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

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Background

- A comprehensive understanding of atmospheric modes of variability is important not only for the robust detection and attribution of climate responses to forcings (e.g. CO_2) but also because of their strong influence on regional climate variability and extremes (e.g. *Coppola et al. (2005), Scaife et al. (2008)*).

- Climate models are generally able to simulate the gross features of many but not all modes of variability with some modes (e.g. the Madden Julian Oscillation (MJO) and the Quasi-Biennial Oscillation (QBO)) being poorly represented in models participating in Phase 5 of the Coupled Model Intercomparison Project (CMIP5).

- Since CMIP5 several studies have documented various improvements in the representation of these modes in more recent models (e.g., *Kim et al. (2013), Bushell et al. (2020)*).

Background

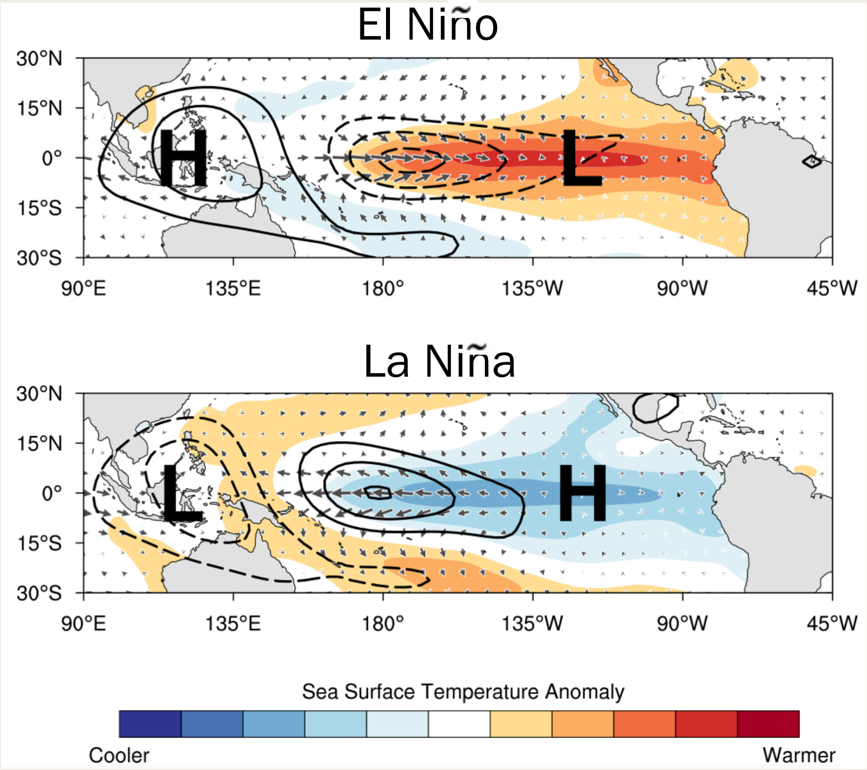
- To this end -- and in wake of the IPCC AR6 WG1 deadline -- a team of scientists from 6 US agencies performed an extensive evaluation of multiple atmospheric modes of variability (MoV) among current CMIP6 U.S. climate models (and a few sub-seasonal forecast models).

- This work, which was supported by NASA, DOE and NOAA, stemmed from the US Climate Modeling Summit held in Washington, DC in April 2019.

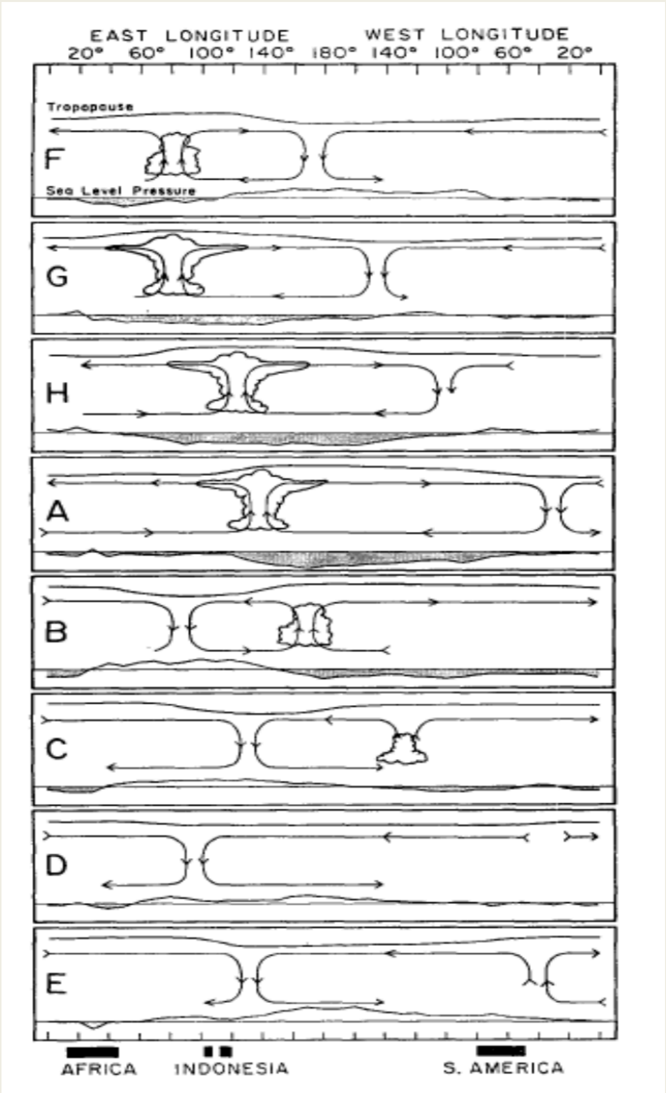
Modeling Center	Model
Department of Energy (DOE)	E3SMv1
NOAA Geophysical Fluid Dynamics Laboratory (GFDL)	CM(3,4)
NASA Goddard Institute for Space Studies (GISS)	GISS E2-R, E2.1-G/H, E2.2-G
NASA Global Modeling and Assimilation Office (GMAO)	GEOS-5
National Center for Atmospheric Research (NCAR)	CESM(1,2)(CAM/WACCM(5,6))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

Background

- Focus was placed on key tropical modes of variability like the El-Niño Southern Oscillation (ENSO) and the Madden-Julian Oscillation (MJO)…



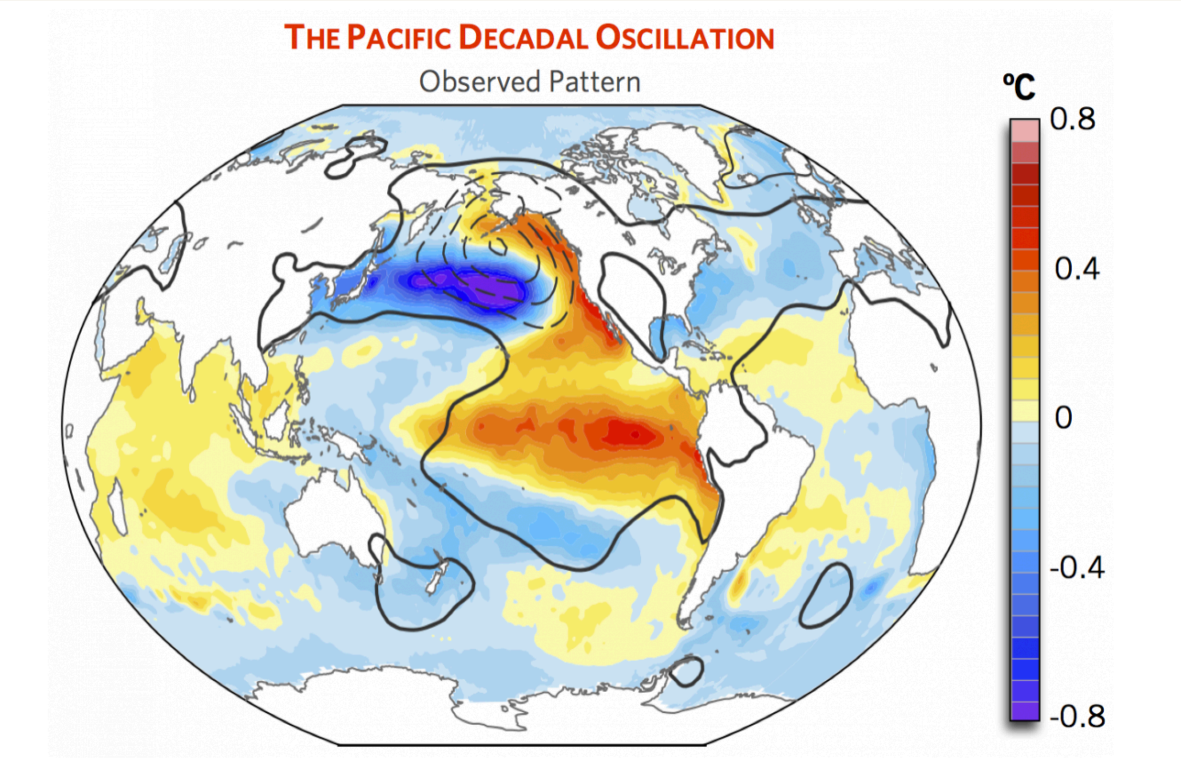
NOAA Physical Sciences Laboratory



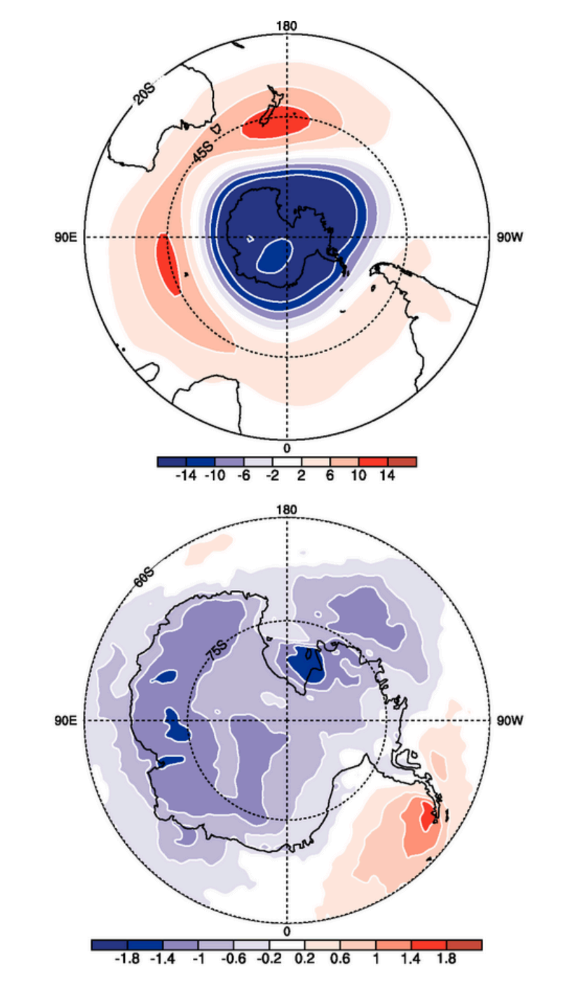
Madden and Julian (1972)

Background

- … as well on extratropical tropospheric modes (e.g. Pacific Decadal Oscillation (PDO) and the Northern and Southern annular modes (NAM, SAM)).



From *Newman et al. (2016)*

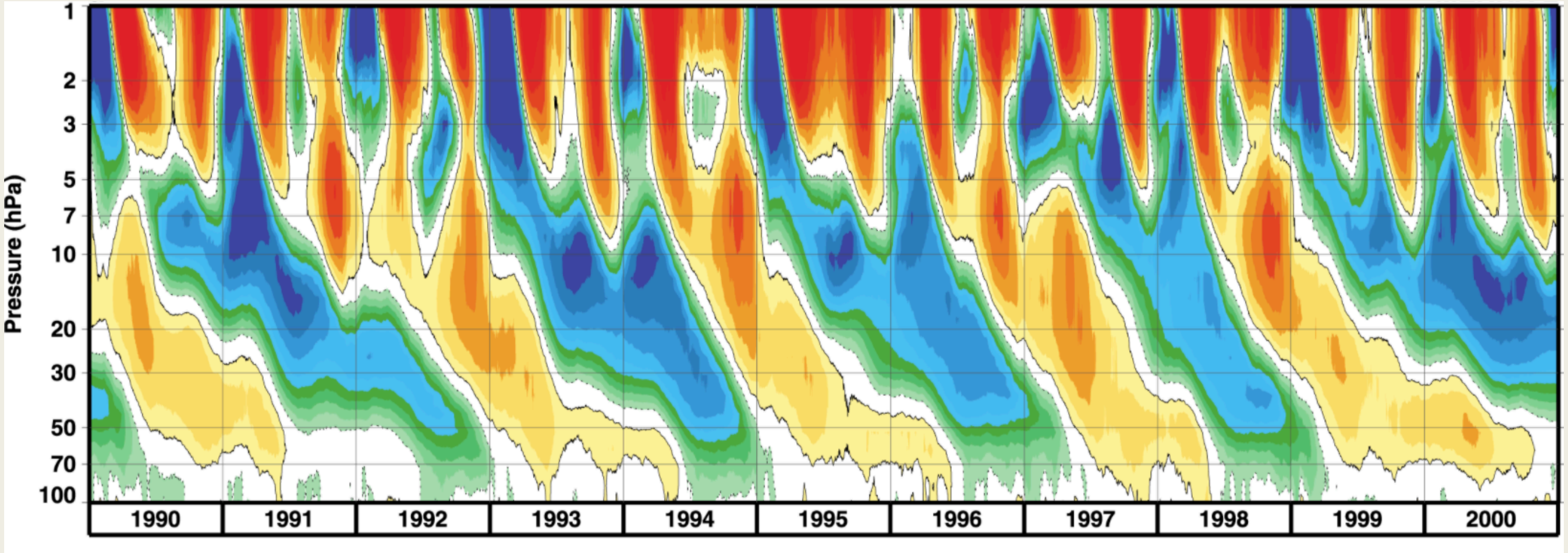


Thompson and Wallace (2000)
Kwok and Comiso (2002b)

Background

- Though mainly tropospheric in scope, our analysis also covered the (stratospheric) Quasi-Biennial Oscillation.

Equatorial Zonal Winds in MERRA-2



Adapted from *Coy et al. (2016)*

Project Goals

The main goals of this effort were oriented around combining:

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

A manuscript summarizing the main results has just been accepted for publication:

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,
Representation of Modes of Variability in 6 U.S. Climate Models, *J. Climate*, Accepted.

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

- Our main focus 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 incorporation of "intermediary" model versions between CMIP5 and CMIP6 was important for identifying 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 Validation: Observations and Reanalyses

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

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

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)*)

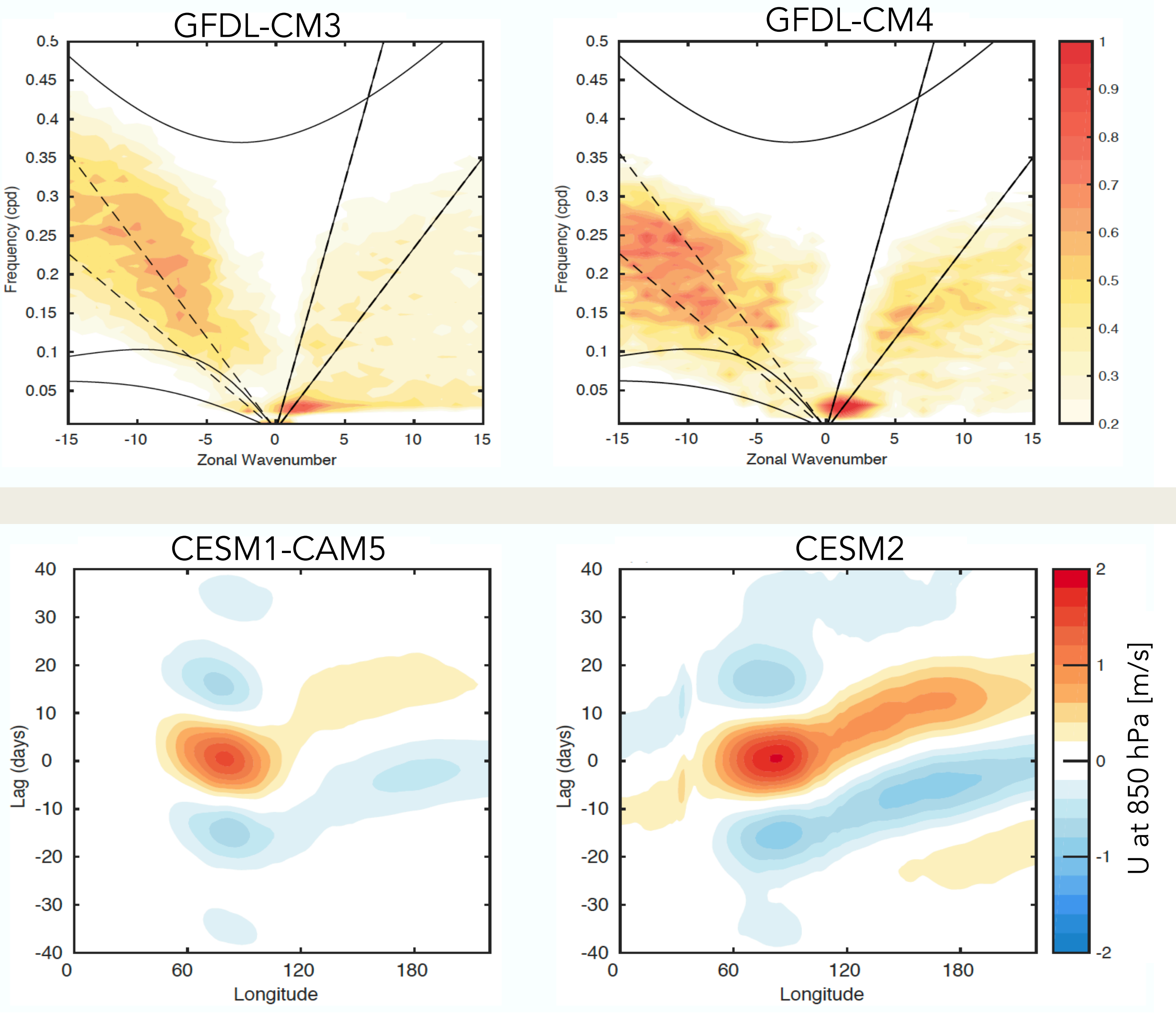
- Tropical Coupled Variability (ENSO, MJO):
  -Climate Variability Diagnostics Package (CVDP, *Phillips et al. (2014)*)
  -MJO global model evaluation measures (*Jiang et al. (2015)*)

- Stratospheric Variability (QBO):
  -Metrics from *Schenzinger et al. (2017)* as applied in the recent SPARC QBO Initiative (QBOi) (*Butchart et al. (2018), Bushell et al. (2020)*)

Main Findings: Overall Performance

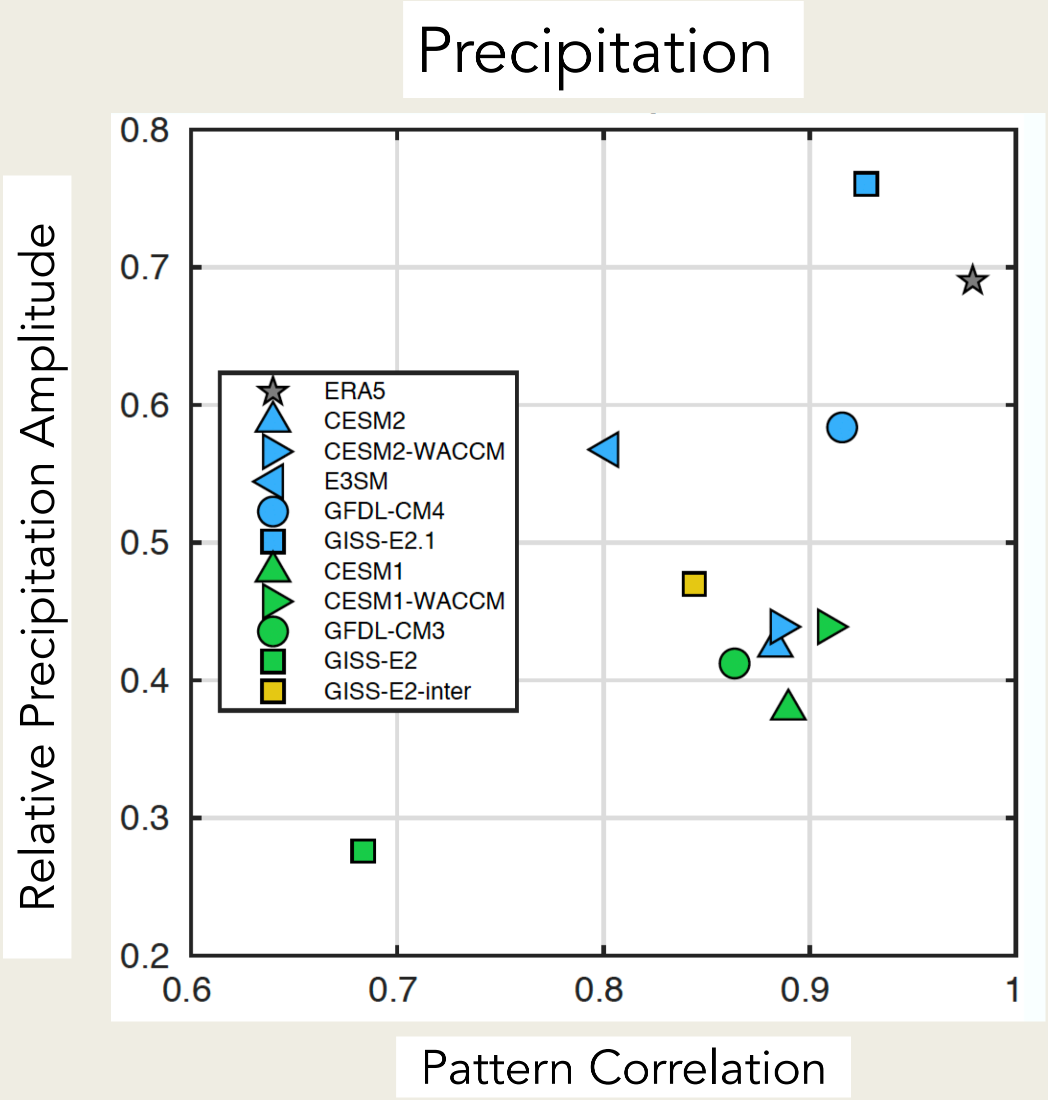
- For some modes (i.e. MJO, QBO) there is unequivocal improvement moving from CMIP5 to CMIP6.
- For other modes (e.g., NAM, SAM, ENSO) improvement in model performance is more clear when conditioning on season, measure, etc. Thus, robust improvements in the representation of these modes will remain important challenges for future model development.
- The incorporation of intermediary model versions helped in identifying which changes in model development (e.g. increased vertical resolution, convective parameterization changes) impact performance *consistently* across models.

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.

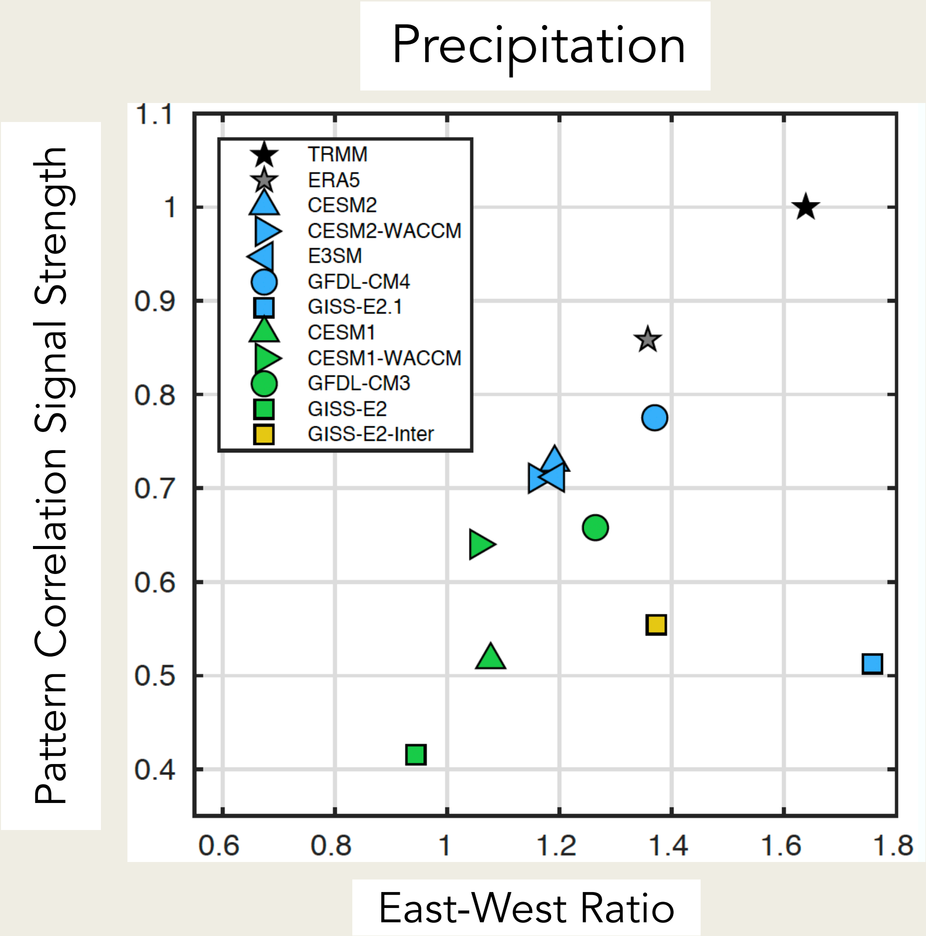
Madden-Julian Oscillation

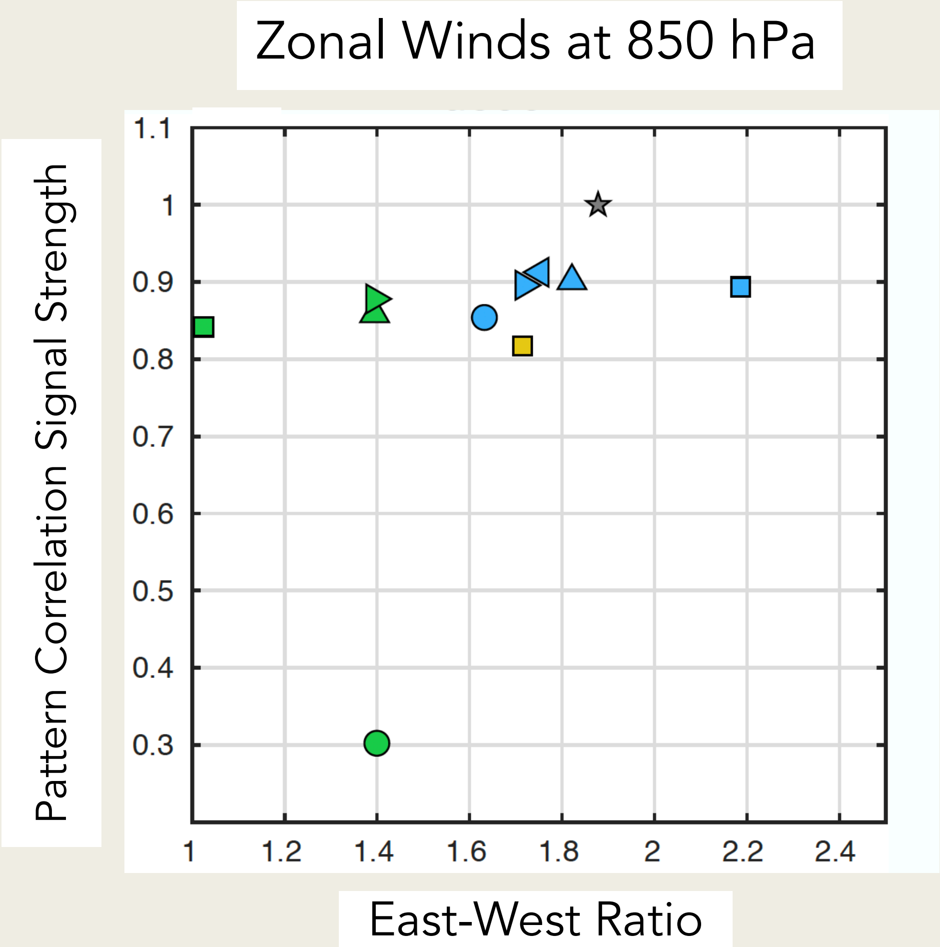


- Clear improvement in MJO performance moving from CMIP5 to CMIP6. This is evident in pattern correlations of precipitation from the MoV models versus observations from TRMM v3b42 (left). Correlations based on other measures (e.g. zonal winds at 850 mb) suggest a similar story.

Madden-Julian Oscillation

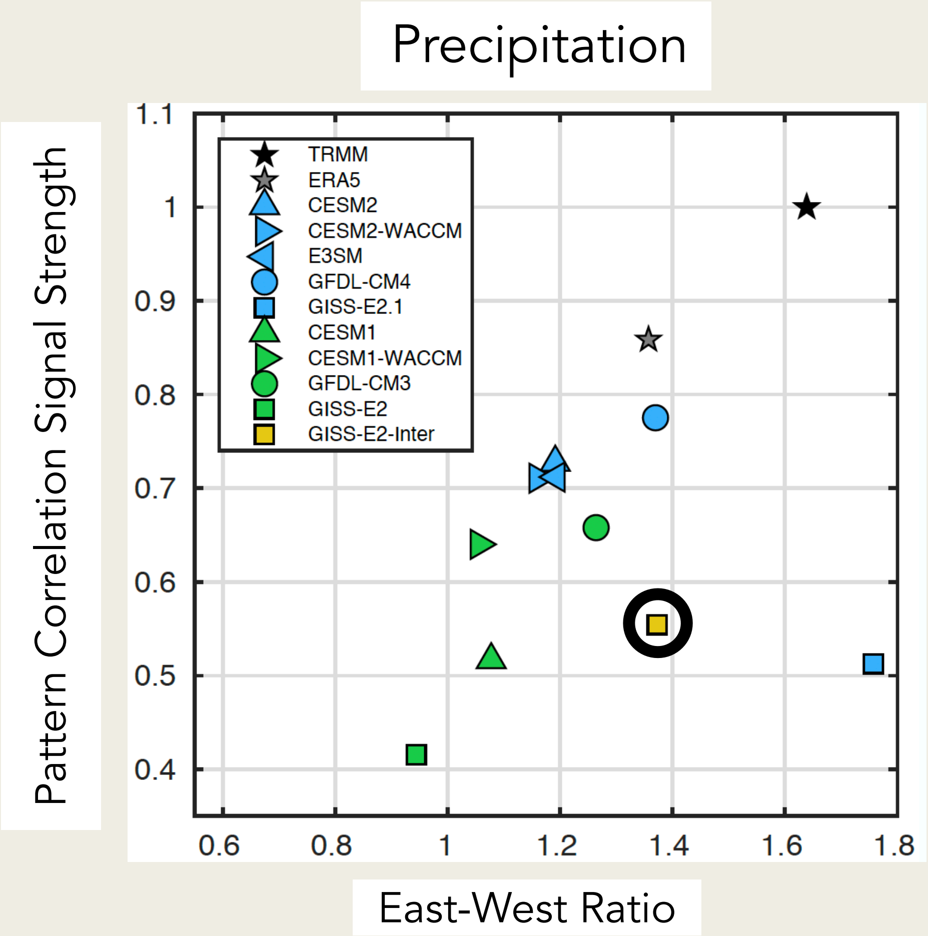
- Evaluations of higher order (more "process-based") measures also point to an improved representation in more recent model versions.

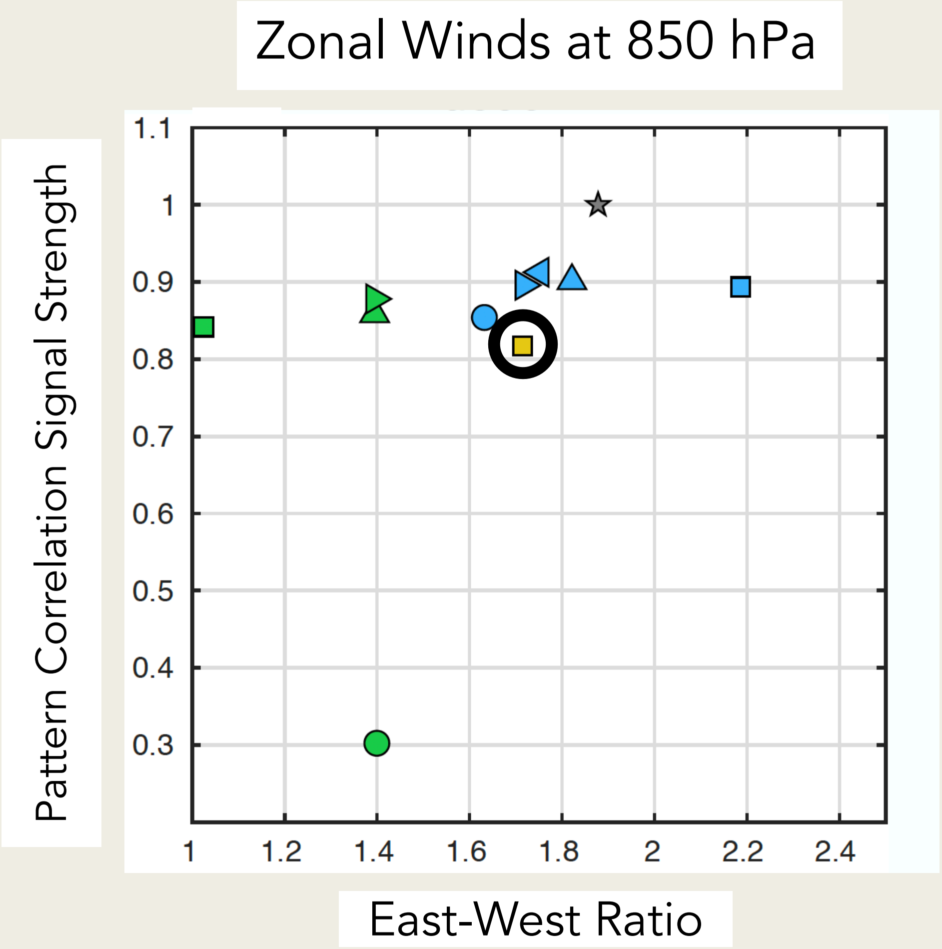




Madden-Julian Oscillation

- 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), Kelley et al. (2020)*).

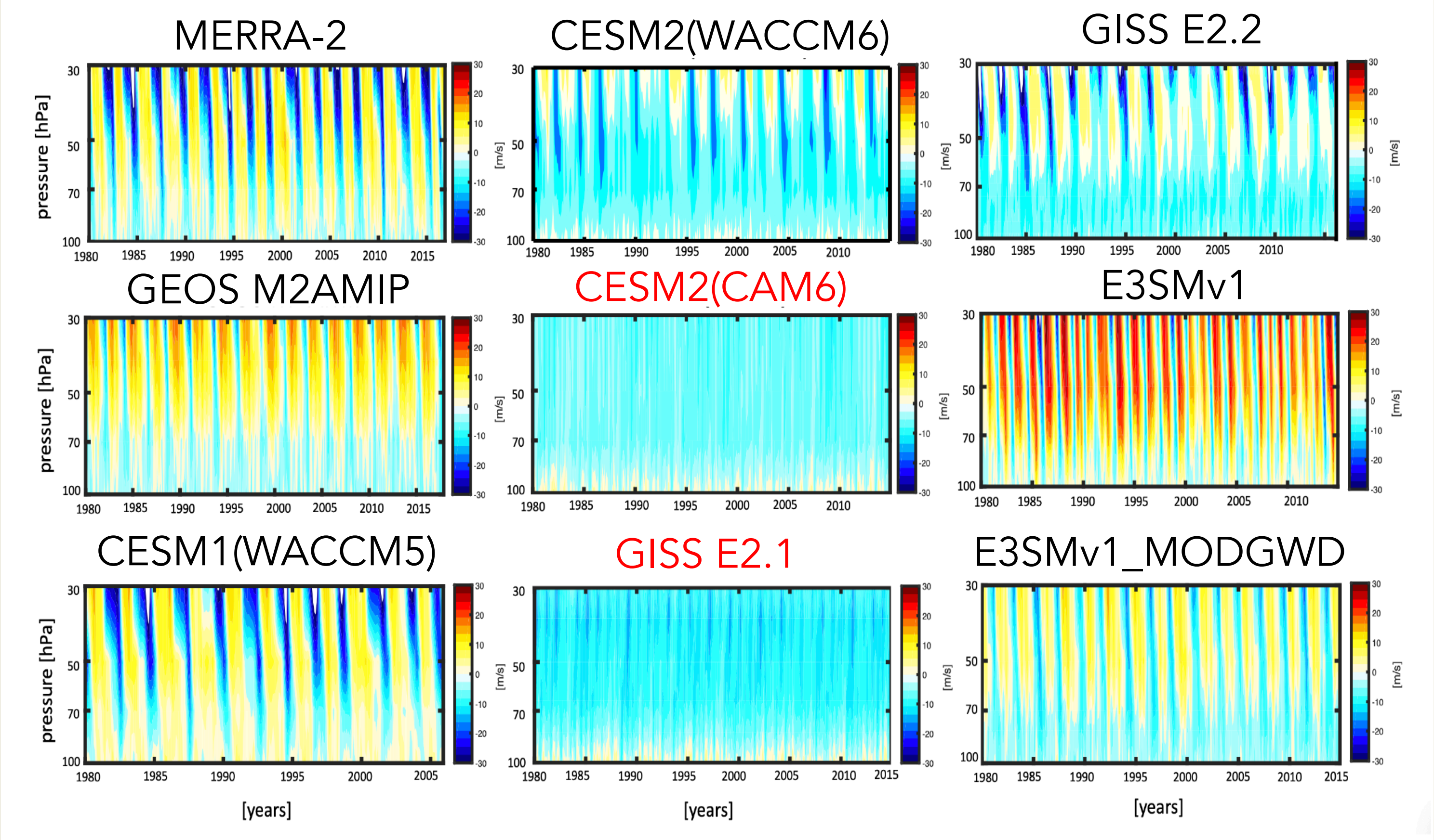




Quasi-Biennial Oscillation

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

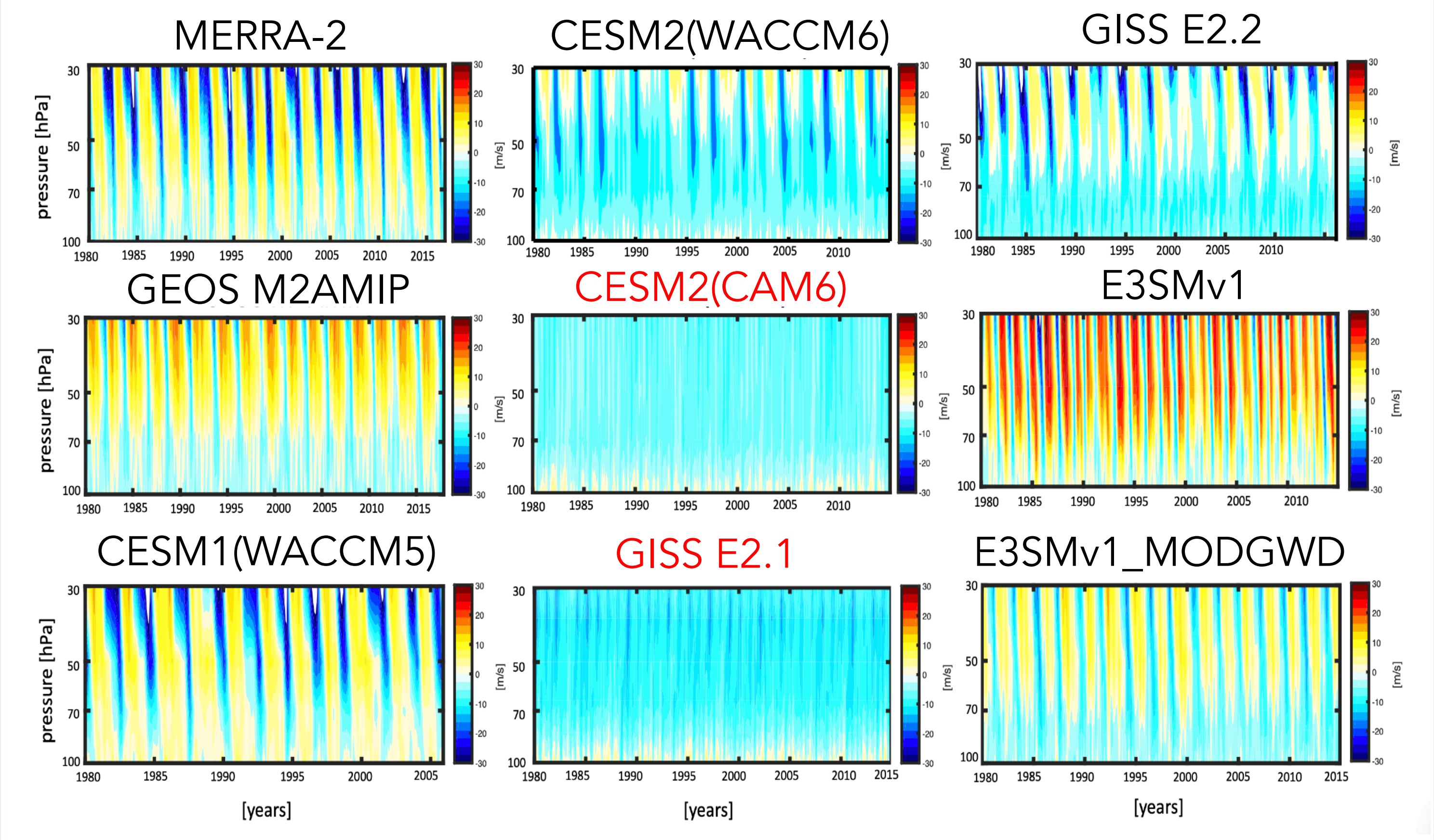
Equatorial Zonal Mean Zonal Winds (1980-2015)



Quasi-Biennial Oscillation

- The overall improvement in QBO representation is consistent with increases in vertical resolution and model top.
- In addition, the incorporation (and tuning) of source-based non-orographic gravity wave drag parameterizations improve the representation of QBO period.

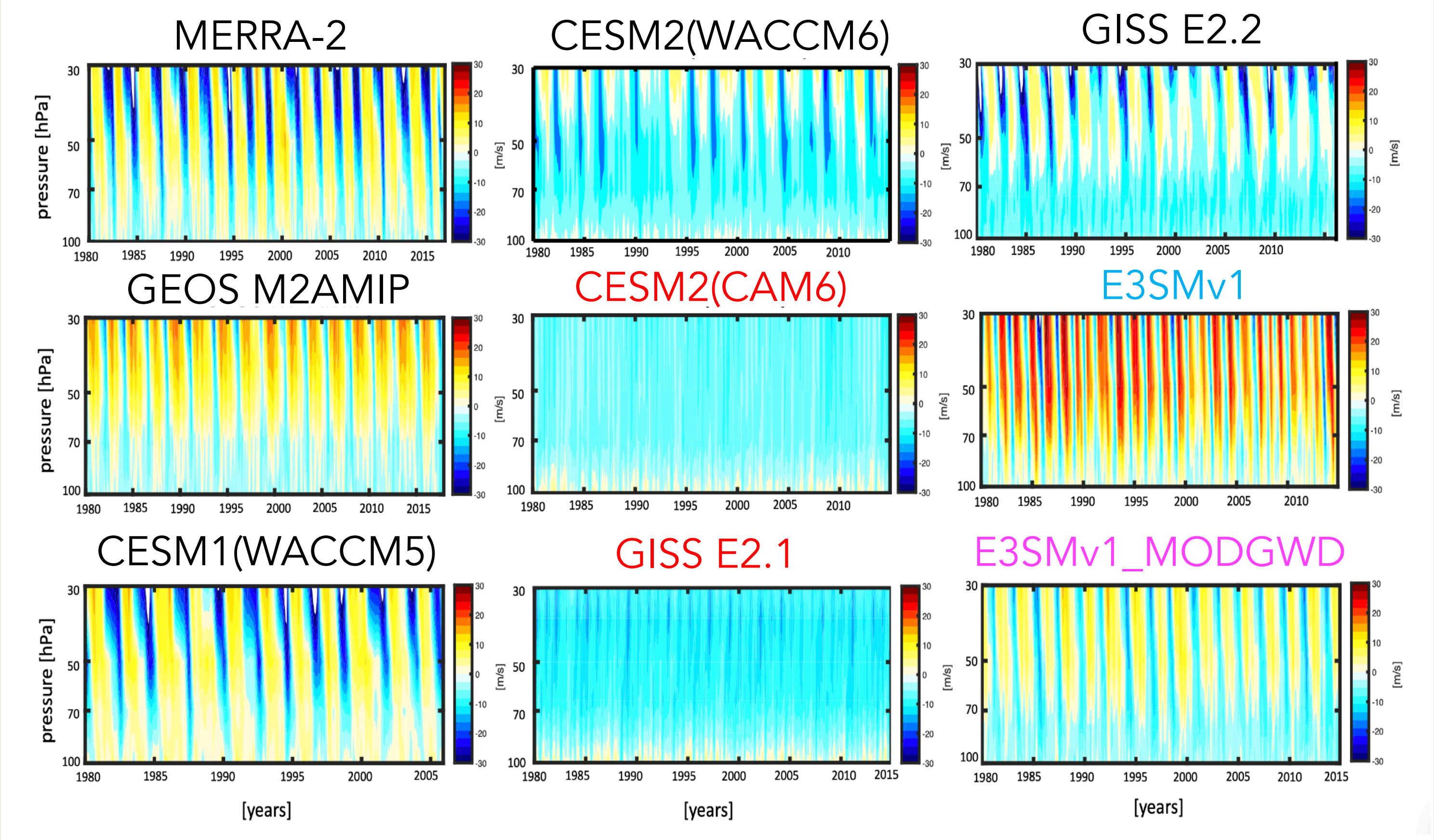
Equatorial Zonal Mean Zonal Winds (1980-2015)



Quasi-Biennial Oscillation

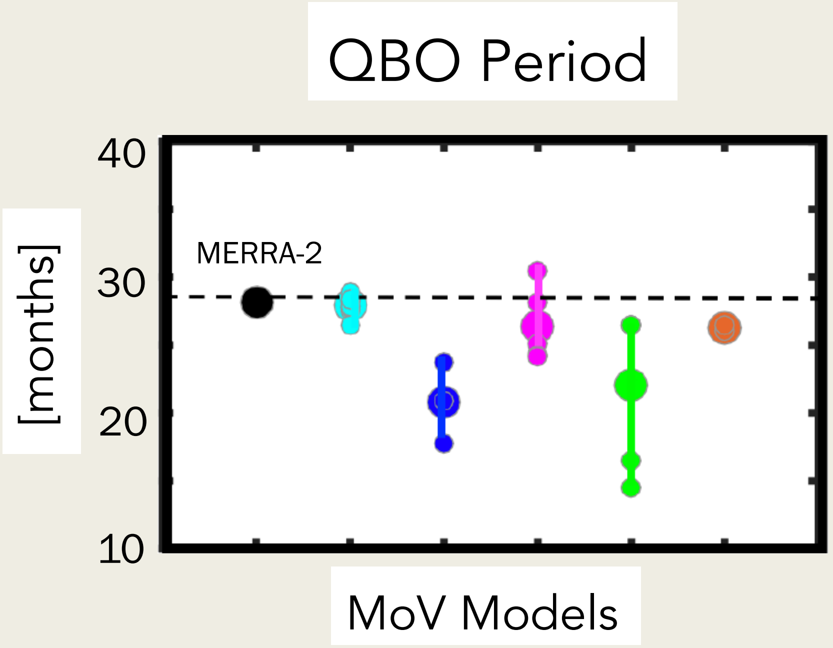
- In particular, comparisons of intermediary version E3SMv1_MODGWD with E3SMv1 unambiguously demonstrates the improvement in QBO period in response to changes to the efficiency with which (parameterized) convection contributes to non-orographic gravity wave momentum flux (*Richter et al. (2019)*).

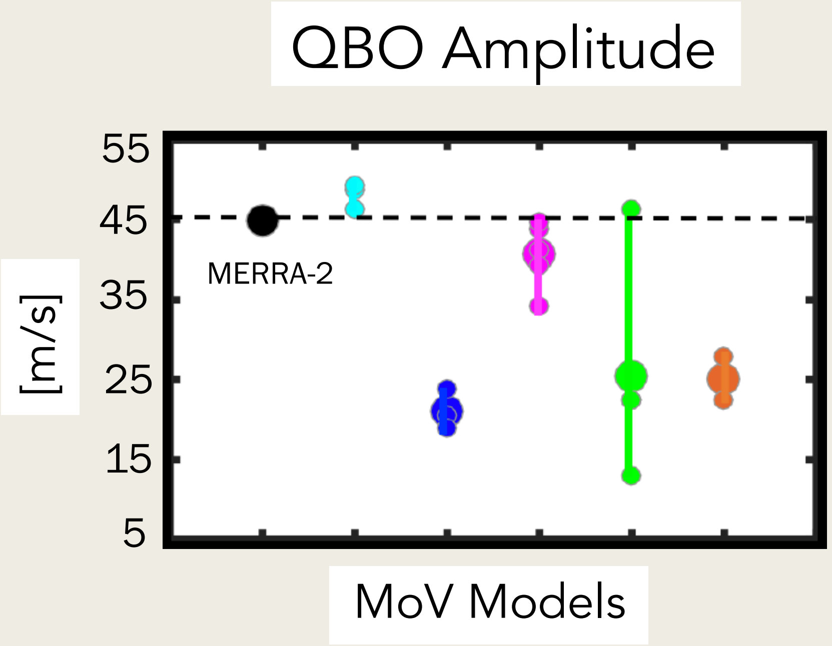
Equatorial Zonal Mean Zonal Winds (1980-2015)



Quasi-Biennial Oscillation

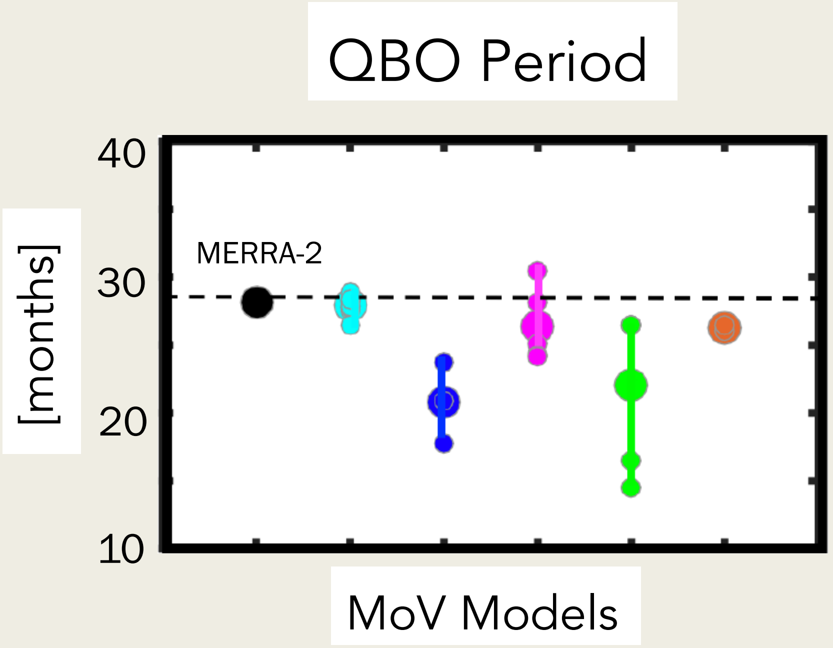
- Nonetheless, while the QBO period can be explicitly tuned in models (provided sufficient vertical resolution), other features like the QBO amplitude are difficult to represent and remain key challenges in QBO modeling.

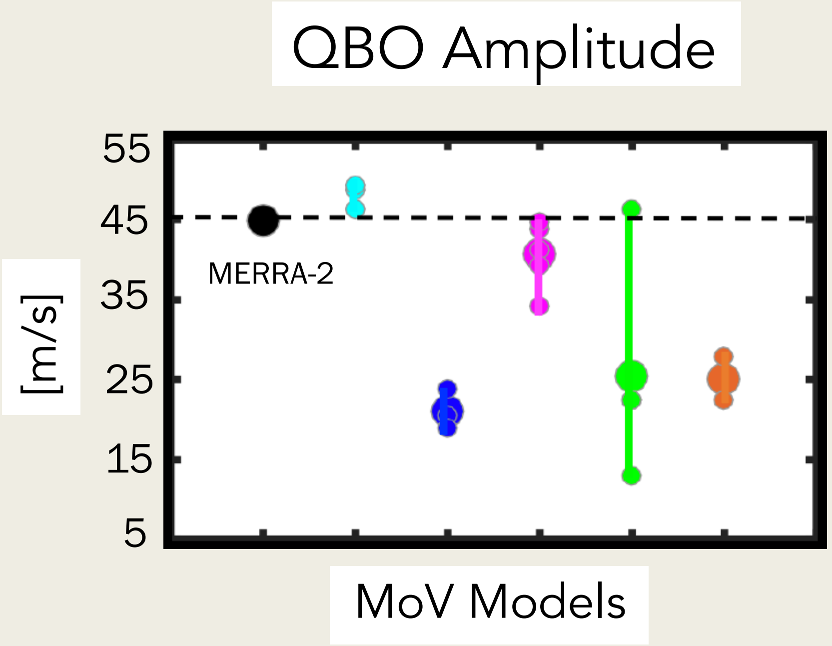




Quasi-Biennial Oscillation

- In particular, the MoV models consistently underestimate the amplitude of the QBO especially in the lower stratosphere (> 50 hPa), a bias more broadly exhibited in the QBOi models (*Bushell et al. (2020)*) and in other analyses of the CMIP6 models (*Butchart et al. (2020)*).

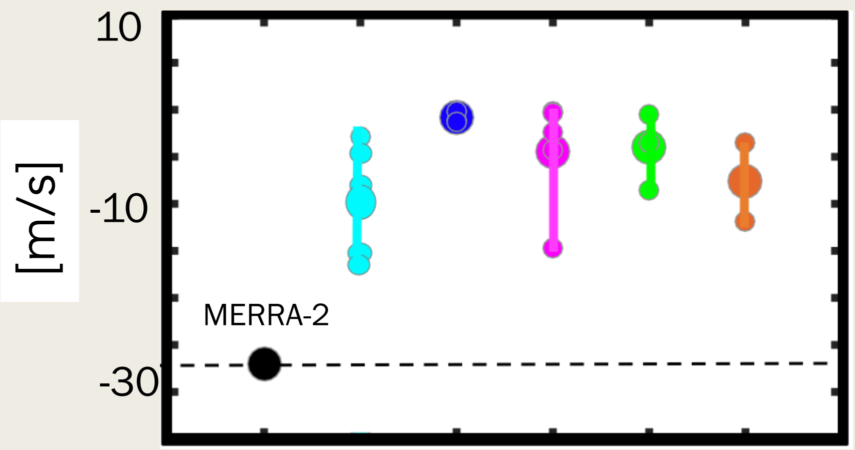




Quasi-Biennial Oscillation

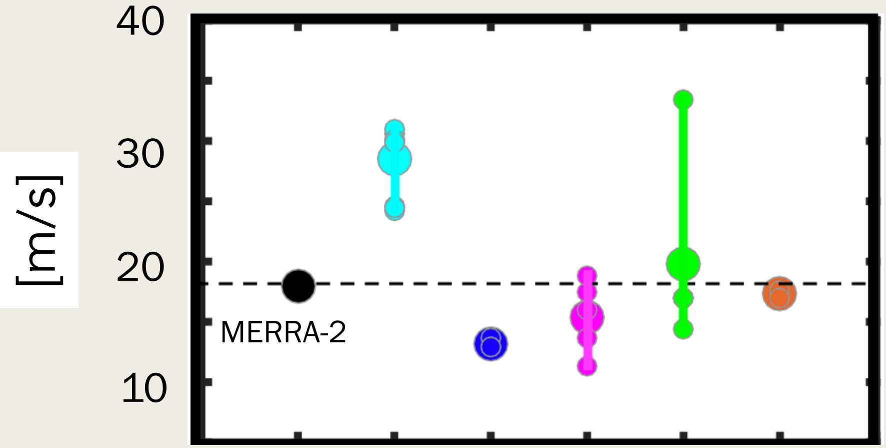
- Further decomposition of the QBO into its westerly versus easterly components shows that most of the amplitude bias reflects a too weak bias in the easterly (westward) component. Similar biases are exhibited in the QBOi models (*Bushell et al. (2020)*).

Maximum Easterly QBO Amplitude



MoV Models

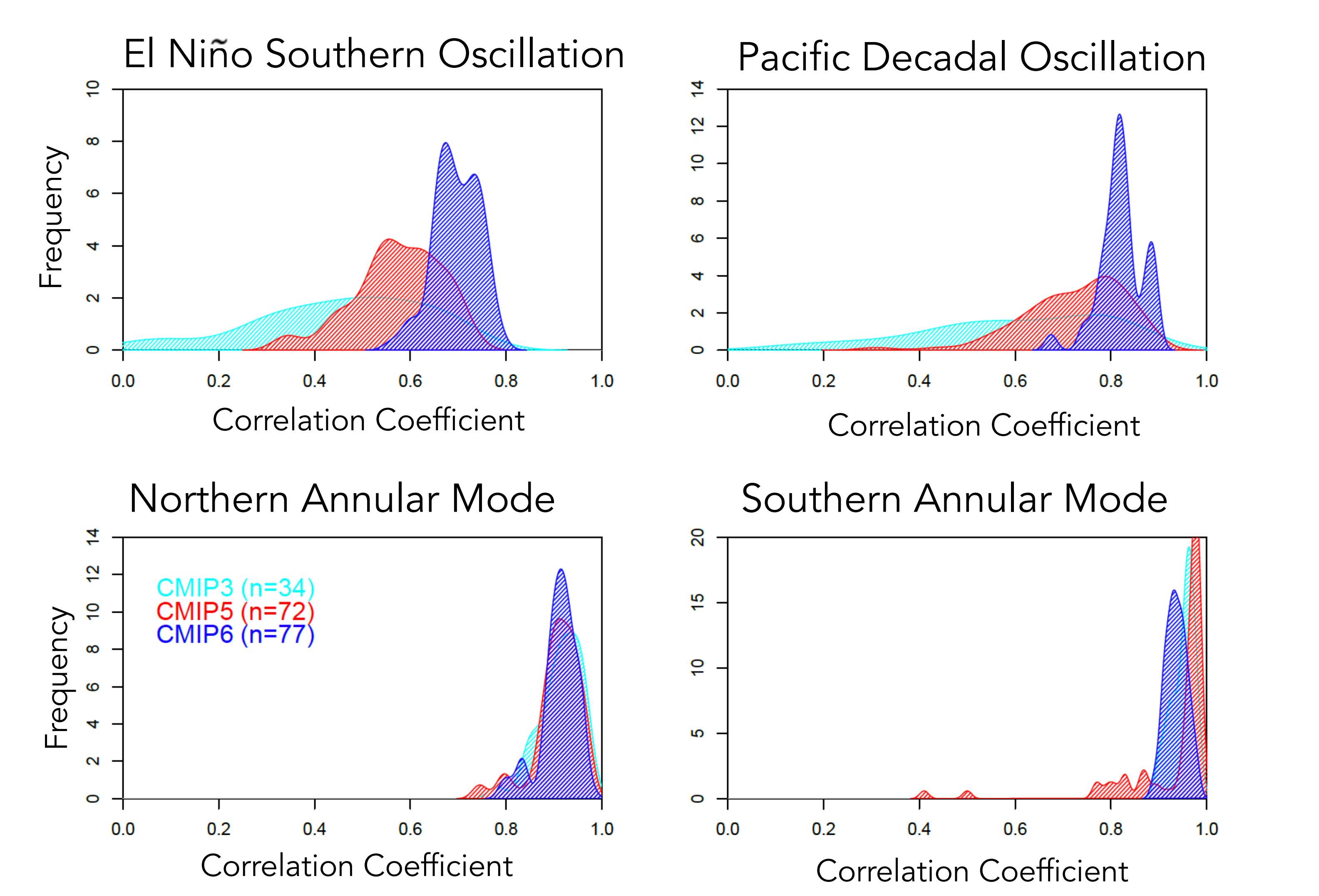
Maximum Westerly QBO Amplitude



MoV Models

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 CMIP Phases.



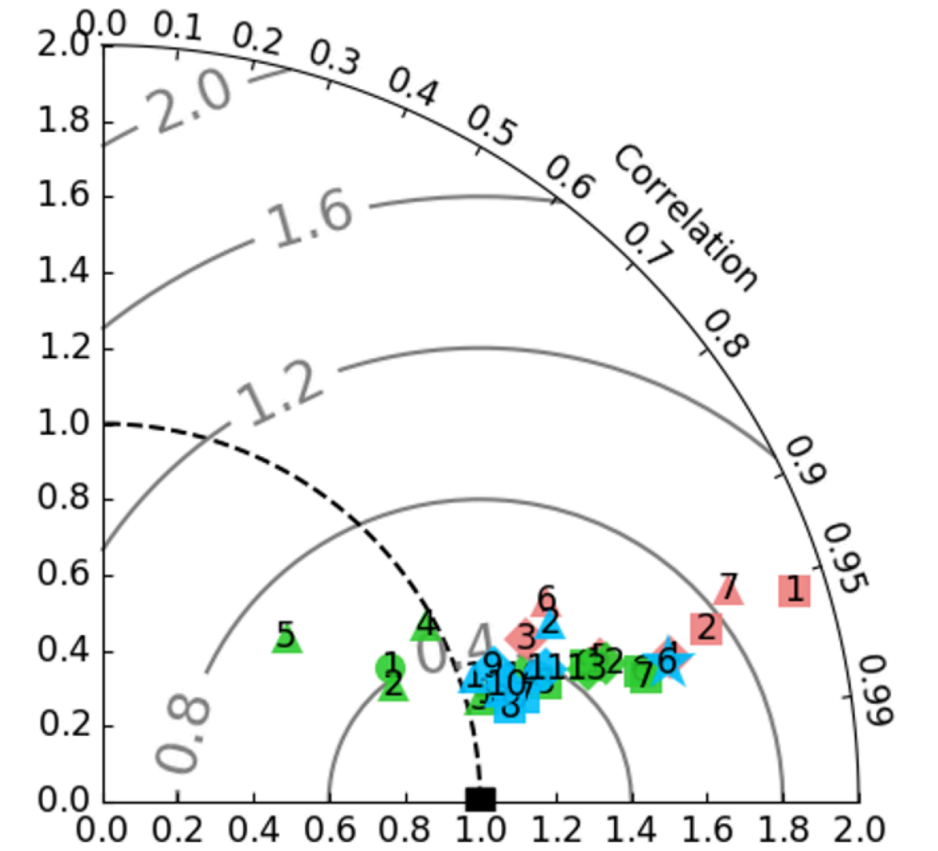
Extratropical Coupled Modes of Tropospheric Variability

- However, upon closer inspection several ``improvements” in extratropical modes are more nuanced, compared to the MJO and the QBO.

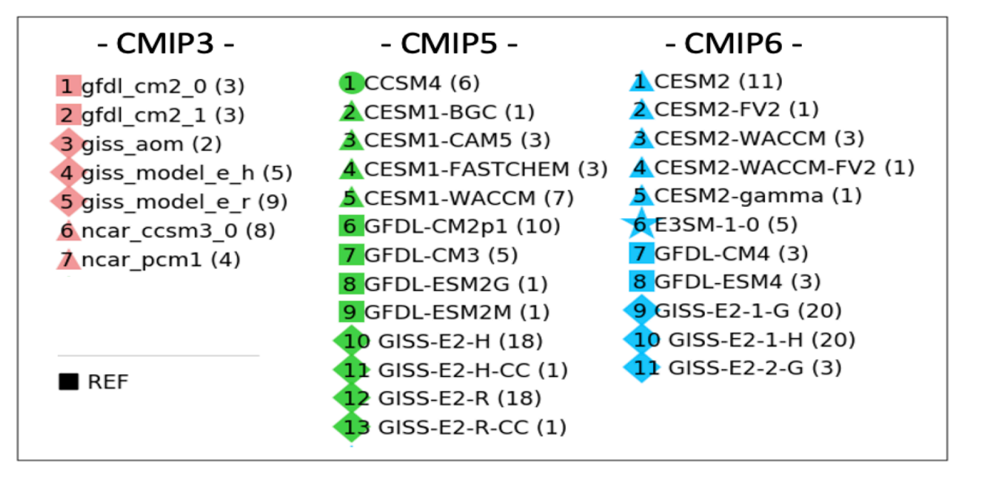
Southern Annular Mode

- In particular, while for some modes during certain seasons (e.g. austral summer SAM) model performance has improved across modeling center (right)…

December-January-February SAM



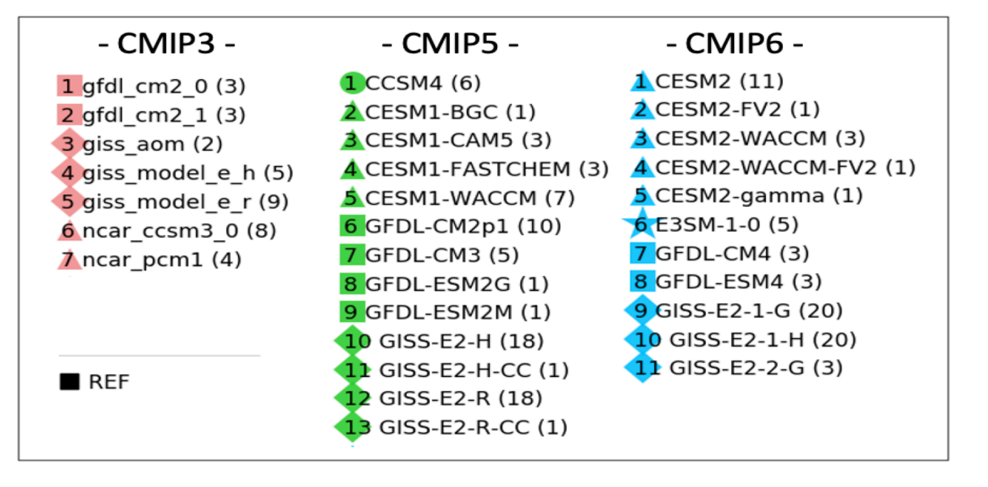
Standard Deviation (Normalized)

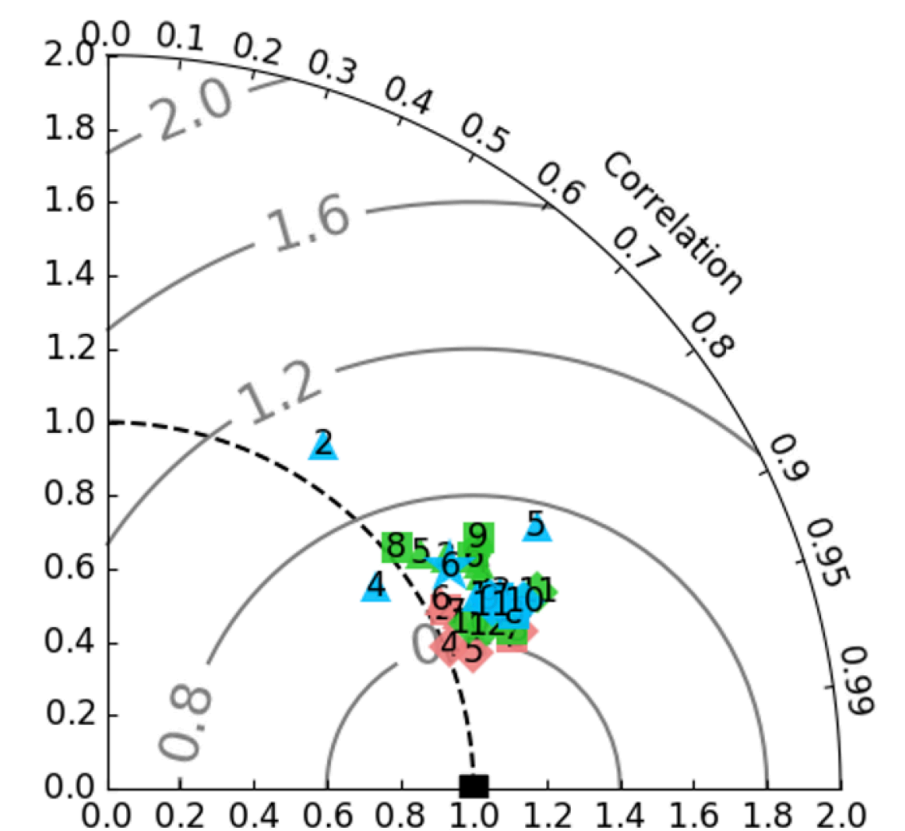


Southern Annular Mode

- … for other seasons (e.g. austral winter SAM) improvements are not as clear.

June-July-August SAM





Standard Deviation (Normalized)

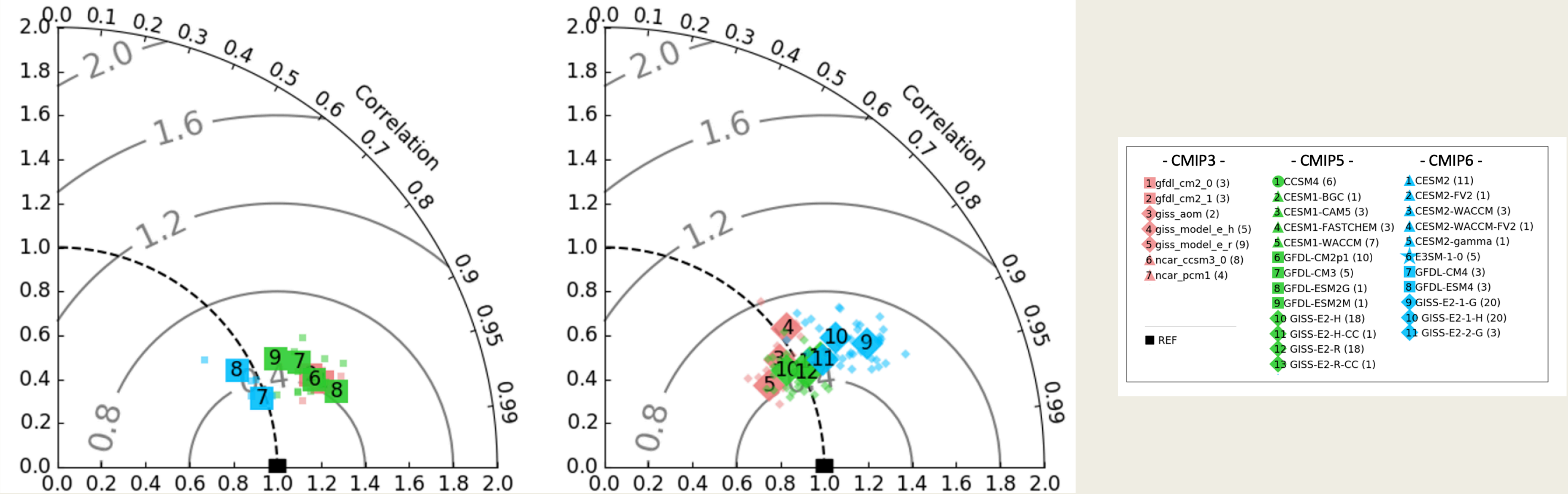
Northern Annular Mode

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

December-January-February NAM

GFDL Models

GISS Models



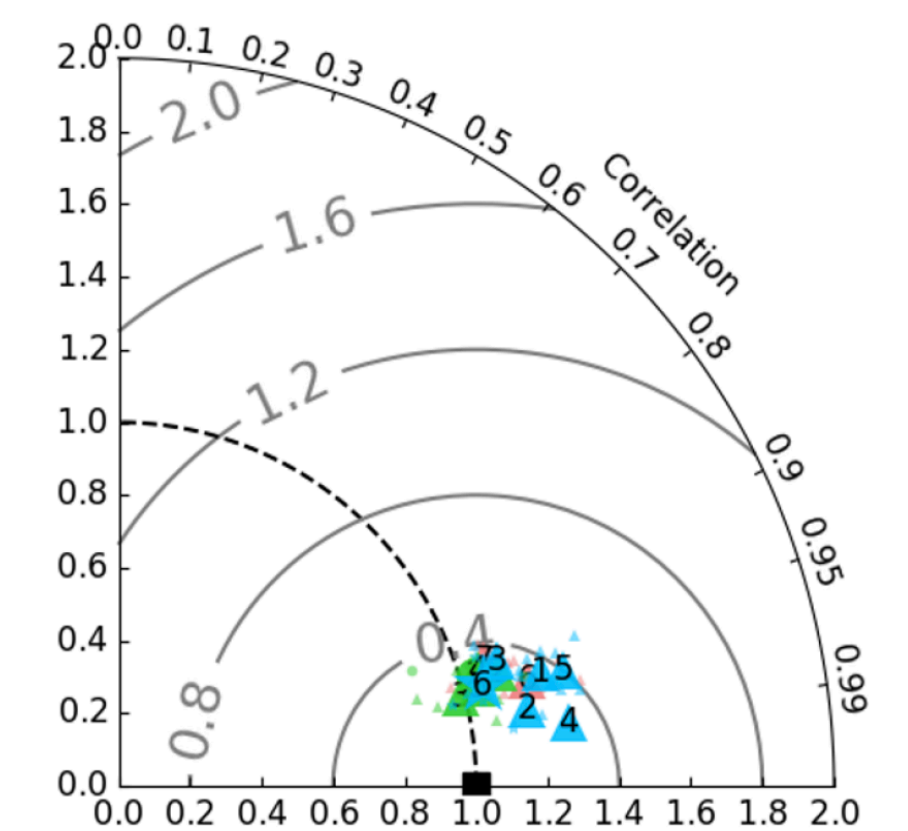
Standard Deviation (Normalized)

Standard Deviation (Normalized)

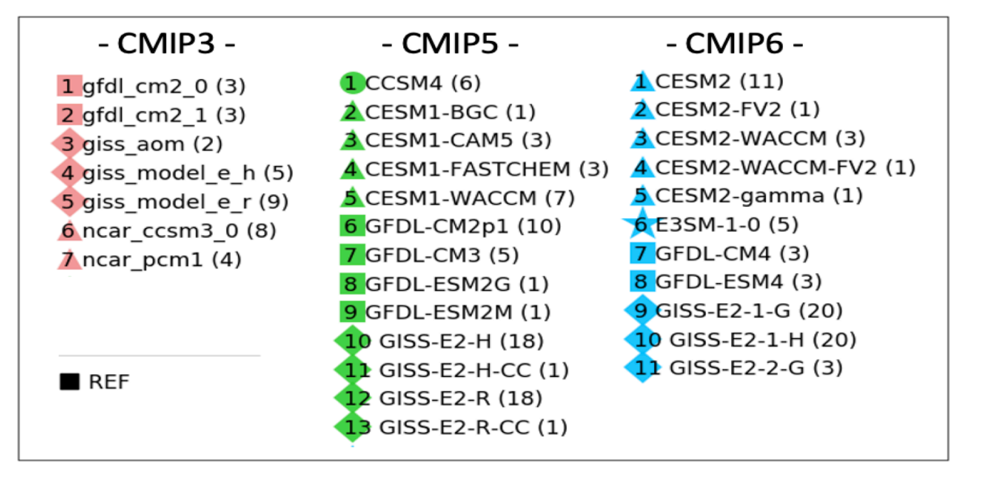
North Atlantic Oscillation

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

December-January-February NAO

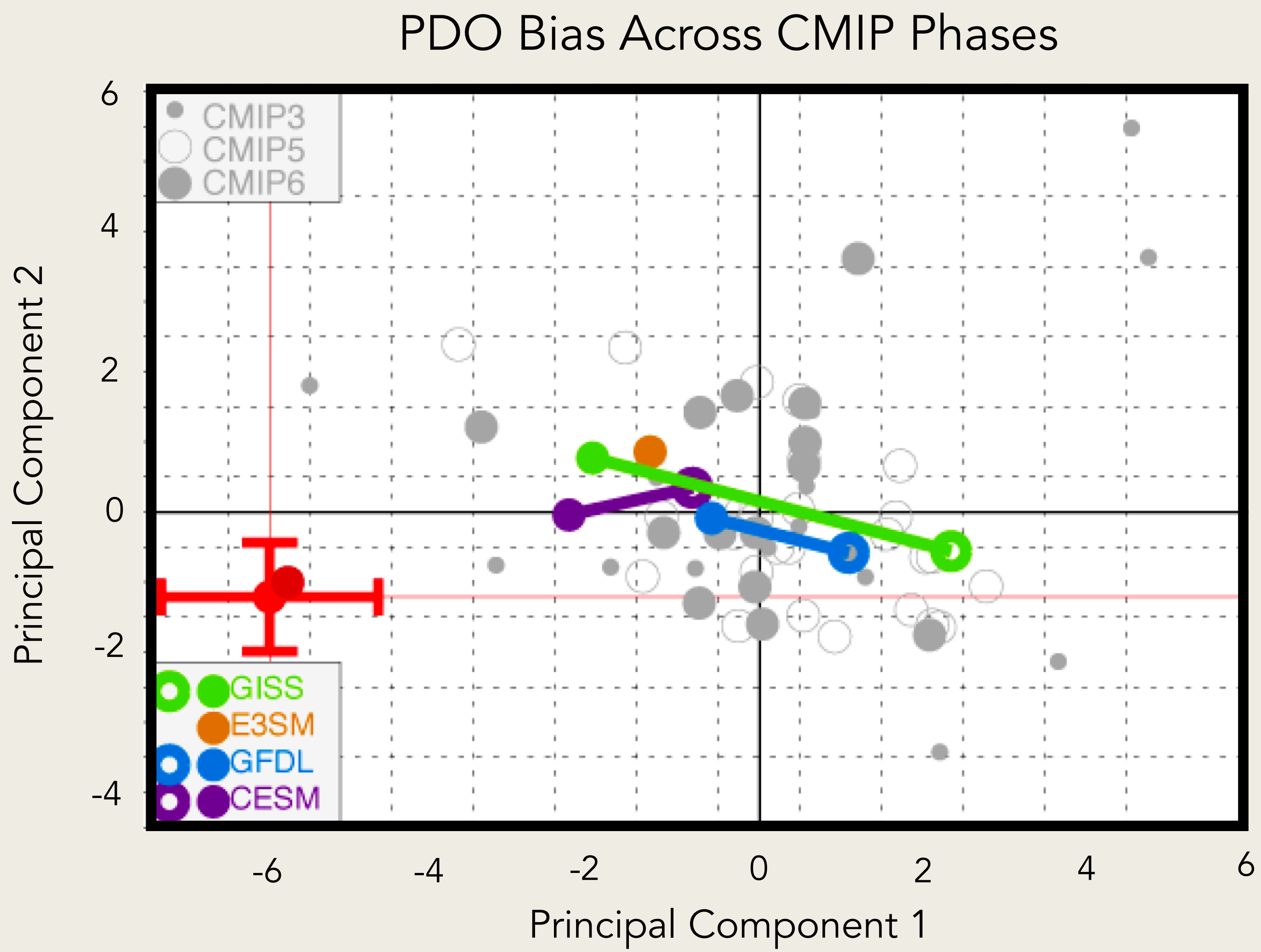


Standard Deviation (Normalized)



Pacific Decadal Oscillation

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

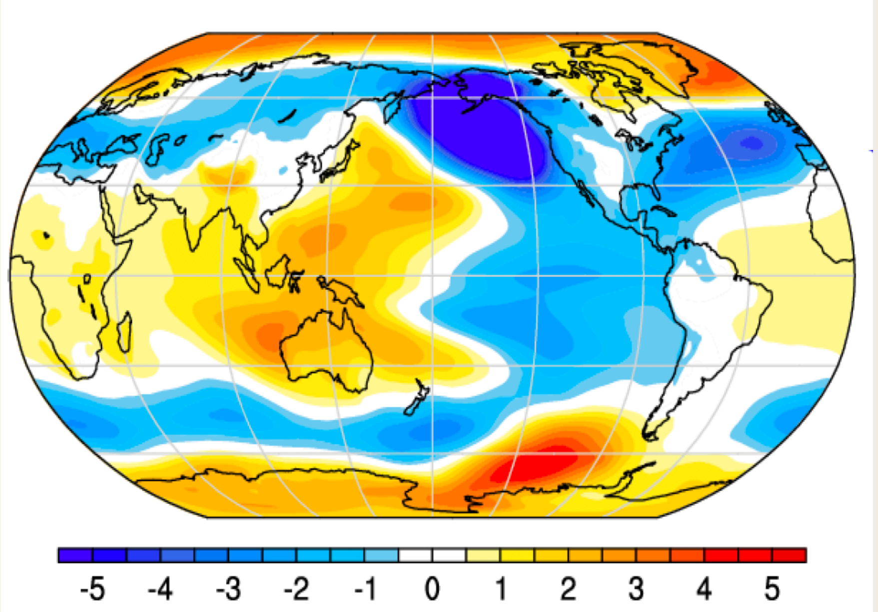


Tropical Coupled Modes: El Niño-Southern Oscillation

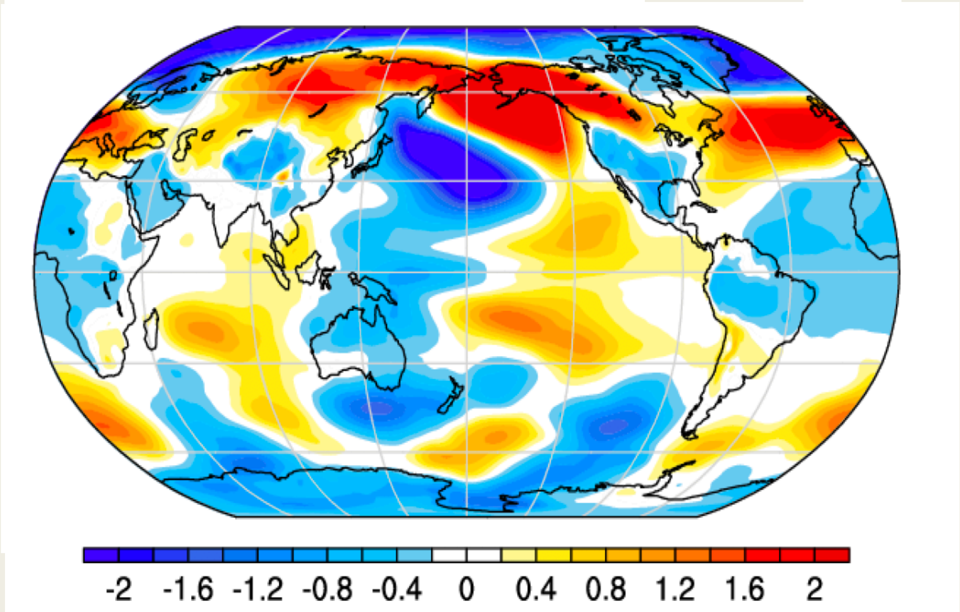
- Composites of El Niño events, compared between ERA20C and the CMIP3/5/6 models, show that on average all models underestimate the strength of ENSO teleconnections.

DJF Sea Level Pressure (hPa) Composited Over El-Niño Events

ERA20C



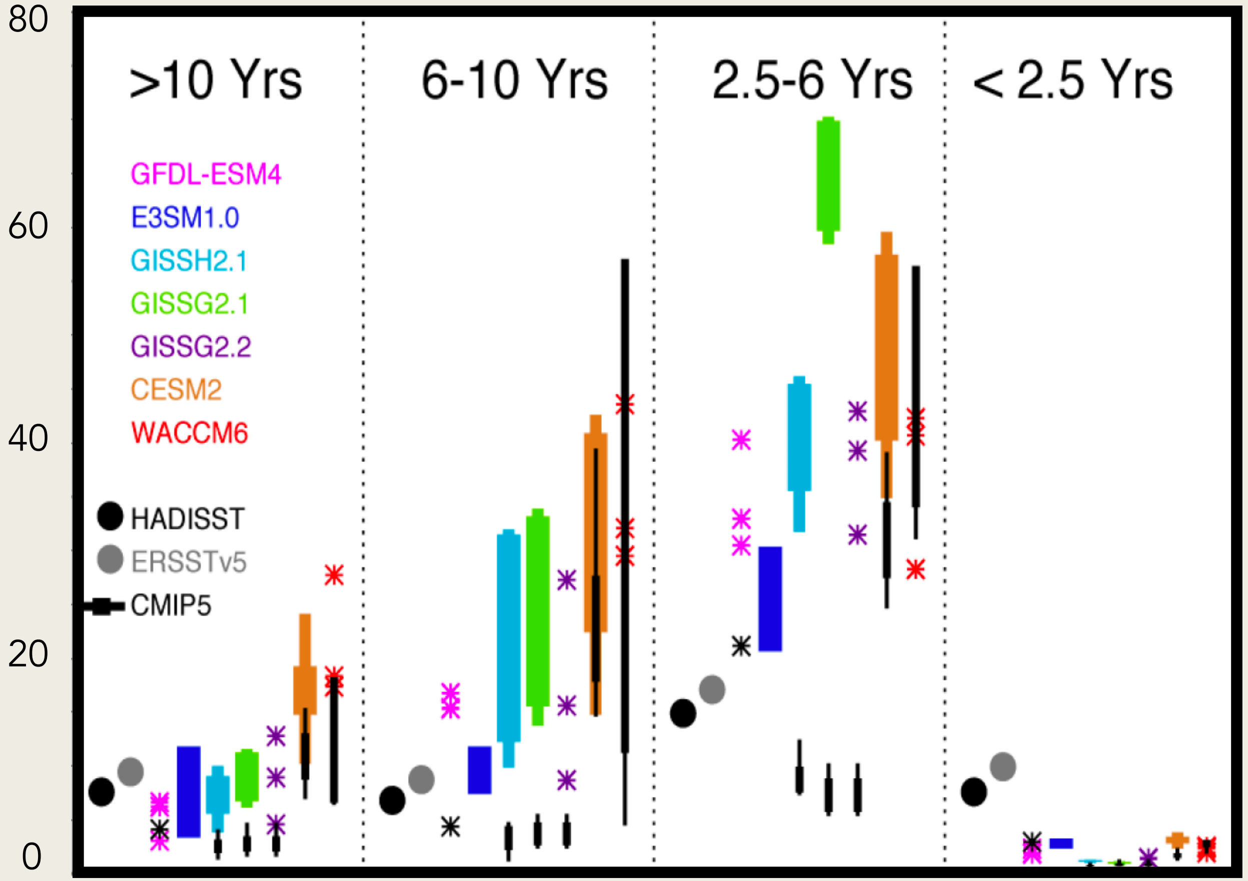
Mean CMIP(3/5/6) Bias Relative to ERA20C



Tropical Coupled Modes: El Niño-Southern Oscillation

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

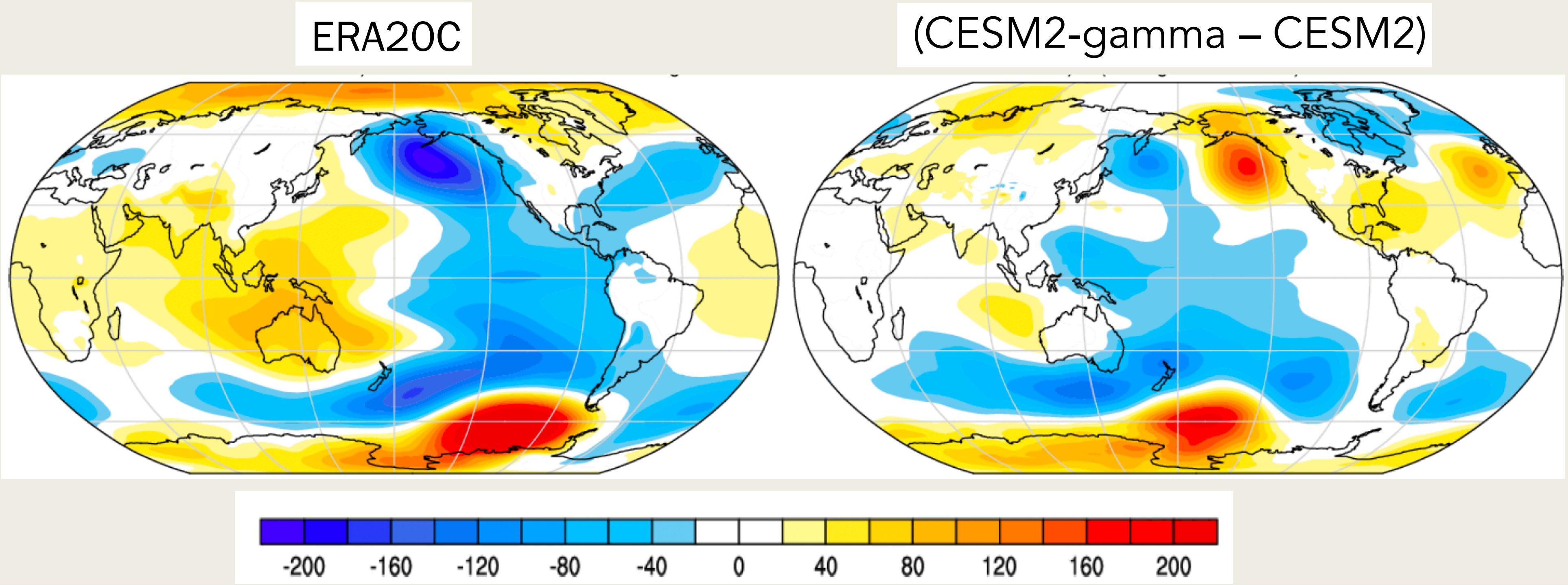
Representation of ENSO Power Across CMIP Phases



Tropical Coupled Modes: El Niño-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)*).

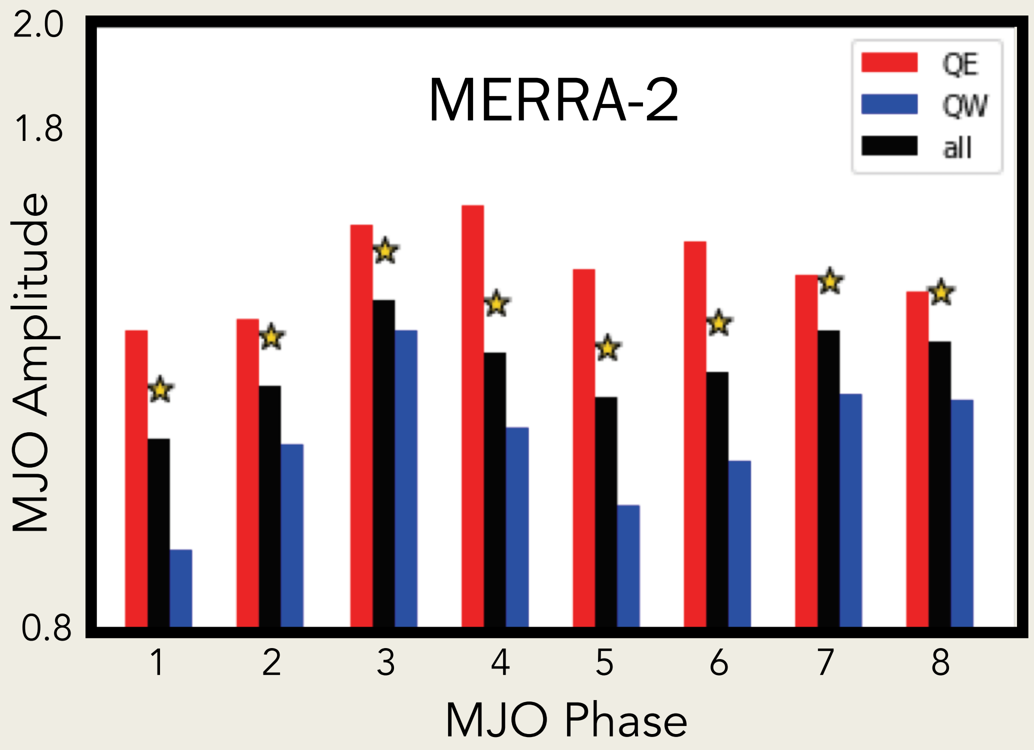
Regression between DJF SLP and Nino3.4 SST



Coupling Between Modes of Variability

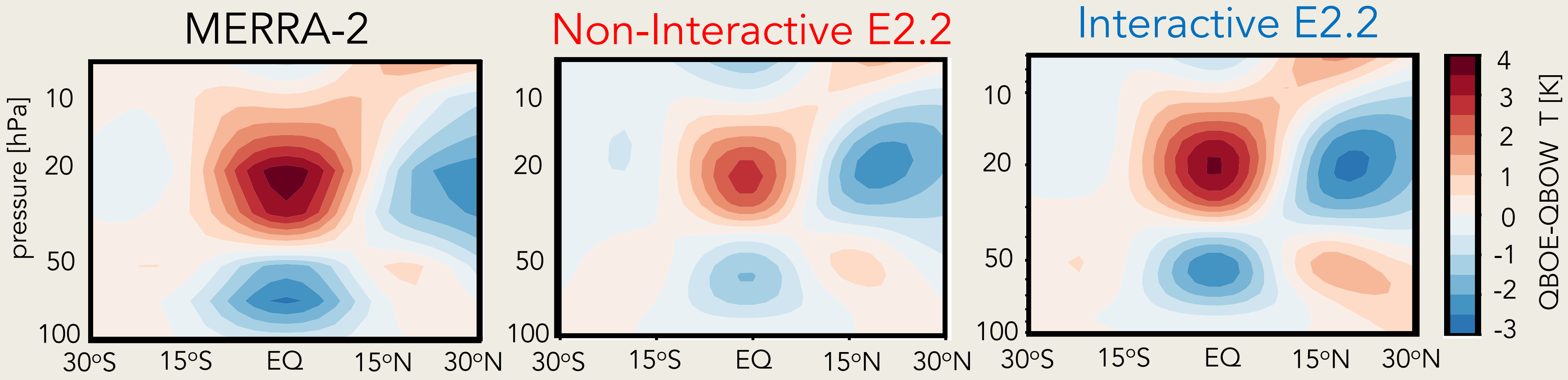
- Biases in atmospheric modes can preclude an examination of their coupling.

- For example, while observations suggest that the QBO modulates the MJO during boreal winter (e.g., *Yoo and Son (2016)*; *Son et al. (2017)*; *Marshall et al. (2017)*), models struggle to reproduce this coupling.



Coupling Between Modes of Variability

- Preliminary experiments using GISS Model E2.2 indicate that using interactive (ozone) chemistry can reduce lower stratospheric temperature and associated wind biases, compared to non-interactive versions.



- This suggests that model development oriented toward an improved representation of modes of variability may also need to consider the influences of (interactive) composition, in addition to changes in underlying resolution, parameterizations, etc.

Conclusions

- Overall, a preliminary analysis of CMIP6 models indicates 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 in the lower stratosphere) 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.

Conclusions

- As our analysis is preliminary it is important that more CMIP6 models be included before drawing general conclusions.
- To the extent that improvements hold as more models are included, the CMIP6 ensemble presents an exciting new tool for exploring cutting-edge problems in atmospheric variability (e.g. coupling between modes, composition feedbacks) that have been relatively unexplored in previous CMIP phases.

Conclusions

- This work arises from the 2019 US Climate Modeling Summit held in Washington D.C and was supported through funding provided by NASA MAP, DOE and NOAA.

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,
Representation of Modes of Variability in 6 U.S. Climate Models, *J. Climate*, Accepted.

THANK YOU FOR YOUR ATTENTION!