QBO-MJO connection

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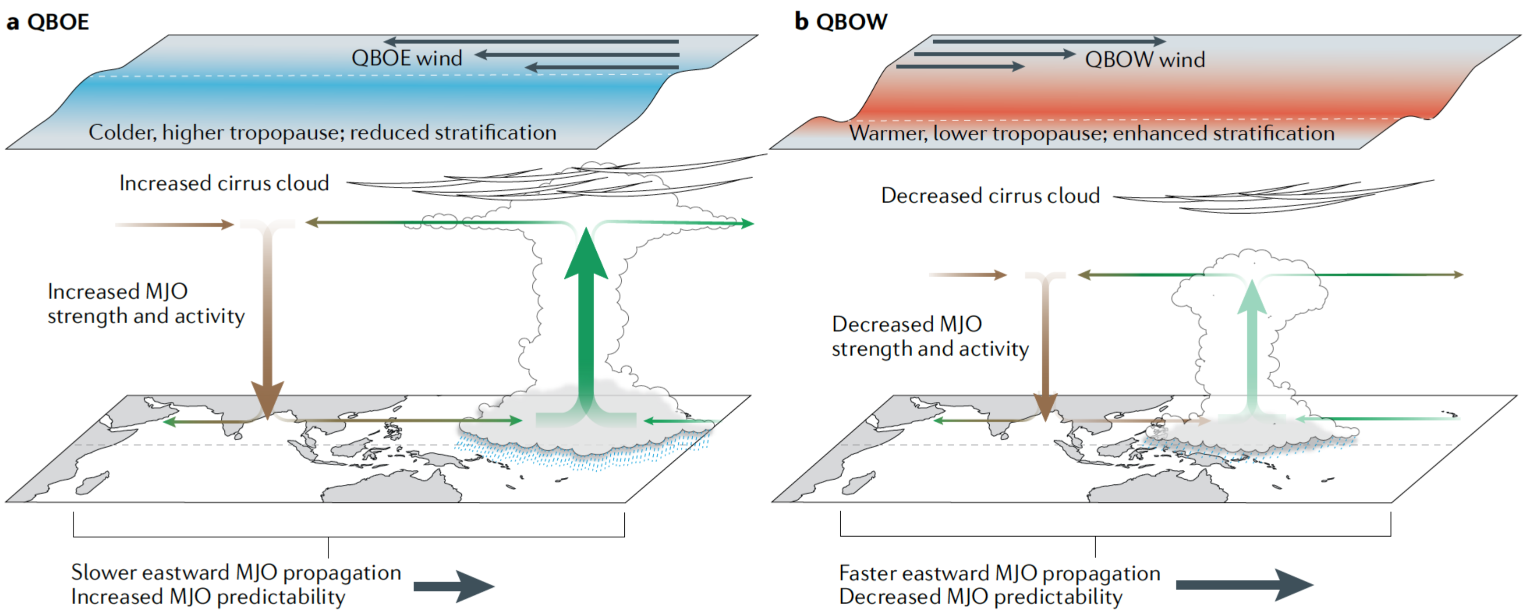
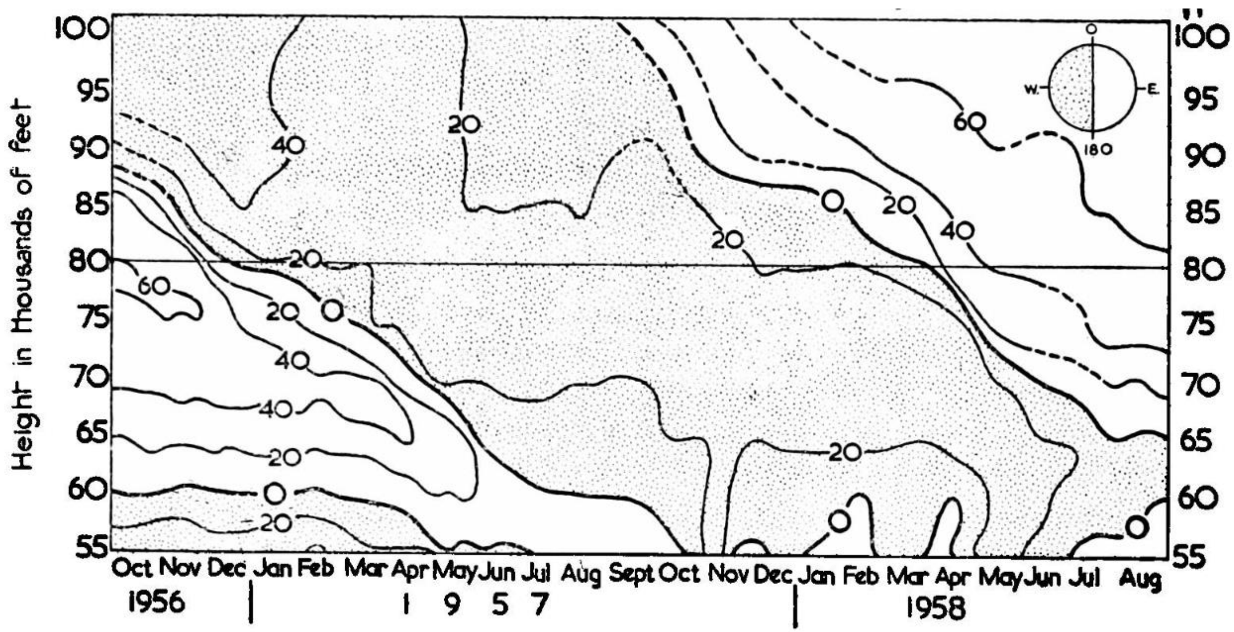


Fig. 5 | **Schematic illustration of the QBO–MJO connection.** Mechanisms and impacts of quasi-biennial oscillation (QBO)-Madden–Julian oscillation (MJO) coupling during QBO easterly (QBOE; panel **a**) and QBO westerly (QBOW; panel **b**) winds.

Martin, Son et al. (2021 Nature Rev. Earth & Env.)

QBO in 1957



30.5 km

16.7 km

FIGURE 4—ZONAL COMPONENTS OF WINDS ABOVE THE TROPOPAUSE AT CHRISTMAS ISLAND USING 10-DAY MEANS

Met. Mag. (1959)

METEOROLOGICAL OFFICE DISCUSSION

Tropical Meteorology

The subject for the Monday Discussion on 15 December 1958 was "Tropical meteorology". Dr. A. C. Best was in the Chair and the opening speakers were Mr. P. F. Emery and Mr. P. Graystone.

MJO in 1957

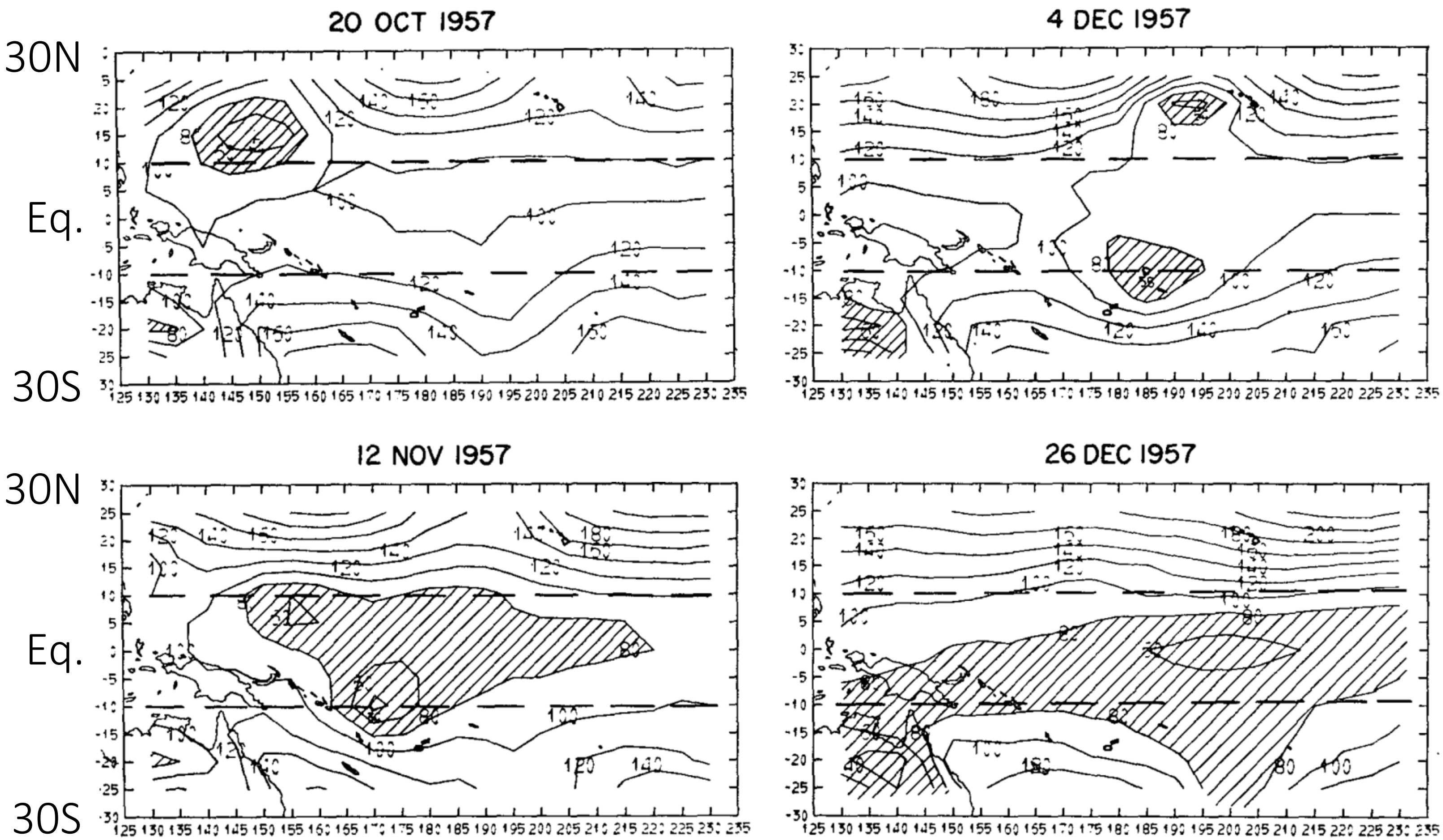
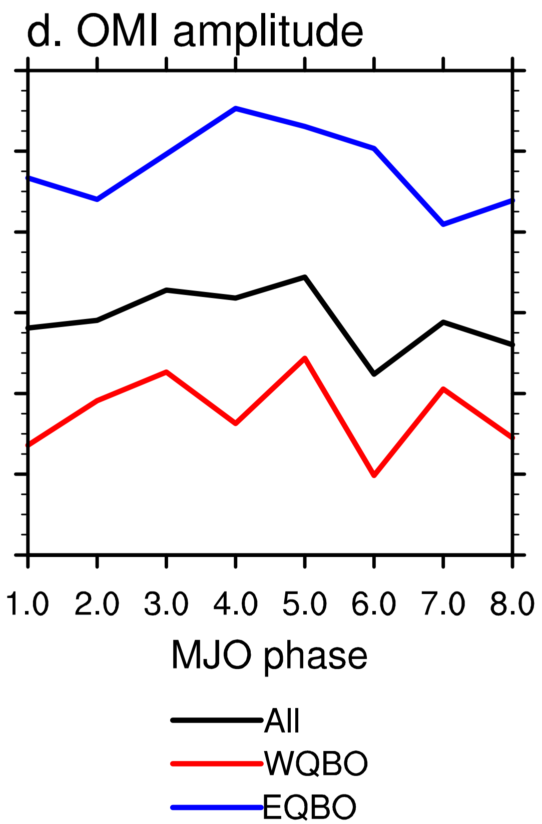


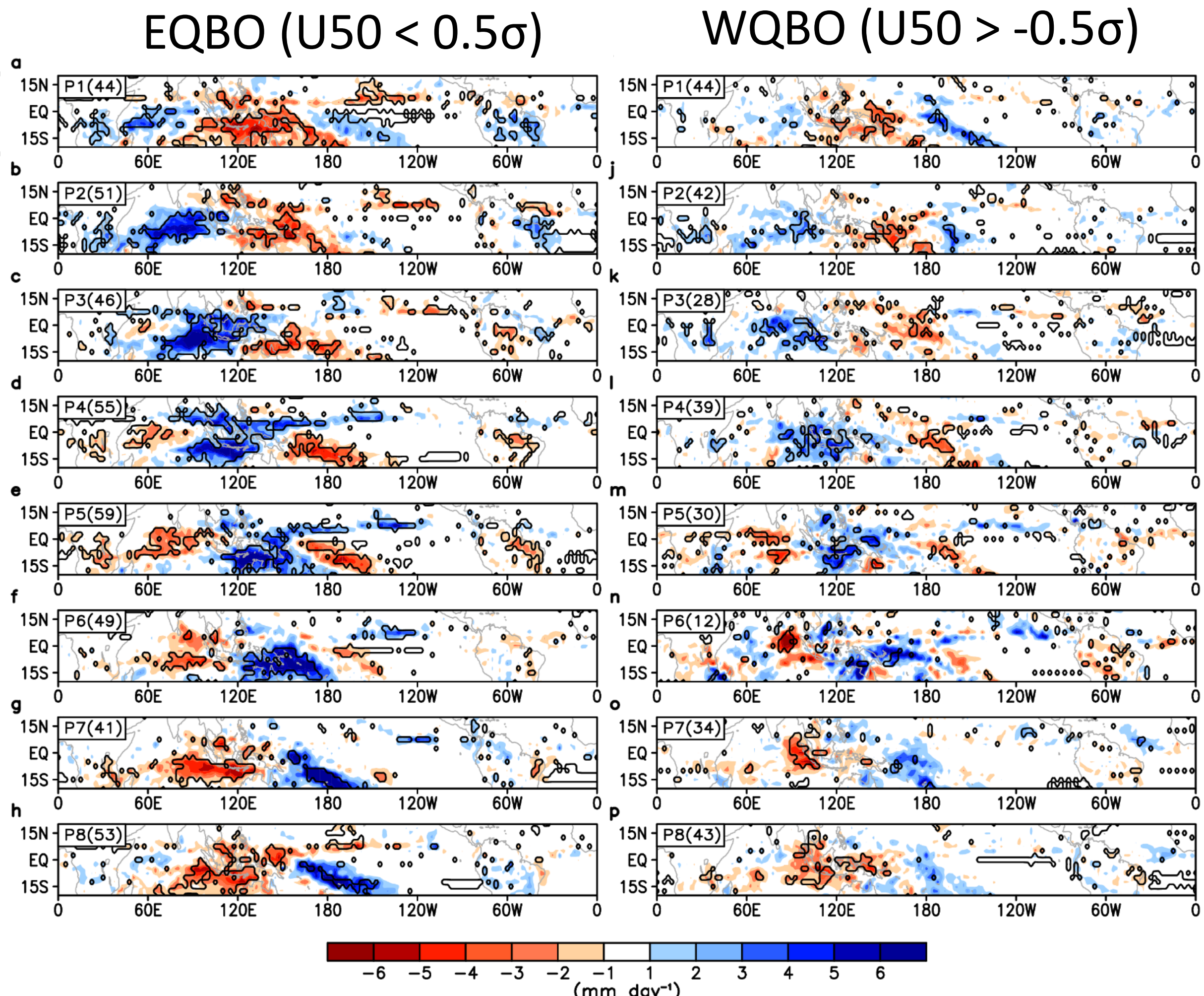
FIG. 10. Analyses of 5-day-averaged sea-level pressures over the Pacific during the IGY. Averages are centered on the date indicated above each chart. Contours are tenths of a millibar above 1000 mb. Hatched areas indicate pressures below 1008 mb. Degrees east longitude are indicated. Horizontal dashed lines represent 10S and 10N.

Madden and Julian (1972JAS)

QBO-MJO connection



Yoo and Son (2016GRL)



Son et al. (2017JCLI)

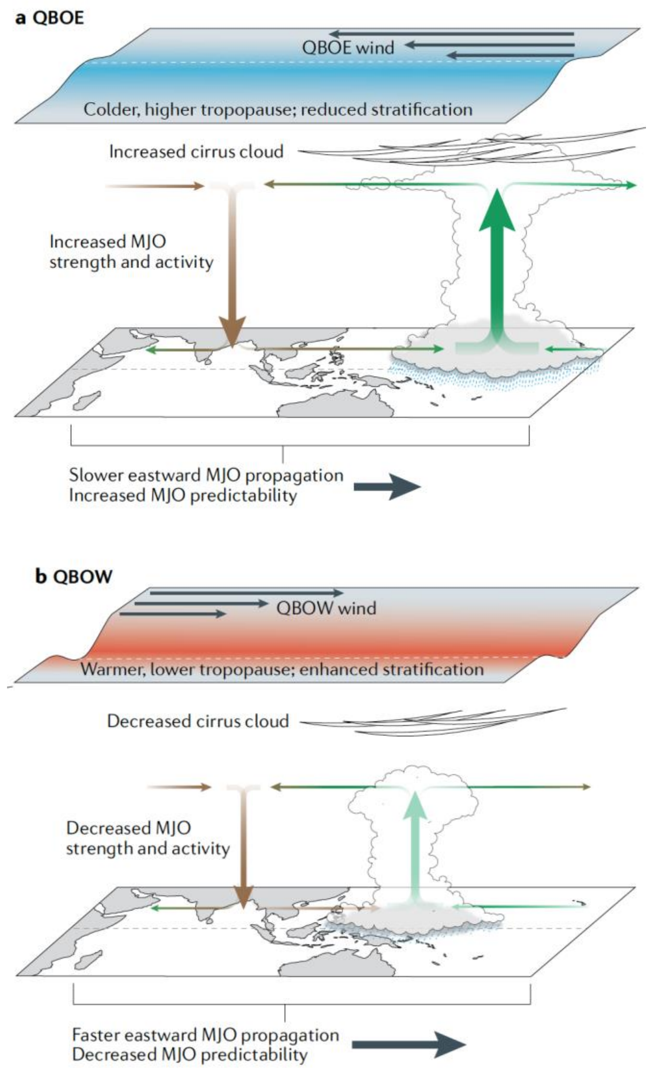
QBO-MJO connection

Observations

- Stronger, slower, and more persistent MJO propagating in EQBO winter In recent decades

Remaining issues

- Mechanism(s) not well understood
- Its teleconnections not well understood
- Modelling very difficult
- Recent emergency not well understood



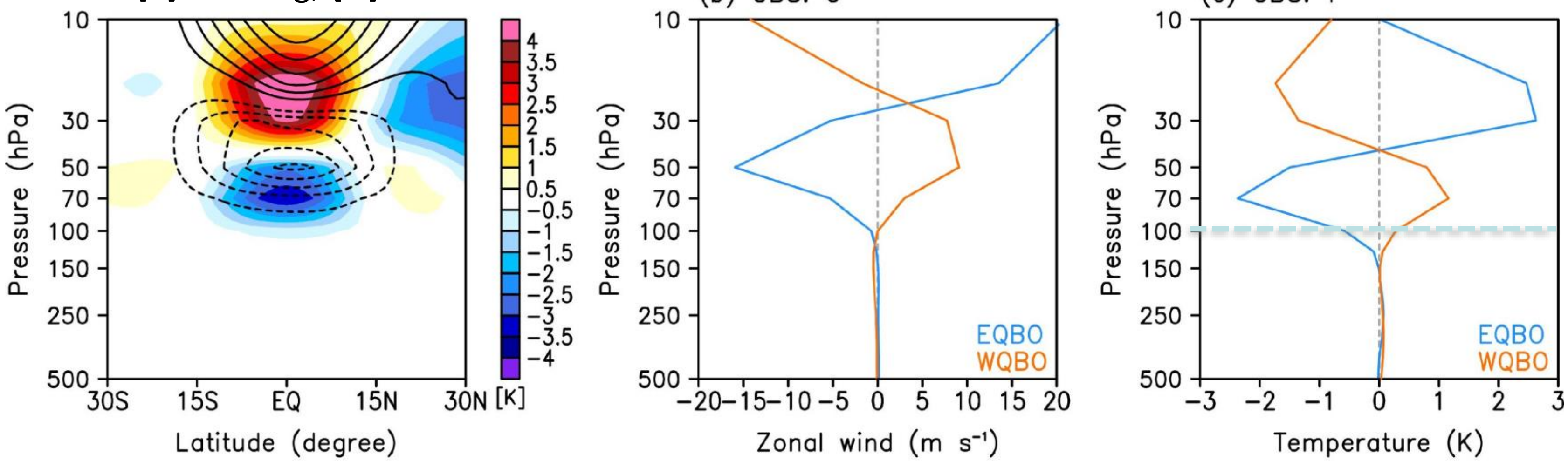
Mechanism(s)

No convincing mechanism(s) yet. There are few hypotheses proposed in the recent studies.

- UTLS instability
- Cloud-Long Wave(LW) radiation feedback

QBO temperature anomaly

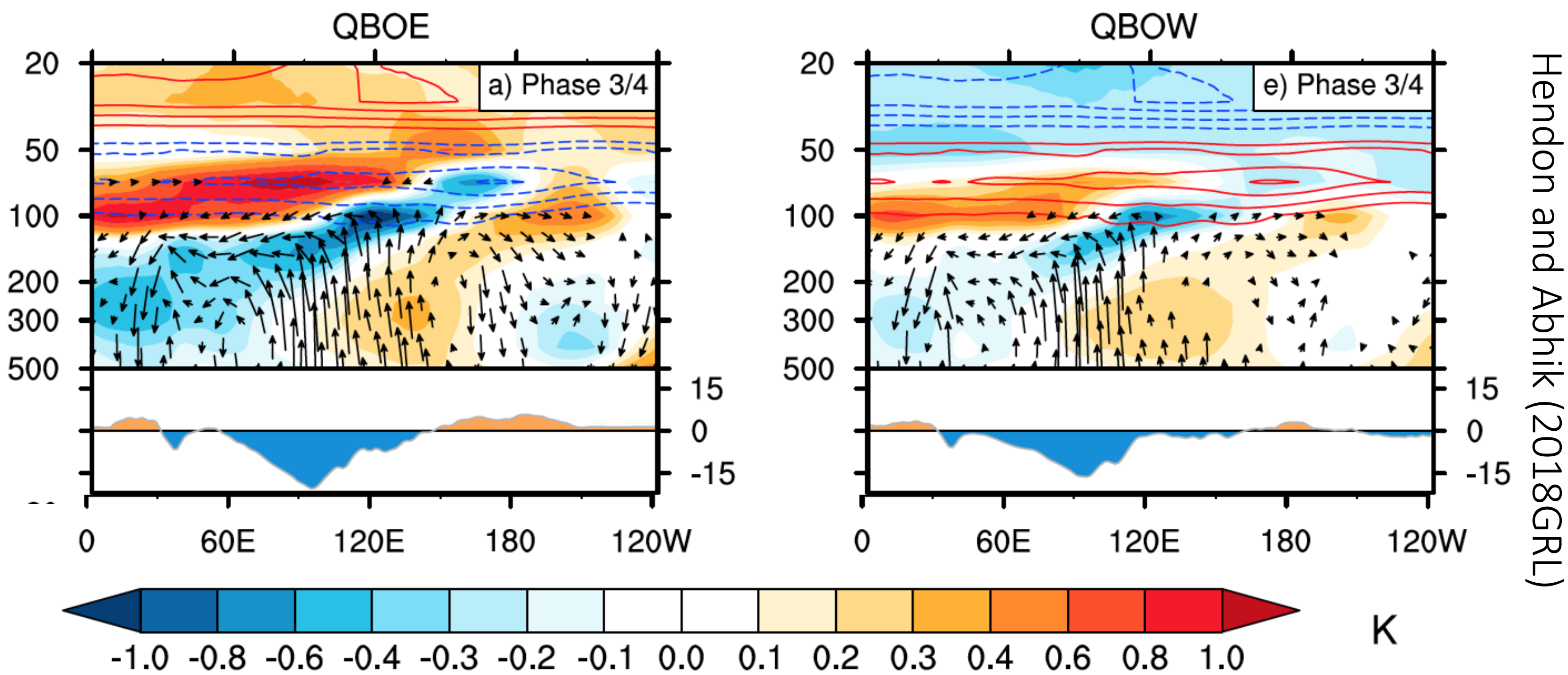
OBS [T] shading, [U] contour



Lim and Son (2020JGR)

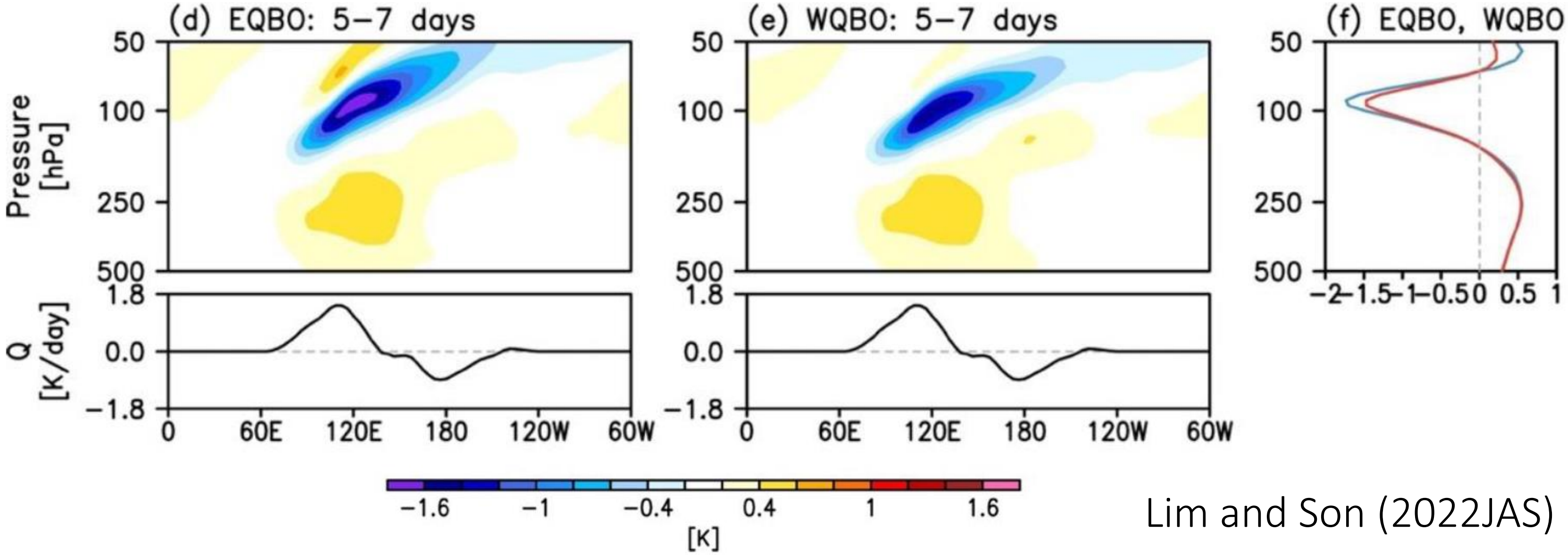
Upper troposphere becomes more unstable (colder and higher tropopause) in EQBO winter due to adiabatic cooling associated with the EQBO-induced secondary circulation. However, QBO-induced temperature and stability changes are too weak in the upper troposphere.

QBO “localized” temperature anomaly



A strong local cold anomaly (+ weak zonal-mean cold anomaly) in EQBO winter may allow a stronger MJO by destabilizing the UTLS. Local temperature anomaly shows a Kelvin-wave-like structure.

QBO “localized” temperature anomaly



Lim and Son (2022JAS)

Linear model experiments with E/WQBO backgrounds show a stronger cold cap under EQBO winds due to convectively-excited Kevin waves.

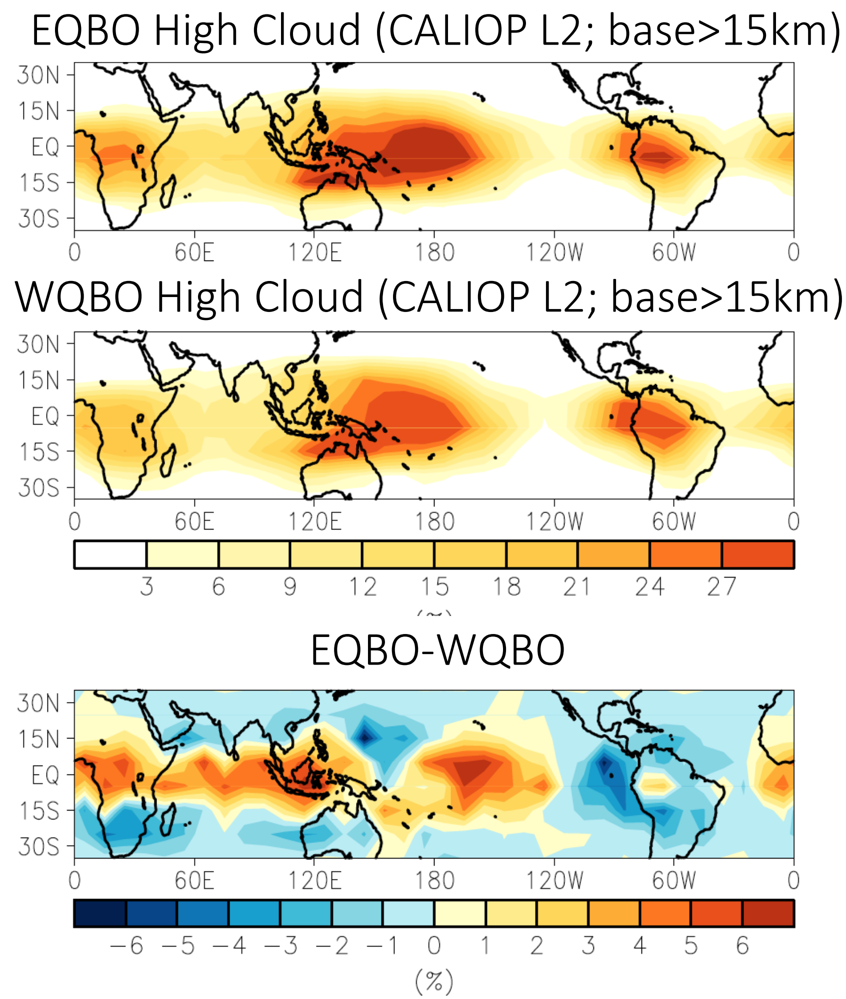
However…

A strong local cold anomaly (+ weak seasonal-mean cold anomaly) in EQBO winter may allow a stronger MJO by destabilizing the UTLS.

However, QBO-induced stability (and the related vertical motion) change occurs at too high altitudes where moisture content is too low.

Cloud-LW radiation (CLW) feedback

QBO can still affect high clouds. High clouds may enhance CLW feedbacks and strengthen MJO convections (Son et al. 2017; Sakaeda et al. 2020; Lin and Emanual 2023).



Son et al (2017JCLI)

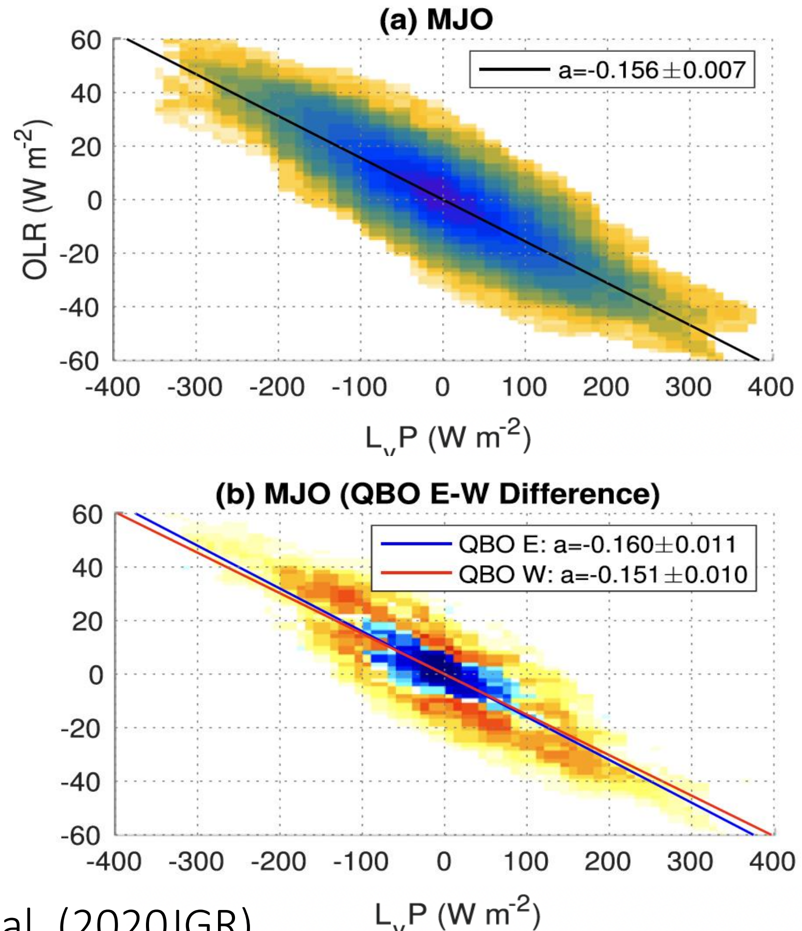
Cloud-LW radiation (CLW) feedback

More high clouds lead to weaker OLR and anomalous longwave heating in the troposphere (enhanced greenhouse effect). This heating needs to be balanced by the upward motion (adiabatic cooling) which moistens the air column. It provides a favorable condition for cloud developments (Adames and Kim 2016JAS).

$$\mathrm{CLW} = \frac{<\text{Anomalous LW radiative heating}>}{<\text{Anomalous condensational heating}>}$$

$$\approx \frac{-\text{OLR anomaly}}{\text{Precipitation anomaly}}$$

A slightly stronger CLW feedback in EQBO, but not statistically significant (Sakaeda et al. 2020JGR).



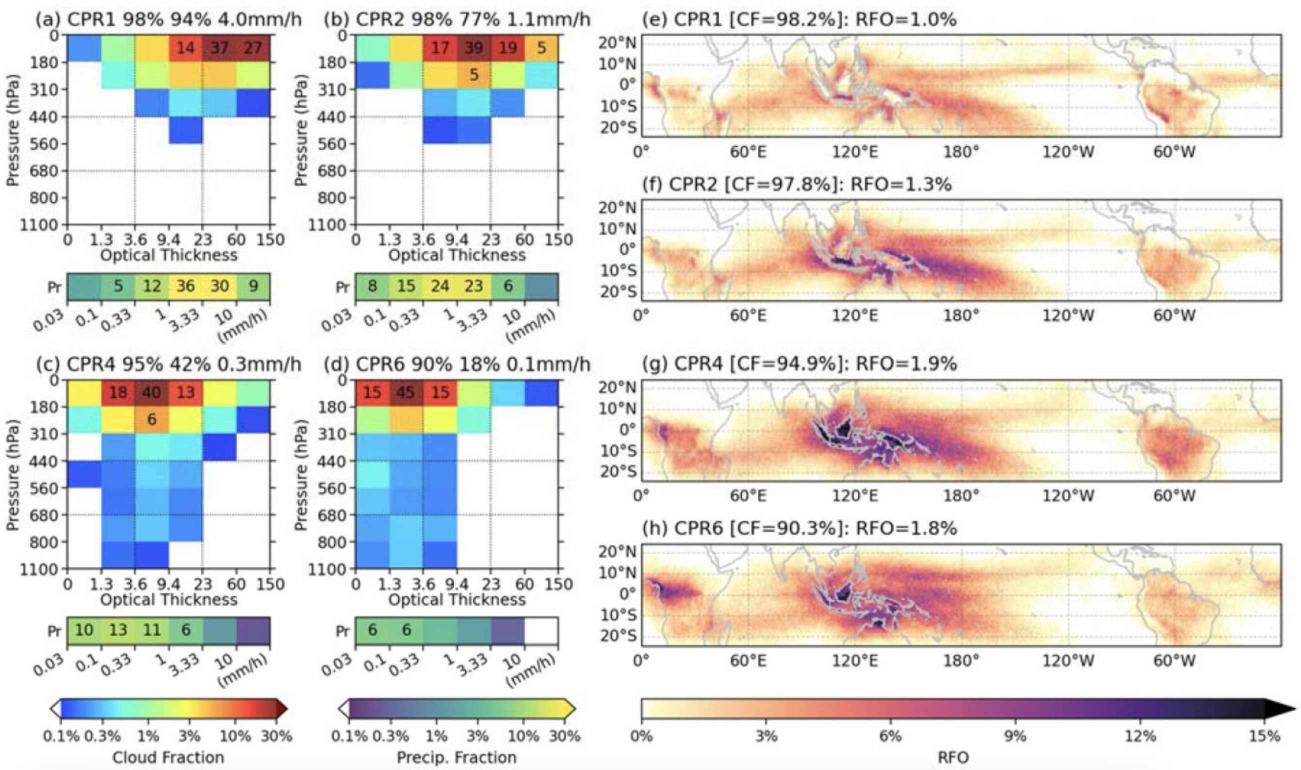
Sakaeda et al. (2020JGR)

Cloud classification: high clouds

We may need to focus on only high clouds not all clouds:
Cloud-Precipitation Regimes (CPRs) of Jin et al. (2021JAMC)

- Cloud data: MODIS 2D joint histogram of cloud top pressure (CTP – 6 classes) and optical thickness (COT – 7 classes) – 1 grid twice a day (Aqua & Terra)
- Precipitation data: IMERG 6 precipitation classes – 0.1 grid very half hour
- k-means clustering of cloud + precipitation features (48 in total) over 25S-25N for the period 2001-2021 => 16 CPRs

Cloud classification: high clouds

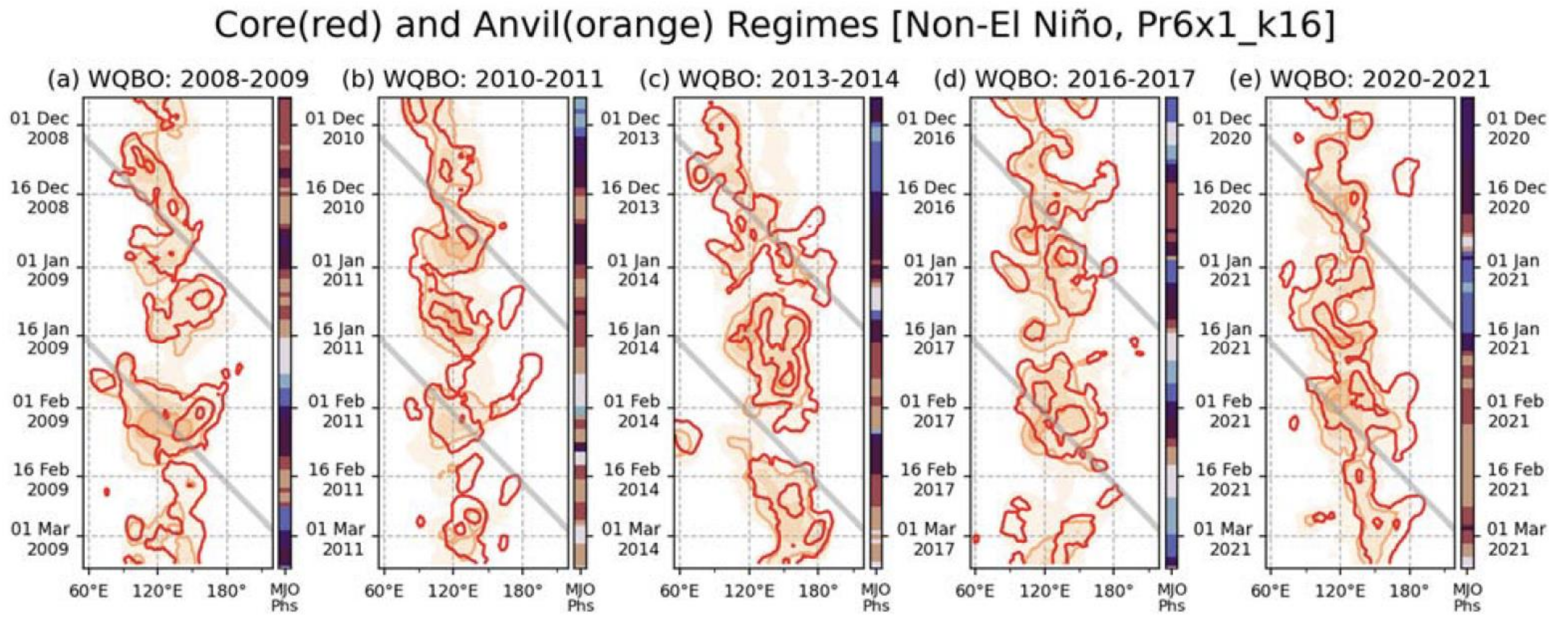


Core Regimes

Anvil Regimes

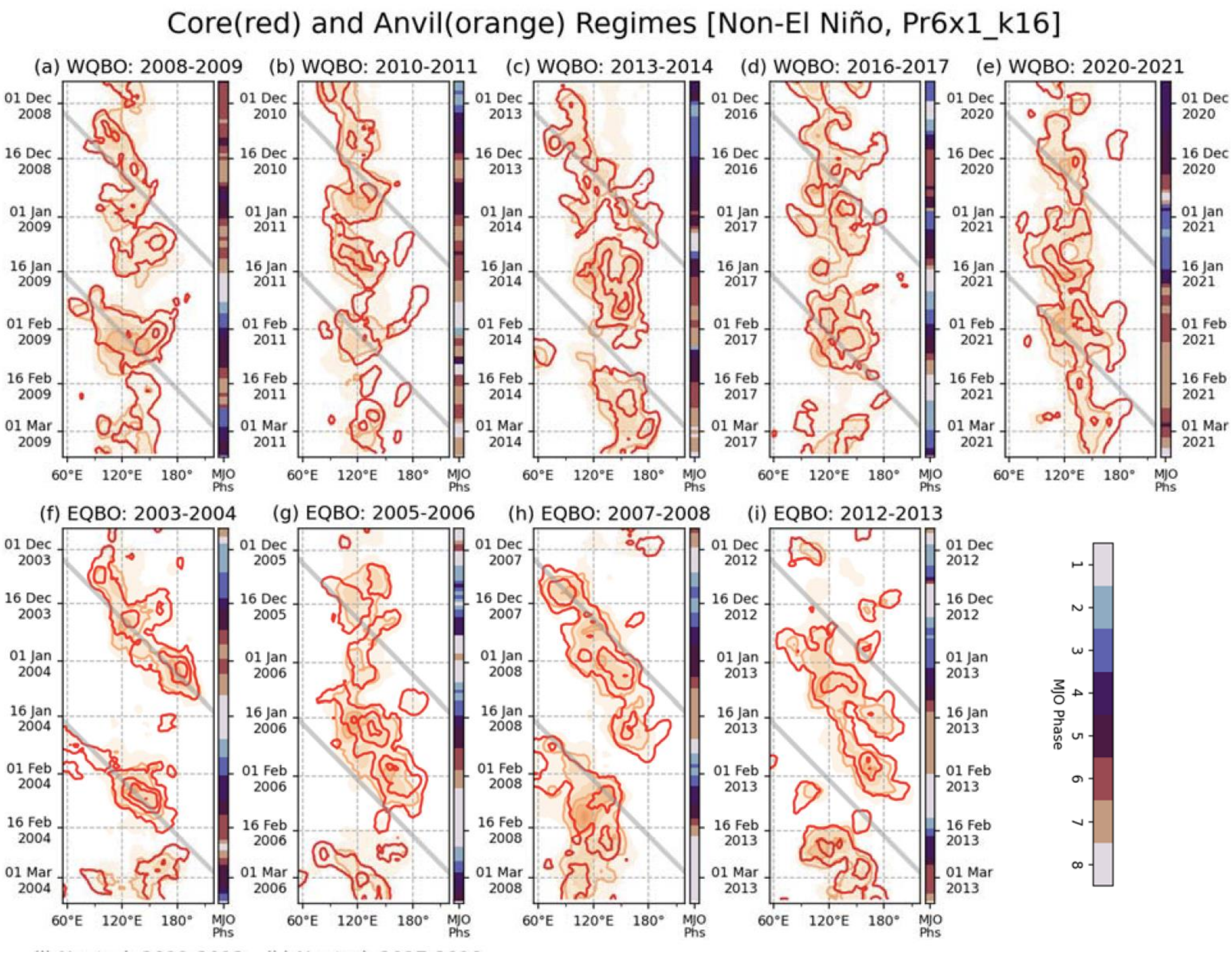
Jin et al. (2021JAMC)

MJO high clouds



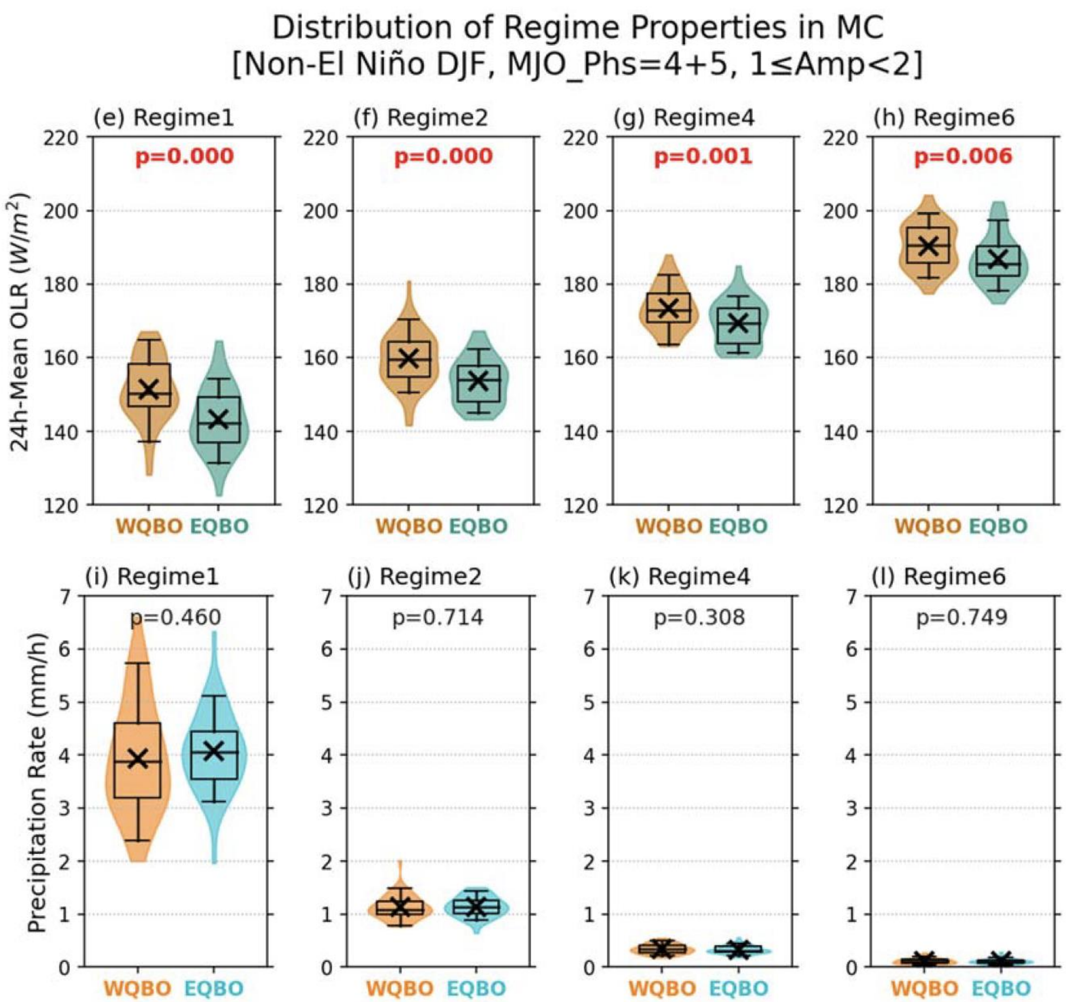
Jin et al. (2023 Nature Comms.)

MJO high clouds



Jin et al. (2023 Nature Comms.)

MJO high clouds



Core Regimes

Anvil Regimes

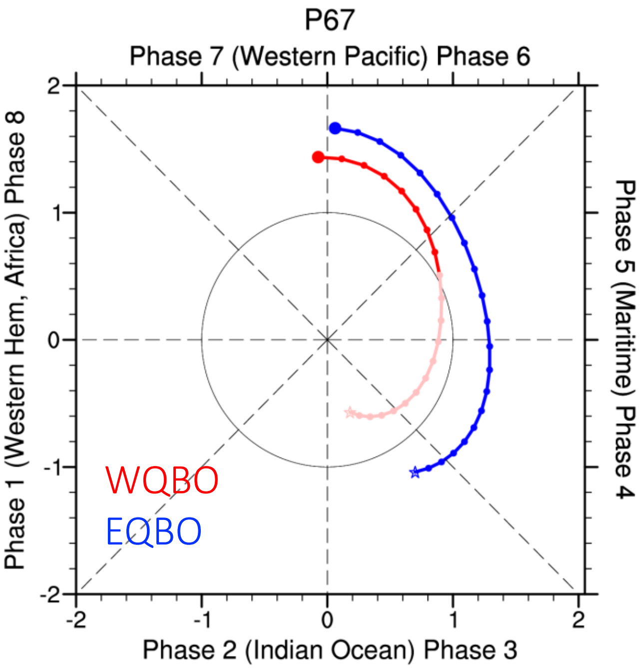
Under EQBO, more trapped OLR but no difference in precipitation => Statistically significant CLW feedback enhancement.

$$\text{CLW} \approx \frac{-\text{OLR anomaly}}{\text{Precipitation anomaly}}$$

What makes higher clouds in EQBO winter? QBO upwelling, cold temperature, unstable upper troposphere, etcs.

Jin et al. (2023 Nature Comms.)

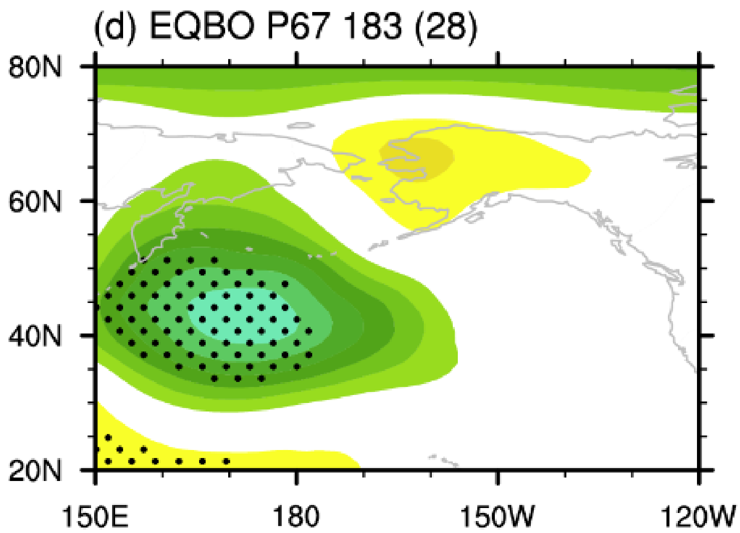
MJO teleconnections over North Pacific

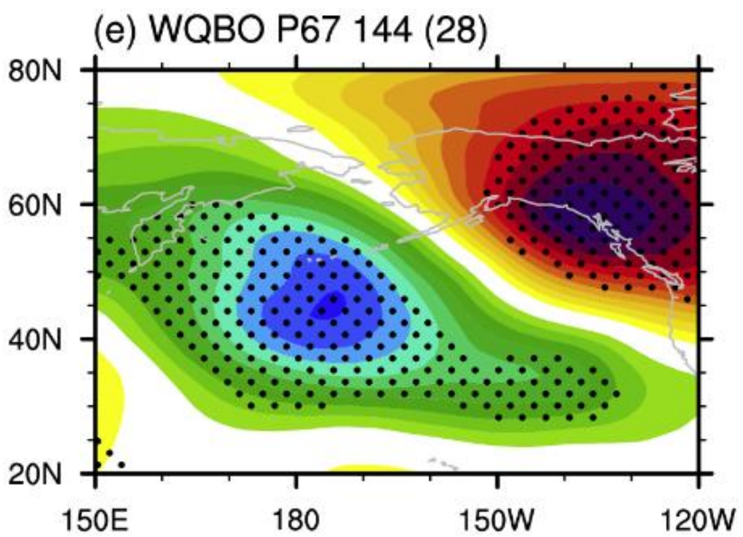


Kang et al. (2024 npjClimAtmos)

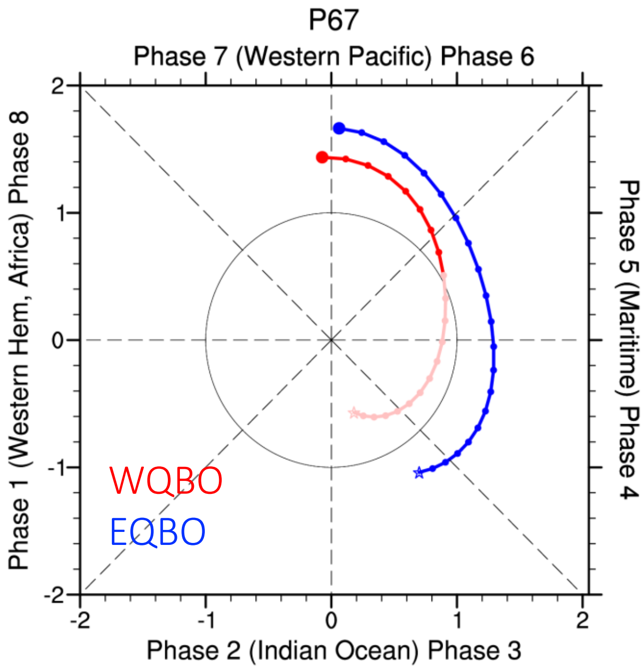
MJO teleconnections are better organized in WQBO winters than EQBO winters although MJO convections are weaker.

MJO teleconnections over North Pacific





Shading: Z500 anomalies



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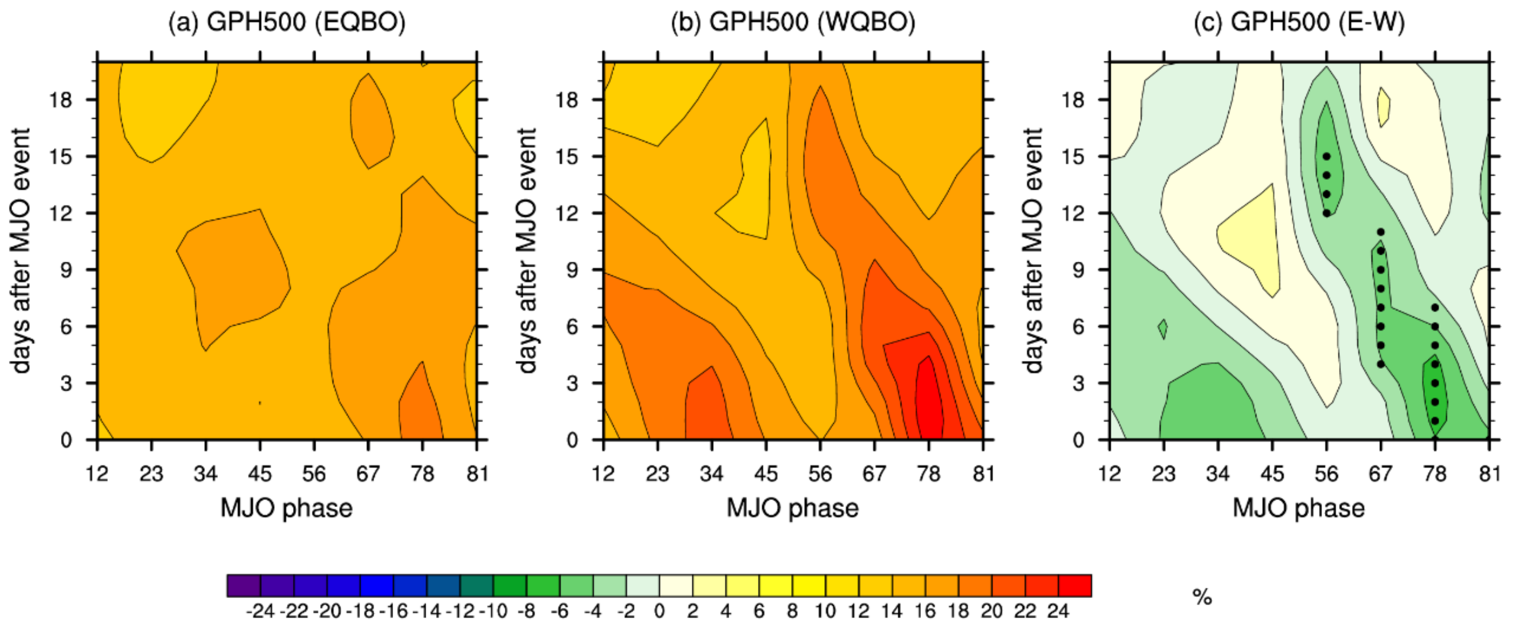


Shading: Z500 teleconnection pattern coherence over the North Pacific

Kang et al. (2024 npjClimAtmos)

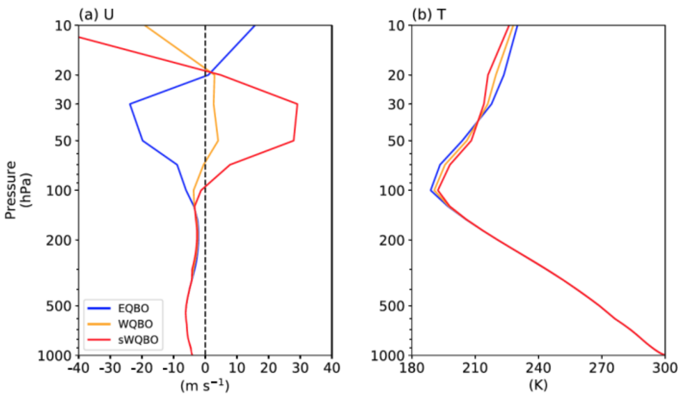
MJO teleconnections are better organized in WQBO winters than EQBO winters although convections are weaker. This is likely due to the opposite-signed teleconnections of preceding MJO (MJO67 teleconnections are partly cancelled by previous MJO23 teleconnections in EQBO)

Modelling

Most models fail to reproduce or substantially underestimate the observed QBO-MJO connection.

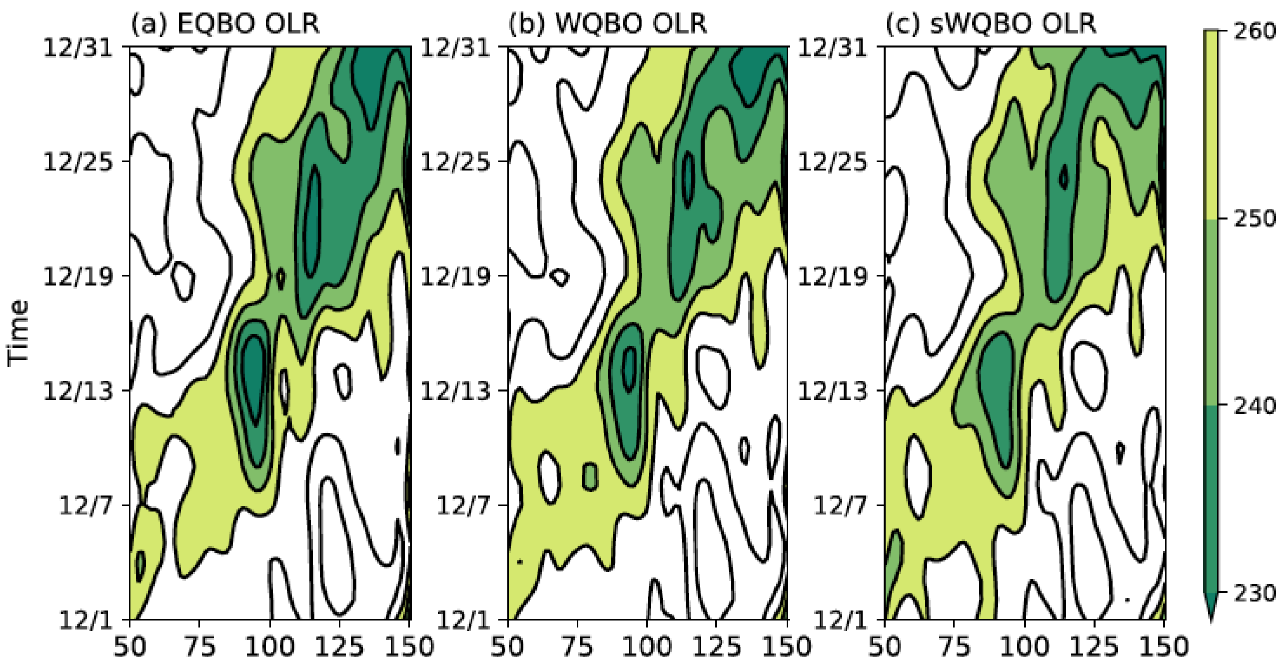
- No evidence in CMIP5/6 models (Lim and Son, 2020JGR; Kim et al. 2020GRL)
- No evidence in QBO-nudged GCM experiments (Martin et al. 2023JGR)
- A hint in QBO-nudged S2S model experiment (Huang et al. 2023GRL)
- A hint in mesoscale model (WRF) experiment (Back et al. 2020GRL)

QBO-nudged experiment (WRF)



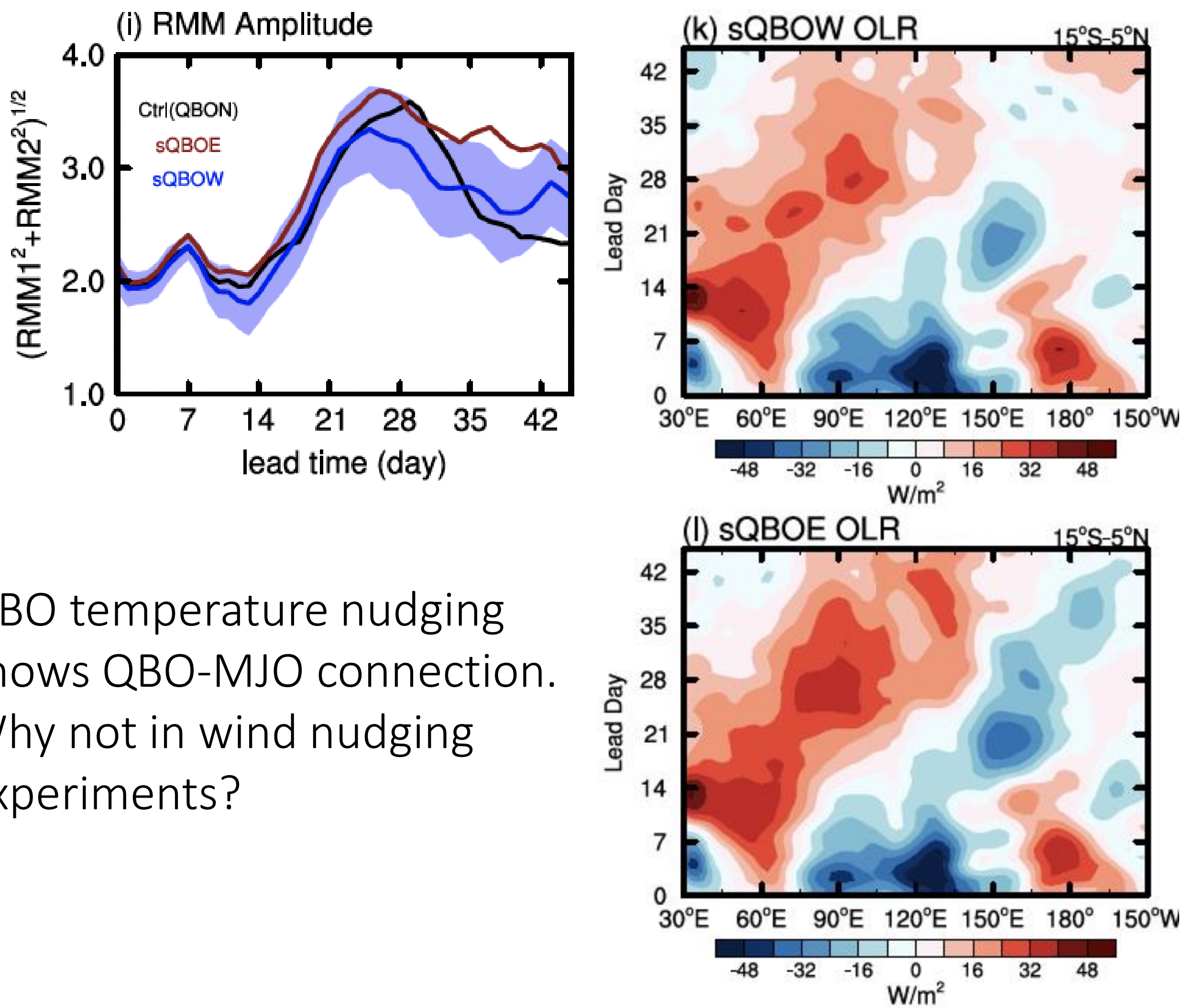
DYNAMO case study:
9 km * 9 km * L45 (top at 20 hPa)

Cloud-resolving model simulations show a hint of stronger MJO in EQBO, but much weaker than the observation.



Back et al. (2020GRL)

QBO-nudged S2S model experiment (CESM2)



Huang et al. (2020GRL)

QBO temperature nudging shows QBO-MJO connection. Why not in wind nudging experiments?

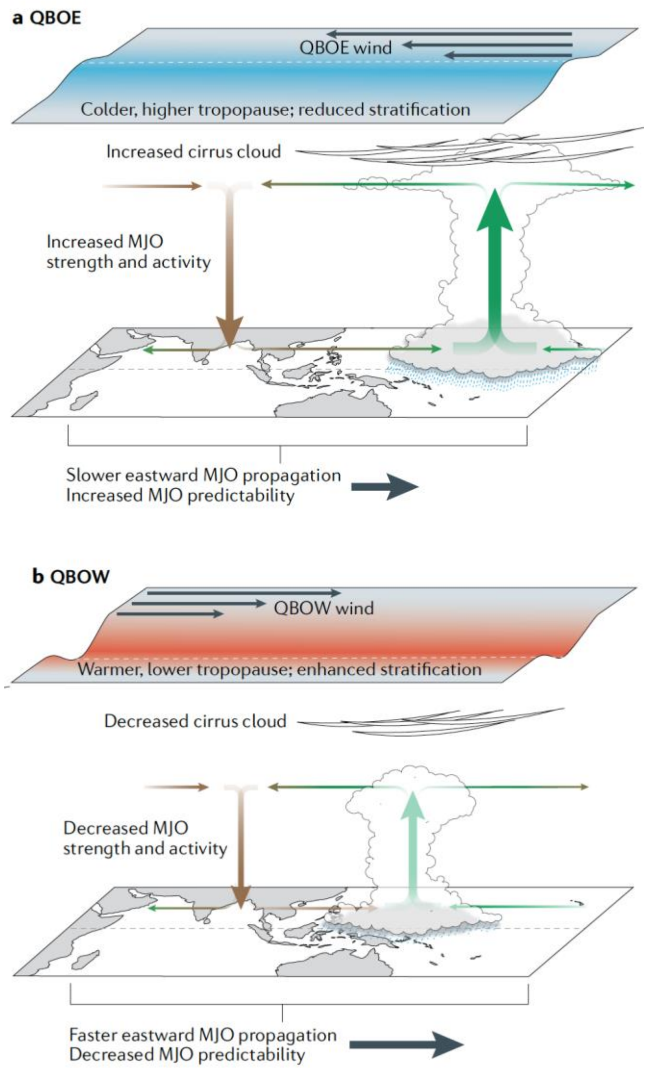
Summary

Observations

- Stronger, slower, and more persistent MJO propagating in EQBO winter In recent decades

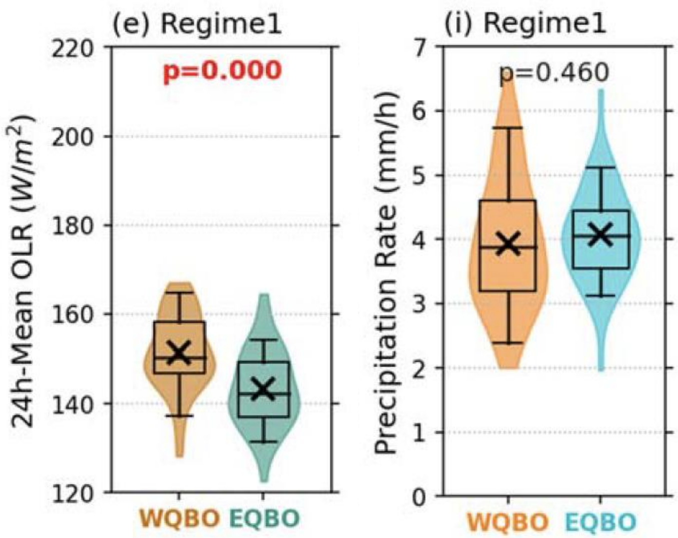
Remaining issues

- Mechanism(s) not well understood
- Its teleconnections not well understood
- Modelling very difficult
- Recent emergency not well understood



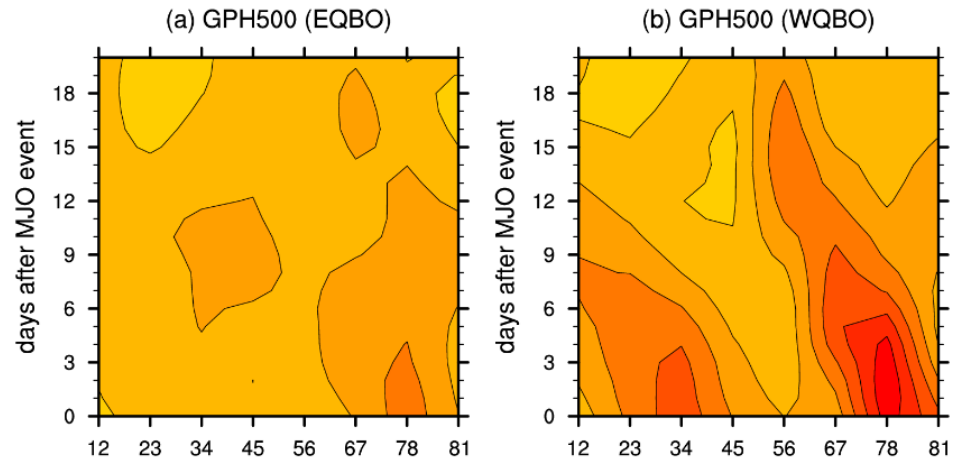
Mechanism:

Strong MJO in EQBO likely due to Cloud-LW radiation feedback



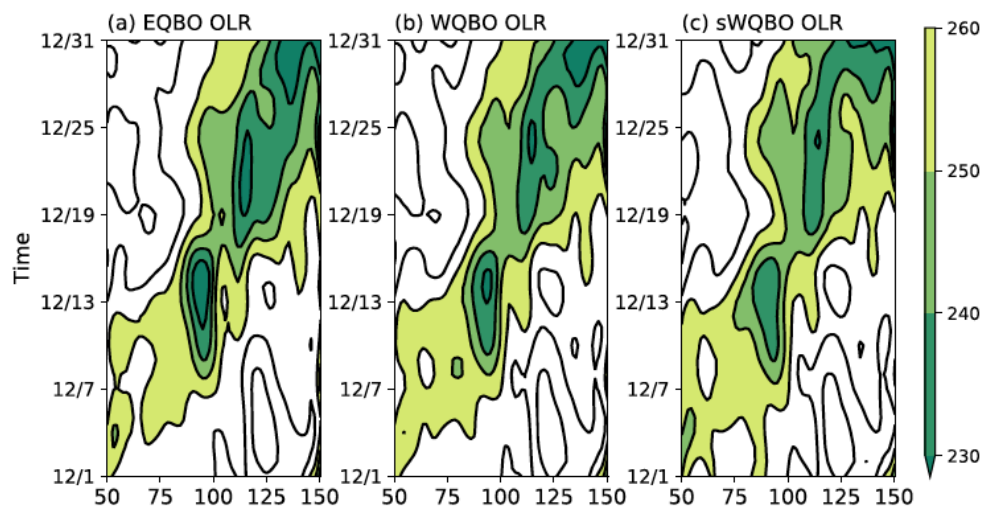
Teleconnections:

Weaker MJO teleconnections in EQBO likely due to preceding teleconnections

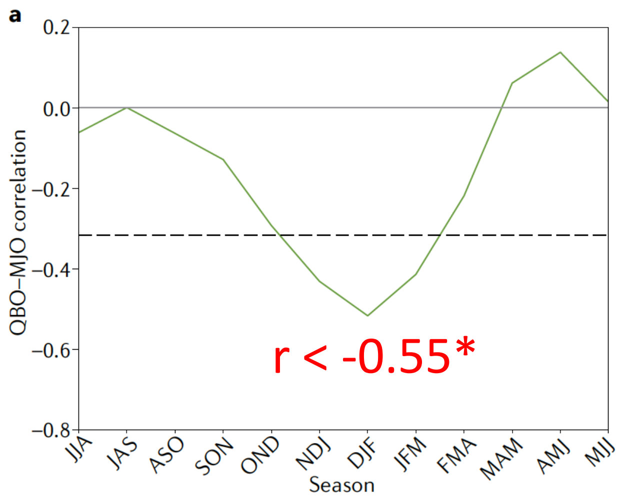


Modelling:

No or weak QBO-MJO connection. Further studies are necessary.

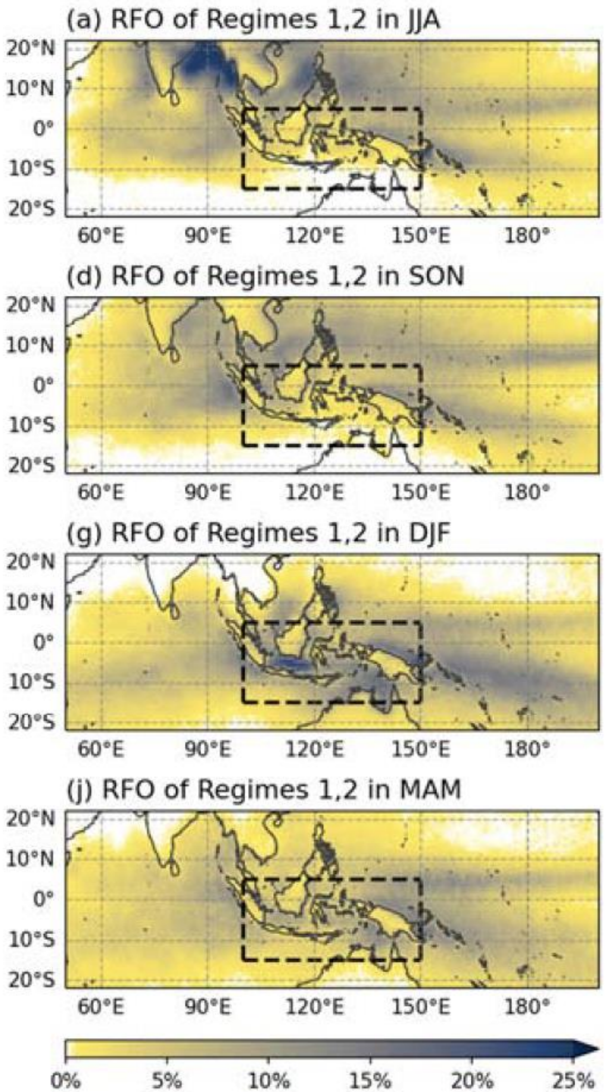


QBO-MJO connection seasonality

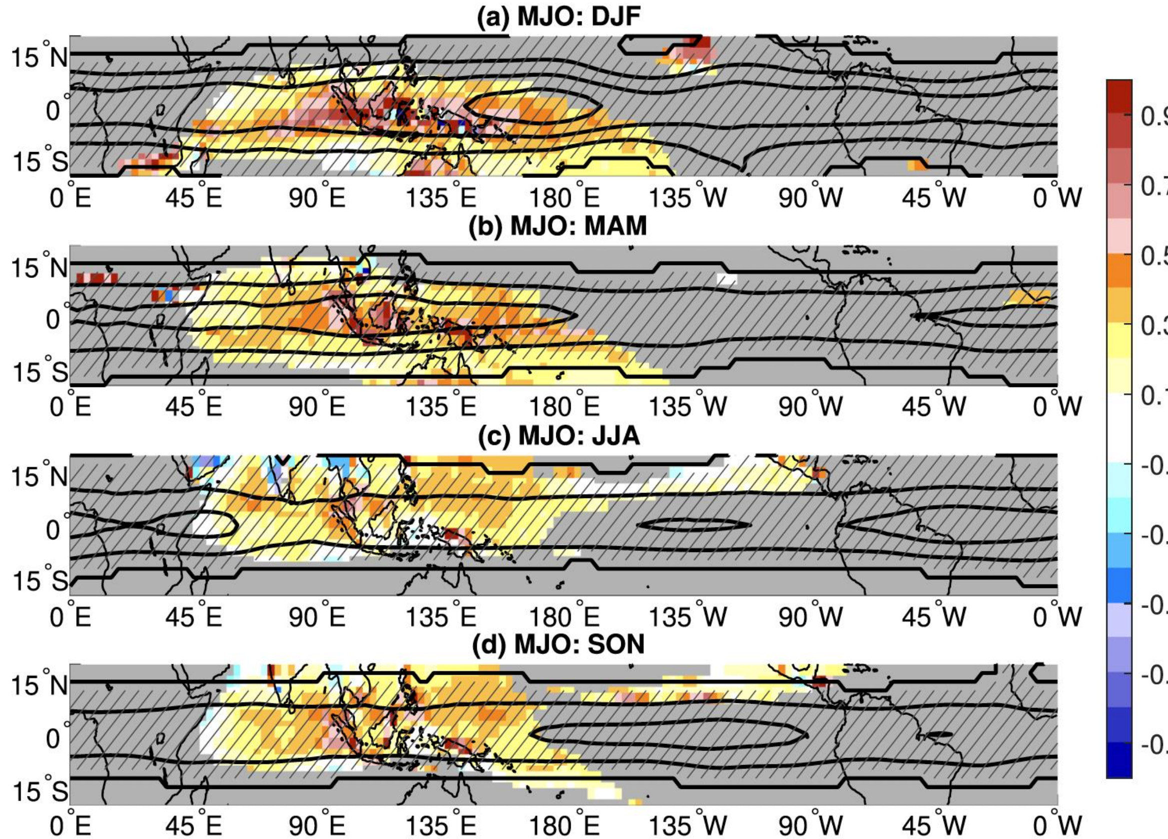


Martin, Son et al.
(2021NREE)

QBO-MJO connection seasonality



Jin et al. (2023NComms)

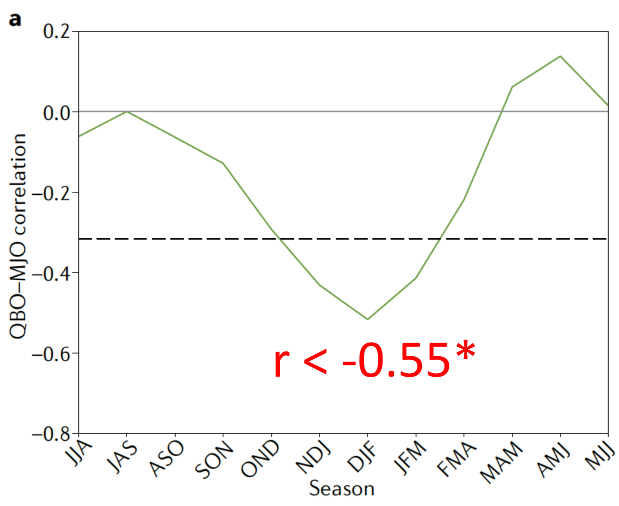


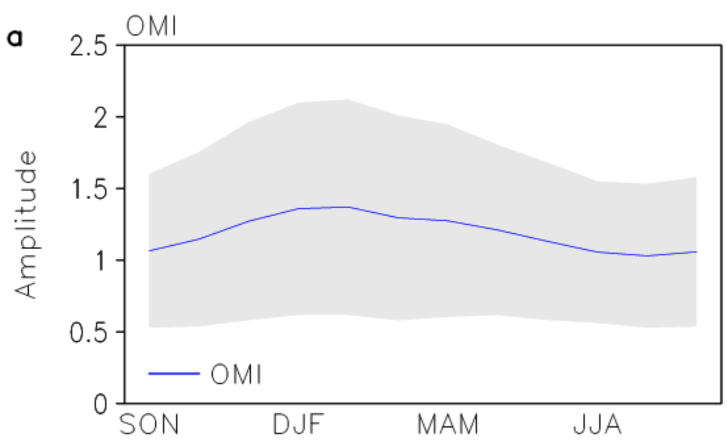
Shading: top-heaviness of MJO
Contour: static stability

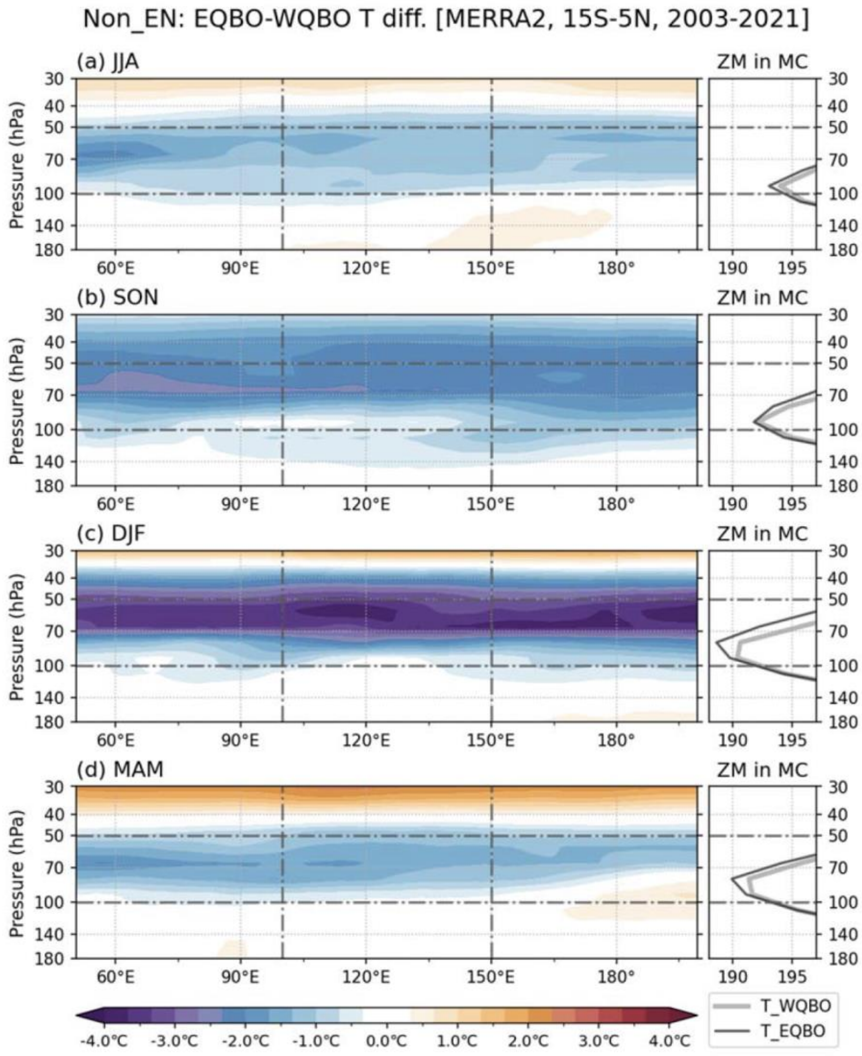
Sakaeda et al. (2020JGR)

QBO-MJO connection in DJF is likely due to more frequent high (and top-heavy) clouds in DJF.

QBO-MJO connection seasonality

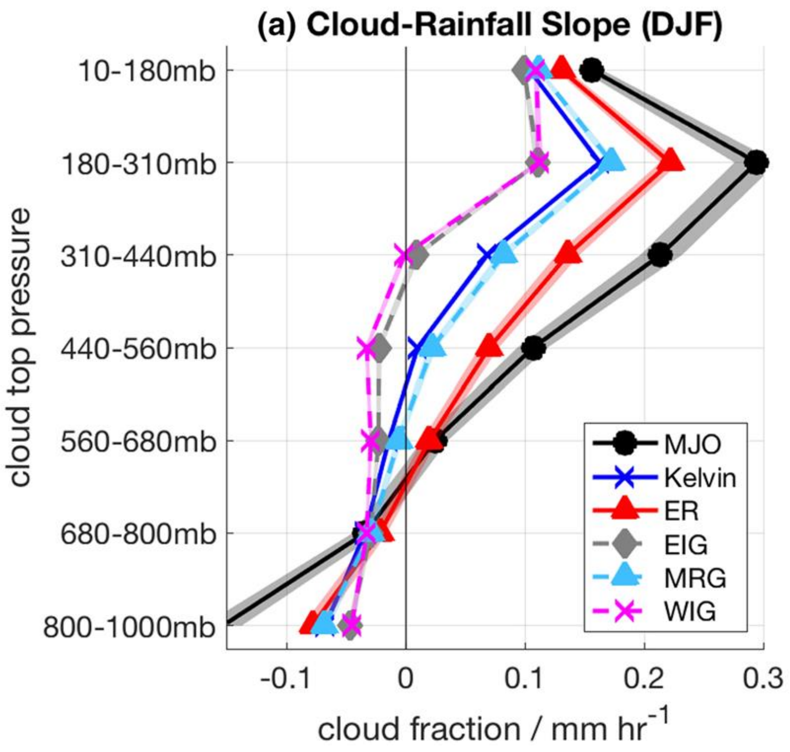






Active MJO and strong QBO-temperature anomalies in DJF.

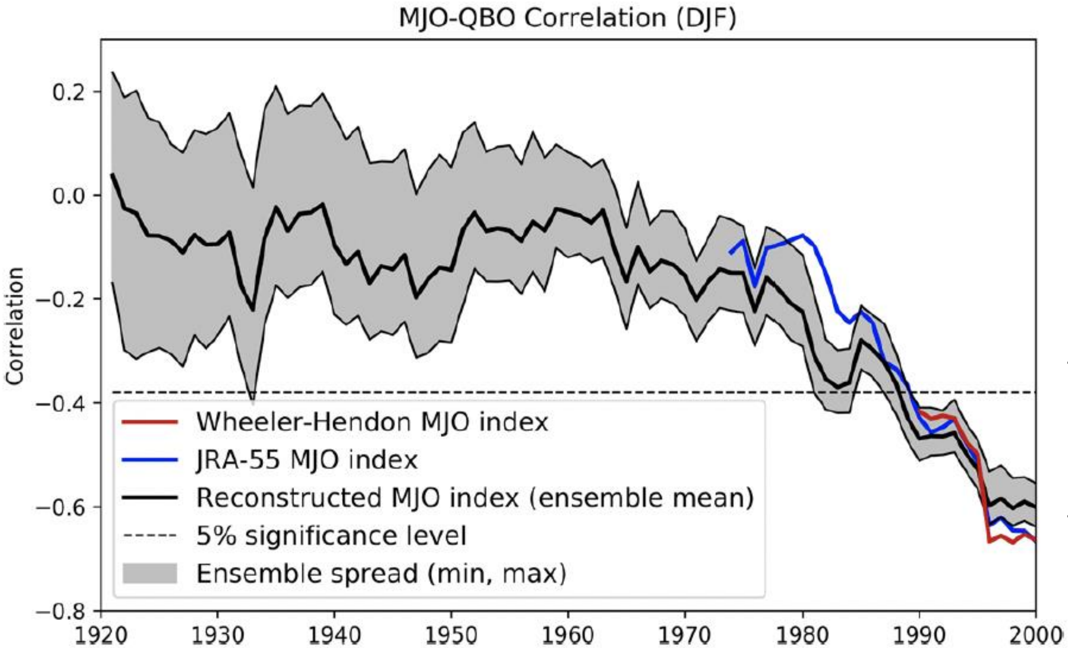
Top heaviness of MJO



Sakaeda et al. (2020JGR)

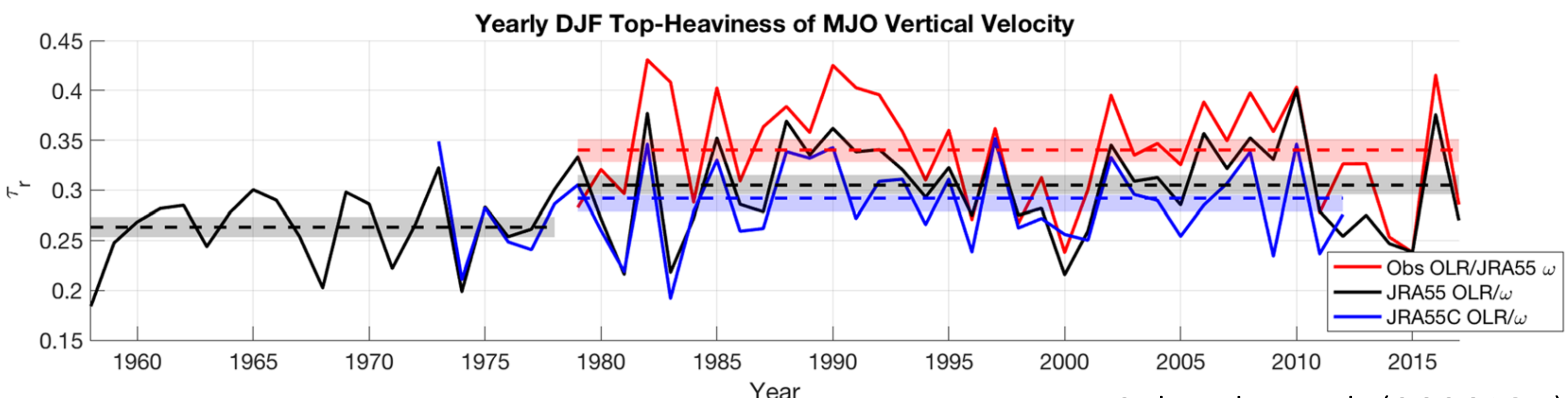
The MJO has top-heavy vertical velocity profile with a great fraction of stratiform (ice) high clouds that can induce anomalous column radiative warming. The QBO may control stratiform high clouds of MJO.

QBO-MJO connection emergence



Klotzbach et al. (2019SR)

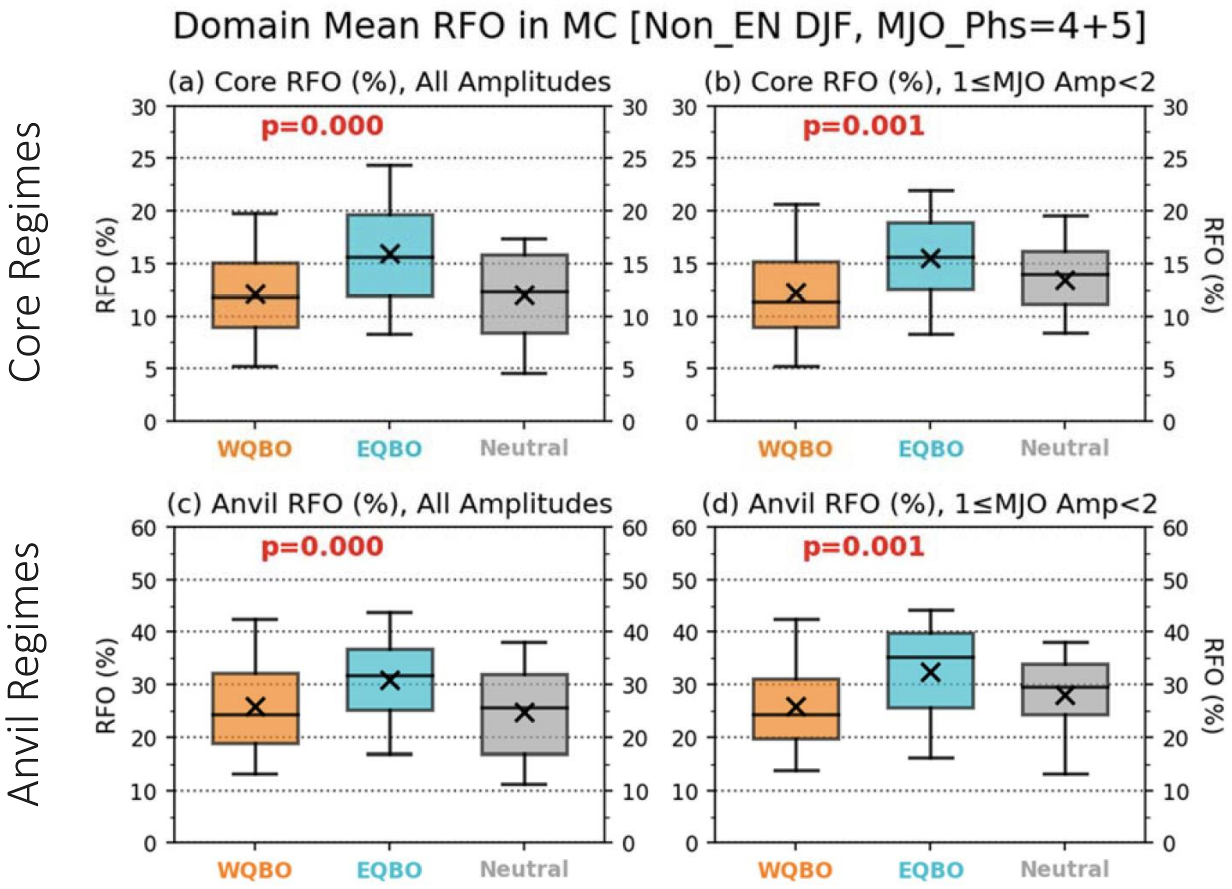
UTLS gets unstable in time. MJO convection itself changes?



Sakaeda et al. (2020JGR)

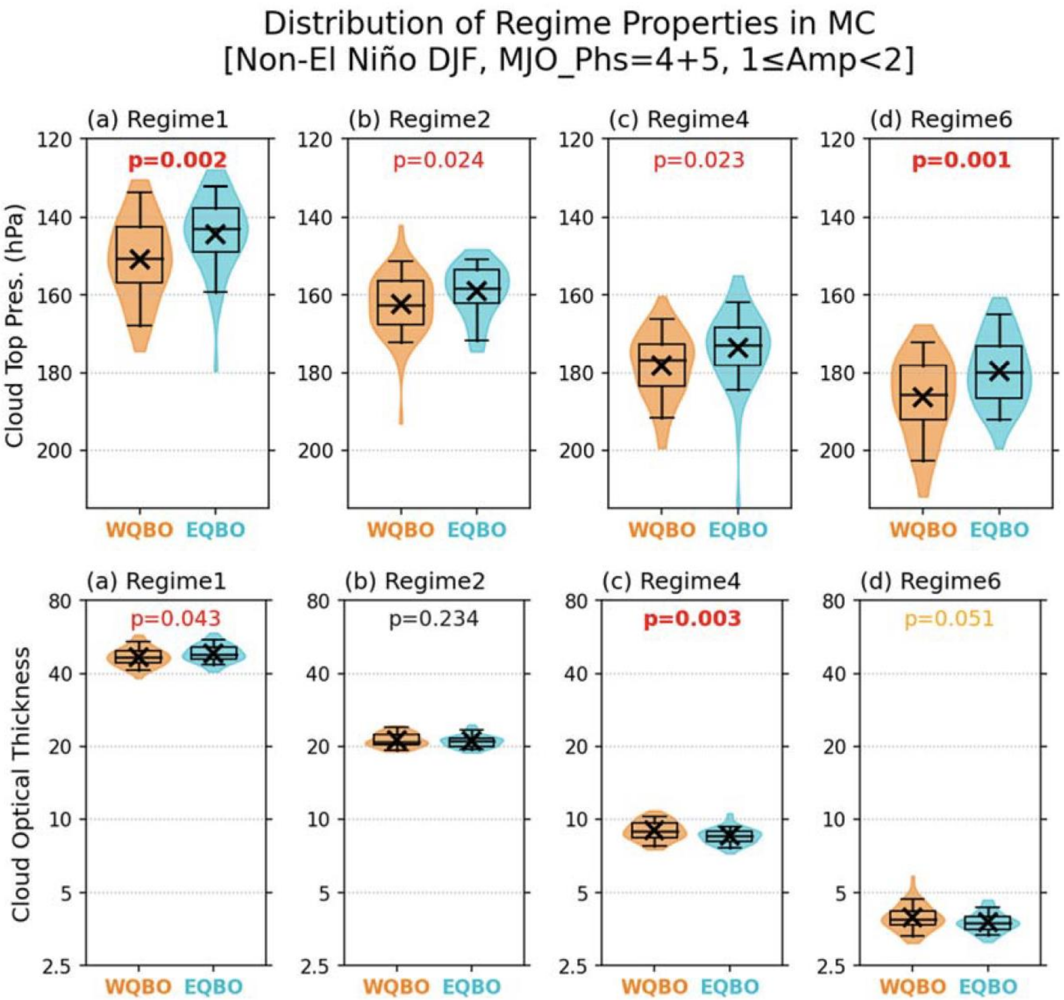
MJO high clouds over MC

More frequent high clouds (core and anvil regimes) in EQBO winter



Jin et al. (2023NComms)

MJO high clouds over MC



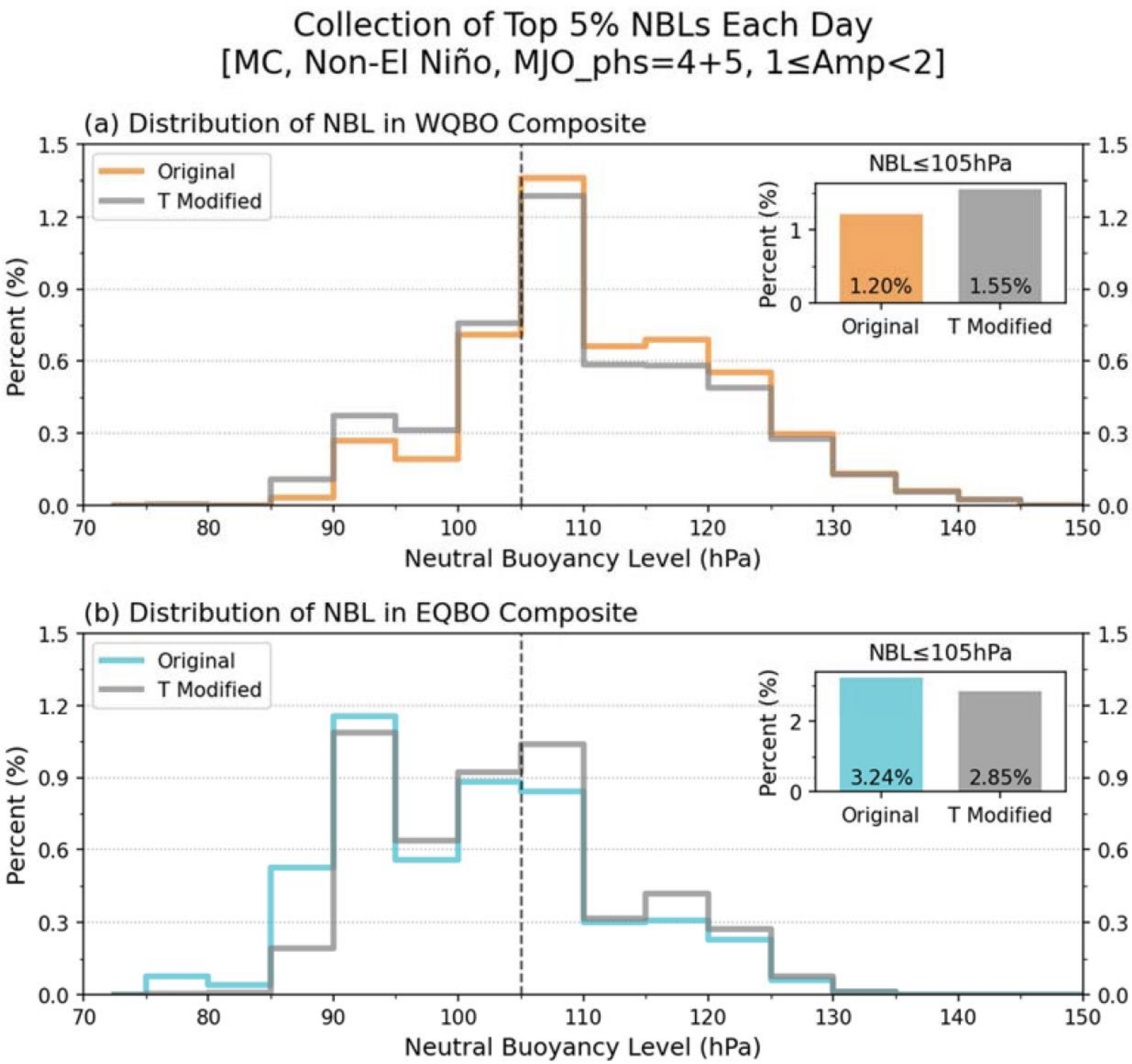
Core Regimes

Anvil Regimes

Under EQBO,

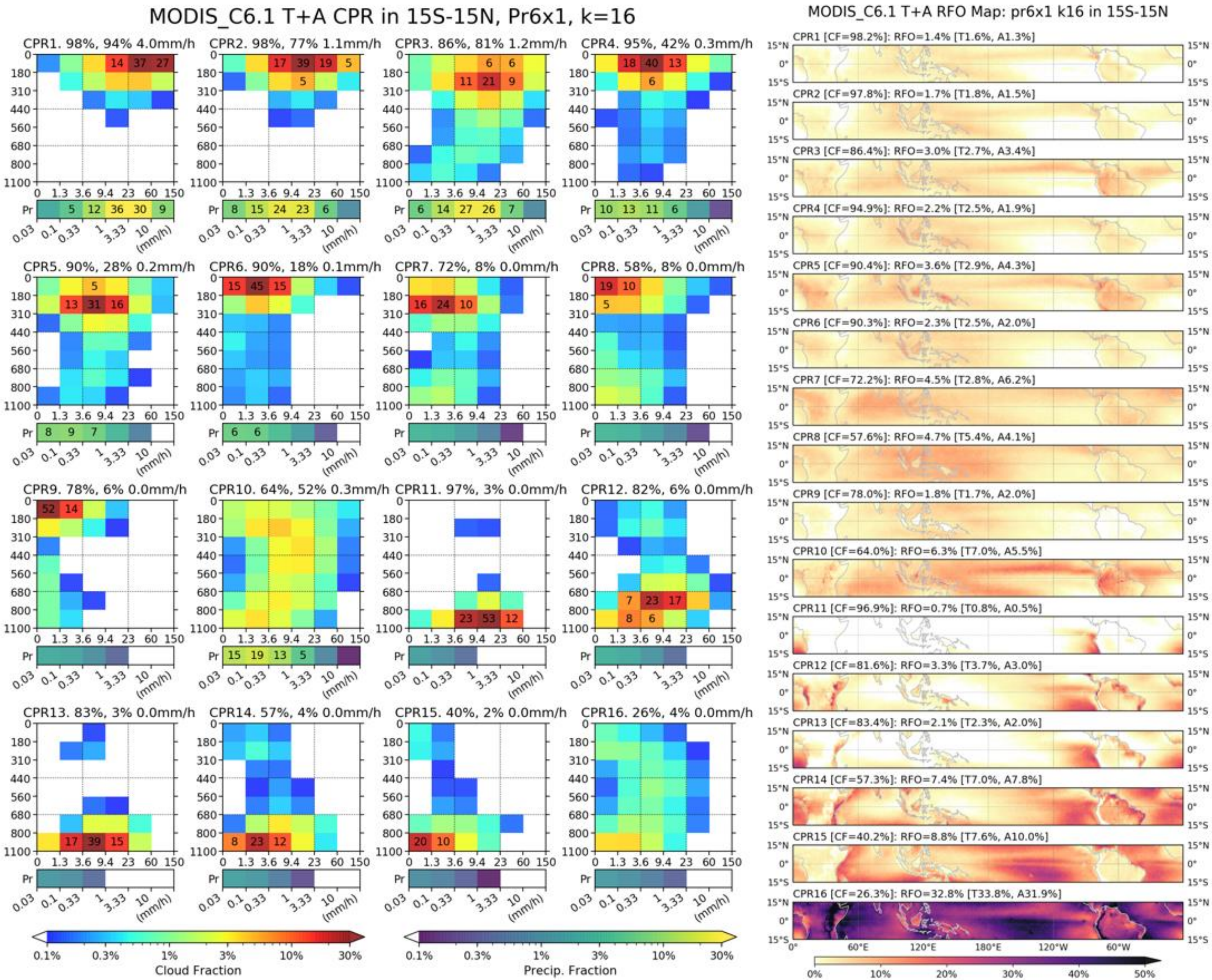
Higher high cloud? Yes

Optically thick? Not much



Neutral buoyancy levels (NBLs; a.k.a. equilibrium level [EL])

The T profile anomalies of MJO-QBO composites are swapped between EQBO and WQBO above 105hPa (MERRA-2). This simple swap results in population diff. of NBL reaching ≤105hPa decreasing from 2.04% to 1.30%, supporting the role of "T stratification mechanism."



Jin et al. (2021JAMC)

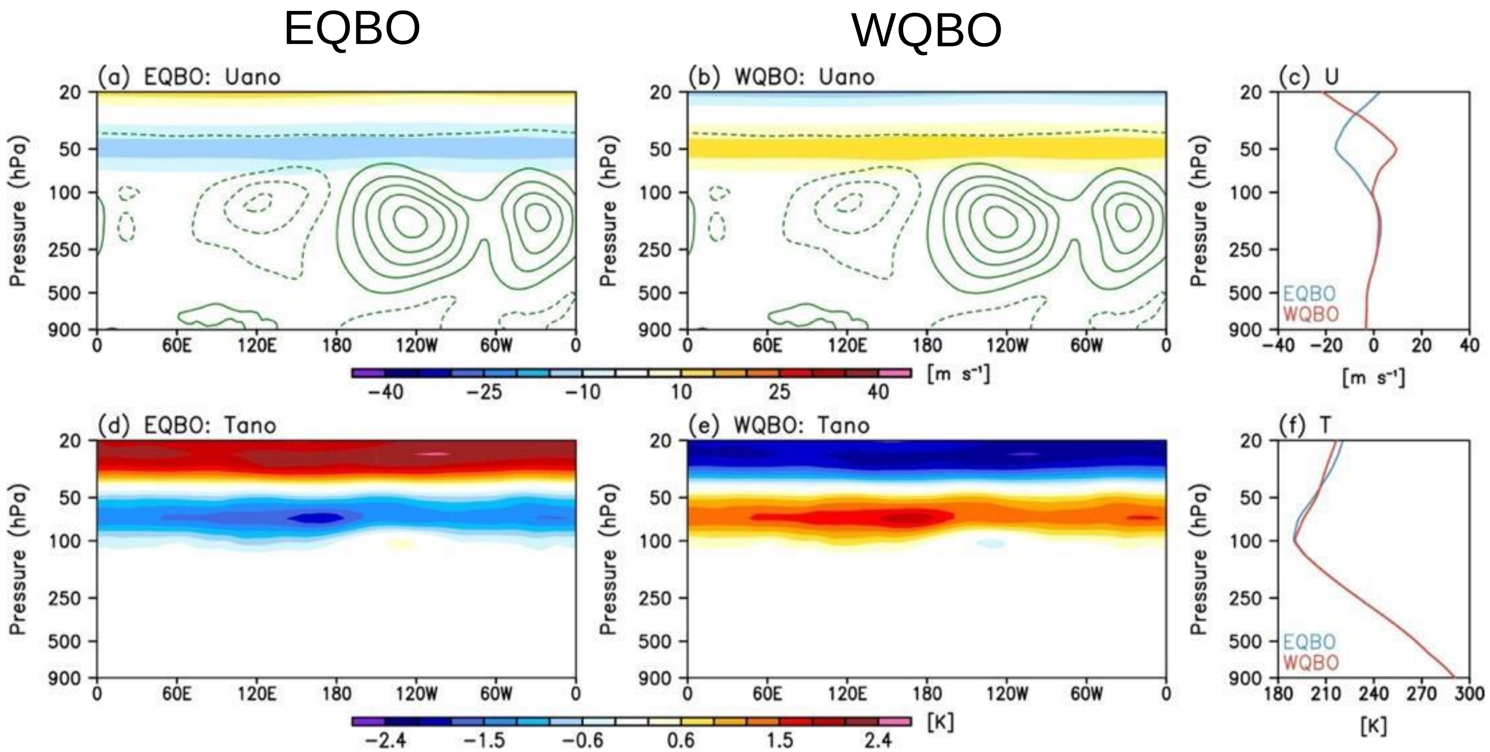
Idealized modeling

A dry primitive equation model based on the dynamical core of the GFDL GCM (e.g., Feldstein 1994; Son and Lee 2005; Ryu et al. 2008)

- Horizontal resolution: R30
- Vertical resolution: 77 layers in uneven sigma coordinate
- Integration time: 11 days
- External forcing that mimics the spatial pattern of MJO phase 3 with an eastward propagation
- Background state: EQBO and WQBO-related background states

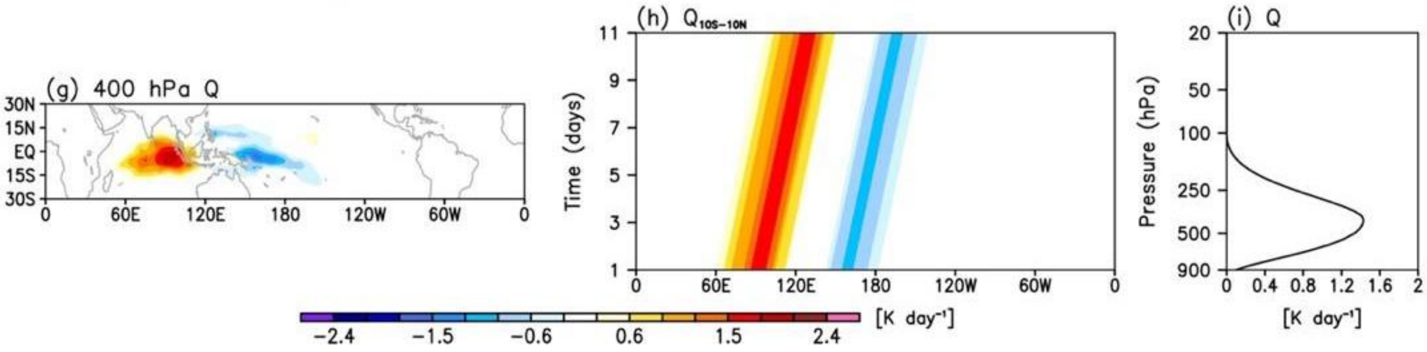
$$\frac{dT}{dt} - \frac{\kappa T}{\sigma p_s}\omega = \nu \nabla^2 T \text{ + MJO-like heating}$$

Idealized modeling: Background state



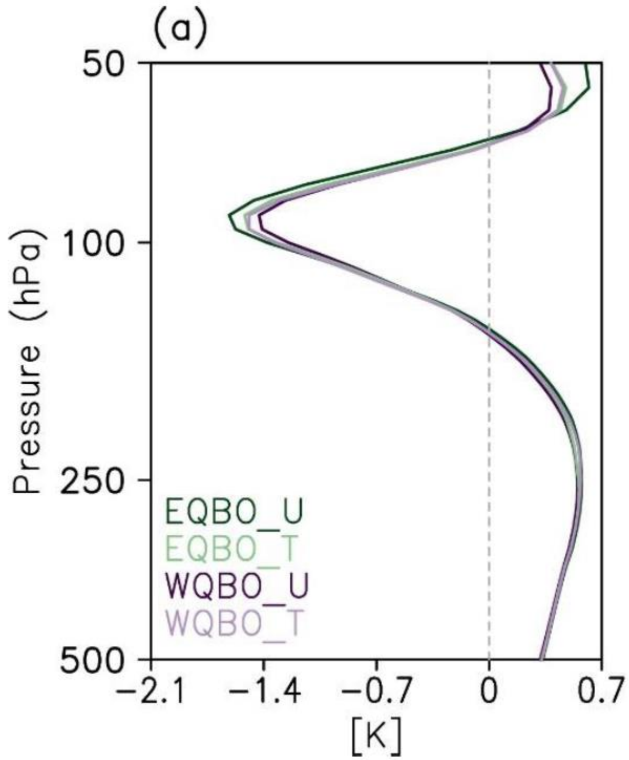
Idealized modelling: External forcing

MJO-like external heating moving eastward in time



$$\frac{dT}{dt} - \frac{\kappa T}{\sigma p_s}\omega = \nu\nabla^2 T$$ + MJO-like heating

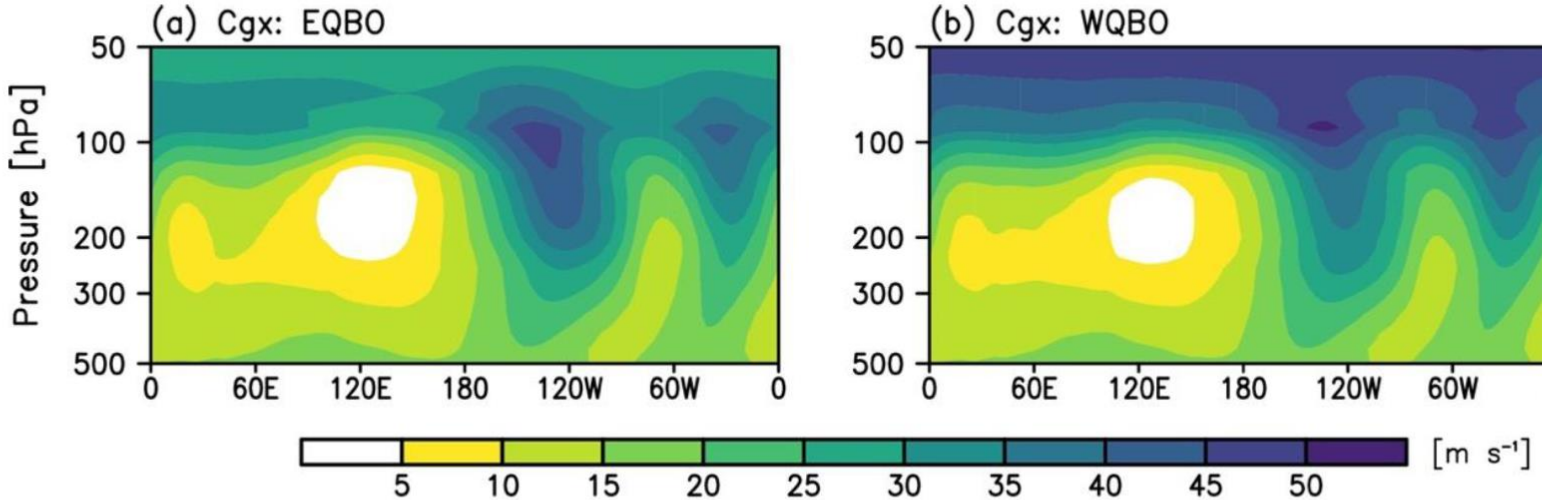
Temperature response



Experiment name	Initial background flow	Temperature at 5-10 days (K)
EQBO	EQBO U, V, T	-1.52
WQBO	WQBO U, V, T	-1.32
EQBO_U	EQBO U + CLM V, T	-1.51
WQBO_U	WQBO U + CLM V, T	-1.34
EQBO_T	EQBO T + CLM U, V	-1.42
WQBO_T	WQBO T + CLM U, V	-1.40

- The UTLS temperature systematically changes: 2*EQBO < EQBO < WQBO < 2*WQBO. Temperature gets colder from WQBO to EQBO states.
- This response is mostly due to wind change.

QBO temp. ano.: Kelvin wave response



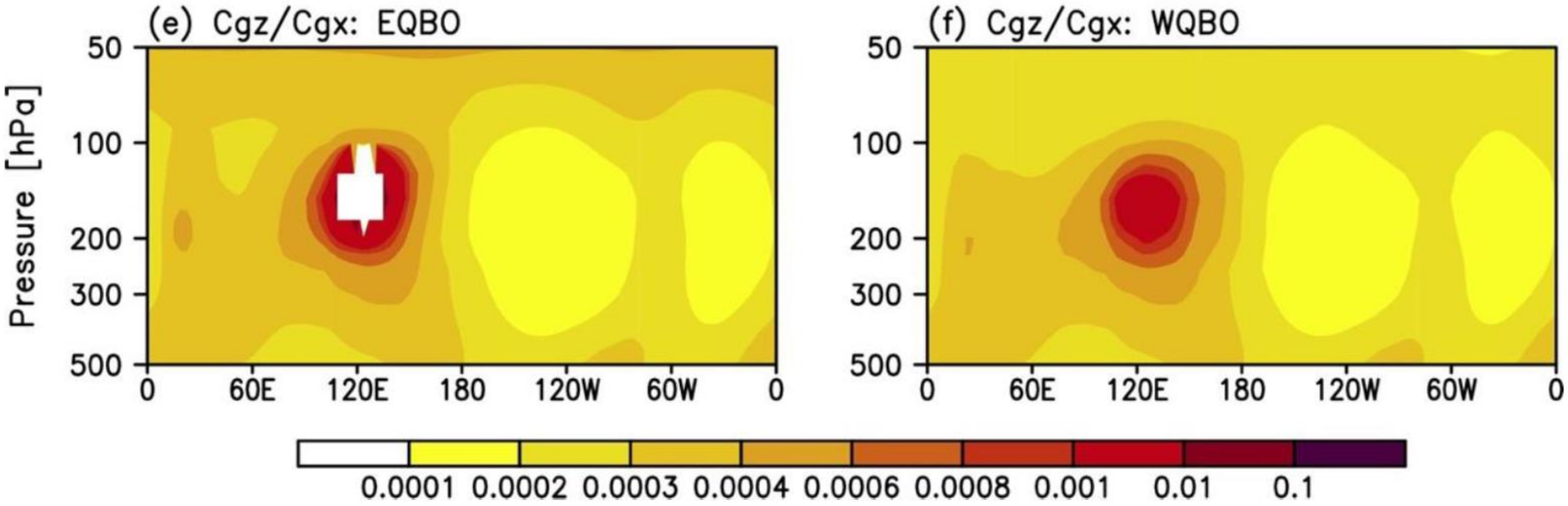
For $k=1.57*10^{-7}\ m^{-1}$ (k=1) & $m=-6.28*10^{-4}\ m^{-1}$ (vertical scale of 10 km)

$$C_{gx}A = \left(U - \frac{N}{m}\right)\left(-\frac{m}{Nk}\right)E = ck^{-1}(c-U)^{-1}E$$
$$\approx constant\ along\ X$$

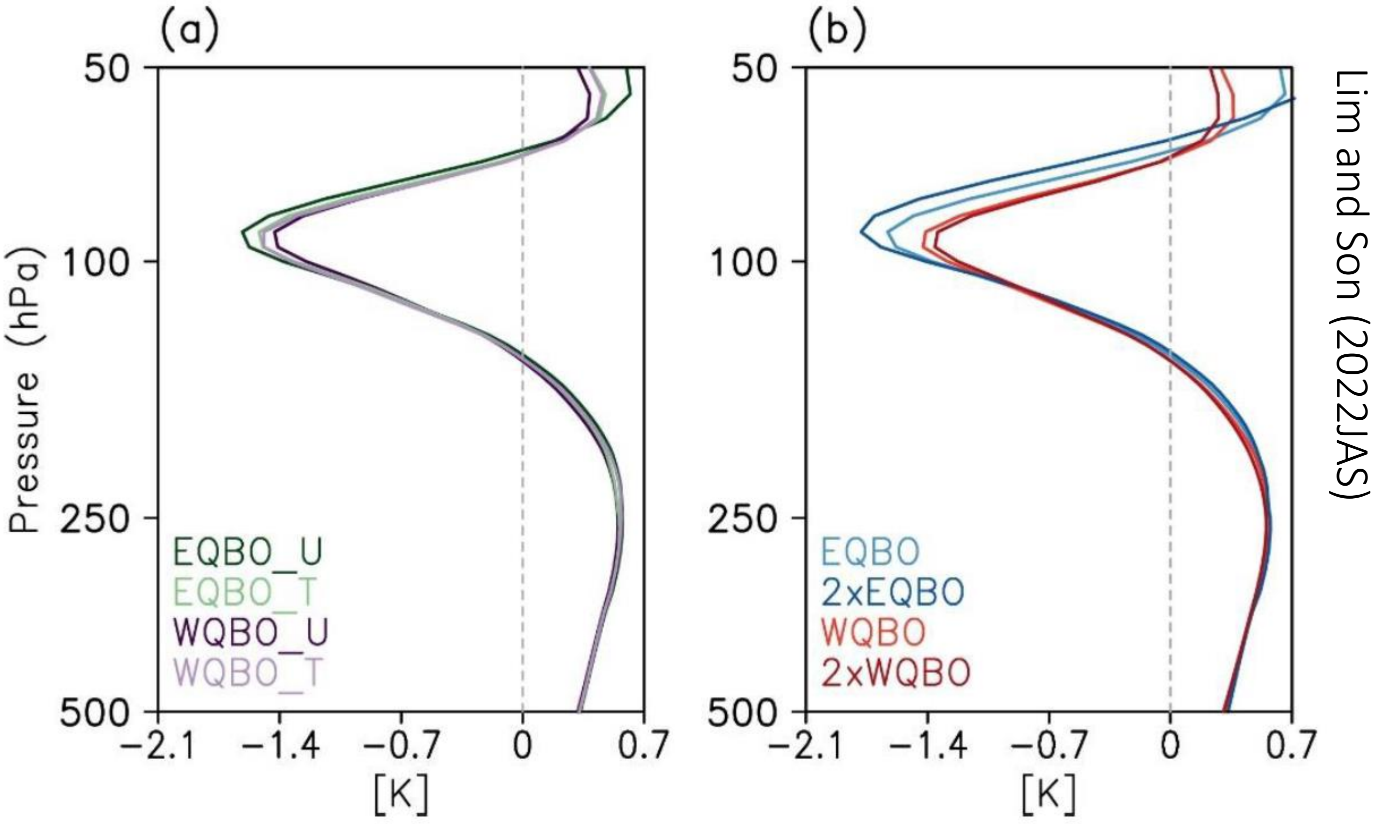
Under EQBO, $(c\text{-}U)^{-1}$ becomes small positive. This implies a large wave energy density. Note that k>0 and m<0 for eastward propagation Kelvin wave whose vertical group velocity is positive (as it is excited from below).

Kelvin wave dynamics

- Cgx is much smaller for EQBO than WQBO background states. At 90 hPa, Cgx = 26.57 m s^{-1} for EQBO and Cgx = 33.91 m s^{-1} for WQBO (Cgz = 9.8 * 10^{-3} m s^{-1} for EQBO and Cgz = 10.2 * 10^{-3} m s^{-1} for WQBO).
- Since Cgz/Cgx determines the vertical slope of Kelvin wave, this result indicates a steeper slope of Kelvin wave in EQBO state.



Linear model experiment



A stronger cooling in EQBO background state (mainly due to wind) as in observations.

Temperature anomaly: Kelvin wave response

Kelvin wave dispersion relationship for positive C_{gz} (Andrews et al. 1987)

$$\nu = Uk - \frac{Nk}{m}$$

Wave action (A) conservation following a ray in steady state (and $C_{gz} << C_{gx}$)

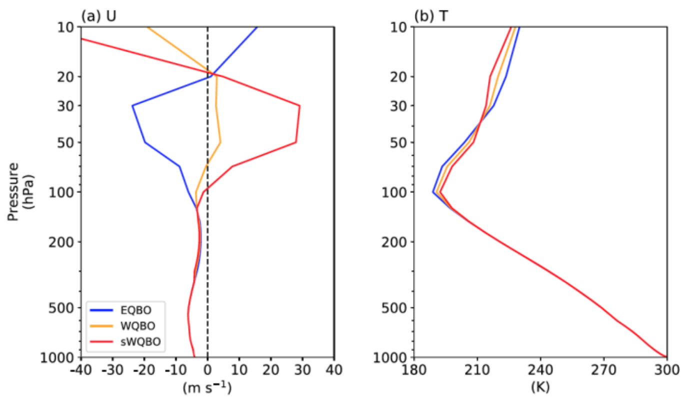
$$\frac{\partial A}{\partial T} + \frac{\partial}{\partial X}\left(C_{gx}A\right) + \frac{\partial}{\partial Z}\left(C_{gz}A\right) = 0$$

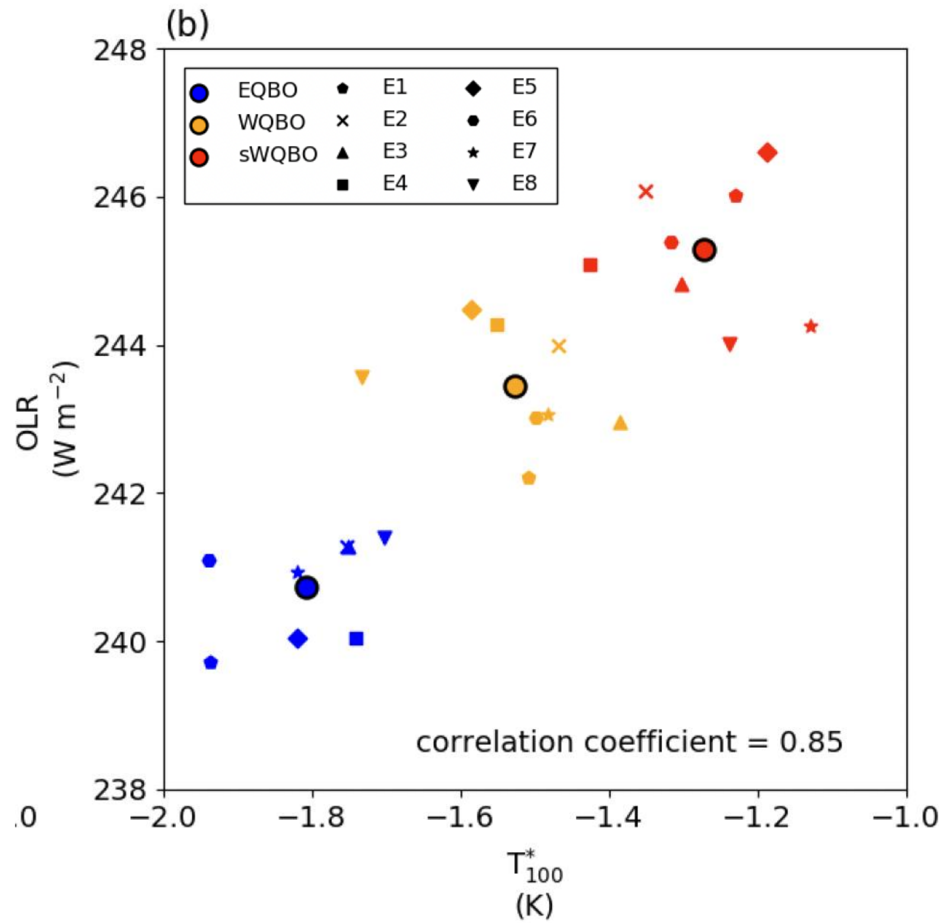
Wave energy density (E) depends on U (Ryu et al. 2008)

$$C_{gx}A = \left(U - \frac{N}{m}\right)\left(-\frac{m}{Nk}\right)E = ck^{-1}(c-U)^{-1}E$$
$$\approx constant\ along\ X$$

Under EQBO, $(c\text{-}U)^{-1}$ becomes small positive and wave energy density becomes large.

QBO-nudged experiment (WRF)





WRF simulations show a hint of stronger MJO in EQBO state, but much weaker than the observation. What's missing?

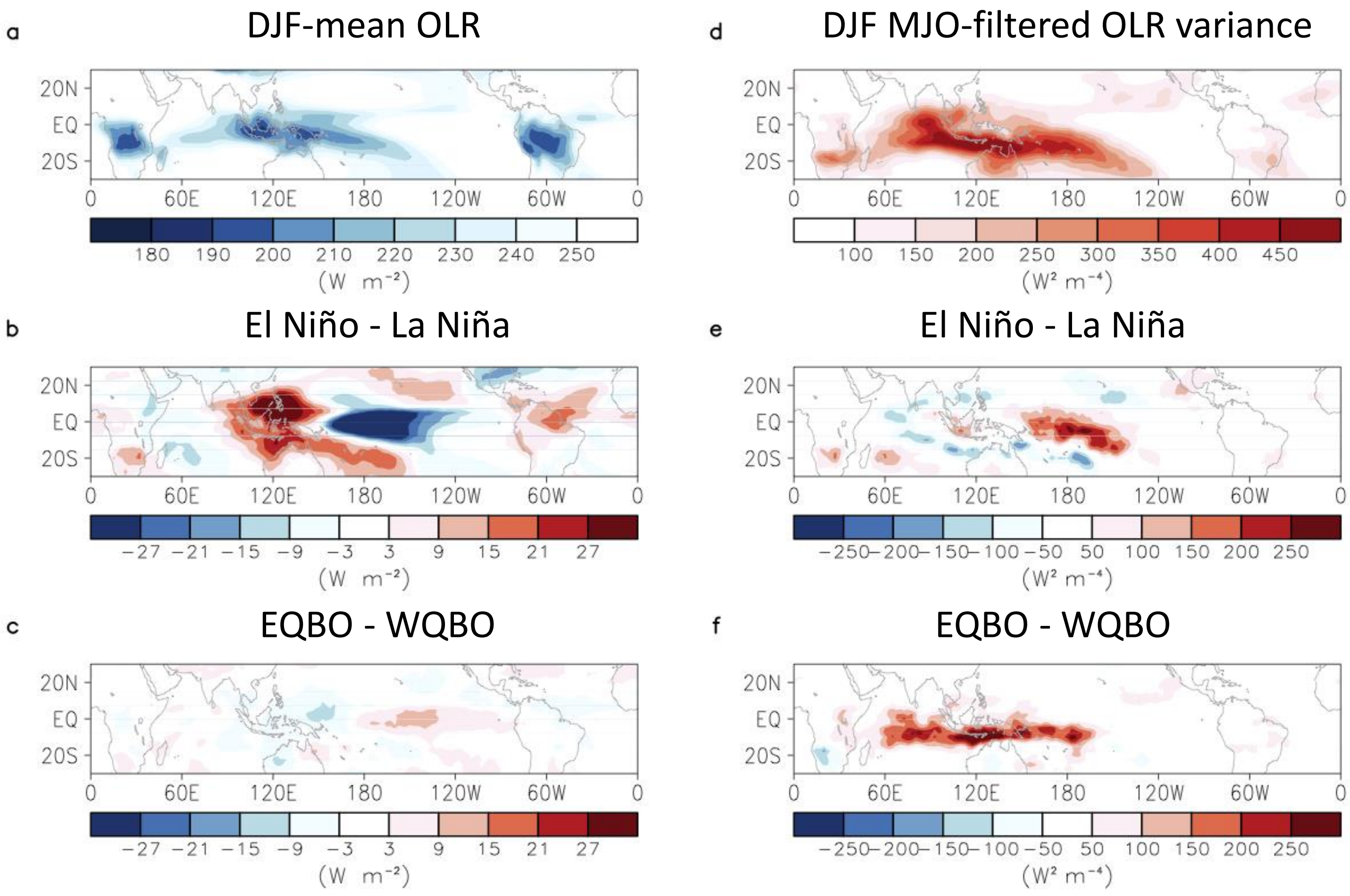
Back et al. (2020GRL)

QBO vs. MJO

Two different phenomena:

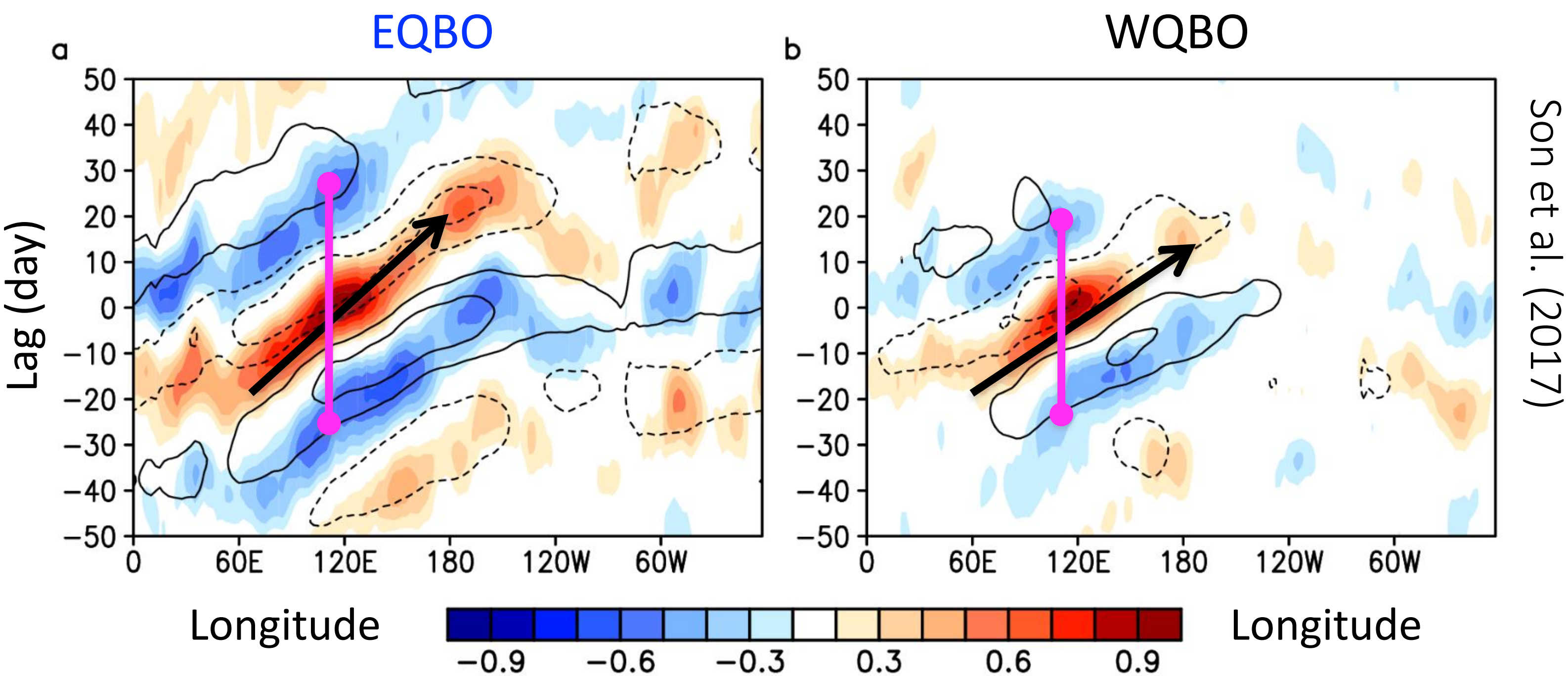
Interannual (~28 months) stratospheric QBO versus

Intraseasonal (30~90 days) tropospheric MJO



Son et al. (2017JCLI)

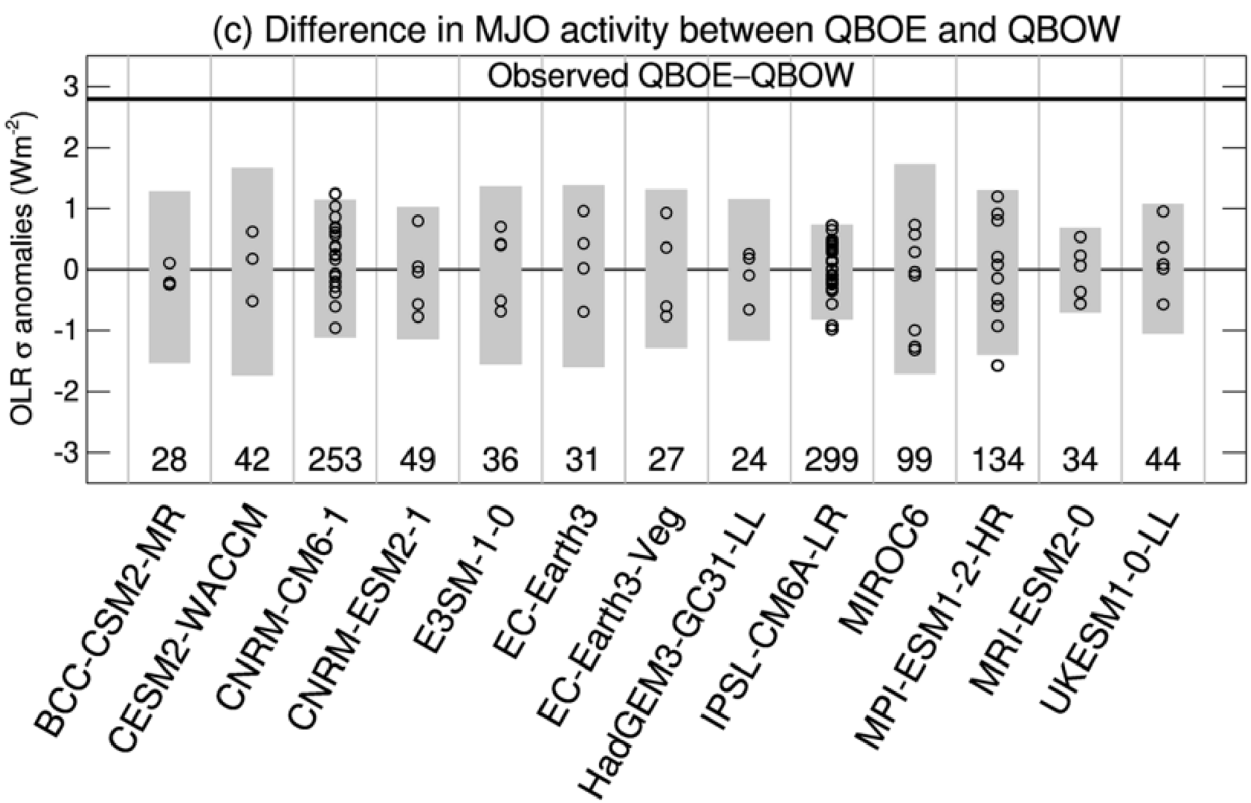
QBO-MJO connection



Shading: OLR corr. against Maritime cont. OLR (100-130E; 15S-5N)
Contour: U850 corr. against Maritime cont. OLR (100-130E; 15S-5N)

A stronger MJO amplitude
A slower and more persistent MJO propagation
A longer MJO period in EQBO winter

QBO-MJO in climate models

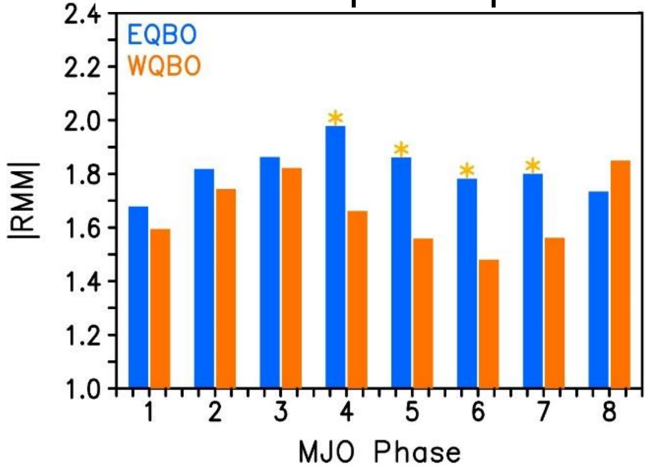


Kim et al. (2020GRL)

No QBO-MJO connection in CMIP5/CMIP6 models. GCMs often fail to simulate realistic QBO and MJO. Given such limitation, the lack of QBO-MJO connection in GCMs is not surprising.

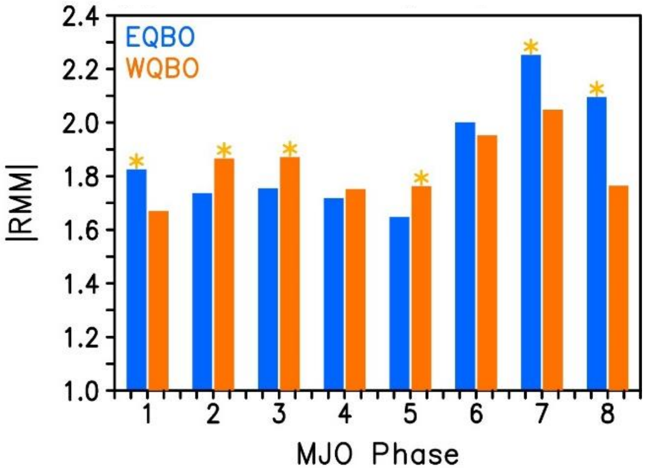
QBO-MJO in climate models

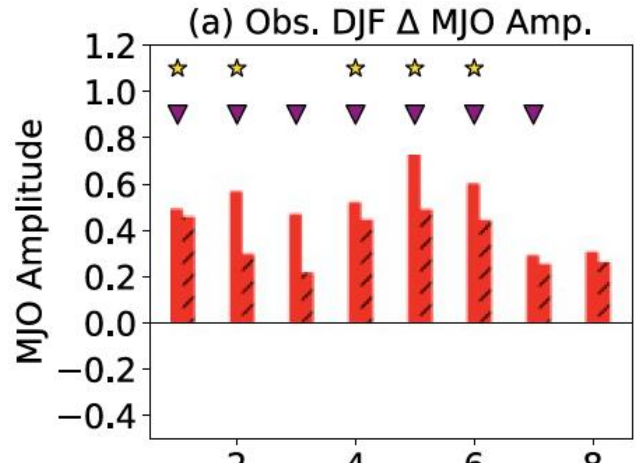
OBS |RMMI|



Lim and Son (2020JGR)

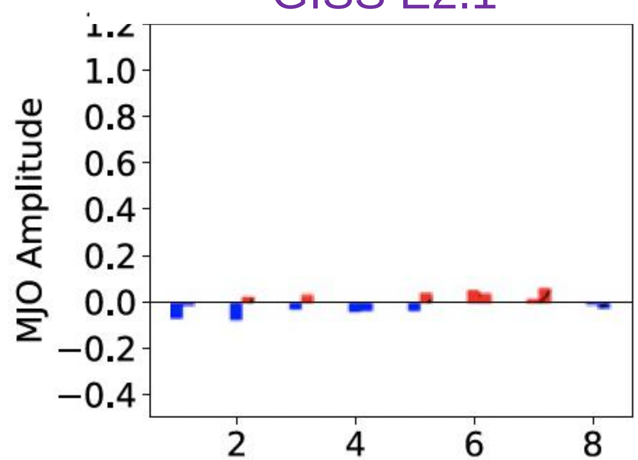
MPI-ESM-MR |RMMI|





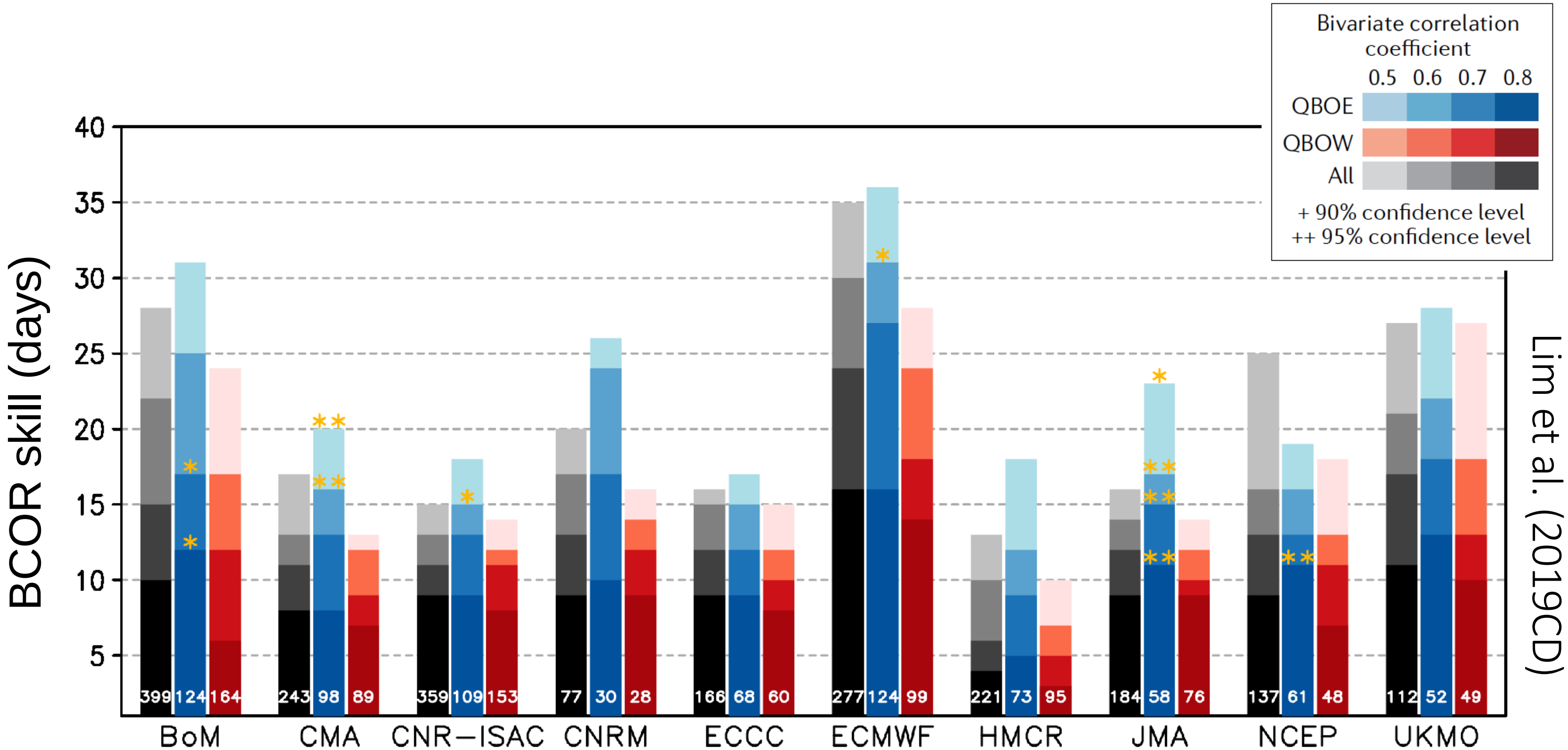
Martin et al. (2021JCLI)

QBO nudging experiment
GISS E2.1



No QBO-MJO connection in the best CMIP5 model and QBO nudging experiment

QBO-MJO in S2S models



S2S models show an improved MJO prediction skill in EQBO winter. The skill improvement is often statistically insignificant. It could result from initial condition not from QBO.