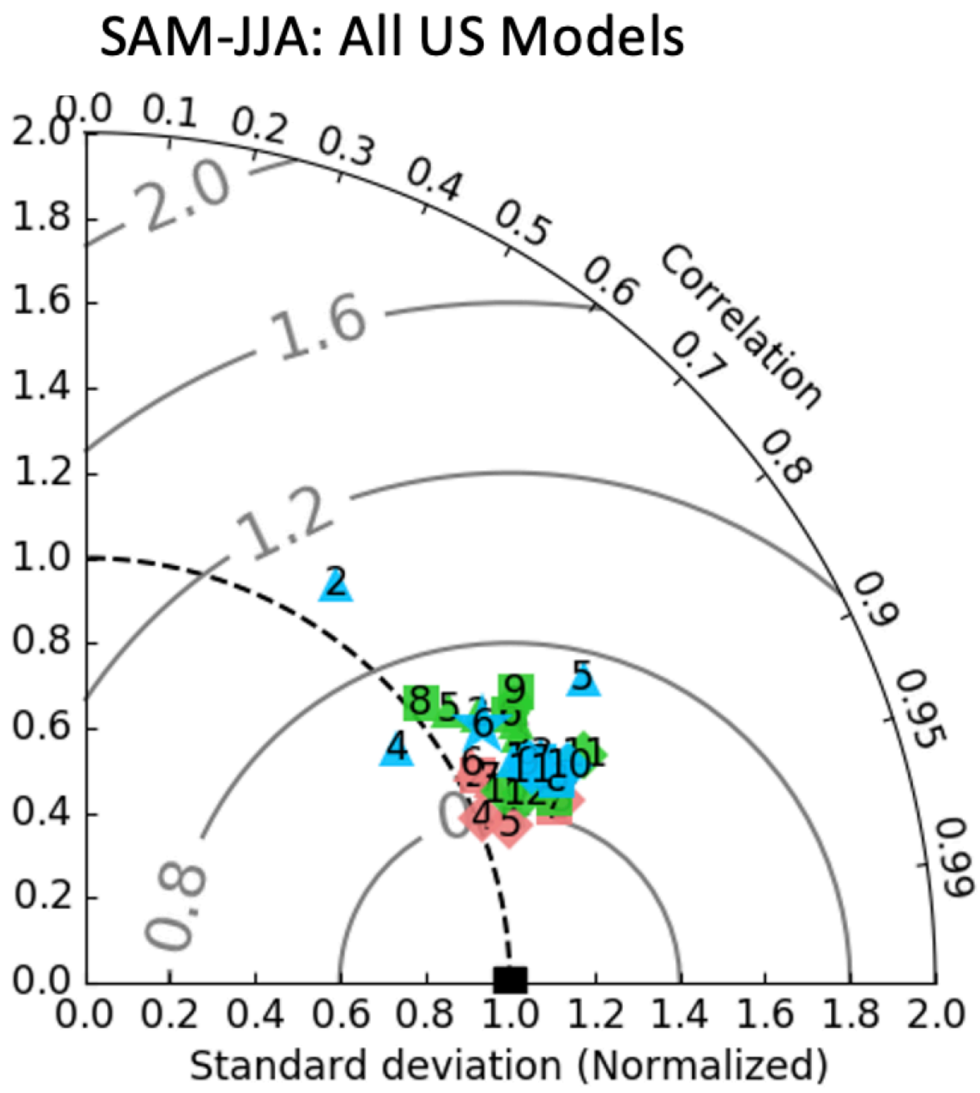
- However, the improvements are more nuanced, compared to the MJO and the QBO.
- In particular, while for some modes during certain seasons (e.g. summer SAM) model performance has clearly improved (right)…

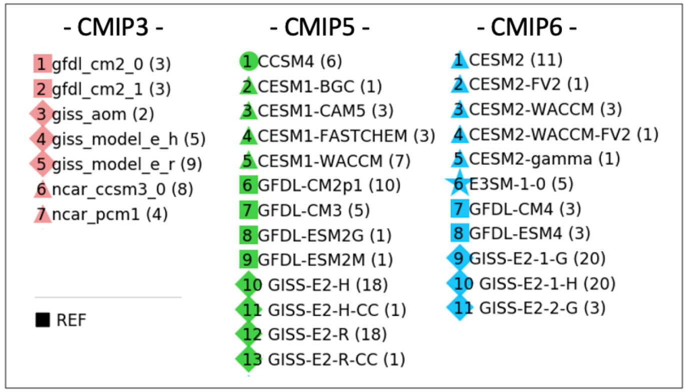




Extratropical Coupled Modes of Tropospheric Variability

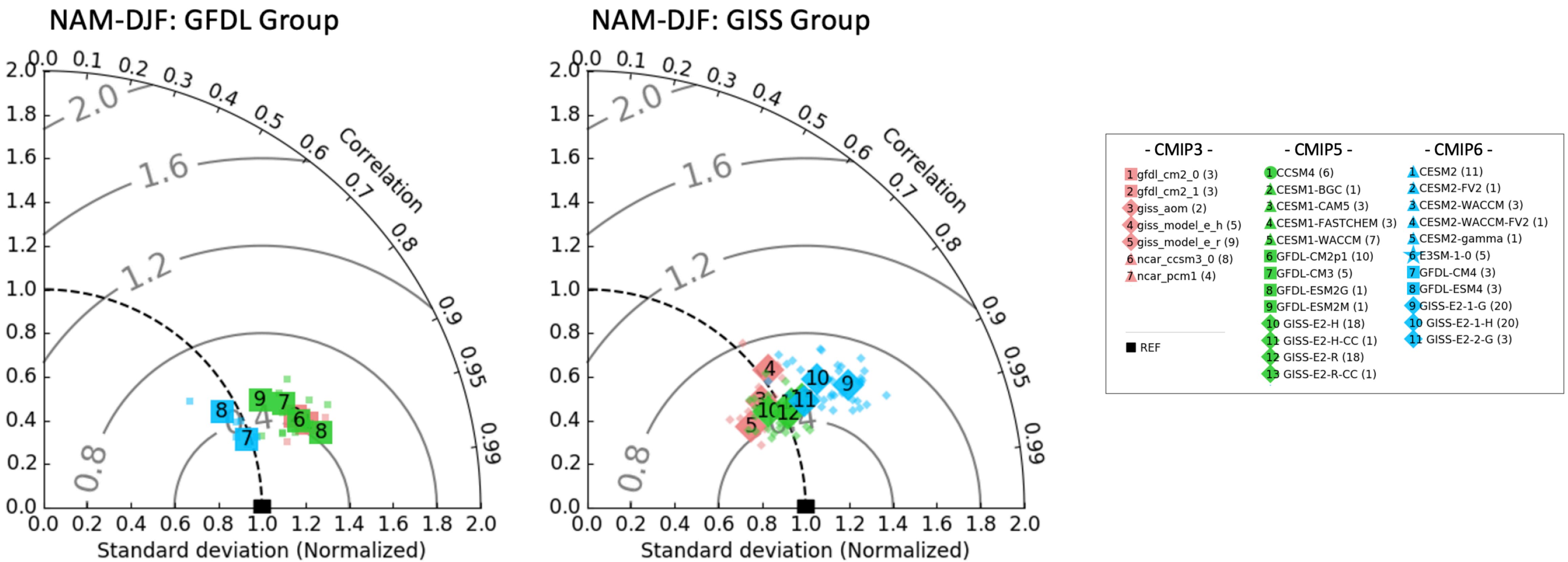
- … for other seasons (e.g. winter SAM) the story is not as clear.





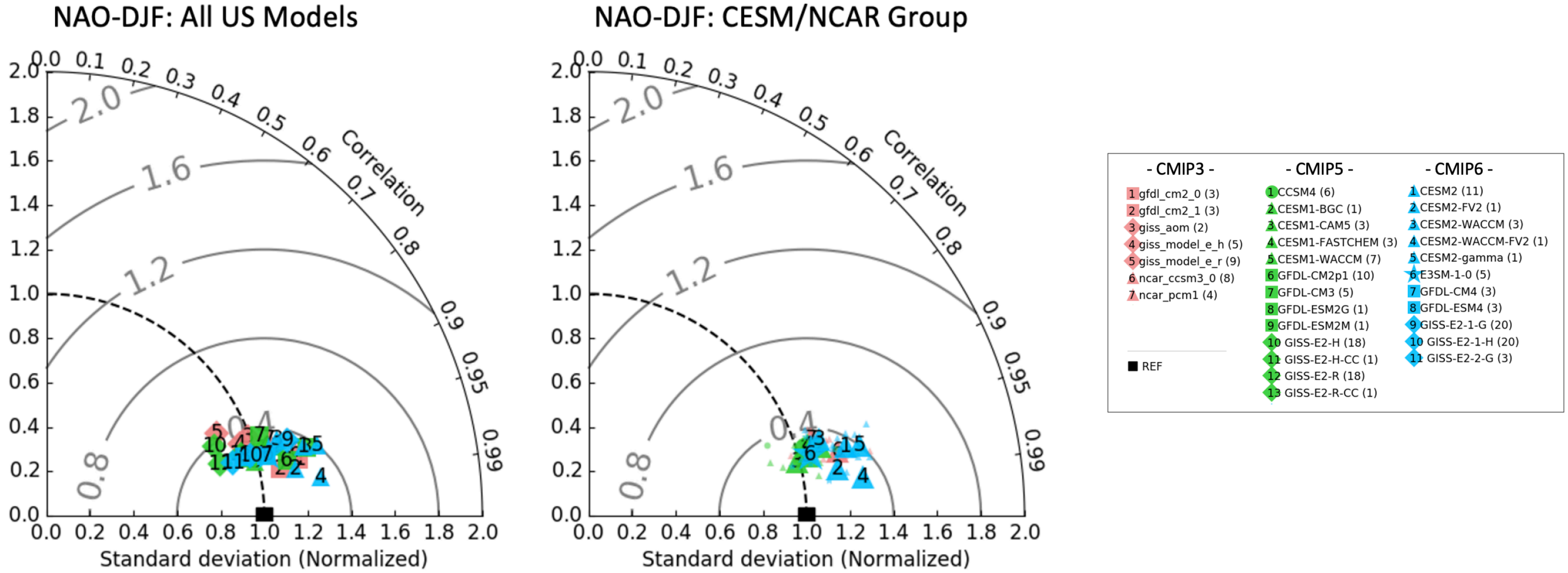
Extratropical Coupled Modes of Tropospheric Variability

- Changes in the performance of the NAM also vary across modeling groups. For example, despite an overall improvement from CMIP3/5 to CMIP6 the performance of the boreal winter NAM worsened in CMIP6 versions of GISS ModelE.



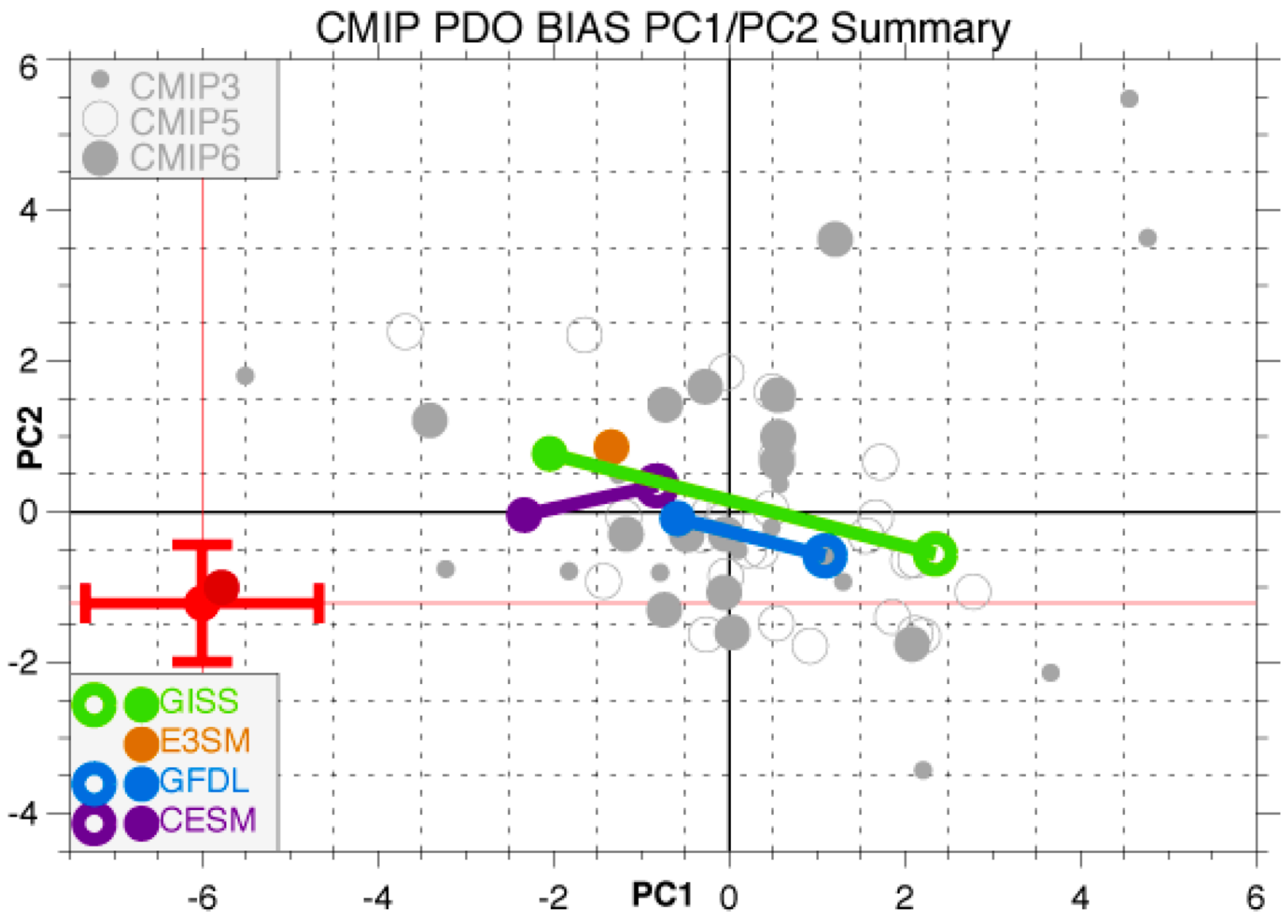
Extratropical Coupled Modes of Tropospheric Variability

- At the same time, the NCAR models exhibit a similar degradation in the performance of the NAO, compared to improvement among other modeling centers.



Extratropical Coupled Modes of Tropospheric Variability

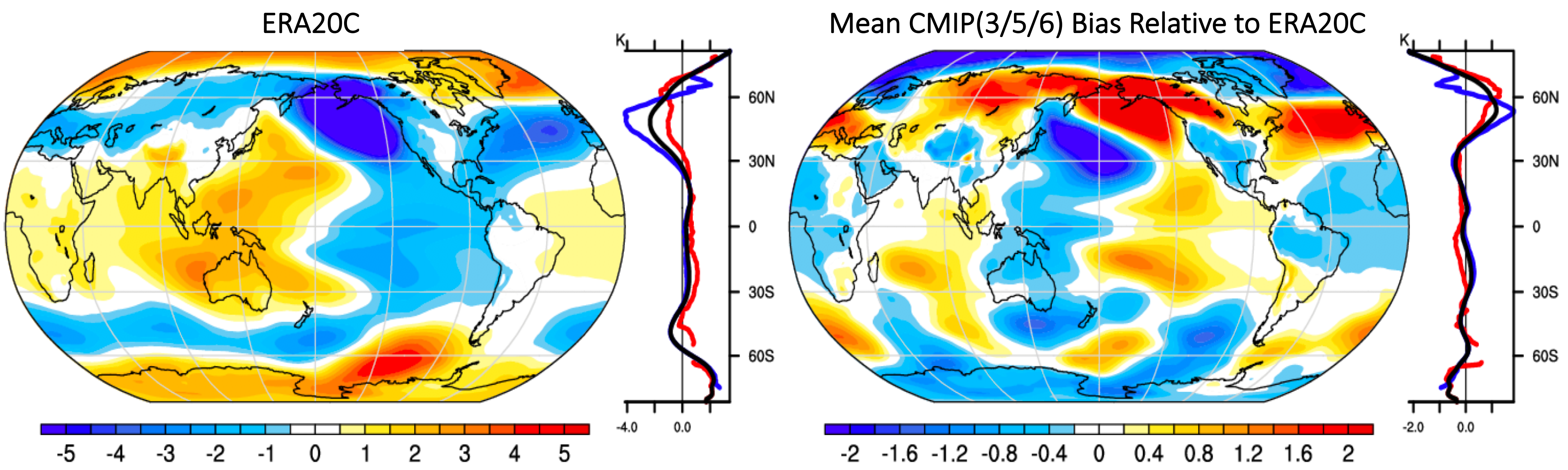
- One clearer indicator of improved simulation of extratropical modes in the MoV models is the Pacific Decadal Oscillation (PDO). Nonetheless, all models still tend to underestimate the total amplitude of the PDO.



Tropical Coupled Modes: El Nino-Southern Oscillation

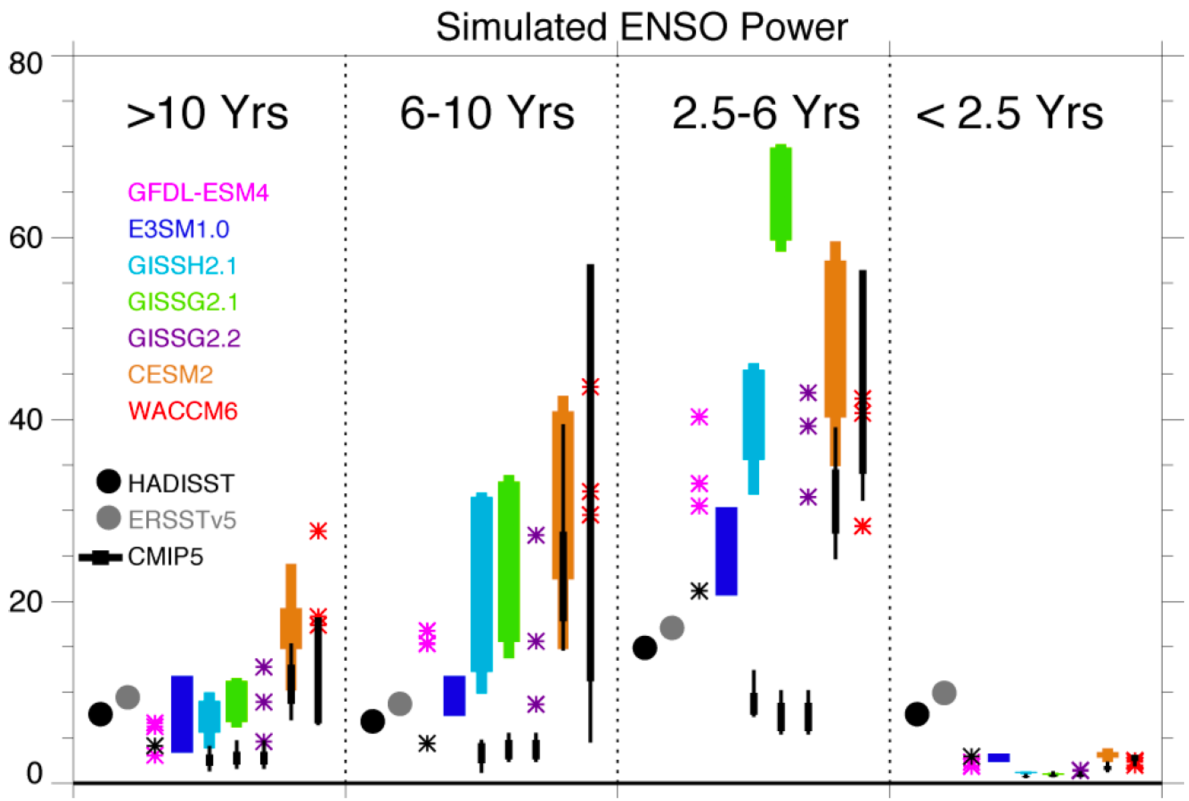
- Composites of El Nino events, compared between ERA20C and the CMIP3/5/6 models, show that on average all models underestimate the strength of ENSO teleconnections

DJF Sea Level Pressure Composited Over El-Nino Events



Tropical Coupled Modes: El Nino-Southern Oscillation

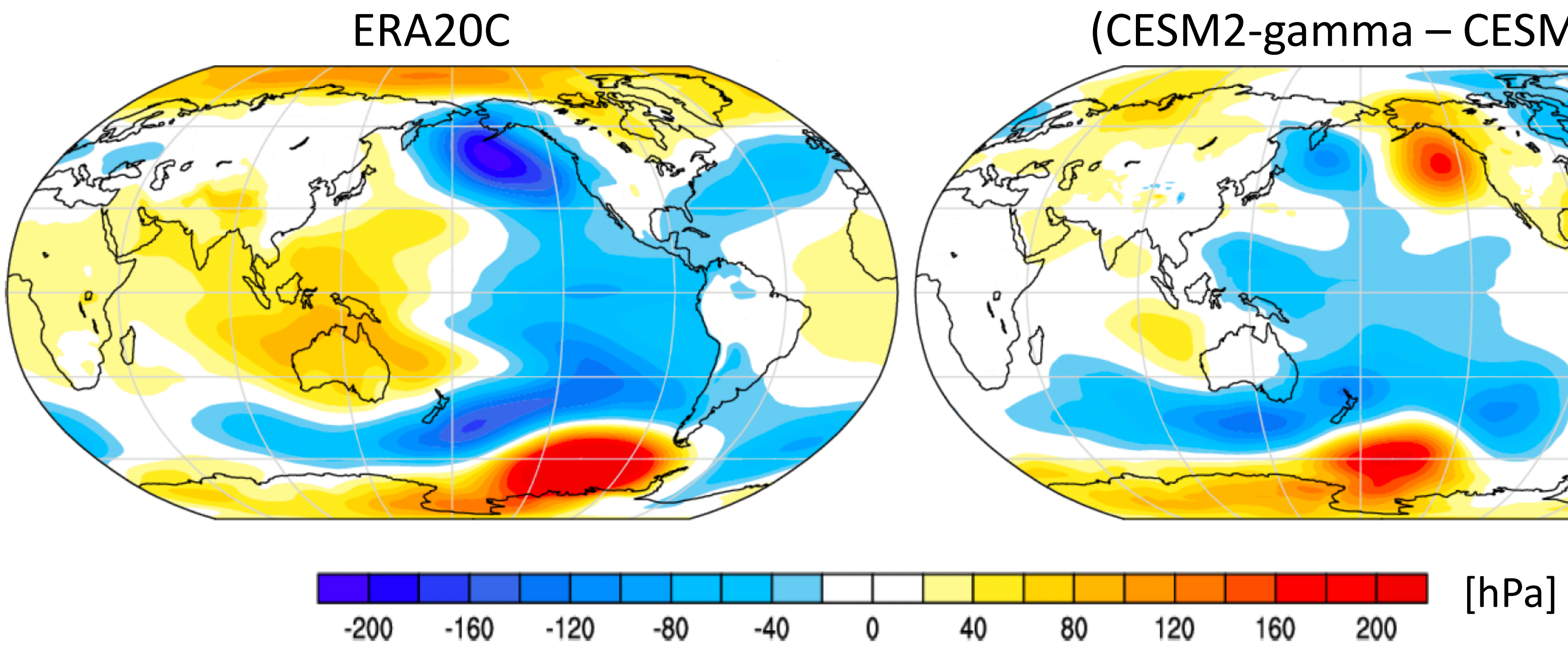
- Comparisons of ENSO spectra (relevant to extreme droughts, floods and other impacts (*Dilley and Keyman (1995)*) reveal high biases at low frequencies in the CMIP6 models. Physically, low biases at high frequencies (< 2.5 years) are associated with models underestimating the transition from El Nino to La Nina.



Tropical Coupled Modes: El Nino-Southern Oscillation

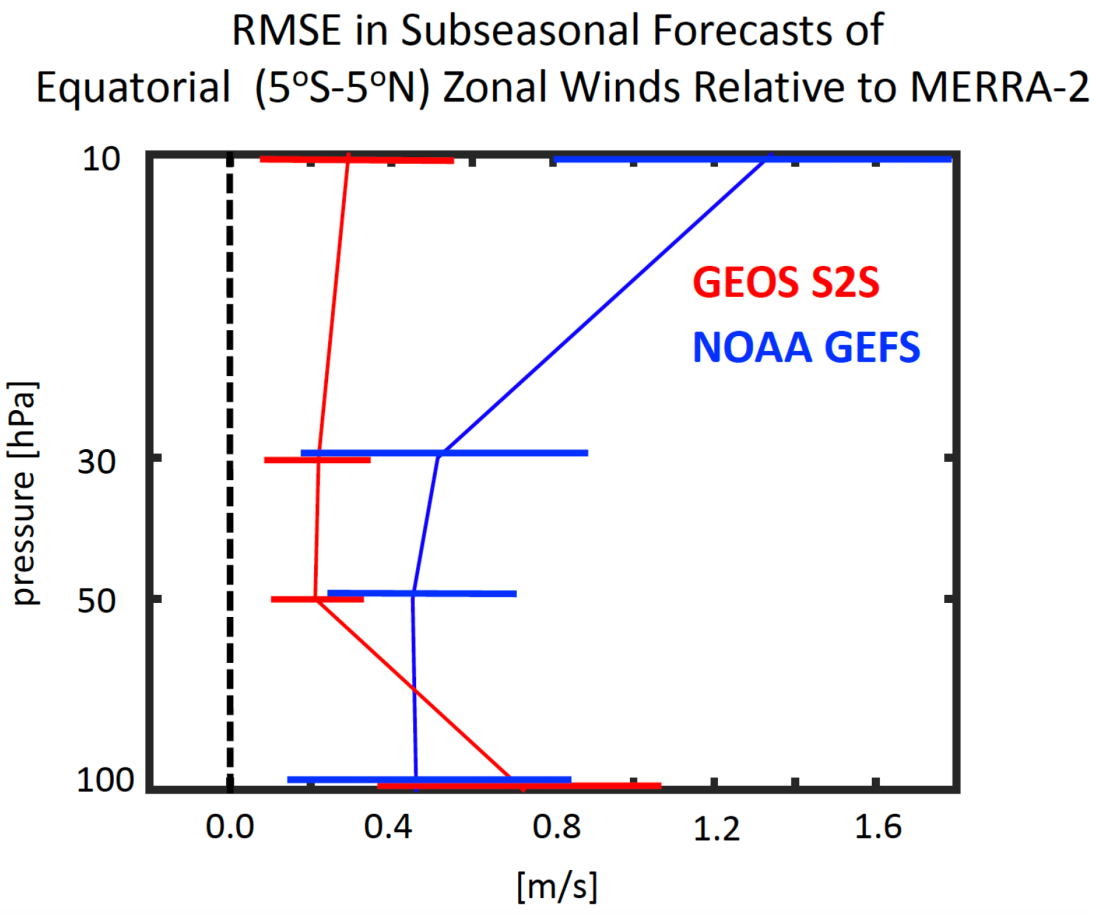
- Intermediary experiments using CESM2 (CESM2-gamma) demonstrate the important influence exerted on ENSO teleconnections by changes in the CLUBB shallow convection scheme, which also affect low cloud feedback responses to climate change (*Gettelman et al. (2019)*).

Regression between SLP and Nino3.4 SST



Analysis of Sub-seasonal Timescales

- Comparison of stratospheric tropical variability on sub-seasonal timescales also suggests some improved skill in models with higher model tops and increased vertical resolution in the upper troposphere/lower stratosphere. However, more rigorous evaluations, sampling a broader range of S2S models are needed before drawing conclusions.



Conclusions

- Funding for the Modes of Variability (MoV) Project enabled a unique collaboration among six U.S. climate modeling groups aimed at identifying robust improvements in recent (CMIP6) models, compared to previous versions.

- This project culminated in the submission of the following manuscript, which is currently under review in Journal of Climate:

Orbe, C., L. Van Roekel, Á. Adames, A. Dezfuli, J. Fasullo, P.J. Gleckler, J. Lee, W. Li, L. Nazarenko, G.A. Schmidt, K. Sperber, and M. Zhao, 2019: Representation of modes of variability in 6 U.S. climate models, *J. Climate*, Under Review.

Conclusions

- Overall, we have shown that for some modes (i.e. MJO, QBO) there has been unequivocal improvement moving from CMIP3/5 to CMIP6. By comparison, for other modes (e.g., NAM, ENSO) the improvement depends on season, measure, modeling group, etc.

- Certain aspects of variability (e.g. ENSO spectra, QBO amplitude) remain challenges for future model development.

- Analysis of intermediary model versions across modeling centers is key for identifying aspects of development (e.g. increased vertical resolution) that may impact performance *consistently* across models.