Impact of the Quasi-Biennial Oscillation on the boreal winter tropospheric circulation in CMIP5/6 models

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4 May 2020, Online

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CMIP5/6 models with QBO

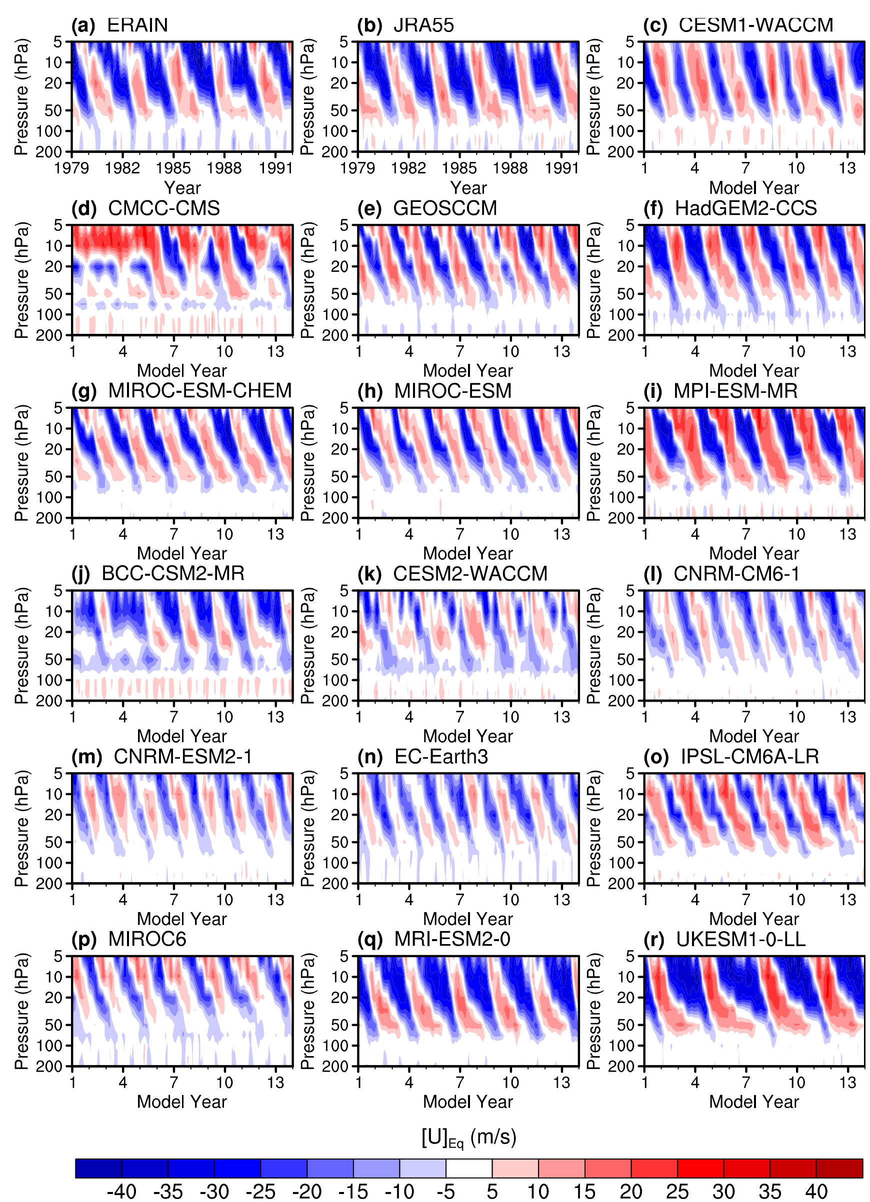
CMIP5 models	Top (lev no.)
CESM1-WACCM	5.1×10^{-6} hPa (L66)
CMCC-CMS	0.01 hPa (L95)
HadGEM2-CCS	85 km (L60)
MIROC-ESM-CHEM	0.0036 hPa (L80)
MIROC-ESM	0.0036 hPa (L80)
MPI-ESM-MR	0.01 hPa (L95)

CMIP6 models	Top (lev no.)
BCC-CSM2-MR	1.46 hPa (L46)
CESM2-WACCM	4.5×10^{-6} hPa (L70)
CNRM-CM6-1	78.4km (L91)
CNRM-ESM2-1	78.4km (L91)
EC-Earth3	0.01hPa (L91)
EC-Earth3-Veg	0.01hPa (L91)
HadGEM3-GC31-LL	85 km (L85)
IPSL-CM6A-LR	80 km (L79)
MIROC6	0.004hPa (L81)
MRI-ESM2-0	0.01hPa (L80)
UKESM1-0-LL	85 km (L85)

QBO nudged with a ~28-month period

QBO generated in models

Simulated QBO in models



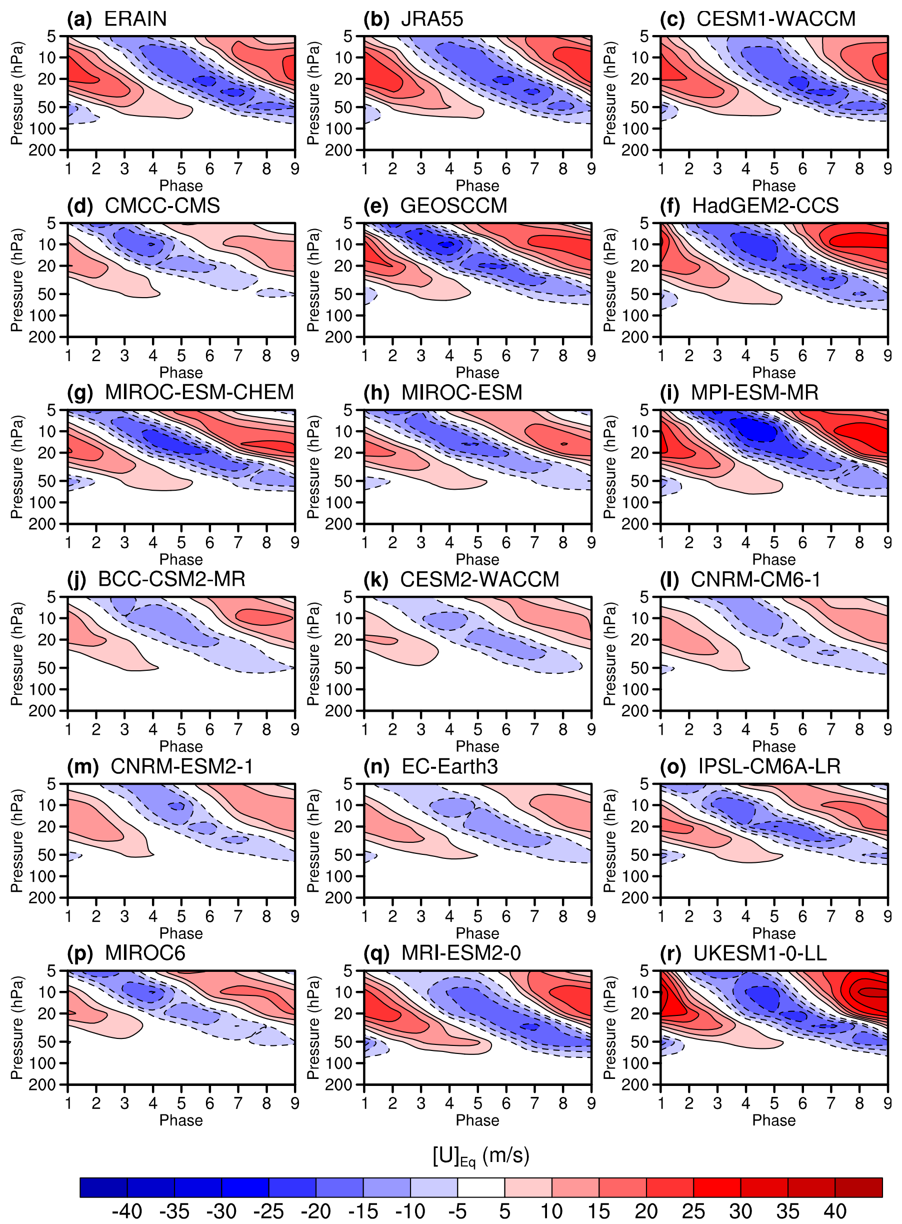
Reanalysis ERA-Interim and JRA55:

- The QBO winds are asymmetric with easterlies stronger than westerlies.
- QBO winds can descend to 100 hPa.
- Easterly period above 30hPa is longer than the westerly period for each QBO cycle; vice versa below 30hPa.

CMIP5/6 simulations:

- More CMIP6 models can produce QBO than CMIP5 models
- No evidence shows that CMIP6 models work better than CMIP5 models.
- QBO amplitude is underestimated in most models.
- Some models show a stalling of the westerly and easterly wind (CMCC-CMS).

QBO amplitude in models



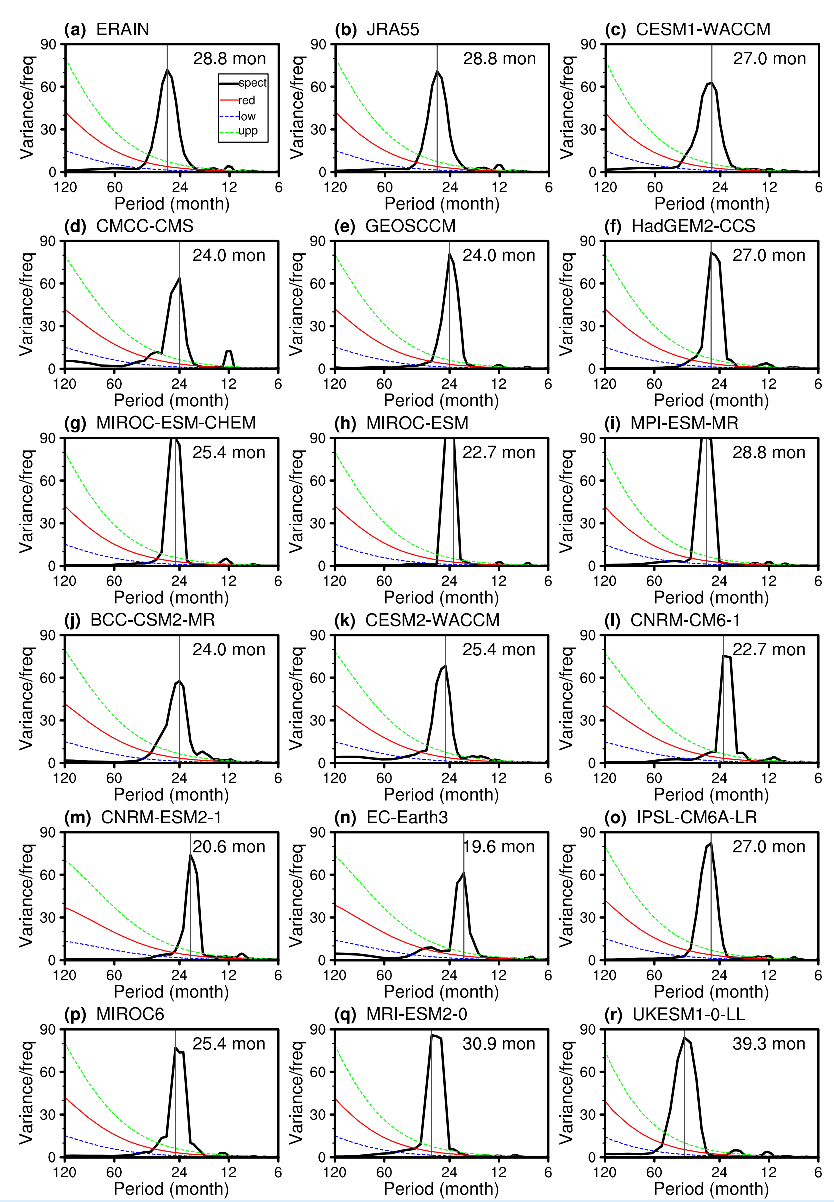
Eight phases composite in reanalysis:

- The maximum QBO variability center is at 30-20hPa, easterlies lower than westerlies.
- QBO winds can descend to 100hPa with large wind anomalies.
- High consistency between ERA-Interim and JRA55.

CMIP5/6 simulations:

- QBO cycle simulated in all models in the middle stratosphere.
- CMIP6 models underestimate the QBO maximum center.
- QBO winds fail to develop below 70-50hPa in some models.

QBO period



Spectral analysis on the QBO30 index in reanalysis:

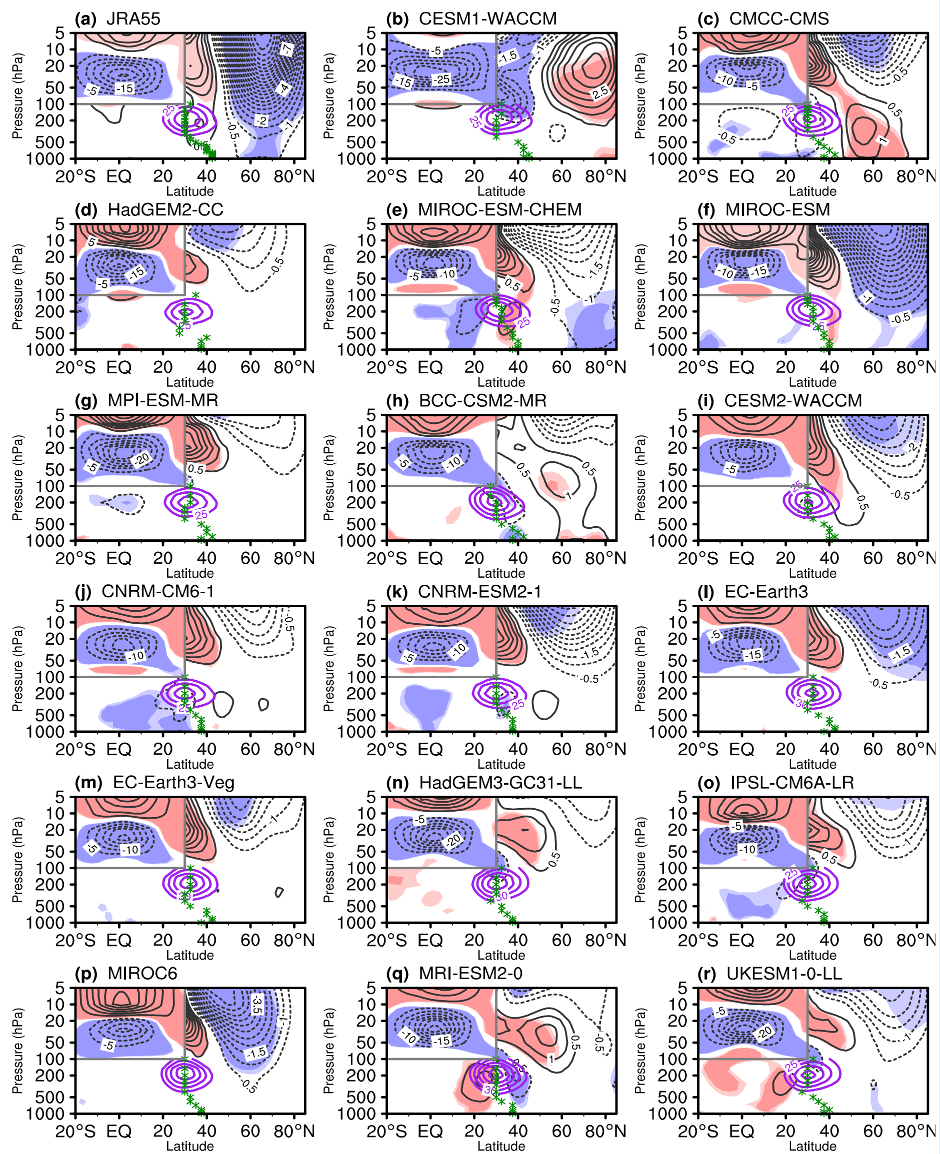
- The maim cycle period is 28-29 months in both reanalyses.
- Significant periods: 25–30 months.

CMIP5/6 simulations:

- The QBO period is better simulated (25–31 months) in CESM1-WACCM, HadGEM2-CCS, MIROC-ESM-CHEM, MPI-ESM-MR, CESM2-WACCM, IPSL-CM6A-LR, MIROC6, MRI-ESM2-0.
- The QBO is faster in CMCC-CMS, GEOSCCM, MIROC-ESM, BCC-CSM2-MR, CNRM-CM6-1, CNRM-ESM2-1, EC-Earth3.
- The QBO is slower in UKESM1-0-LL .

Rao, J., C.I. Garfinkel, and I.P. White, 2020: Impact of Quasi-Biennial Oscillation on the northern winter stratospheric polar vortex in CMIP5/6 models. *J. Climate*, https://doi.org/10.1175/JCLI-D-19-0663.1

Holton-Tan (HT) relationship in models



Zonal-mean zonal wind

EQBO (QBO30≤ -7.5 m/s) minus WQBO (QBO30≥7.5 m/s) composite in reanalysis:

- The stratospheric polar vortex is weakened in EQBO winters (HT relationship).
- The extratropical response develops throughout the stratosphere and troposphere.

CMIP5/6 models:

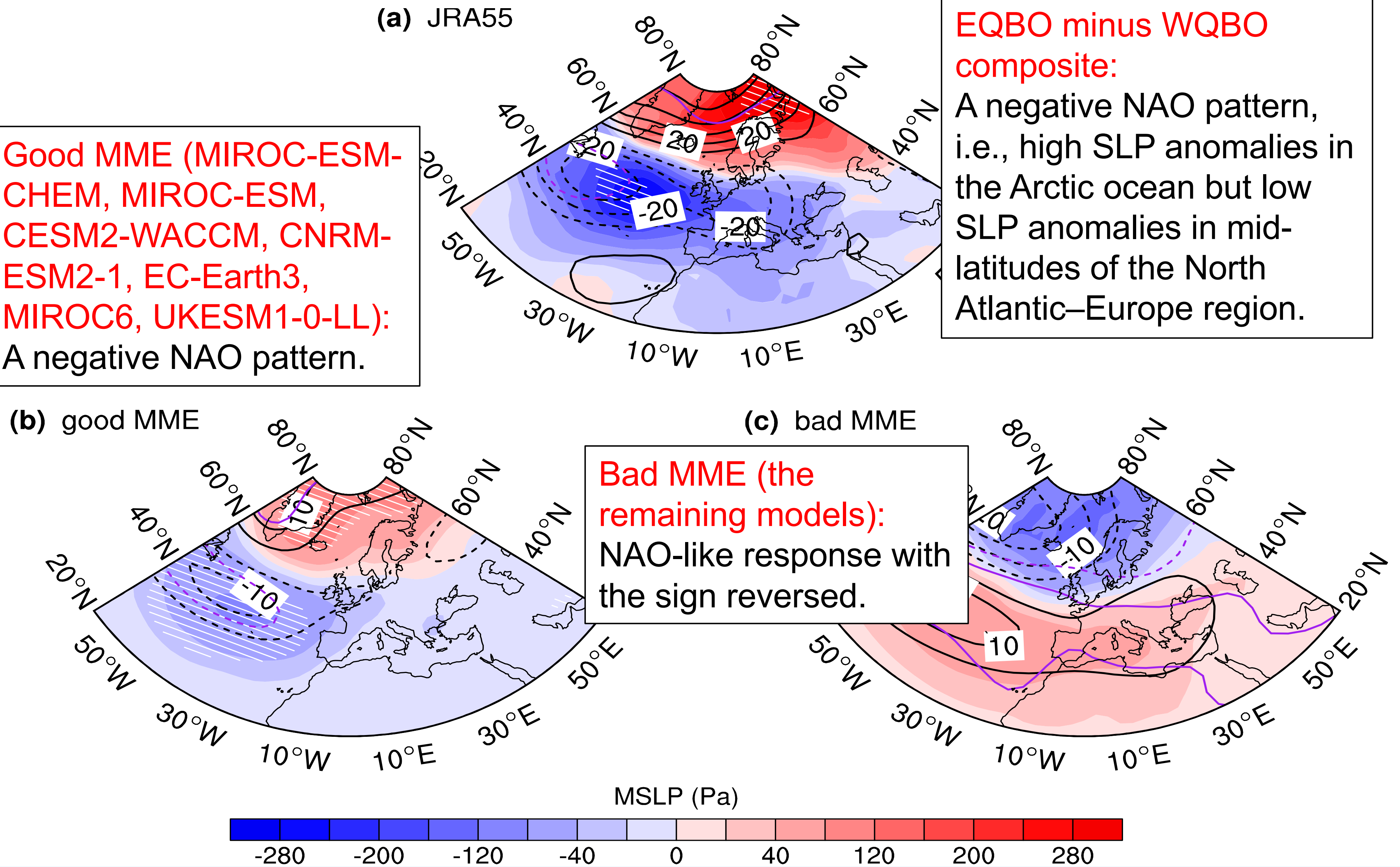
- The HT relationship can be produced qualitatively in all models, but underestimated quantitatively.
- In contrast, the response in the Arctic stratosphere is much shallower in most models than in the reanalysis.
- The extratropical zonal wind response develops downward into the upper troposphere in a few models (MIROC-ESM-CHEM, MIROC-ESM, CESM2-WACCM, CNRM-ESM2-1, EC-Earth3, MIROC6, UKESM1-0-LL).

Pathway 1 for tropospheric response: the stratospheric polar vortex

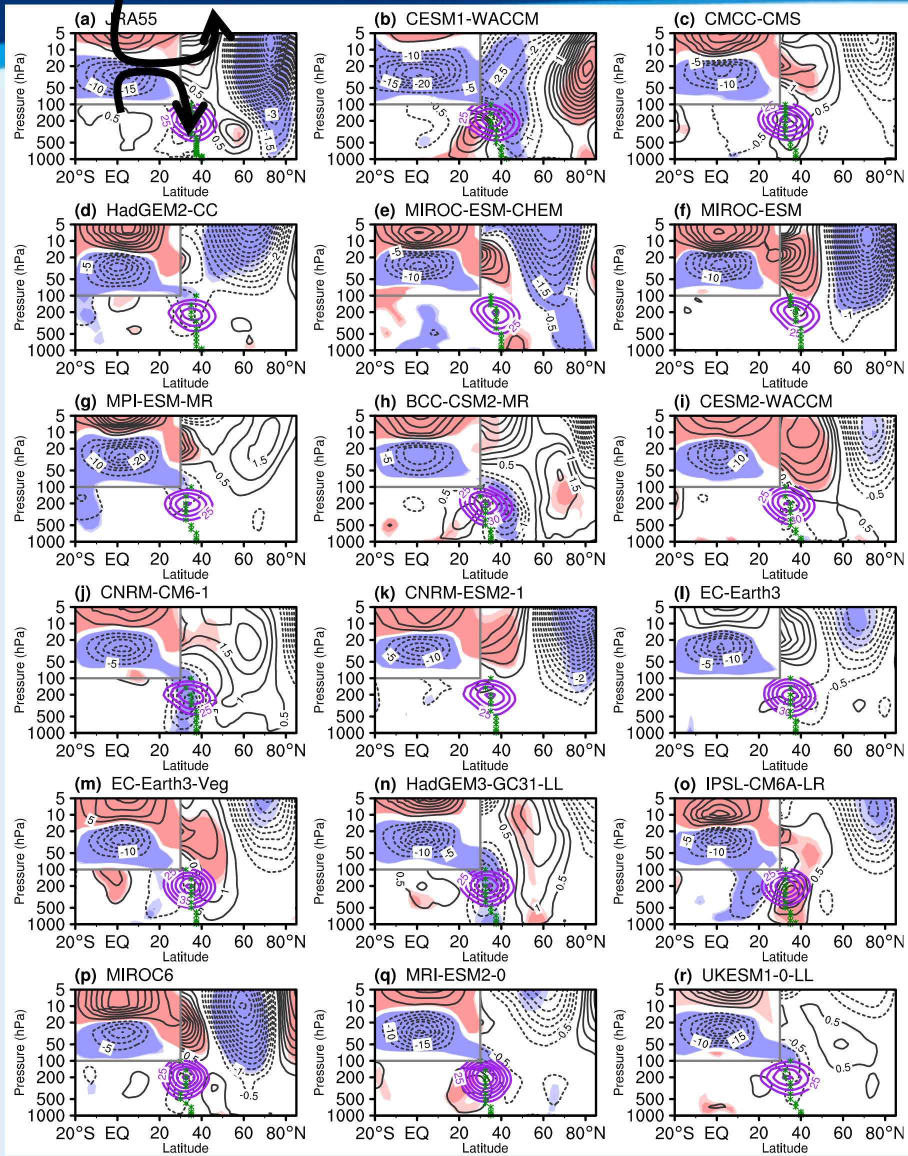
EQBO minus WQBO composite:
A negative NAO pattern, i.e., high SLP anomalies in the Arctic ocean but low SLP anomalies in mid-latitudes of the North Atlantic–Europe region.

Good MME (MIROC-ESM-CHEM, MIROC-ESM, CESM2-WACCM, CNRM-ESM2-1, EC-Earth3, MIROC6, UKESM1-0-LL):
A negative NAO pattern.

Bad MME (the remaining models):
NAO-like response with the sign reversed.



Pathway 2 for tropospheric response: downward arching of the QBO winds over Pacific



Zonal wind in the Pacific sector (160–220E)

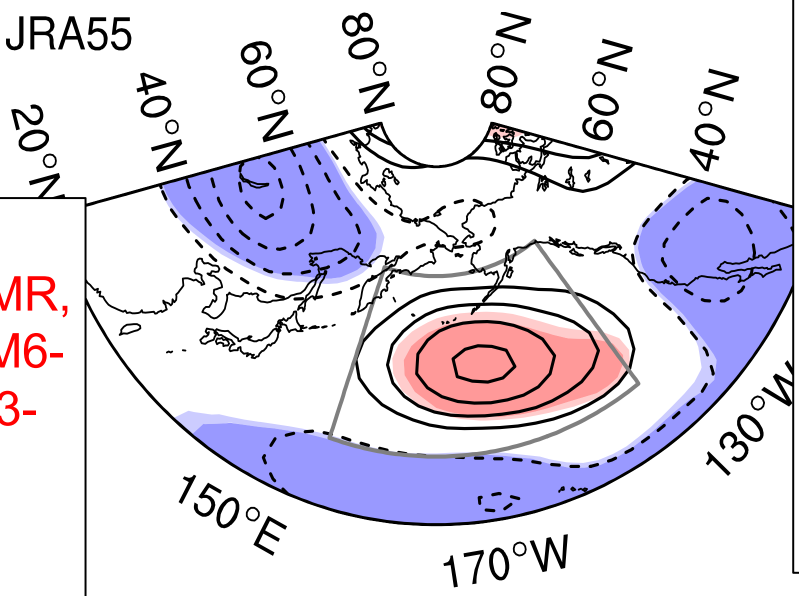
EQBO minus WQBO composite in reanalysis:

- The HT effect seldom reaches the Pacific sector.
- The direct meridional circulation cell response associated with the QBO makes the zonal wind anomalies arch downward to the subtropical Pacific in the troposphere (20-40N)

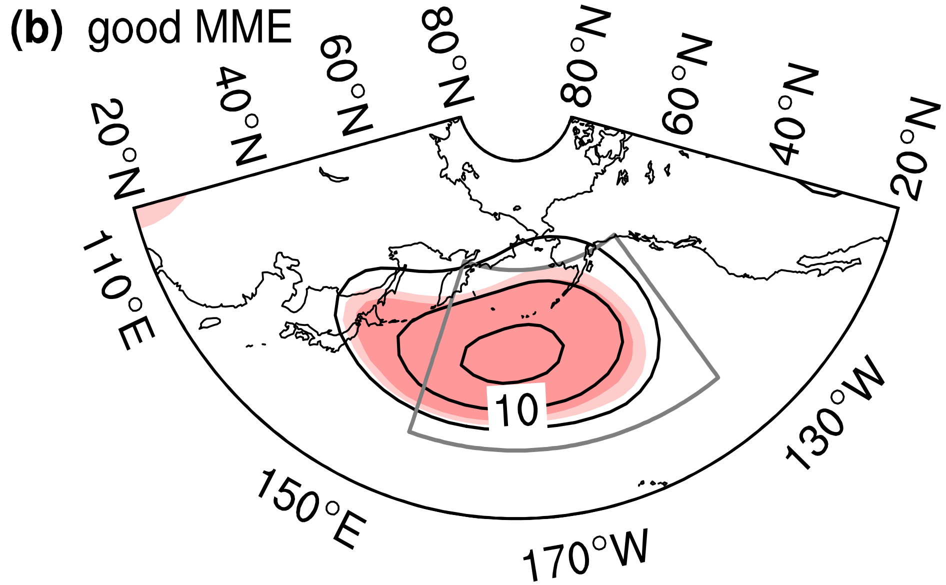
CMIP5/6 models:

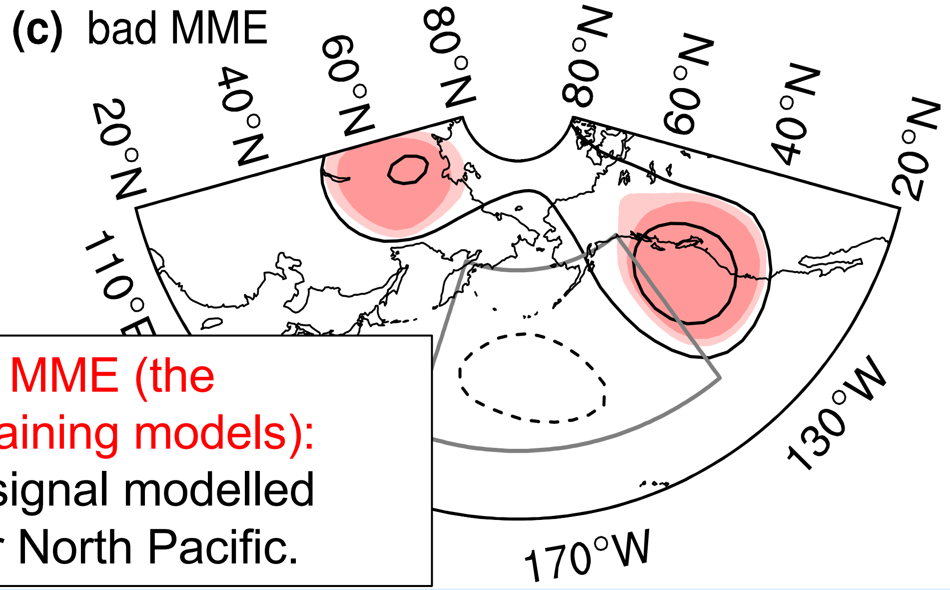
- Half of the models (HadGEM2-CC, MPI-ESM-MR, BCC-CSM2-MR, CESM2-WACCM, CNRM-CM6-1, EC-Earth3-Veg, HadGEM3-GC31-LL, MIROC6) simulate the extratropical easterly anomaly center over 20–40N in the Pacific sector during EQBO.

Good MME (HadGEM2-CC, MPI-ESM-MR, BCC-CSM2-MR, CESM2-WACCM, CNRM-CM6-1, EC-Earth3-Veg, HadGEM3-GC31-LL, MIROC6):
A high anomaly center is induced over North Pacific.



EQBO minus WQBO composite in JRA55:
The Pacific extratropical easterlies in the upper troposphere create negative relative velocity poleward of the easterly center, which explain a North Pacific high center ($v' \ll u'$, $\zeta' = -\partial u'/\partial y \approx -\partial u_g'/\partial y \sim \partial^2 z'/\partial y^2 \sim -z'$).

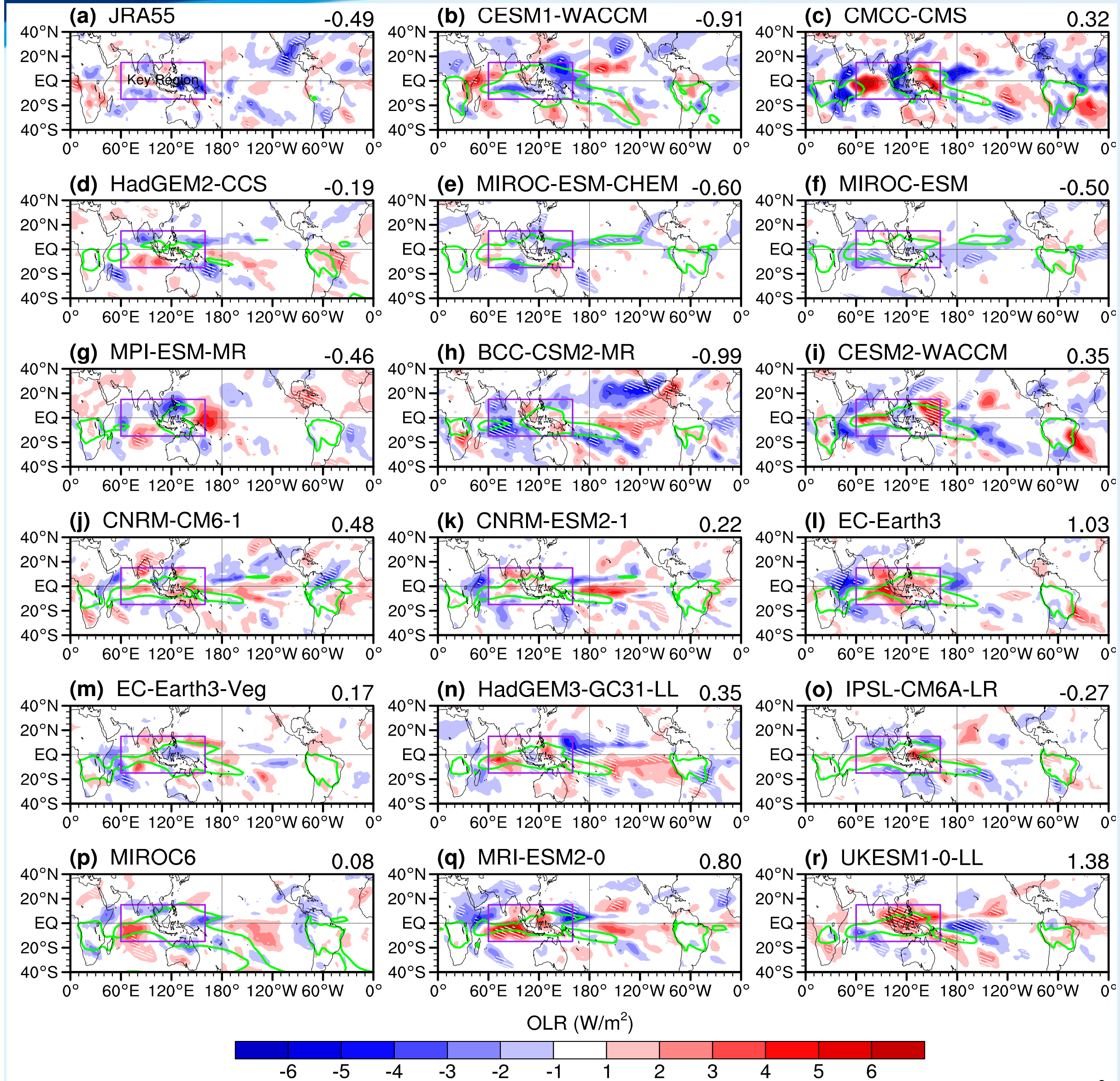




Bad MME (the remaining models):
No signal modelled over North Pacific.

Geopotential height response at 200hPa

Pathway 3 for tropospheric response: deep convection over the Indo-Pacific Ocean

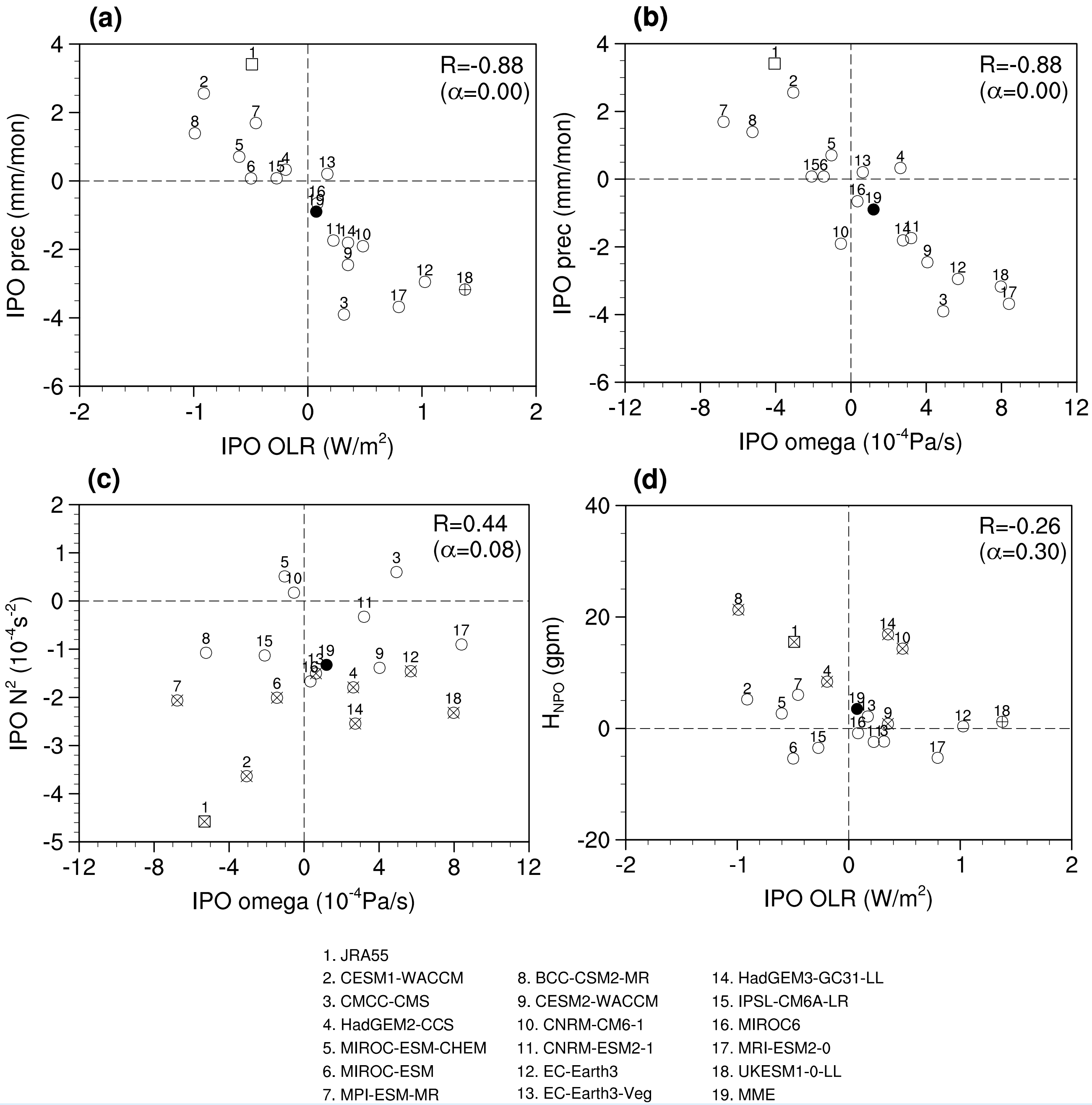


EQBO minus WQBO composite based on the observation:

- The QBO signal is only observed in the region with the strongest climatological convection.

CMIP5/6 models:

- Seven models (e.g., CESM1-WACCM, HadGEM2-CCS, MIROC-ESM-CHEM, MIROC-ESM, MPI-ESM-MR, BCC-CSM2-MR, IPSL-CM6A-LR) simulate the convection anomalies associated with the QBO over the Maritime Continent.



All indicators are based on the EQBO minus WQBO composite with the ENSO signal removed:

(a) OLR vs precipitation in the key region (15S–15N, 60–160E);

(b) Omega (1000–100hPa) vs precipitation in the key region;

(c) Omega (1000-100hPa) vs 100-hPa buoyance frequency square (N^2) in the key region;

(d) OLR in the key region vs North Pacific height (30–60N, 160–220E) .

Rao, J., C. I. Garfinkel, I. P. White, and C. Schwartz, 2020: How does the Quasi-Biennial Oscillation affect the boreal winter tropospheric circulation in CMIP5/6 models? Revised for *J. Climate*.

Conclusions

- Few models can reproduce all aspects of the QBO, including its amplitude, period, the HT relationship, and the three tropospheric QBO routes.
- No evidence shows that the CMIP6 models work better than the CMIP5 models in simulating the amplitude and period of the QBO, although the number of models with a QBO increases.
- Most models are able to simulate a weakened polar vortex during EQBO winters. However, the weakened polar vortex response during EQBO winters is underestimated or not present at all in other models, and hence the chain for QBO, vortex, and tropospheric NAM/AO is not simulated.
- For the second pathway associated with the downward arching of the QBO winds, nine models incorrectly simulate the extratropical easterly anomaly center over 20-40N in the Pacific sector during EQBO, and hence the negative relative vorticity anomalies poleward of the easterly center is not resolved, leading to an underestimated or incorrectly modelled height response over North Pacific. However, the other eight do capture this effect.
- The third pathway is only observed in the Indo-Pacific Ocean, where the strong climatological deep convection and the warm pool are situated. Seven models can simulate the convection anomalies associated with the QBO over the Maritime Continent, which is likely caused by the near-tropopause low buoyancy frequency anomalies

Summarizing Table

Model or baseline	Pathway 1: HT mechanism and polar vortex	Pathway 2: QBO winds downward arching	Pathway 3: Tropical convection over Indo-Pacific Ocean
JRA55 (baseline)	EQBO → weak polar vortex → negative NAO	EQBO → locally negative vorticity → North Pacific high center	EQBO → enhanced convection → more rainfall and cold tropopause
CESM1-WACCM	Poorly simulated	Badly simulated	Stronger convection (fairly simulated)
CMCC-CMS	A shallow vortex response (poorly simulated)	Badly simulated	Large convection center bias (poorly simulated)
HadGEM2-CCS	A shallow vortex response (poorly simulated)	Fairly simulated	Fairly simulated
MIROC-ESM-CHEM	Well simulated	Poorly simulated	Fairly simulated
MIROC-ESM	Well simulated	Poorly simulated	Fairly simulated
MPI-ESM-MR	A much shallower vortex response (badly simulated)	Fairly simulated	Fairly simulated
BCC-CSM2-MR	A much shallower vortex response (badly simulated)	Fairly simulated	Fairly simulated
CESM2-WACCM	Fairly simulated	Fairly simulated	Unrealistic WC response (Poorly simulated)
CNRM-CM6-1	A much shallower vortex response (badly simulated)	Well simulated	Badly simulated
CNRM-ESM2-1	Well simulated	Poorly simulated	Badly simulated
EC-Earth3	Fairly simulated	Poorly simulated	Badly simulated
EC-Earth3-Veg	A shallow vortex response (poorly simulated)	Fairly simulated	Badly simulated
HadGEM3-GC31-LL	A much shallower vortex response (badly simulated)	Much better simulated	Unrealistic WC response (badly simulated)
IPSL-CM6A-LR	Poorly simulated	Poorly simulated	Fairly simulated
MIROC6	Well simulated	Fairly simulated	Poorly simulated
MRI-ESM2-0	Badly simulated	Poorly simulated	Incorrect convection center (poorly simulated)
UKESM1-0-LL	Fairly simulated	Poorly simulated	Large convection center bias (badly simulated)