QBO impacts on MJO through mesoscale convective systems in the observations and models

[1]Kai Huang, [1]Chih-Chieh-Jack Chen, [1]Mitchell Moncrieff, and [1]Jadwiga Richter

[1]U.S. National Science Foundation National Center for Atmospheric Research, Boulder CO, USA

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catalyst

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Madden-Julian Oscillation (MJO)

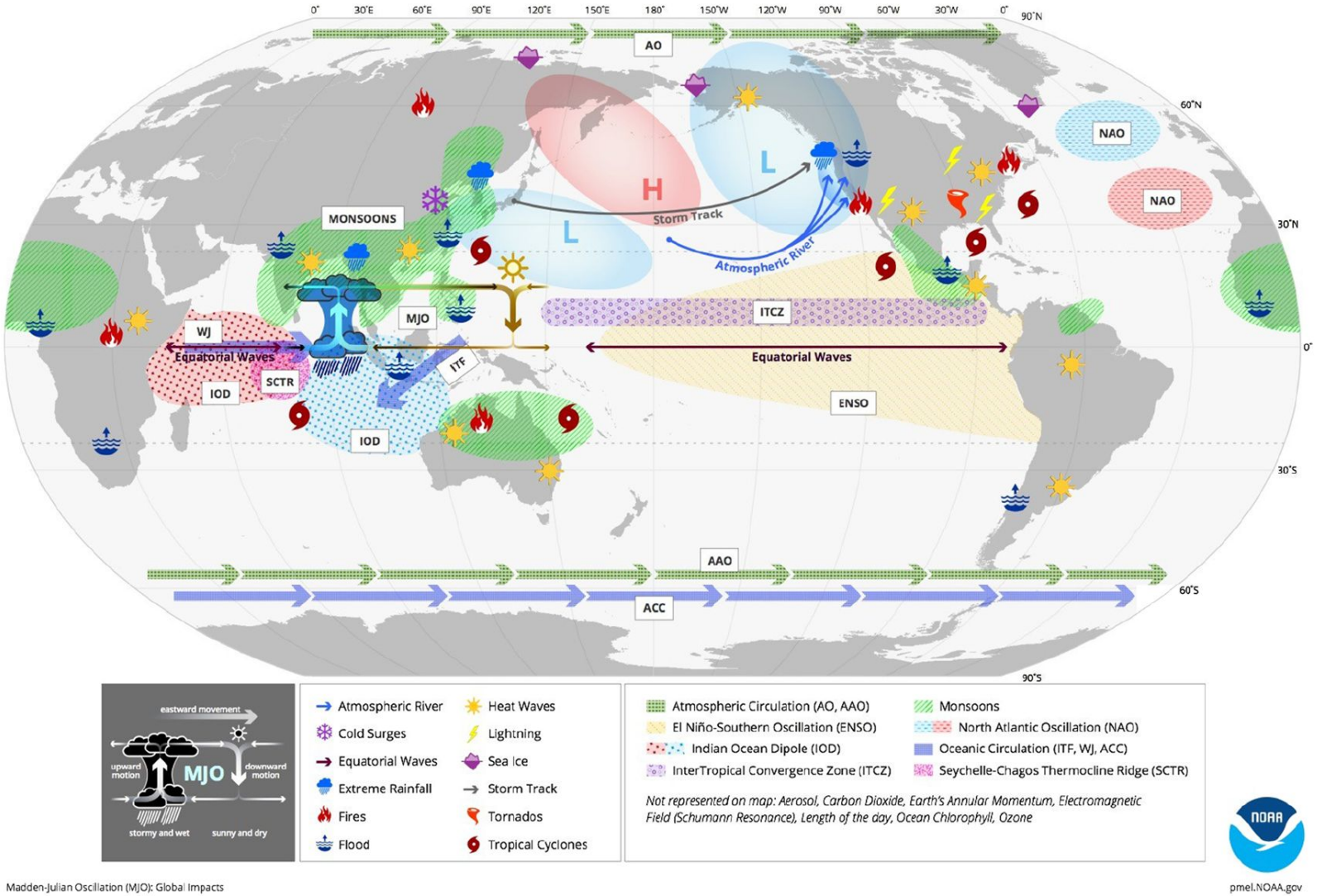
- Dominant subseasonal mode in the tropical troposphere
- Bridging weather and climate
- Downscale impacts on weather patterns

  PNA, CCEWs,
  tropical cyclone
  atmospheric river
  cold surges/heat waves
  extreme rainfalls/droughts

- Upscale impacts on climate modes

  IOD, monsoons
  ENSO, AO, NAO/AAO, ACC
  ITCZ

- Important predictability source for S2S/S2D predictions



Madden-Julian Oscillation (MJO): Global Impacts

Yoneyama, K., & Zhang, C. (2020). Years of the Maritime Continent. *Geophysical Research Letters*, 47, e2020GL087182. https://doi.org/10.1029/2020GL087182

QBO Impacts on MJO

- MJO is stronger and more likely to propagate across the Maritime Continent in the easterly phase of QBO than the westerly phase of QBO.
  - **Seasonality** → only in the boreal winter seasons
  - **Location Preference** → centered around the MC
  - **Uniqueness** → no impacts on other convectively coupled equatorial waves
  - **Emergence** → not detected before the 1980s in reanalyses

- Several mechanisms are proposed in the past decade, but the connection is not thoroughly understood.

  wind shear (Collimore et al., 2003), **tropopause stability** (Hendon & Abhik, 2018), **cloud-radiative feedback** (Son et al., 2017), **extratropical wave forcing** (Hood & Hoopes, 2023), **solar cycle** (Hood et al., 2023), **sea surface temperature** (Randall et al., 2023) …

- All climate models fails to reproduce the QBO-MJO connection.

  even with a prescribed stratosphere **same as** the observations (e.g., Martin et al., 2021, Martin et al., 2023).

- The QBO-MJO connection is slightly captured by the forecast systems and MJO case simulations.

  Martin et al., (2019) Martin et al., (2020) Back et al., (2020) Huang et al., (2023)

DJF MJO OLR Variance

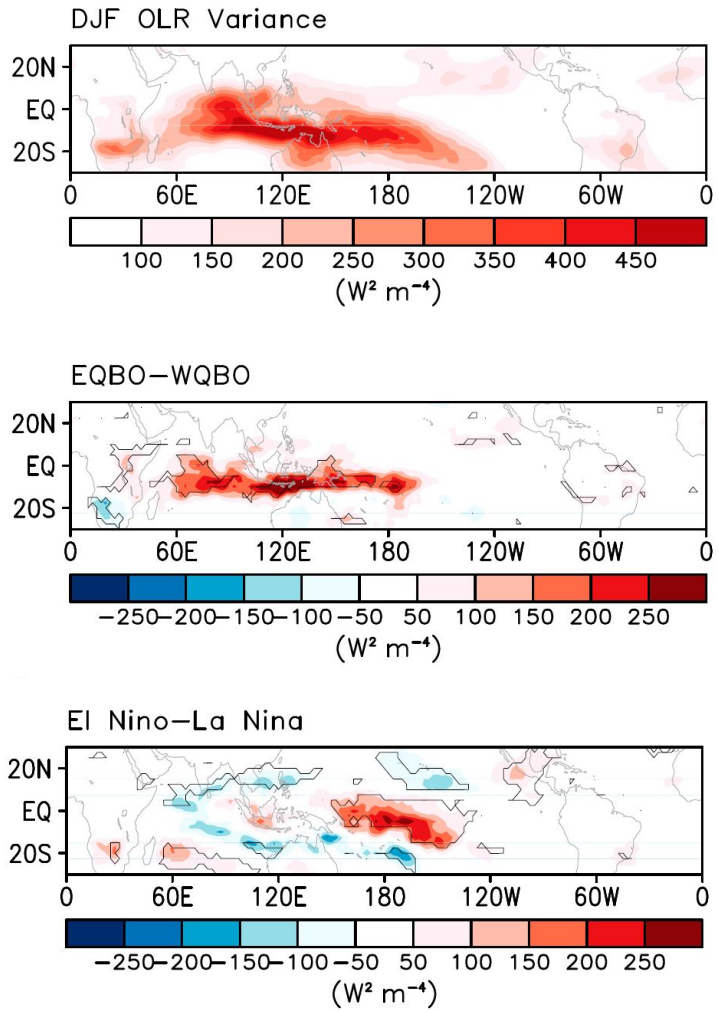
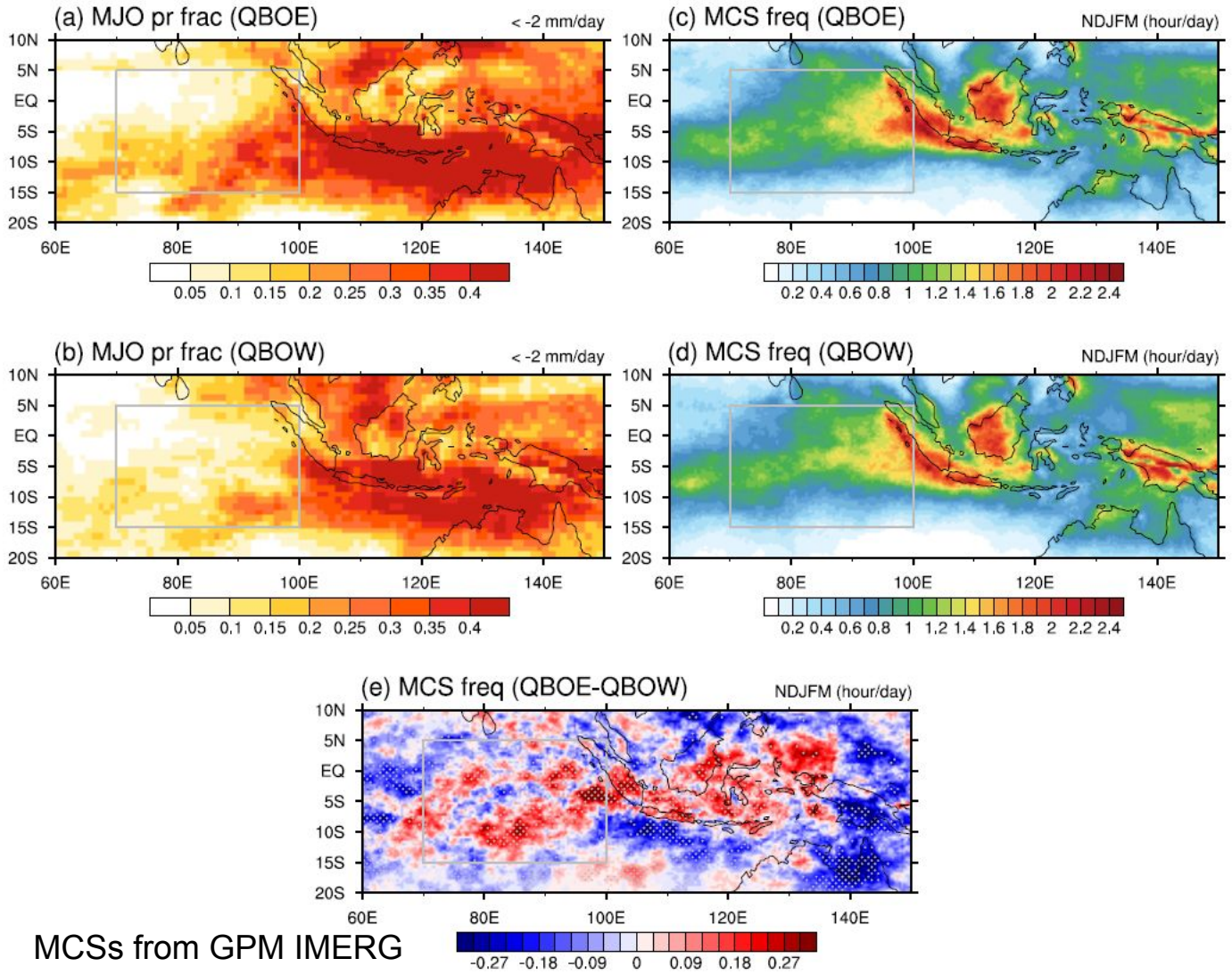


Figure from Son et al., (2017)

QBO Modulation on MCSs

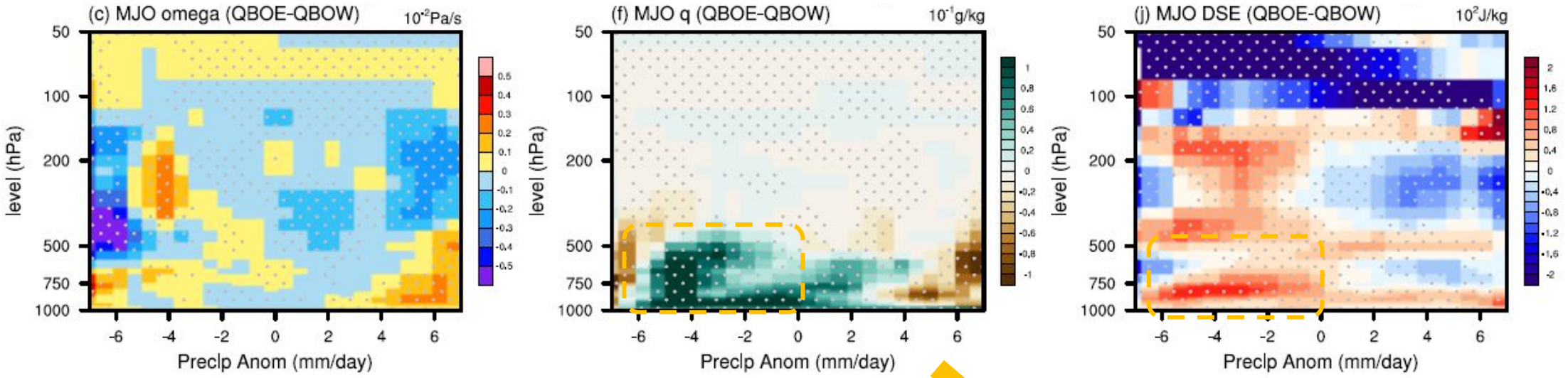
- Enhanced MCS frequency west of the maritime continent.
- The enhancement overlaps the negative MJO precipitation anomalies when MJO crosses the maritime continent.



MCSs from GPM IMERG

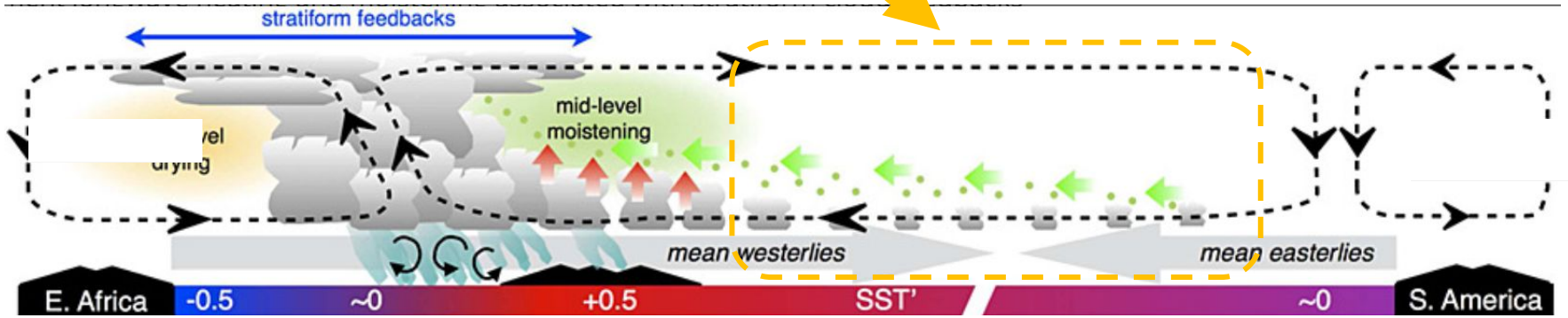
Preconditioning from MCSs to MJO

MJO Vertical Profiles over the Indian Ocean Domain
(70E-100E,15S-5N)



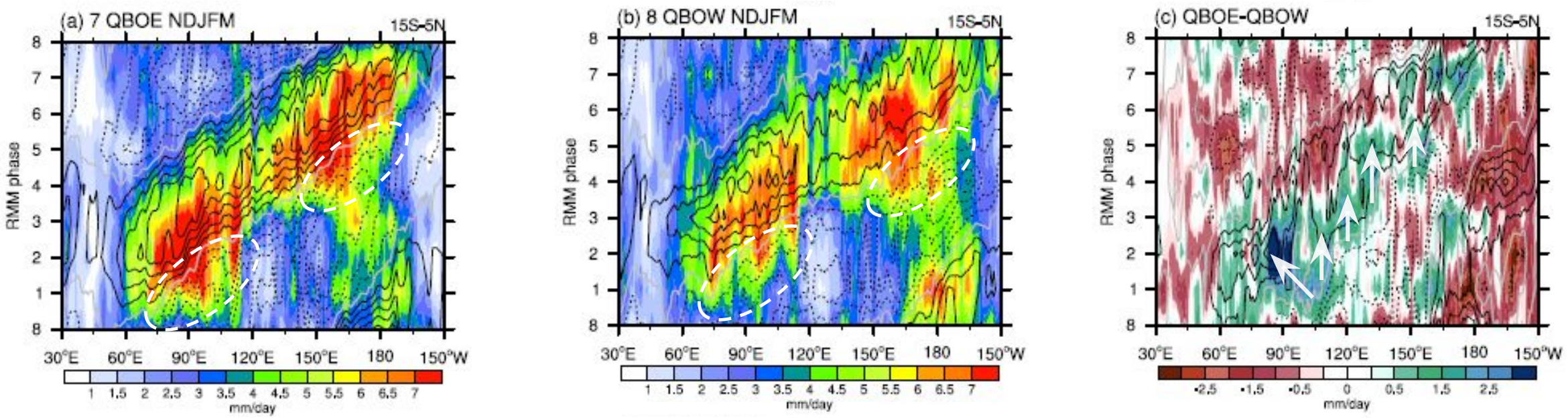
Schematic for the MJO Multi-convection Structure

from DeMott et al., (2015)



QBO Modulates MJO through MCSs

Hovmöller Diagrams of MJO (lines) and MCSs (shading) Precipitation

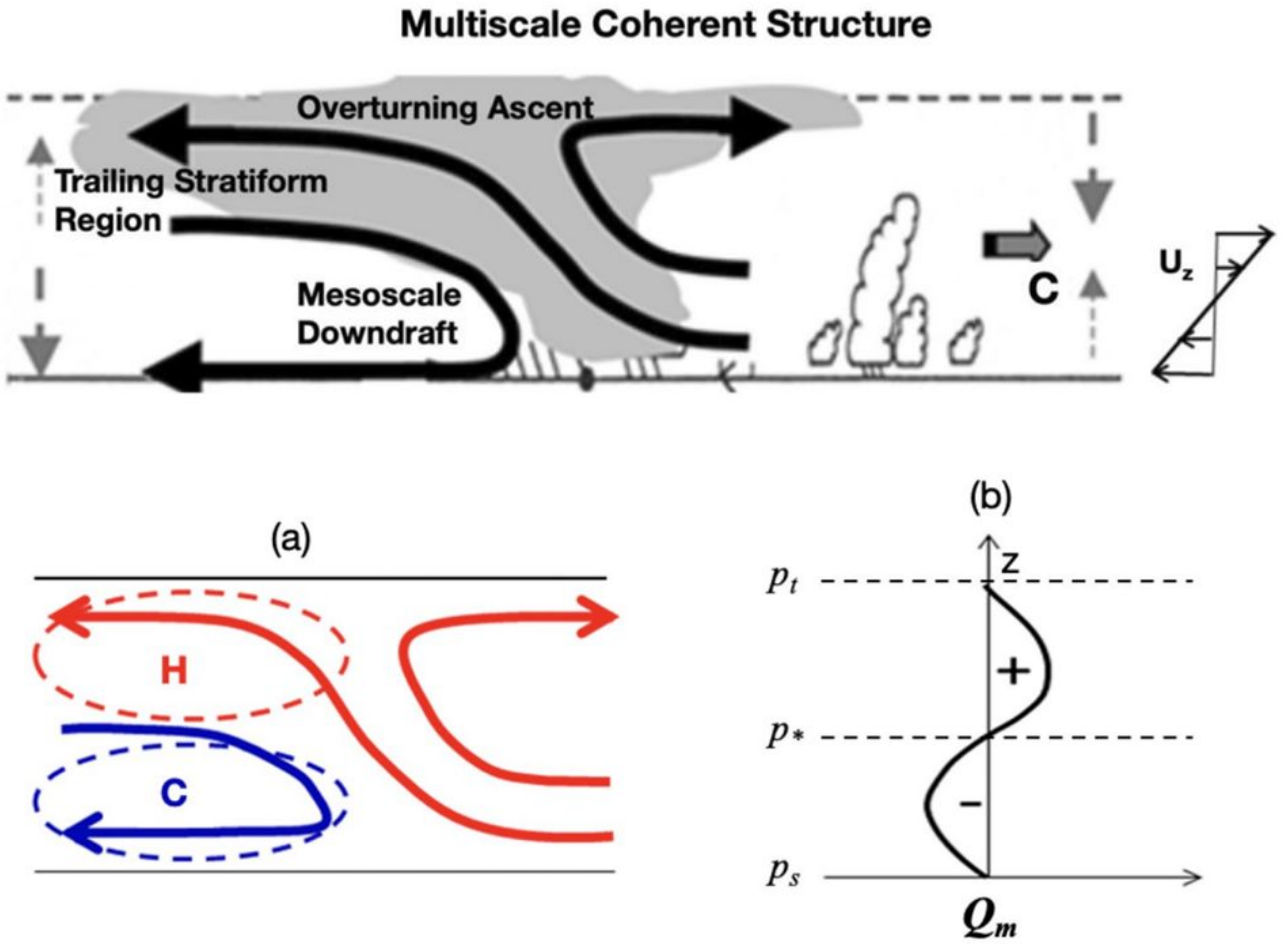


- MCSs leading the MJO convection are found at the both sides of the MC
- Enhanced MCSs MC in the QBOE phase
  amplify MJO convection west of the MC, propagating into the MJO convection
  promote MJO propagation over the MC, leading the stronger MJO convection

Incorporation of the MCS Effects in CAM7

The Multiscale Coherent Structure Parameterization (MCSP)

- Represents the effects of MCSs on convective heating.
  - triggered when the convection depth is greater than 500hPa
  - adding sinusoidal cooling (warming) tendencies in the lower (higher) half of the convection
  - intensity controlled by the heating coefficient (mcsp_hc)
- Improves the convective variabilities in the tropics (Chen et al., 2021, Zhang et al., 2025).



from Chen et al., (2021)

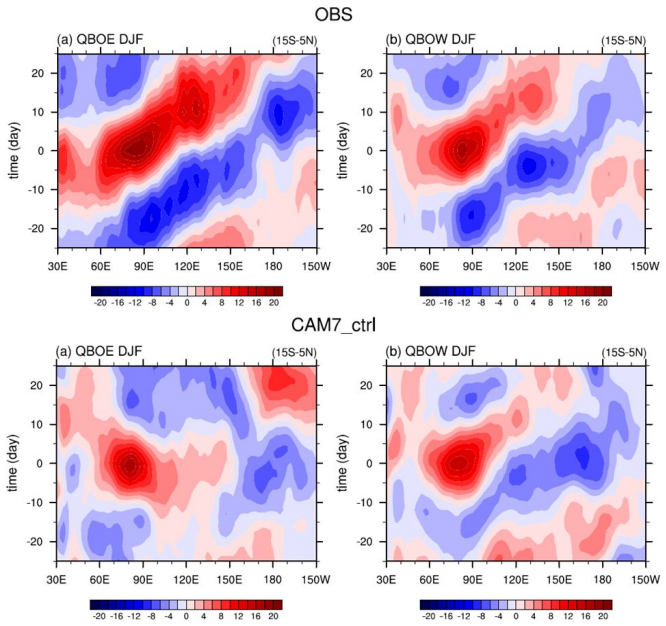
Relating the MCSP to Stratospheric Wind

CAM7_ctrl
- mcsp_hc=0.4

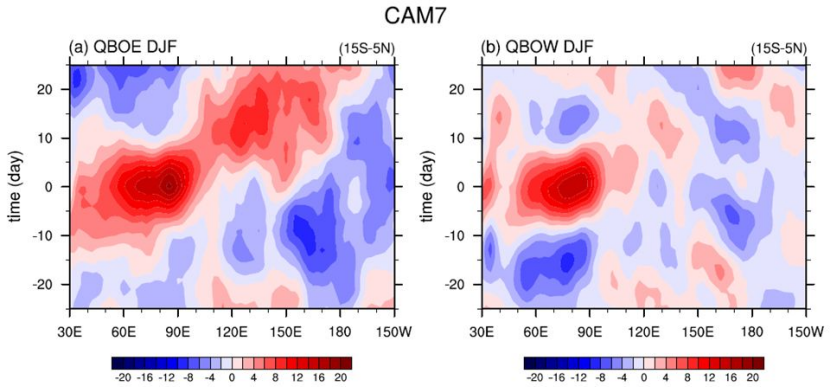
CAM7
- mcsp_hc=0.1, u50>0
- mcsp_hc=0.7, u50<0

- Prescribe the QBO modulation of MCSs from the observations.
  - Could the model capture QBO-MJO connection?

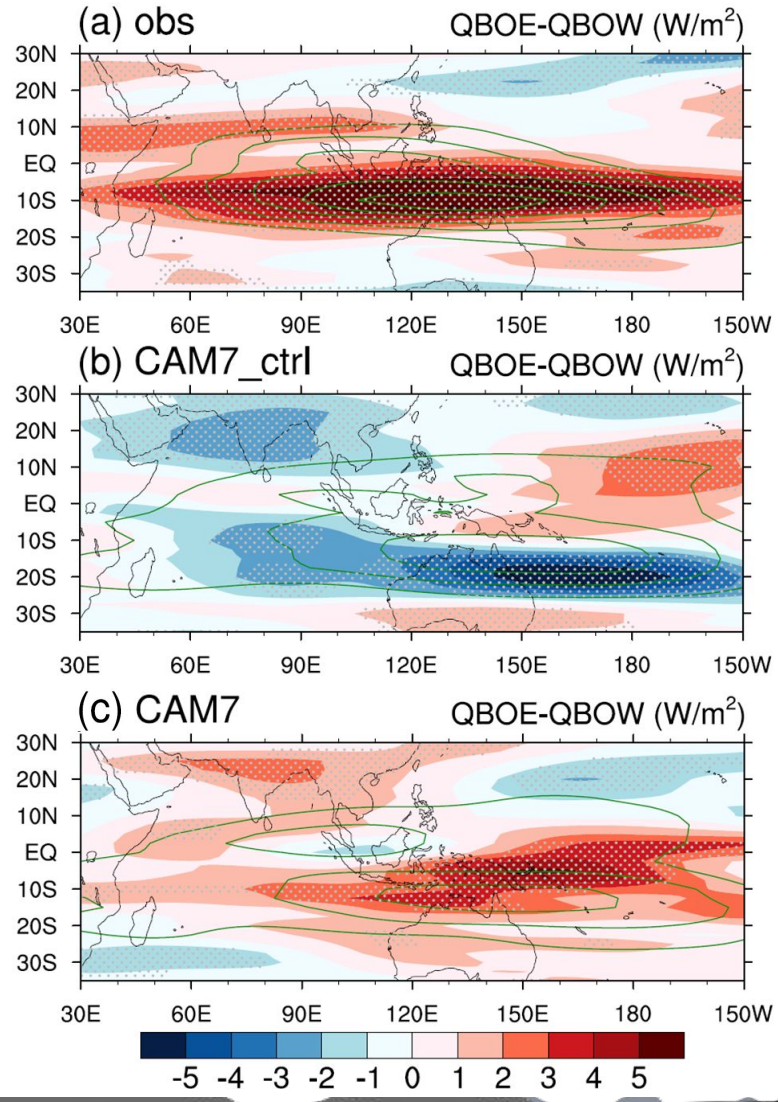
- Promising results:
  - significantly enhanced MJO activity in the QBOE phase
  - MJO crosses the MC more smoothly in the QBOE phase



Lead/lag-regressed MJO OLR



MJO-filtered OLR Stddev in DJF



Take-away Messages

We propose a new multiscale interaction mechanism for QBO-MJO connection.

How?

- MJO is preconditioned by the MCSs around the MC, favoring its eastward propagation.
- QBO modulates the MCSs around the MC, causing a decoupling between MJO and MCS in the QBOW phase.
- The lack leading MCSs around the MC leads to a weaker and stalled MJO in the QBOW phase.

We see promising results of the QBO-MJO connection by connecting the MCSP intensity to the stratospheric wind

- ensemble simulations are needed to confirm the robustness of the captured QBO-MJO connection
- diagnostics for the effects of MCSP on MJO multi-convection structure

Huang, K., Chen, CCJ., Moncrieff, M., & Richter, J., A Multiscale Interaction Mechanism for the Observed QBO-MJO Connection.
Under Revision at *Geophysical Research Letters*.

Event-by-event View of QBO-MJO Connection

- MJO tracking method focusing on the large-scale intraseasonal precipitation anomalies propagating eastward (Zhang and Ling, 2017).

  propagating speed between 2-7 m/s
  propagating range at least 20 degrees in longitude
  initiation longitude west of 100E
  time gap between consecutive events longer than 10 days

- Nov-Mar (NDJFM) season of 1979 to 2020 in ERA-5.

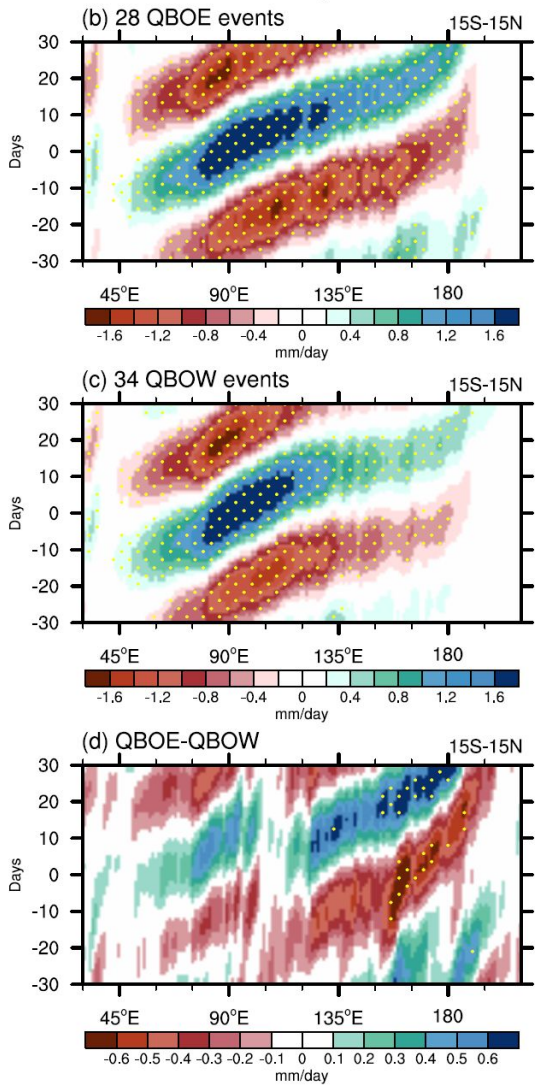
  81 MJO events in total

- QBO phase defined by the NDJFM-mean global u50 in the tropics (10S-10N).

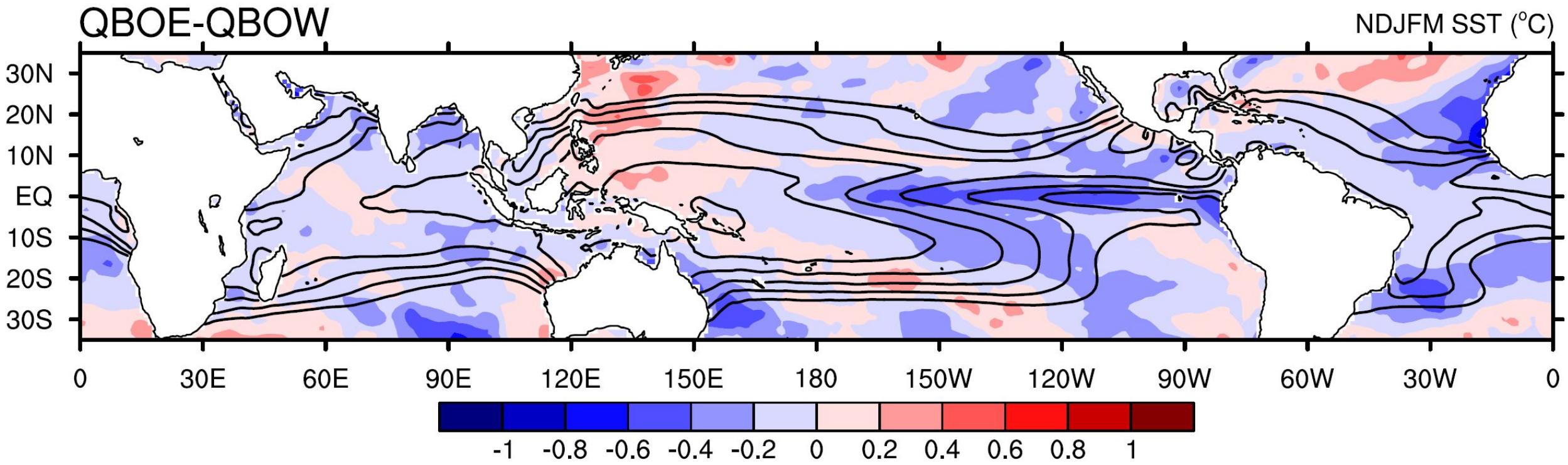
  28 MJO events in 13 QBOE seasons
  34 MJO events in 18 QBOW seasons

- Distinct propagating features for the tracked MJO events in QBOE versus QBOW seasons.

MJO Precipitation (15S-15N)

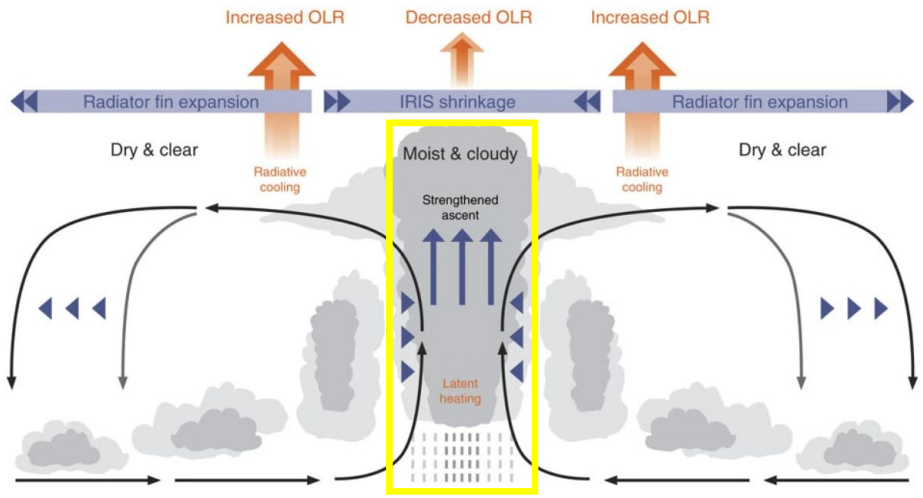


SST Differences conditioned by QBO



Open Question: How MCS preconditions MJO?

Schematic of a Tropical Moist Convection



from Su, H., Jiang, J., Neelin, J. et al. (2017). https://doi.org/10.1038/ncomms15771

horizontal advection **vertical advection**

$$\frac{\partial q}{\partial t} = -u\frac{\partial q}{\partial x} - v\frac{\partial q}{\partial y} - w\frac{\partial q}{\partial z} + Evap - Precip$$

$$\frac{\partial q}{\partial t} = -w\frac{\partial q}{\partial z} + Evap - Precip$$

1-D column without lateral transports

$$\frac{\partial q}{\partial t} = -w\frac{\partial q}{\partial z} - Precip$$

for convective column

What is the net effect from the competition between these two terms?

Quasi-Equilibrium Dynamics of the Tropical Atmosphere

Kerry Emanuel
Massachusetts Institute of Technology

first proposed by Arakawa and Schubert (1974)

1) Moist convection always acts to maintain a moist adiabatic (virtual) temperature profile, and
2) Convection always acts to maintain the neutral buoyancy of air lifted from the subcloud layer to levels above cloud base.

Taken together, these findings suggest that convective equilibrium fails on time scales shorter than around 2 days and space scales less than around 100 km, but a more precise determination of these limiting scales awaits further research.

- For large-scale convection, the net effect would dry out the excessive moisture towards climatological states.
- For small-scale convection?
  - net effect of **drying**? Or **wetting**?
  - if wetting, how is the net gain in moisture distributed?
    - **moisture pumped through PBL, redistributed by the divergence wind and downdrafts?**
      - **shallow clouds, moisture accumulation**

More Evidence for MCS preconditioning MJO?

nature

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Article | Open access | Published: 30 November 2022

Strong cloud–circulation coupling explains weak trade cumulus feedback

Raphaela Vogel, Anna Lea Albright, Jessica Vial, Geet George, Bjorn Stevens & Sandrine Bony

Nature **612**, 696–700 (2022) | Cite this article

17k Accesses | **60** Citations | **403** Altmetric | Metrics

- Mesoscale motions are equally important as entrainment for shallow trade-wind cumulus clouds formation.

JGR Atmospheres

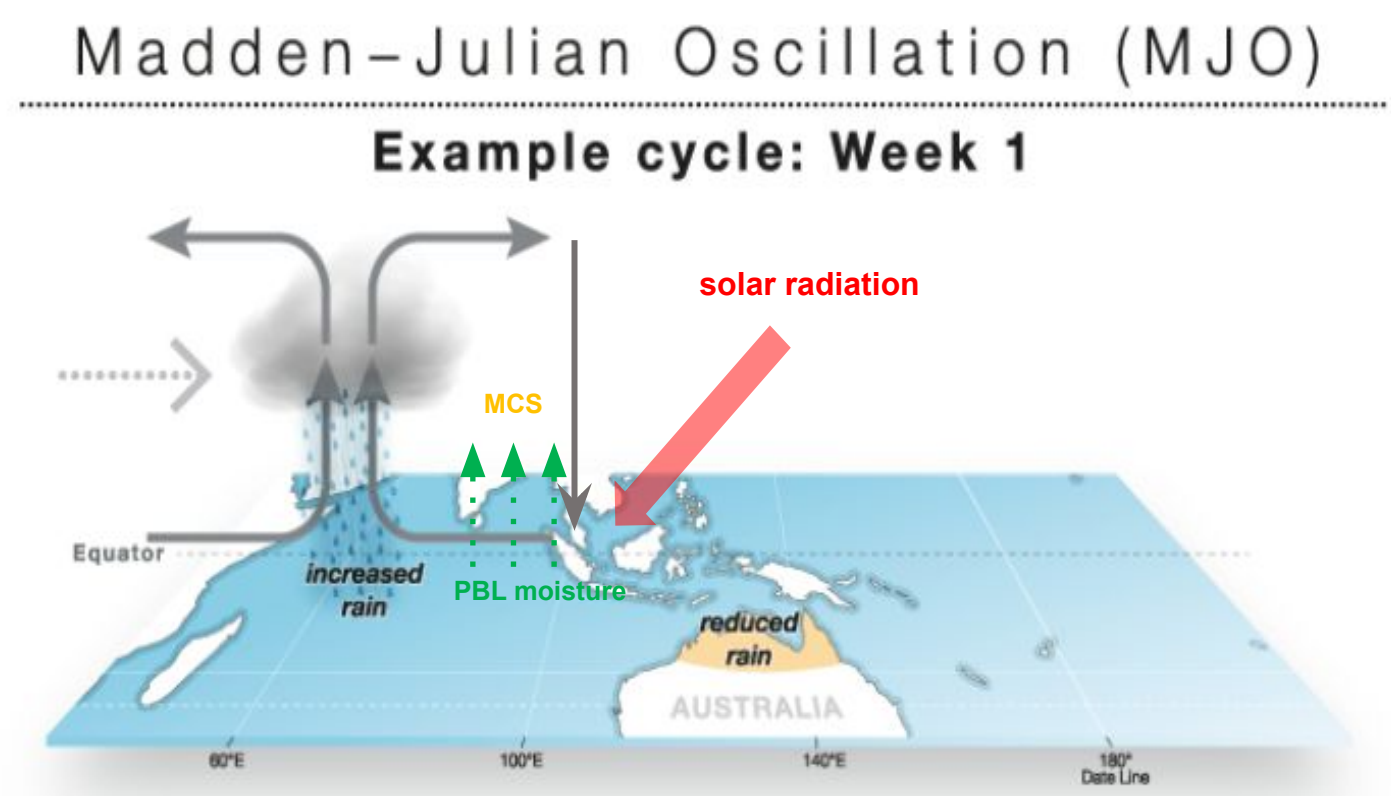
Research Article

Development of Shallow Convection and the Slow Eastward Propagation of Super Cloud Clusters in the Madden-Julian Oscillation

Yan Liu, Zhe-Min Tan

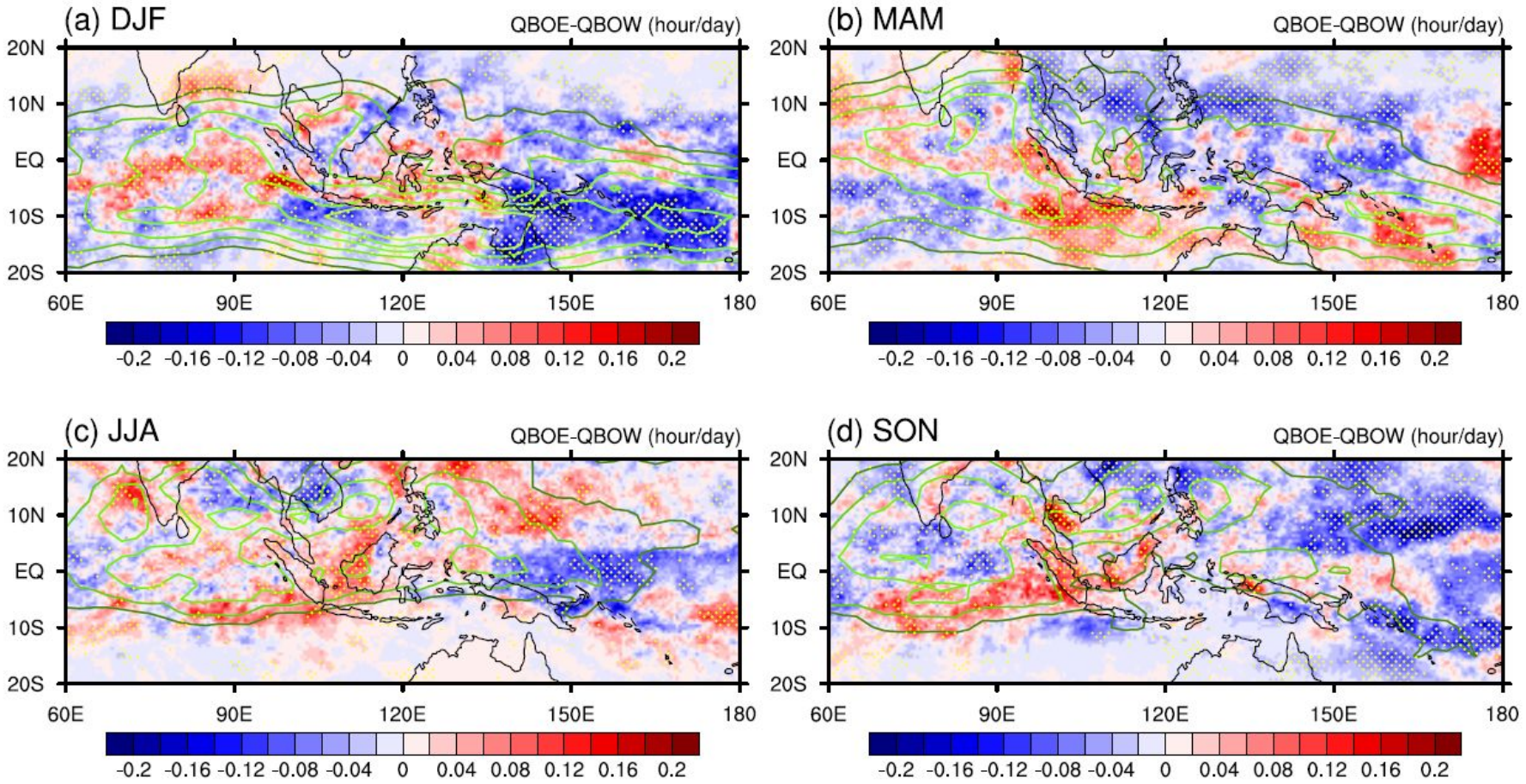
First published: 26 May 2025 | https://doi.org/10.1029/2025JD043516 | VIEW METRICS

- Convection west of the MC intersects with the MJO, favoring the MJO timescale selection and eastward propagation.



- **exaggerated barrier effect of MC on MJO propagation in GCMs?**
- **MCS as seeds for MJO initiation?**

Seasonality of the QBO Modulation on MCSs



Open Question: How QBO modulates MCS?

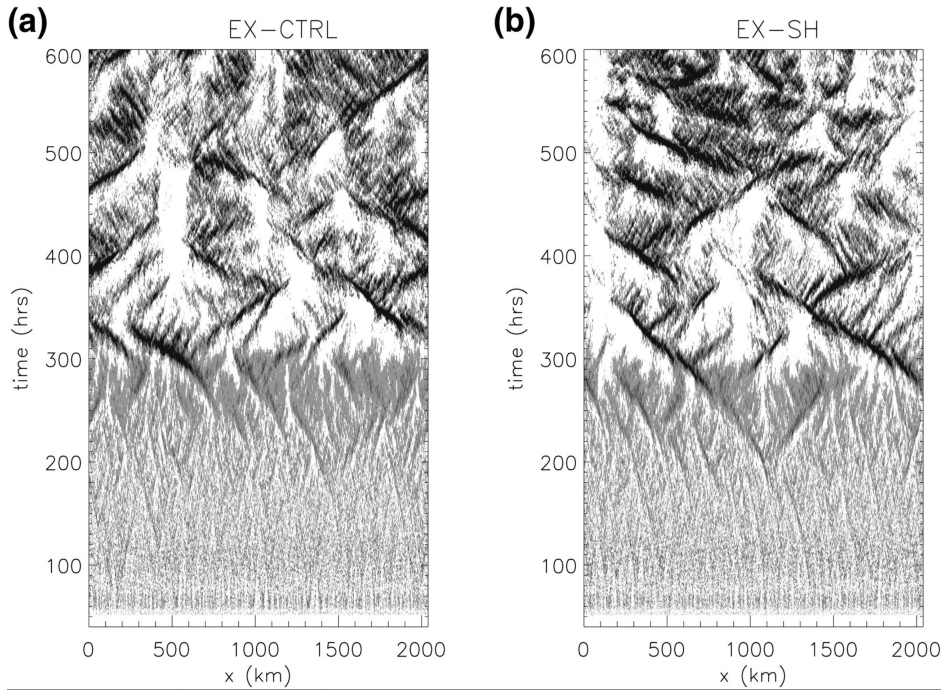
Geophysical Research Letters

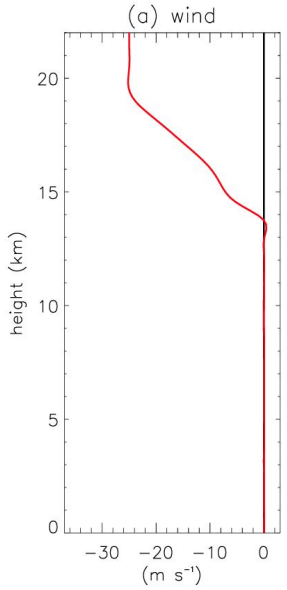
Research Letter | Free Access

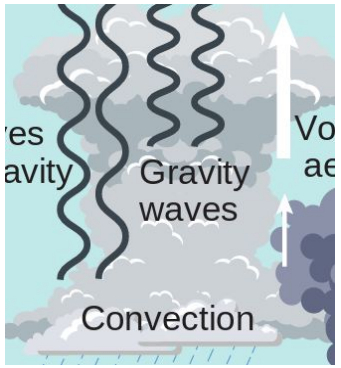
Does Lower-Stratospheric Shear Influence the Mesoscale Organization of Convection?

Todd P. Lane

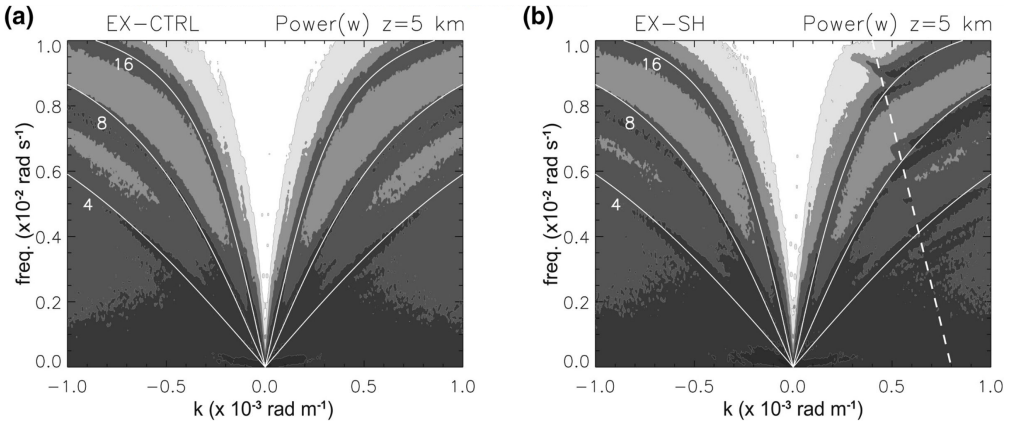
First published: 12 January 2021 | https://doi.org/10.1029/2020GL091025 | Citations: 6

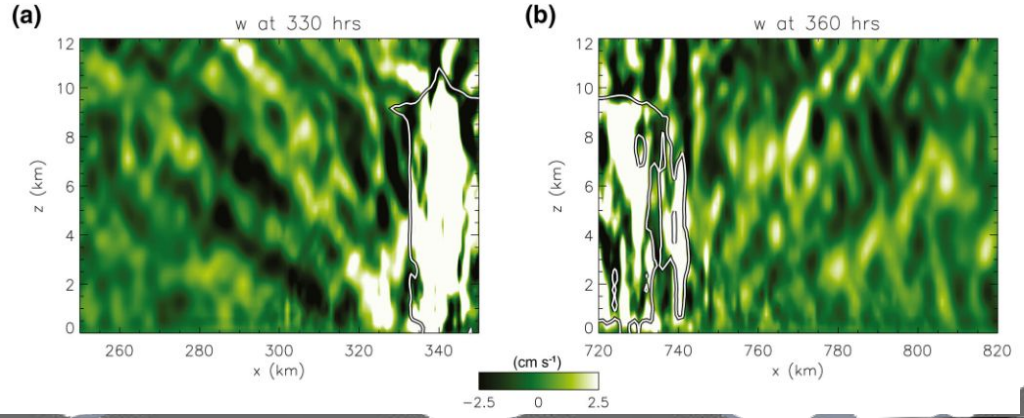






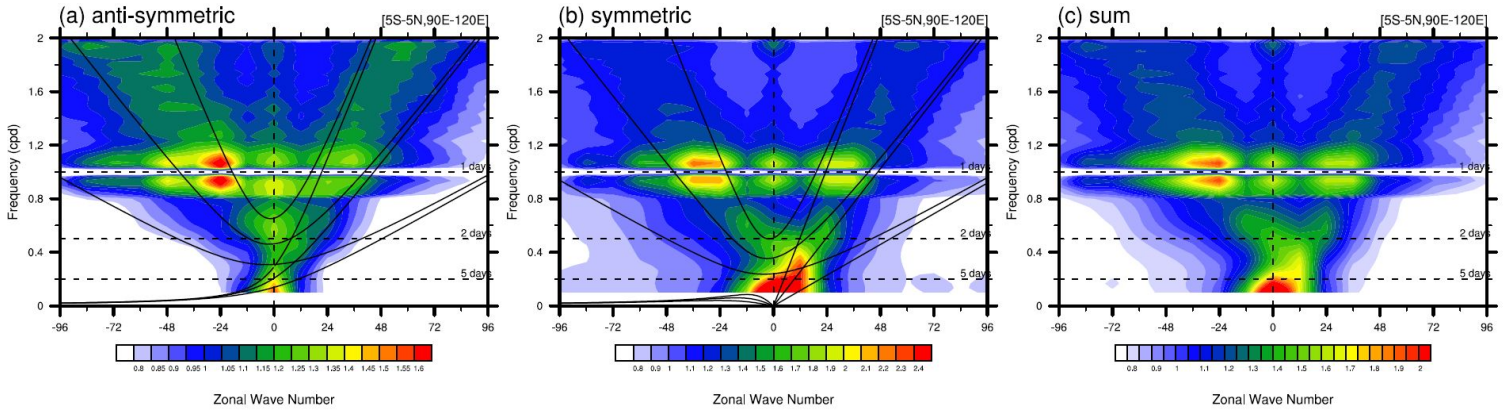
- QBOE wind shear reflects the GW downward at the east side of MCS, hindering CAPE build-up and promoting its westward propagation.



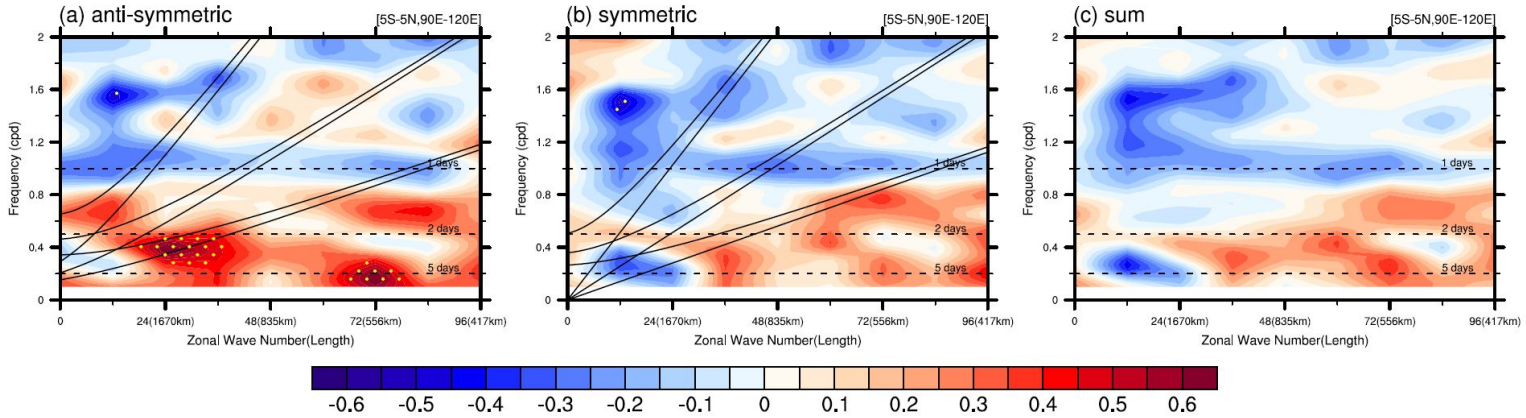


Open Question: How QBO modulates MCS?

Wavenumber-Frequency Power Spectrum of Precip over Western MC (5S-5N, 90E-120E)



Eastward/Westward Ratio against the QBO u50 index



- Some supports from the high-res satellite observations (GPM IMERG precipitation).
- More observational and modeling studies are needed.
  - In-situ observations from field campaigns (e.g., DYNAMO, YMC…)
  - High-resolution model simulations (e.g., SCREAM, MPAS, WRF…)