Understanding MJO Dynamics Using a Hierarchy of Models and Reanalysis

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The Palette of Models Used in Last 1.5 Decades

- **Sp-CESM** (e.g. Wolding et al. 2016 a,b)
- **Conventional GCMs** (e.g. Hannah and Maloney 2014; Benedict et al. 2014)
- **Aquaplanet GCMs** (e.g. Maloney et al. 2010; Maloney and Wolding 2015; Maloney and Xie 2013)
- **GCM with regional mesh refinement** (Wolding et al 2017?)
- **Regional model** (WRF; IROAM, Rydbeck et al. 2013)
- **Cloud system resolving model** (Riley Dellaripa et al. 2016)
- **Linear baroclinic model** (Rydbeck et al. 2013; Wolding et al. 2016b)
- **Atmospheric mixed layer model** (Maloney and Xie 2013)
- **Idealized models (**MJO; Sobel and Maloney 2012; 2013)
- **1D ocean model** (KPP; PWP, van Roekel and Maloney 2012)
- **Barotropic model** (Hartmann and Maloney 2001; Shaman et al. 2009)
- **Statistical models** (Slade and Maloney 2013)

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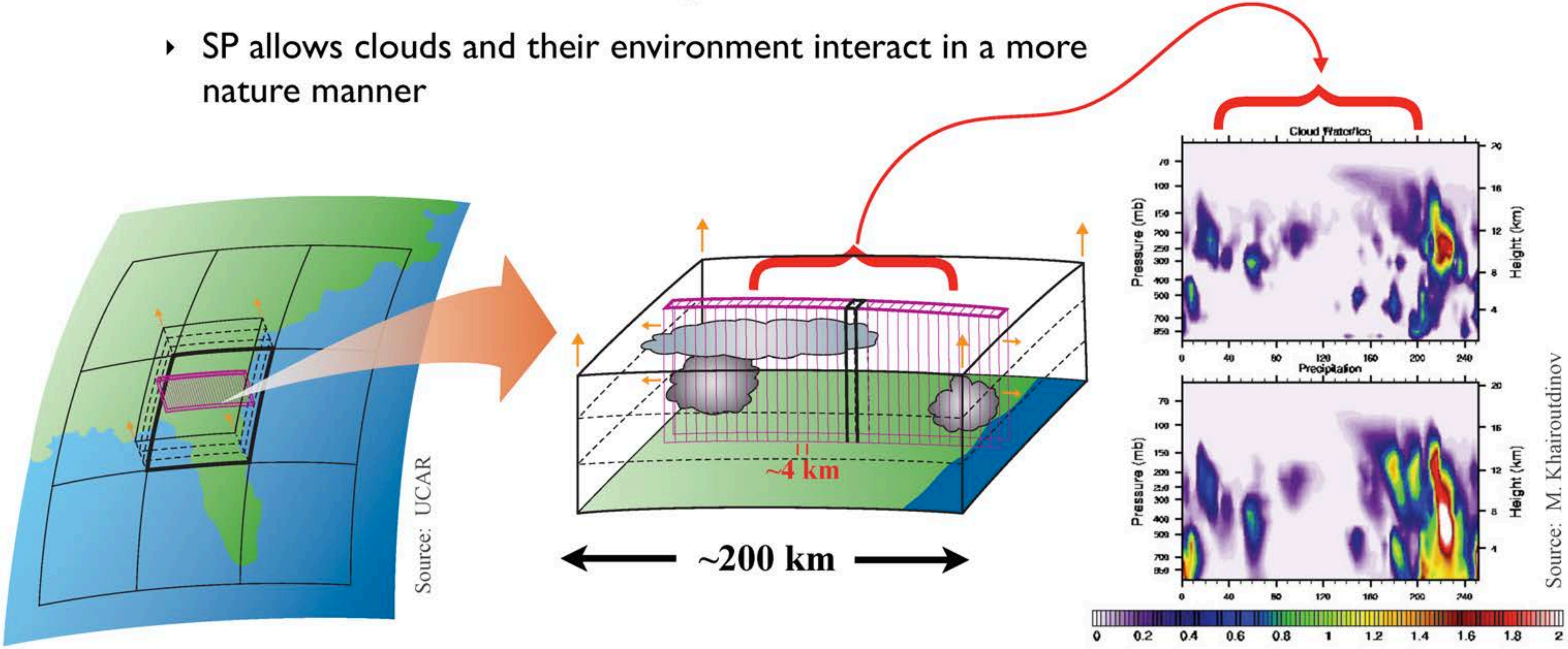
Superparameterization (SP)

- Parameterization: Statistical theory that attempts to explain the general behavior of an unresolved process (e.g., a cumulus cloud)
- SP: Replaces cloud-related parameterizations by embedding a cloud-resolving model into each climate model grid cell
- SP allows clouds and their environment interact in a more nature manner



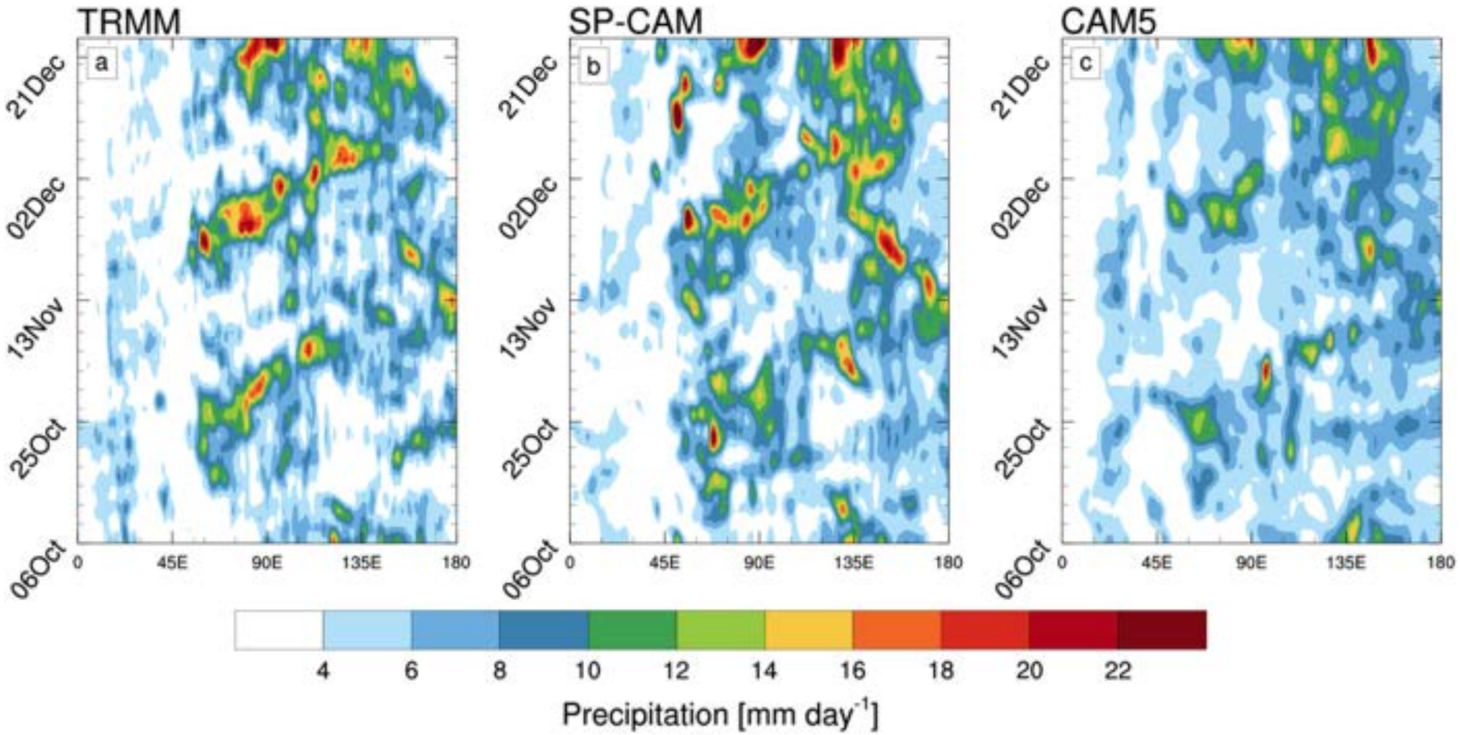
Within each climate model grid cell… …is a "curtain-shaped" high-resolution cloud-resolving model… …that explicitly simulates clouds and precipitation.

Courtesy of Jim Benedict

Success at Modeling the MJO in Sp-CAM

Model that exhibits many characteristics consistent with new theoretical frameworks for understanding the tropics.

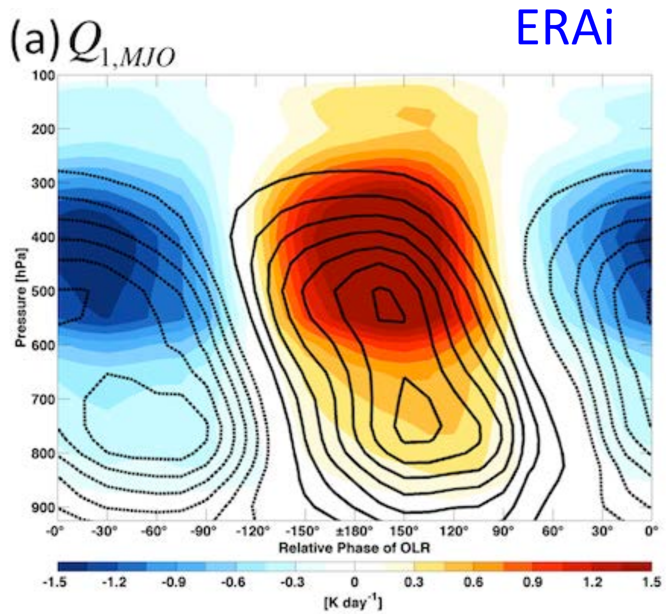
- *Convection realistically sensitive to free tropospheric humidity*
- *Realistic simulation of processes that control tropospheric humidity*

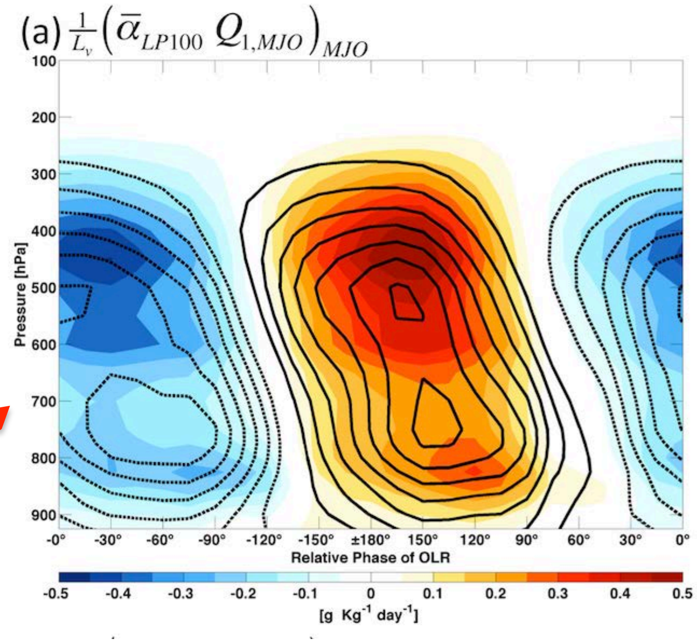


Hannah et al. (2015)

Tool: Diabatic Heating and Vertical Moisture Advection Under WTG

- Composite diabatic heating (and moisture) anomalies in warm pool have the following form
- If WTG balance holds, $\omega \frac{\partial s}{\partial p} = Q$
- We can generate a vertical velocity to balance this diabatic heating: $\omega_{WTG} = Q\left(\frac{\partial s}{\partial p}\right)^{-1}$
- This vertical velocity can advect moisture $-\omega_{WTG}\frac{\partial Lq}{\partial p} = -Q\left(\frac{\partial s}{\partial p}\right)^{-1} \cdot \frac{\partial Lq}{\partial p}$





Wolding and Maloney (2015)

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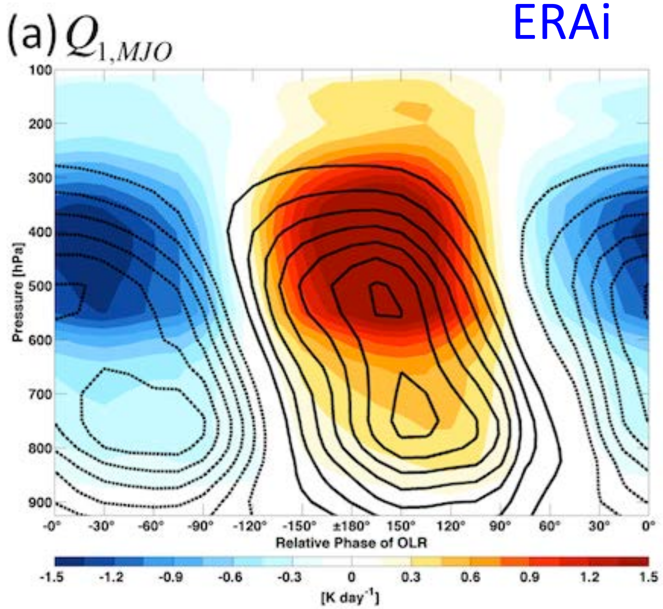
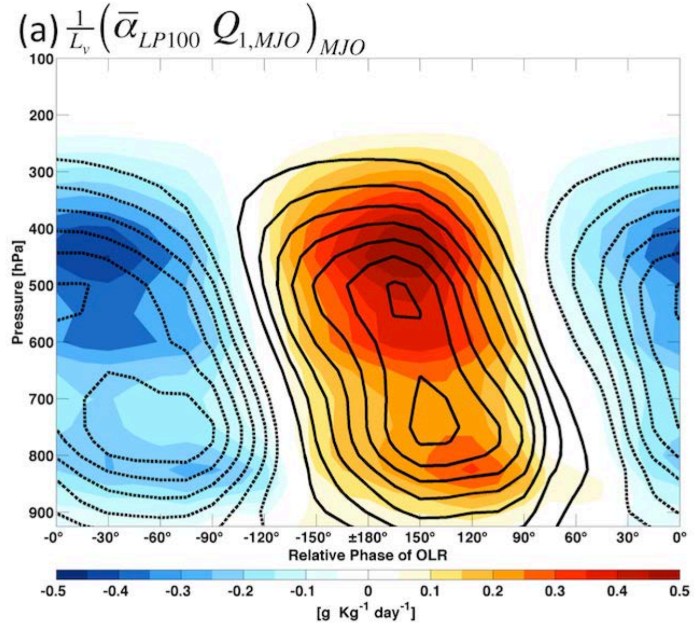
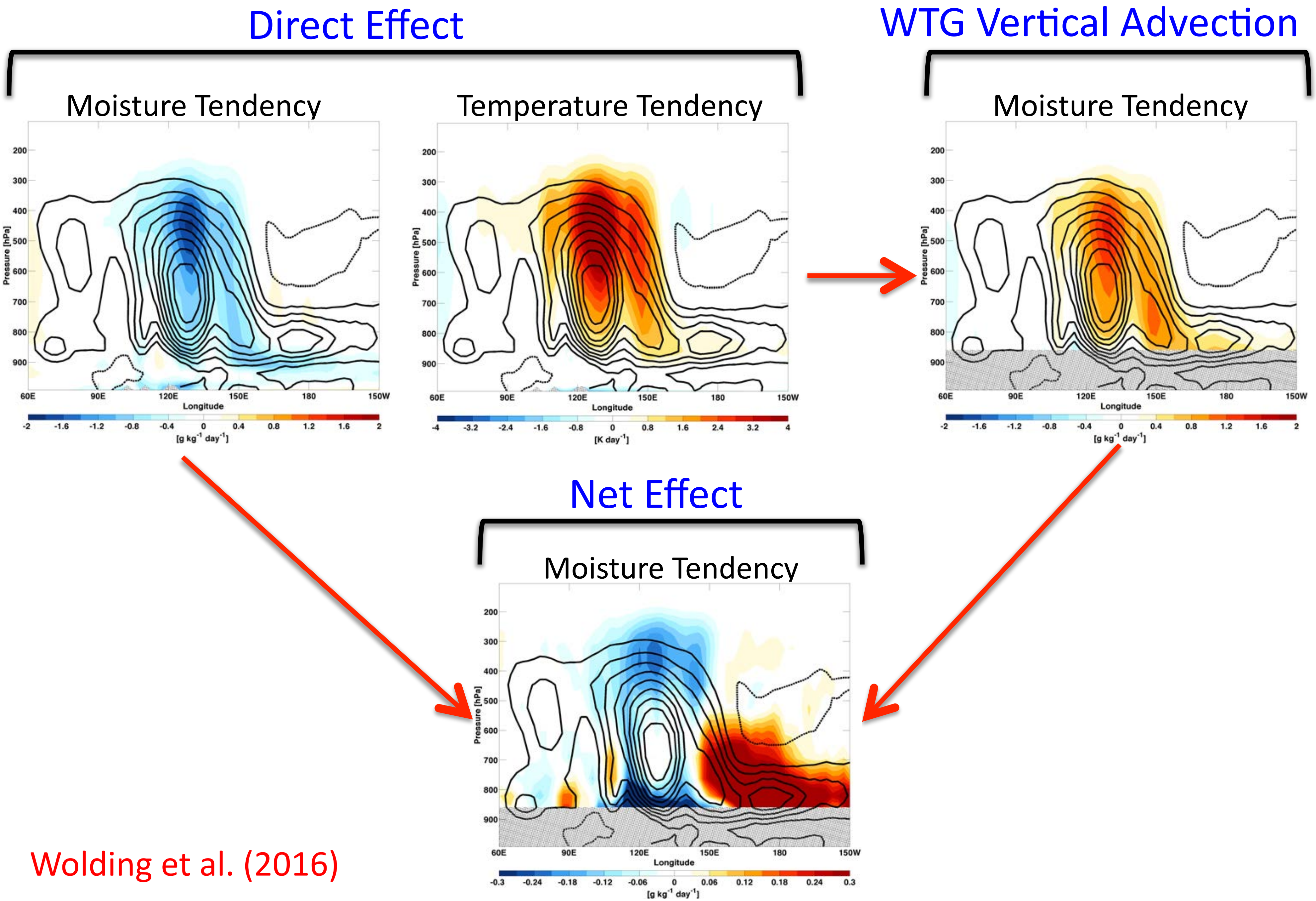




Wolding and Maloney (2015)

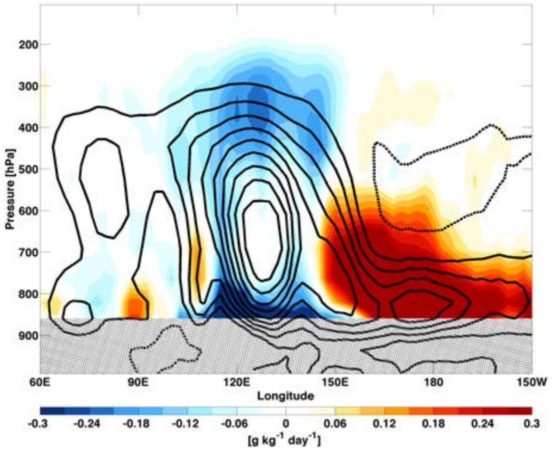
SP: Net Moistening Due to Microphysics + SGS Eddy Fluxes



Wolding et al. (2016)

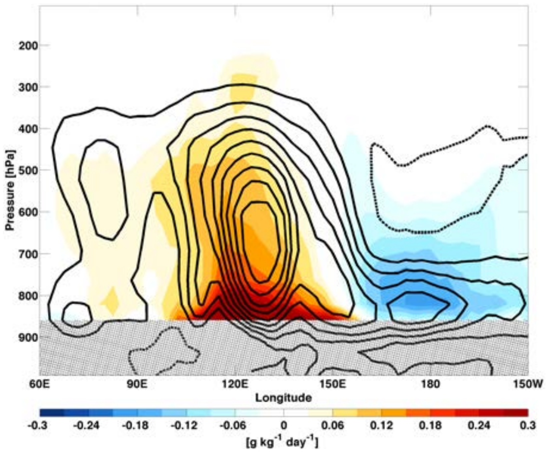
SP: Sum of the Moistening Effects from Diabatic Terms

Microphysics + SGS Eddy Fluxes

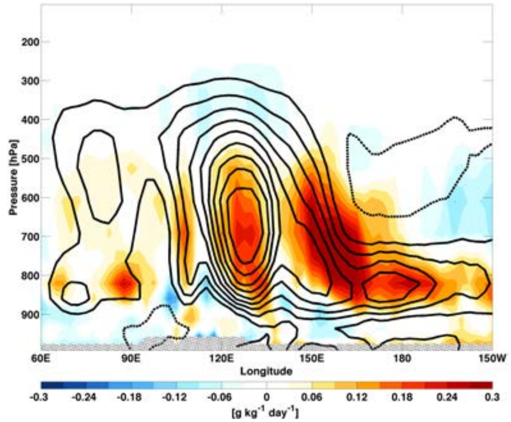


+

Radiation

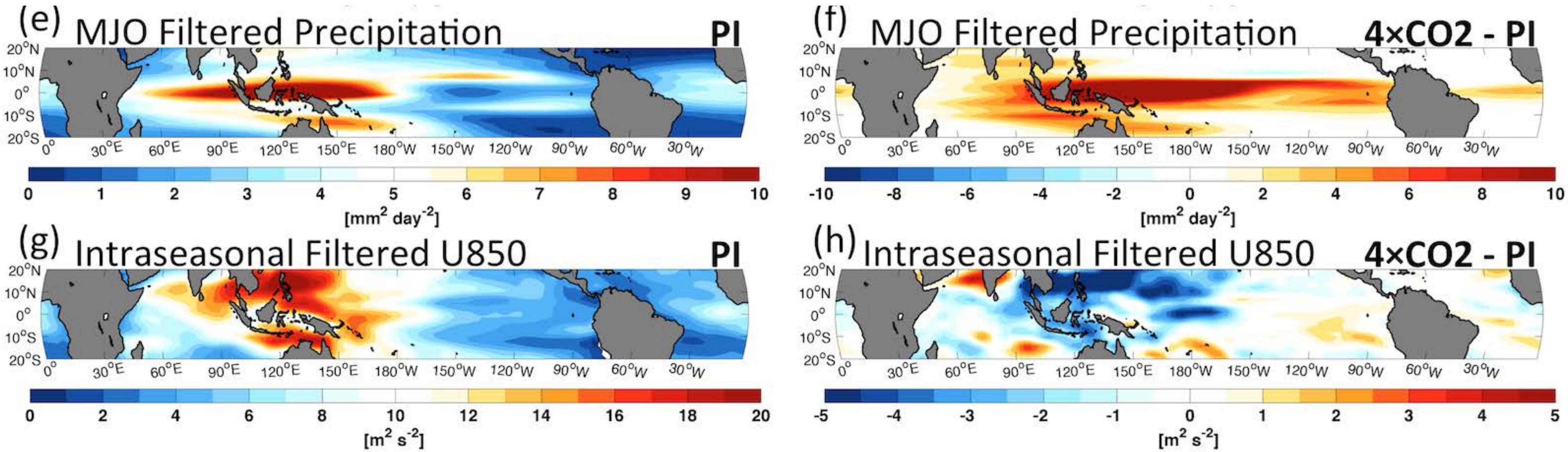


Column Process



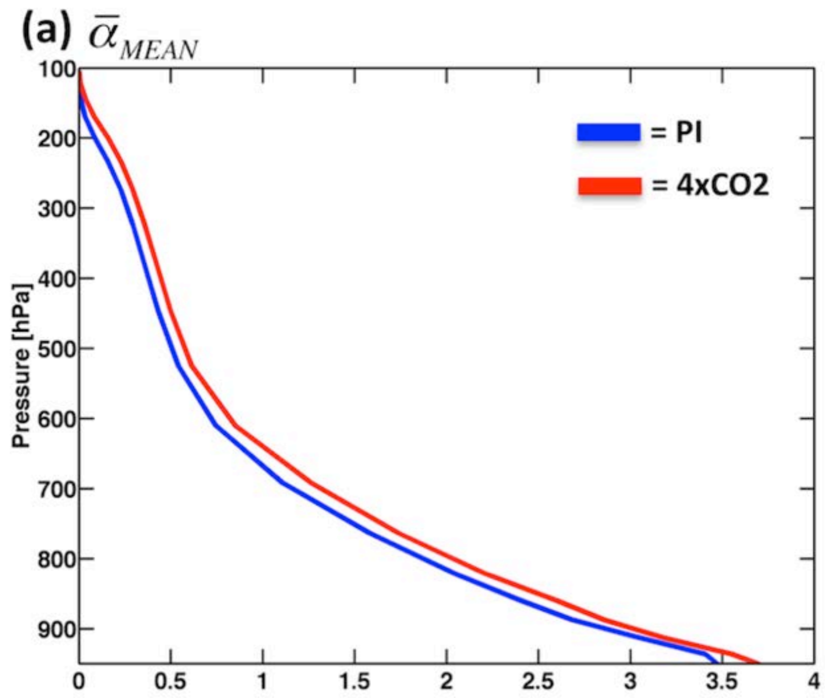
Radiative driven instability damped by horizontal advection

How Does MJO Activity Change in $4xCO_2$ Climate?

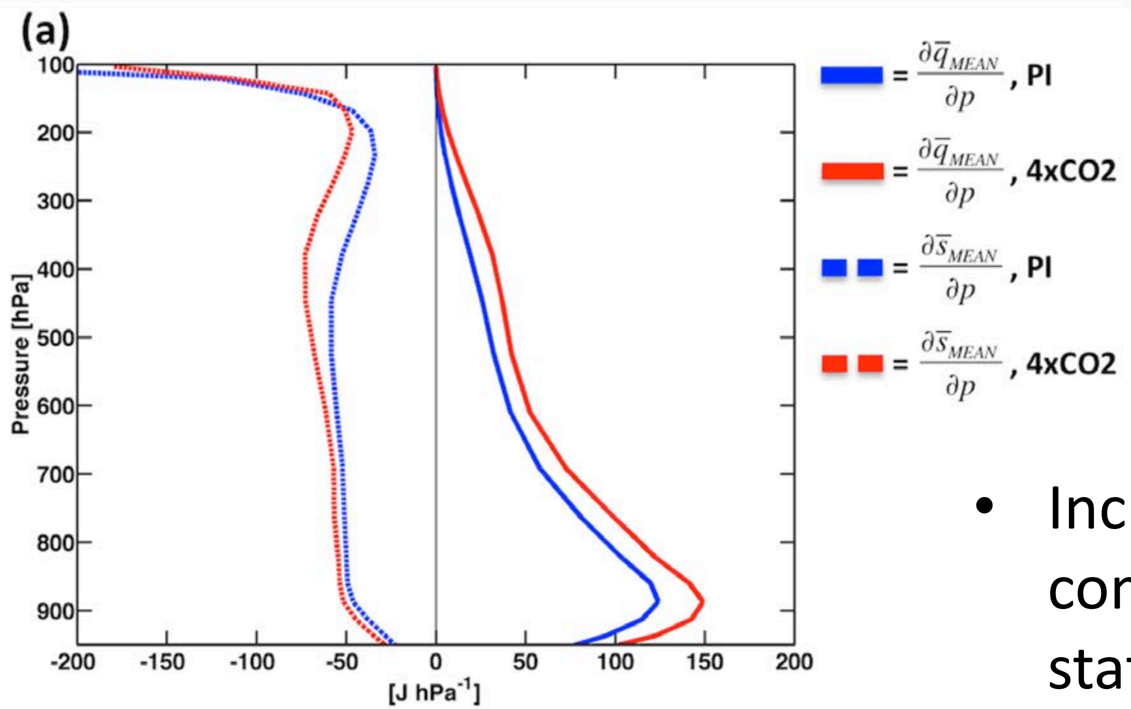


- Even though MJO precipitation variance goes up, MJO wind variance goes down
- Consistent with findings from Maloney and Xie (2013)

Resulting Change in "Alpha" Parameter (PI vs. $4xCO_2$)



- Alpha parameter (ability of diabatic heating to drive a moistening through vertical advection) goes up in future climate:

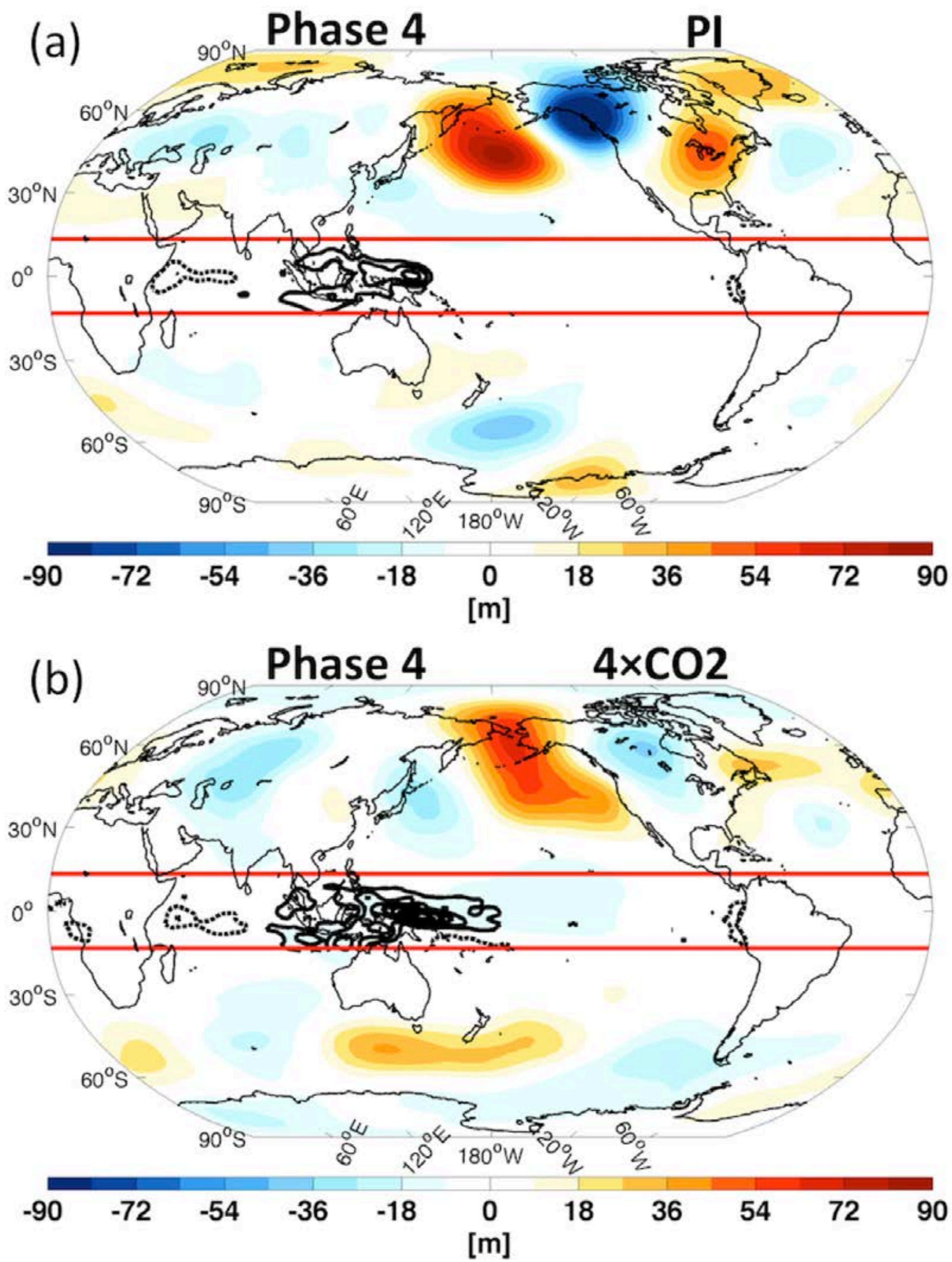


$$-\omega_{WTG}\frac{\partial Lq}{\partial p} = -Q\underbrace{\left(\frac{\partial s}{\partial p}\right)^{-1}\cdot\frac{\partial Lq}{\partial p}}_{a}$$

- Increased moisture gradient compensates for increased static stability

MJO Teleconnection Strength

- Although MJO precipitation anomalies increase in amplitude, MJO teleconnection strength decreases
- Consistent with static stability change



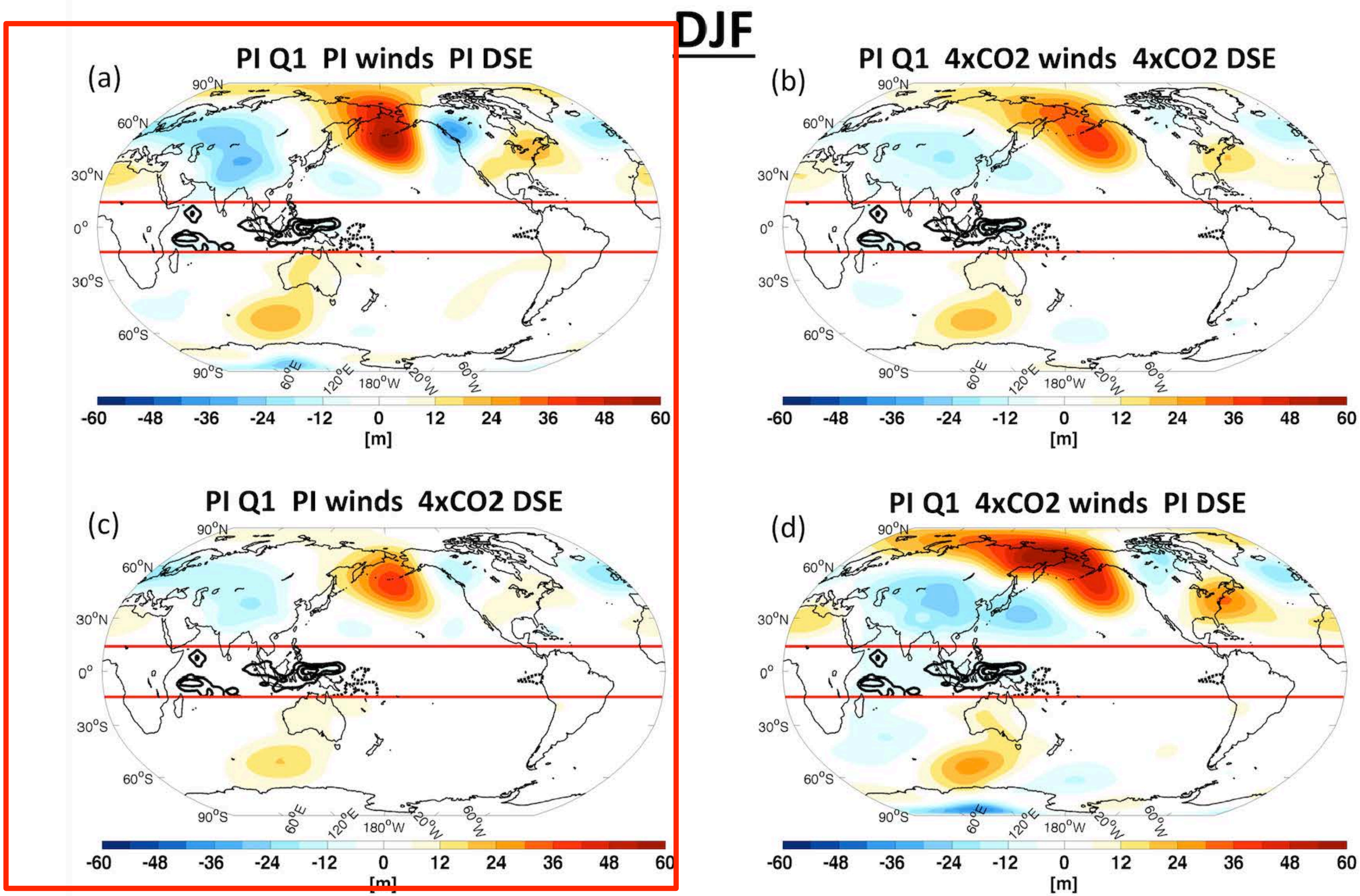
Dry Linear Baroclinic Model

- Watanabe and Kimoto (2000, 2001)
- Primitive equations at T42 resolution linearized about a climatological DJF basic state
- Application of MJO tropical diabatic heating

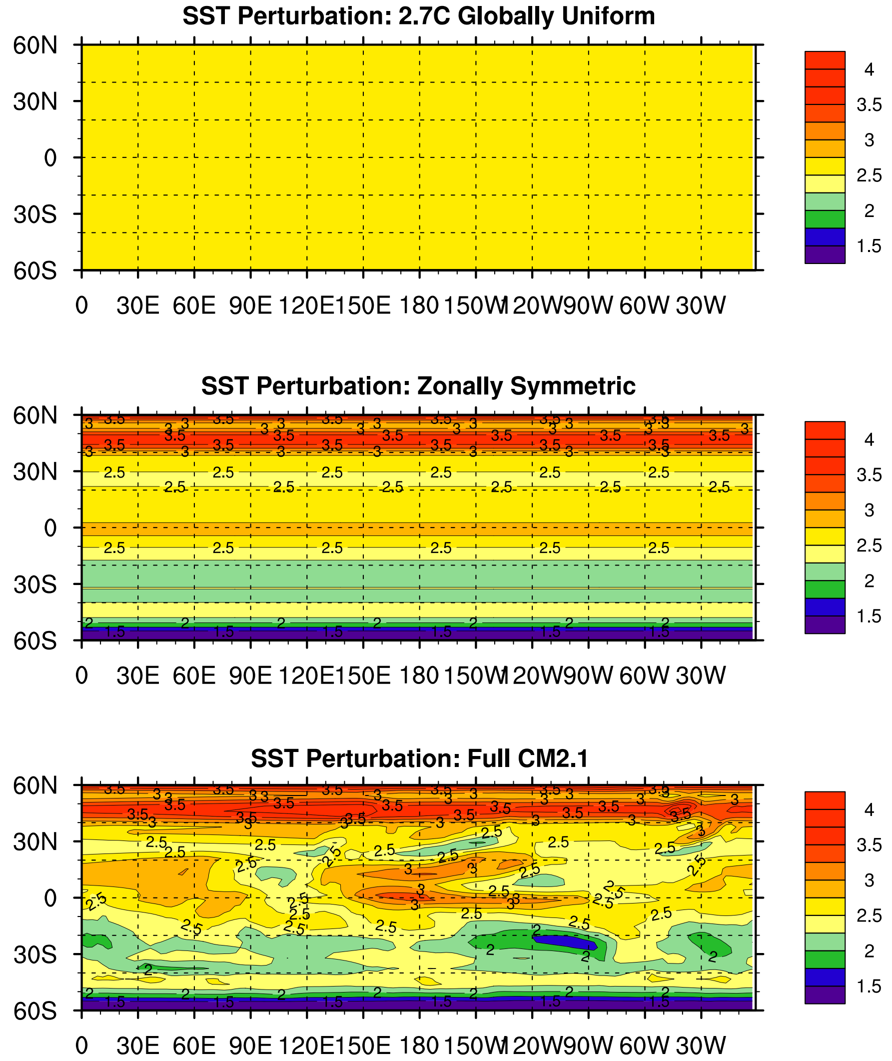
Four simulations with PI MJO Q_1:

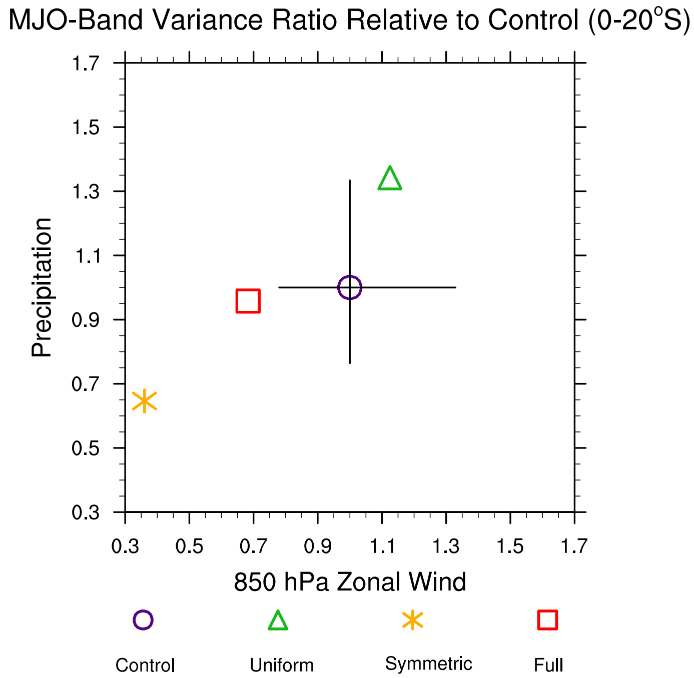
1) PI basic state winds and static stability
2) $4xCO_2$ basic state winds and static stability
3) $4xCO_2$ basic state static stability, PI basic state winds
4) PI basic state static stability, $4xCO_2$ basic state winds

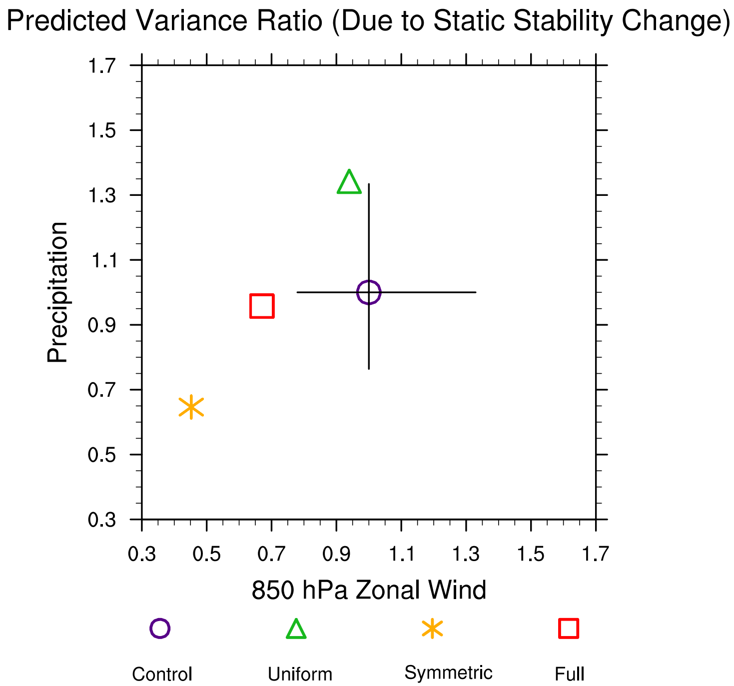
Linear Baroclinic Model Runs



Sp-CESM Mismatch of Precip and Wind Variance Change Consistent with an Aquaplanet GCM







Maloney and Xie (2013)

Conclusions

- Using the paradigm that the MJO is a moisture mode, we developed weak temperature gradient diagnostics to diagnose major MJO moistening processes in the Sp-CESM:
  - Radiative feedbacks are necessary to destabilize the MJO
  - Horizontal advection provides a damping mechanism
- MJO precipitation variability goes up in a $4xCO_2$ Sp-CESM climate, although wind variance goes down
- The strength of MJO teleconnections may decrease in future climate, with implications for modulation and prediction of weather extremes
- We used a linear baroclinic model to link changes in static stability to reduction in teleconnection strength

Extra Slides

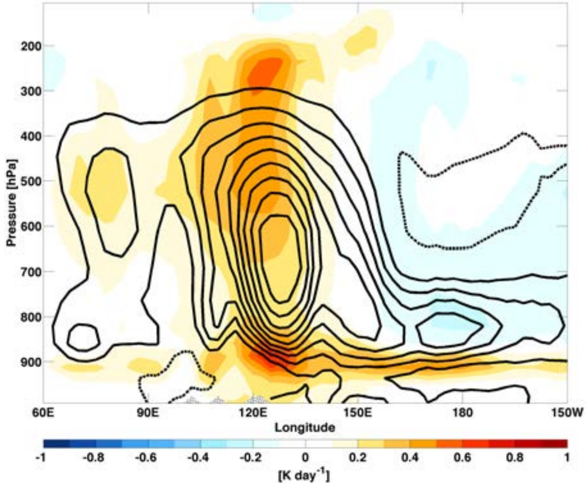
SP: Net Moistening Effect of Radiative Heating

Direct Effect

Moisture Tendency

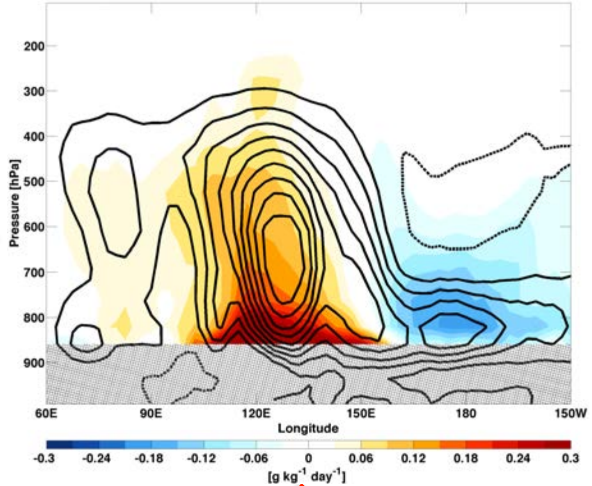
None

Temperature Tendency



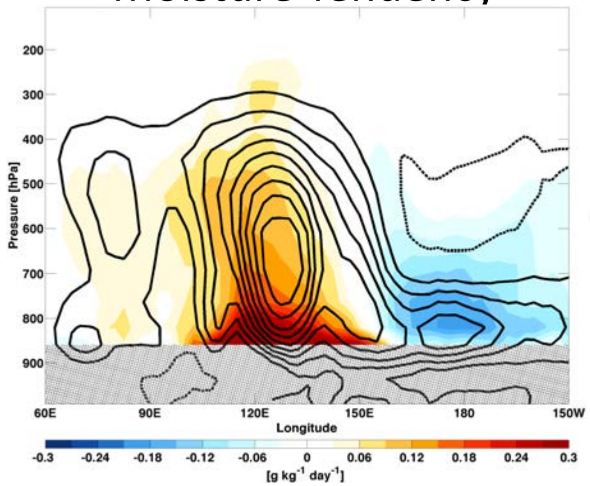
WTG Vertical Advection

Moisture Tendency

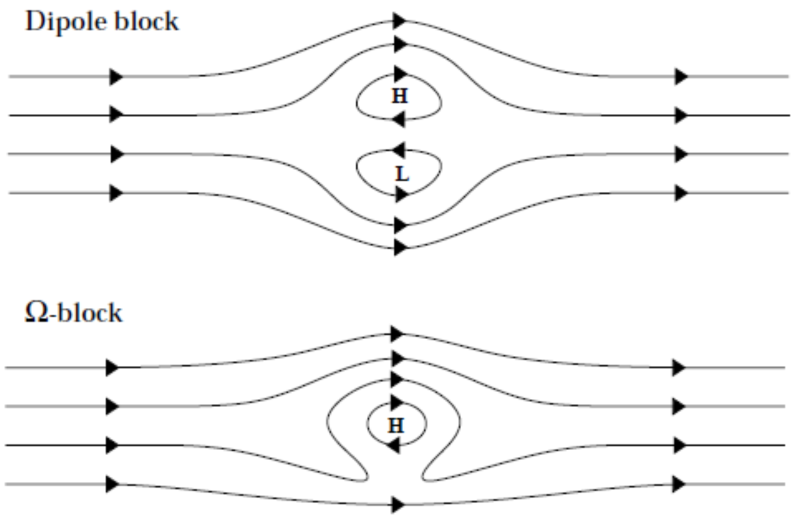


Total Effect

Moisture Tendency

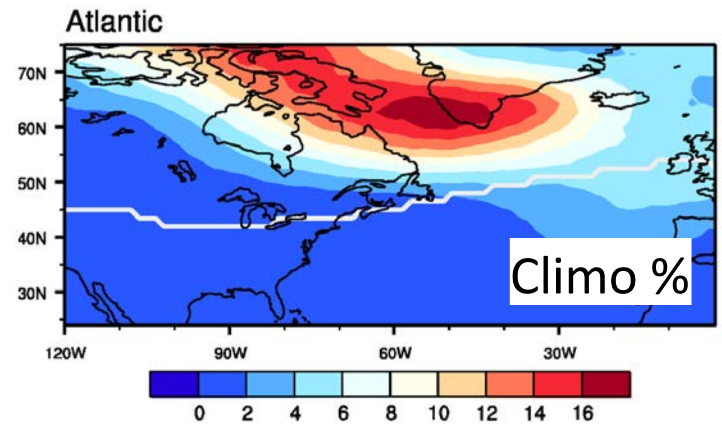


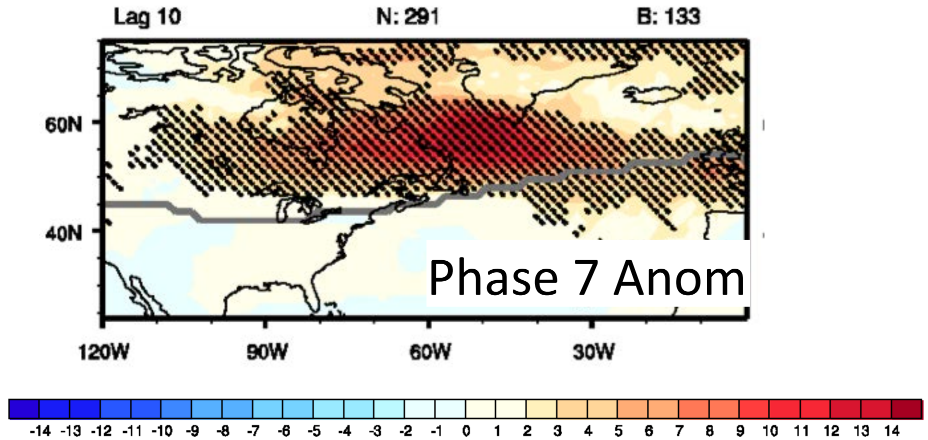
Atmospheric Blocking and the MJO

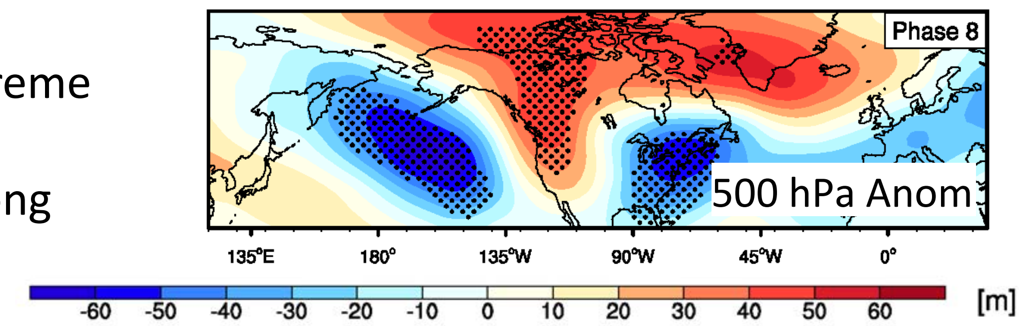


Pelly and Hoskins (2001)

- Quasi-stationary pattern that disrupts the mean westerly flow and can persist for several weeks.
- Split in storm tracks can result in redistribution of rainfall Also influences extreme events: flooding, dry spells, extreme cold outbreaks, etc
- Henderson et al. (2016, right) shows strong MJO-induced modulation of N. Atlantic blocking







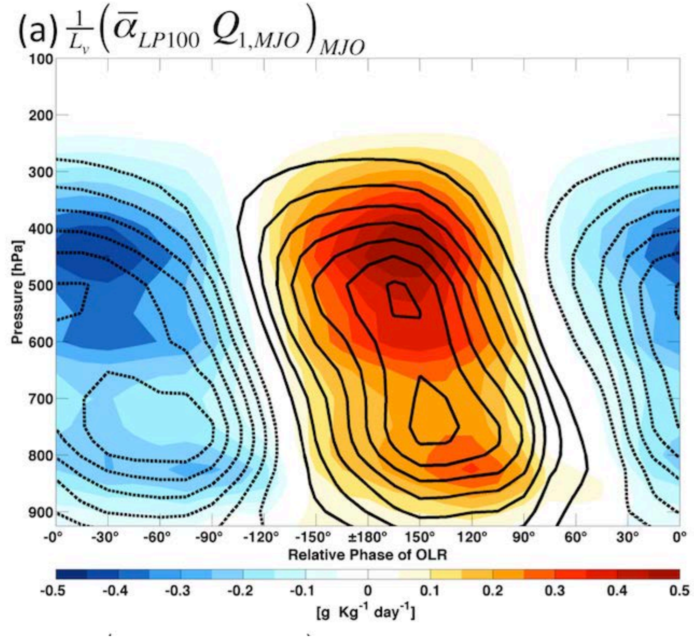
Henderson et al. (2016)

Diabatic Heating and Vertical Moisture Advection Under WTG (cont'd)

- Then, this vertical motion that balances diabatic heating can drive a latent heat advection:

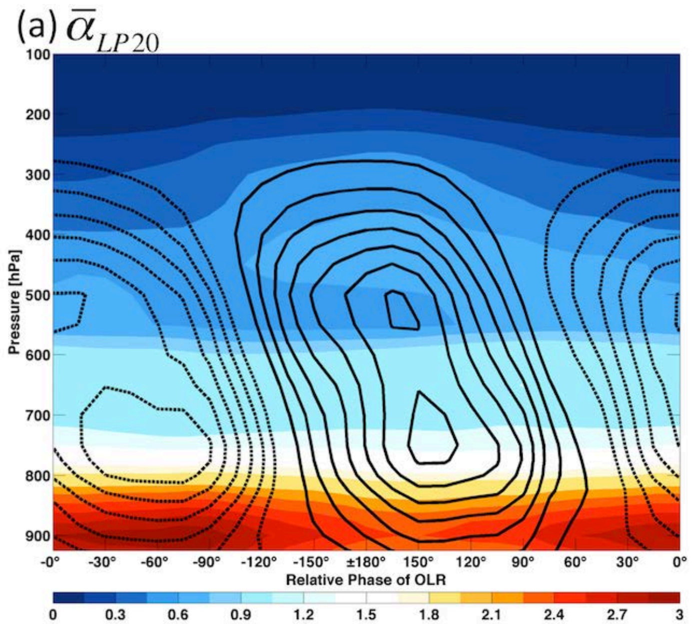
$$-\omega_{WTG}\frac{\partial Lq}{\partial p} = -Q\left(\frac{\partial s}{\partial p}\right)^{-1}\cdot\frac{\partial Lq}{\partial p}$$

$$-\omega_{WTG}\frac{\partial Lq}{\partial p} = Q\times\alpha$$

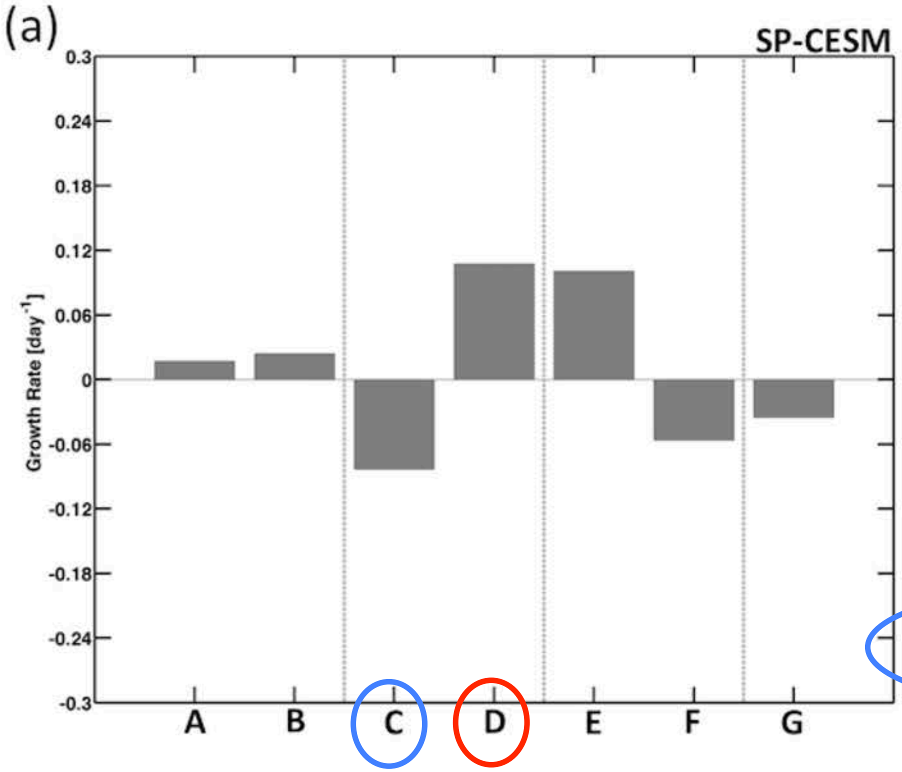


- The parameter *a* conveniently gives the amount of latent heat tendency per unit diabatic heating driven by an MJO heating anomaly

$$\alpha = -L\left(\frac{\partial s}{\partial p}\right)^{-1}\frac{\partial q}{\partial p}$$



Warm-Pool Wide Contributions to Column Moisture Growth Rate



A = $\frac{\partial \bar{q}_{MJO}}{\partial t}$

B = $-\left(\bar{\vec{V}} \bullet \vec{\nabla}_h \bar{q}\right)_{MJO} - \left(\bar{\omega}\frac{\partial \bar{q}}{\partial p}\right)_{MJO} + \left(\bar{M} - \frac{\partial \overline{w'q'}}{\partial p}\right)_{MJO}$

C = $-\left(\bar{\vec{V}} \bullet \vec{\nabla}_h \bar{q}\right)_{MJO}$ Horizontal advection

D = $-\left(\bar{\omega}\frac{\partial \bar{q}}{\partial p}\right)_{MJO} + \left(\bar{M} - \frac{\partial \overline{w'q'}}{\partial p}\right)_{MJO}$ Convection plus Radiation

E = $\frac{1}{L_v}\left(\bar{\alpha}_{LP20} Q_{R,LP20}\right)_{MJO}$

F = $\bar{M}_{MJO} - \frac{\partial \overline{w'q'}}{\partial p}_{MJO} + \frac{1}{L_v}\left(\bar{\alpha}_{LP20}\left(\bar{Q}_M - \frac{\partial \overline{w's'}}{\partial p}\right)_{LP20}\right)_{MJO}$

G = SLHF

$$G_P(p,t) = \frac{\iint P(p)\,\langle q\rangle\,dx\,dy}{\iint \langle q\rangle^2\,dx\,dy}$$

How Good is the Representation of Vertical Advection?

SP-CESM

$$\bar{\omega} = \frac{Q_1}{\left(\frac{\partial \bar{s}}{\partial p}\right)}$$

Apparent heating processes include:

Radiative heating

Net condensation

Net freezing

Net deposition

Sub-grid scale vertical eddy fluxes of DSE

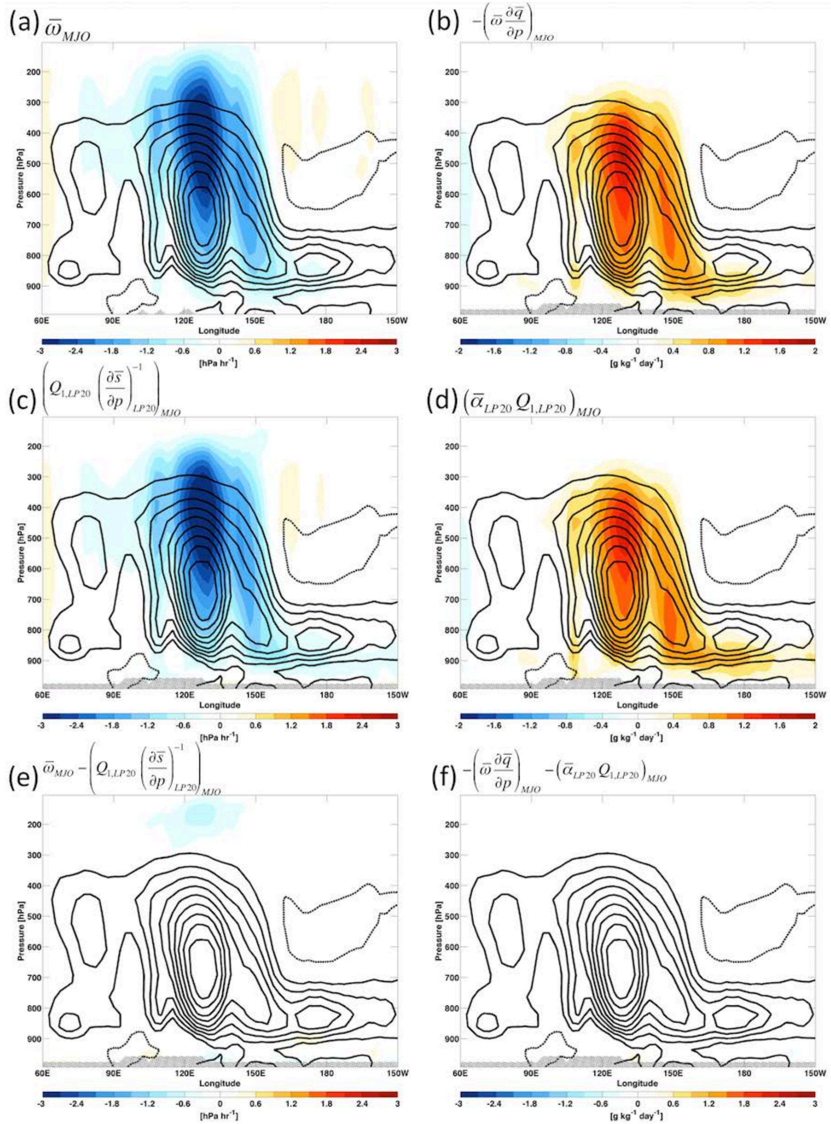
Wolding et al. (2016)

Omega | **Vertical Moisture Advection**

Actual

Diagnosed

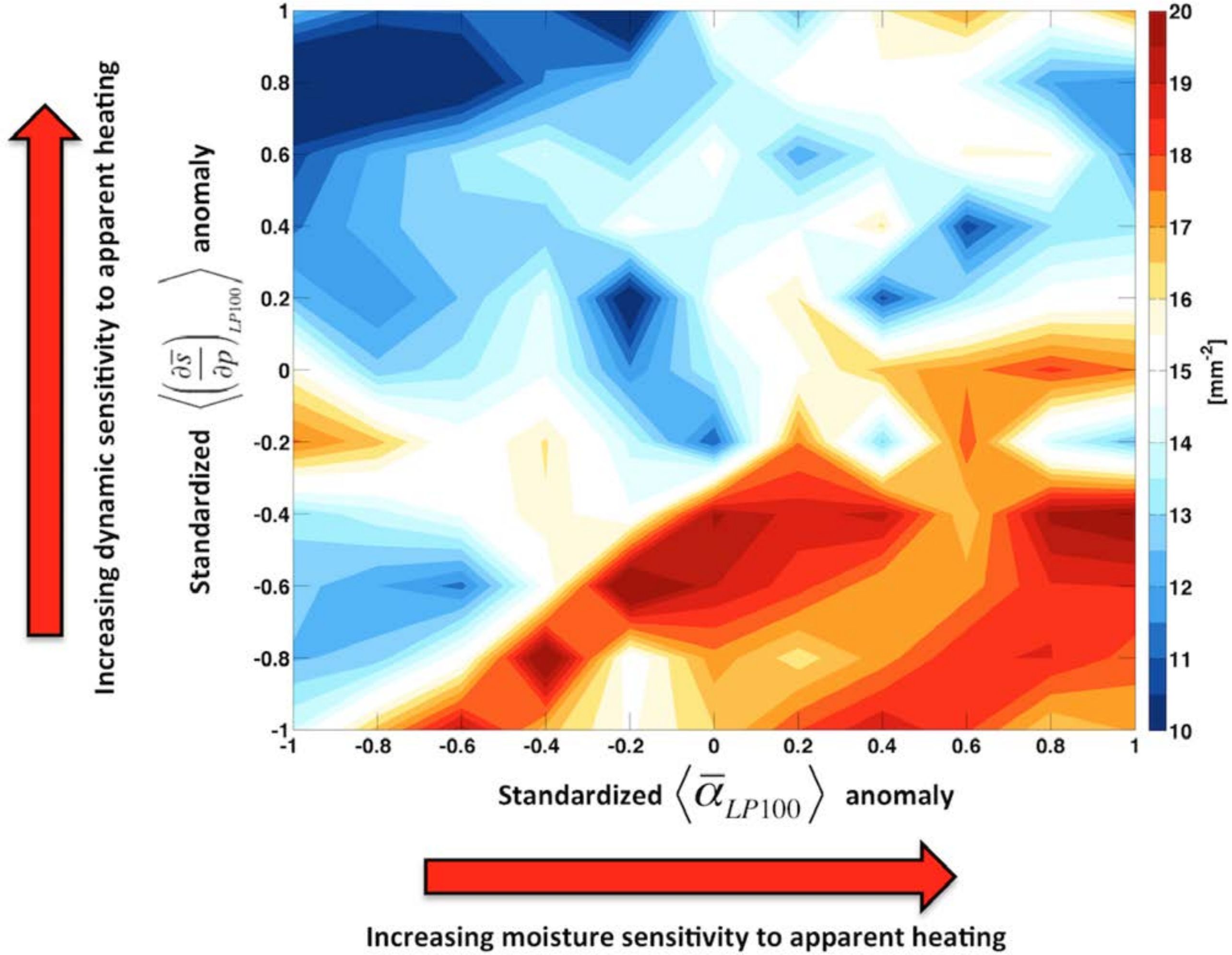
Difference (error)



Strength of MJO Versus Key Parameters

$$-\omega_{WTG}\frac{\partial Lq}{\partial p} = Q \times \alpha$$

$$\alpha = -L\left(\frac{\partial s}{\partial p}\right)^{-1}\frac{\partial q}{\partial p}$$



High moisture variance (i.e. high aggregation) associated with:

high moisture sensitivity to apparent heating

low dynamic sensitivity to apparent heating