MJO Propagates as Coupled Buoyancy Wave in Western Hemipshere and Moisture Wave over Warm Pool[1]

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1. Introduction

- Circumnavigating MJO signals have long been identified in observations and models[2,3,4].

- More than half of MJO events are successive and occur as the upward branch of a circumnavigating MJO signal arrives over the warm pool[4,5].

- The circumnavigating wave appears to trigger MJO onset by reducing convective inhibition just above the boundary layer, allowing cumulonimbus clouds to extend into the middle troposphere and moisten it[6,7].

- Few studies have examined MJO propagation characteristics as it moves over the Western Hemisphere (when it is usually considered inactive). Those that have identified the circumnavigating signal as a dry Kelvin wave[3,4,8,9]; however, the observed propagation is much slower than the expected 50 m s^{-1} of a first baroclinic dry wave in the tropics.

- Can the MJO in the Western Hemisphere be described as a convectively coupled buoyancy wave, whose phase speed is reduced by reduction of "effective static stability" felt by the wave?

2. Impact of "effective static stability" on wave propagation

Static stability felt by a buoyancy wave is reduced by the diabatic heating associated with that wave[10,11,12].

Starting from a state of rest, such that

$$\nabla \cdot \mathbf{u} = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}\left(\frac{\partial \phi}{\partial z}\right) + N^2 w = Q \qquad (2)$$

Observations and reanalysis[13] suggest that diabatic heating Q can be approximated as a linear function of the adiabatic heating, N^2w, such that $Q=\mu N^2 w$. Then,

$$\frac{\partial}{\partial t}\left(\frac{\partial \phi}{\partial z}\right) + (1-\mu) N^2 w = 0 \qquad (3)$$

$$\frac{\partial \phi}{\partial t} + (1-\mu)\frac{N^2}{\lambda}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = 0 \qquad (4)$$

in which λ is a constant eigenvalue of a function related to the vertical gradient of geopotential[14]. Eq. 4 takes the form of the mass conservation equation in shallow water theory in which the phase speed is defined as

$$c = \sqrt{g h_e}$$

in which h_e is an "equivalent depth". Rewriting Eq. 2[13], we get

$$\frac{\partial T}{\partial t} - S\omega = Q \qquad (5)$$

in which ω is the pressure vertical velocity, T is temperature, and $S=-T\partial \log\theta/\partial p$ is the static stability. From the above, we can derive a moist wave speed, c_m, that is reduced from the dry wave speed by the reduction of "effective static stability" felt by a wave.

$$c_m = \sqrt{(1-\mu) g h_e} = \sqrt{\left(1 + \frac{Q}{S\omega}\right) g h_e} \qquad (6)$$

For a completely dry wave (Q=0), Eq. 6 reduces to the dry phase speed. **The goal herein is to find μ as a function of longitude for the circumnavigating MJO.**

3. Data and Method

MERRA2 reanalysis[15] is used. Output is used every 6 hours within 15.75° of the equator. Data spans 1980-2015 and is spaced to a 1.5°x1.5° grid. 3D analysis temperature, geopotential fields and model outputted 3D velocity (u,v,ω) are used. 3D latent (Q_L) and radiative (Q_R; longwave only is important) heating tendencies are used. All fields were decomposed into (as shown in below example) a time mean (T with overbar), seasonal cycle (with circumflex) and a residual.

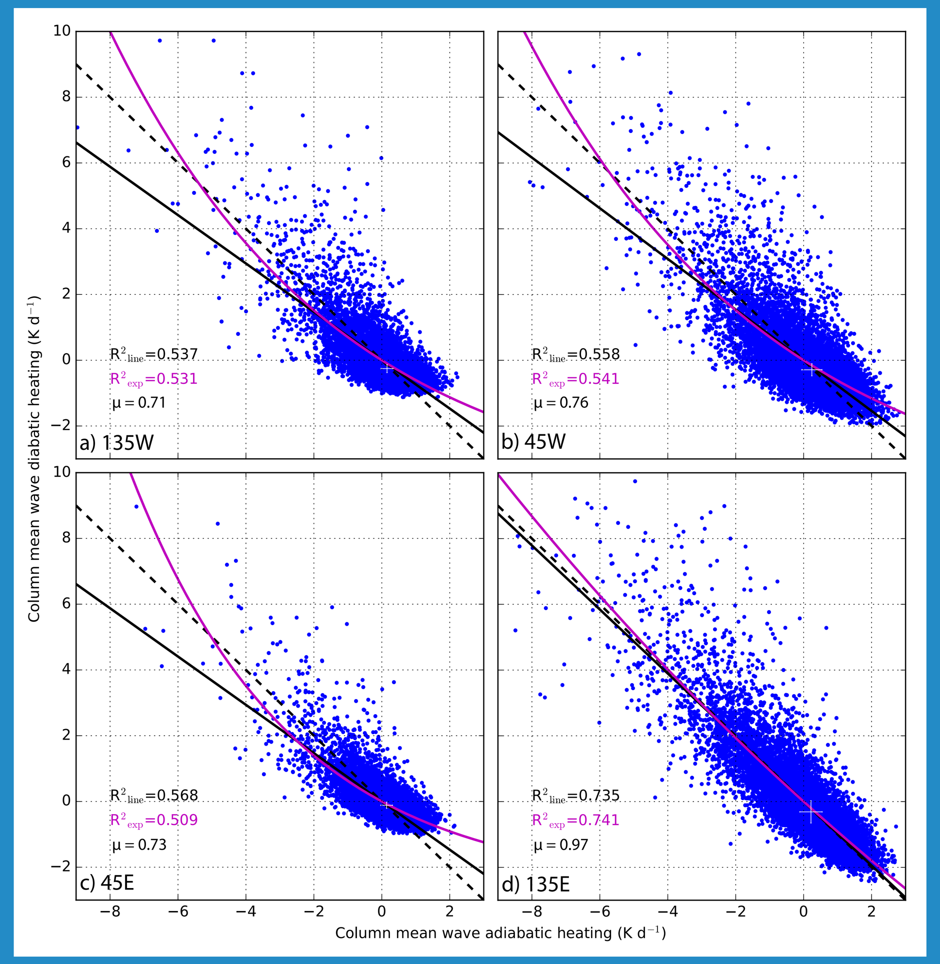
$$T = \overline{T} + \widehat{T} + T'$$

The residual is split into a 20-100 day band-passed component (T_{MJO}) and a further residual that is not analyzed itself, such that

$$T' = T_{MJO} + T''$$

OMI[16] is used to determine when a strong MJO is present. Strong MJO is classified when OMI > 1.82. Strong MJO occurred in a month if OMI exceeded 1.82 for at least 7 days in that month. MJO upward branch is assigned a category[4] (A, B, C, D, or N for a weak MJO) based on the first two principal components making up the OMI. 71 successive, circumnavigating MJO events are identified.

4. Is the relationship between diabatic and adiabatic heating linear?



Left: Column-mean Q' vs. $S\omega'$, averaged within 15.75° of equator, at 135°W, 45°W, 45°E, and 135°E. Blue dots represent data points. Black solid line is best linear fit. Magenta curve is best exponential fit $a(e^{bS\omega}-1)$. Black dashed line represents μ = 1. R^2 values for each fit and μ for the solid black line are in bottom right of each panel. White bars: 95% confidence interval of mean for 71 blue dots picked at random, without replacement.

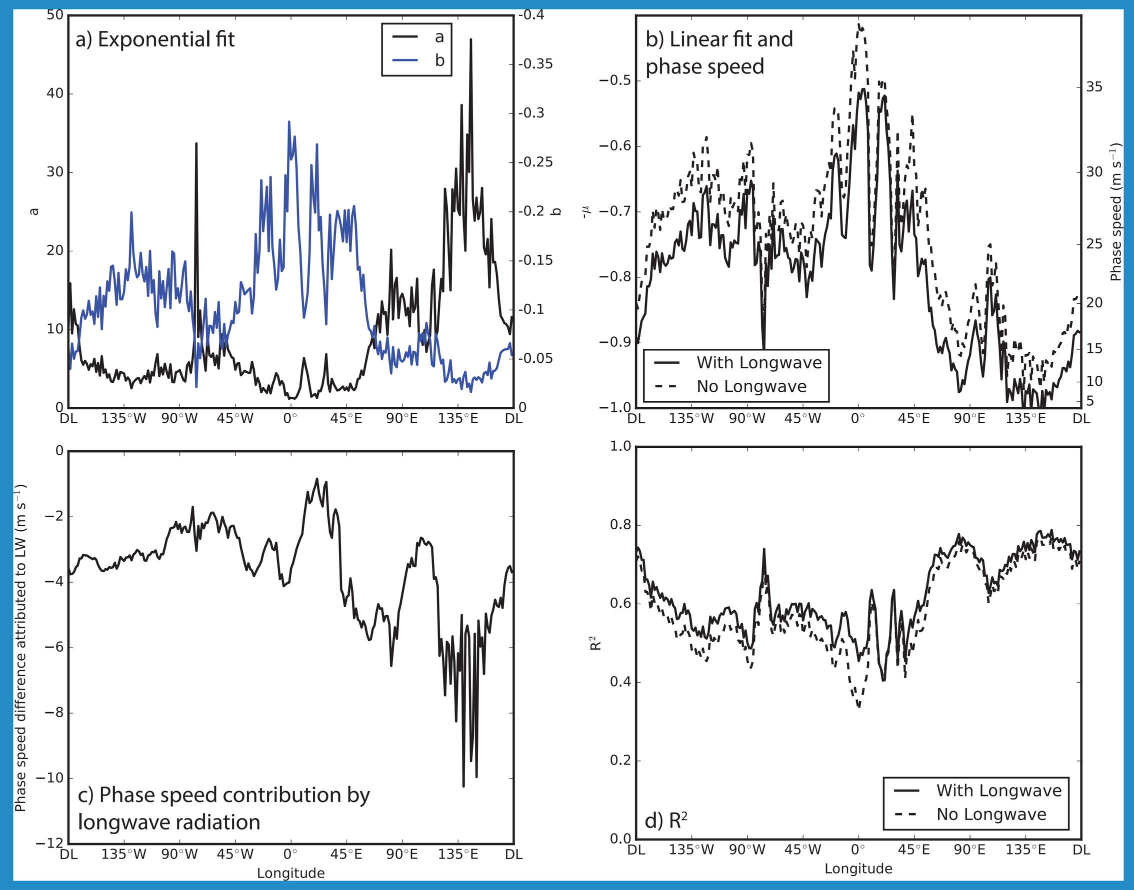
- Except for strongest vertical motions, relationship between diabatic and adiabatic heating for the composite MJO is approximately linear, therefore Eq. 3 is valid.

- Likely the same as the precipitation vs. moisture relationship?

Right: As a function of longitude:
a) parameters a and b for the exponential fits
b) μ and corresponding c_m including longwave in Q (solid) and without longwave (dashed)
c) contribution to c_m by longwave heating
d) R^2 for the linear fits

- Exponential fit is closest to linear over warm pool, where convective adjustment time scale is small. b closely related to μ.

- Longwave radiation causes propagation to take about 1 day longer from 180° to 0°.



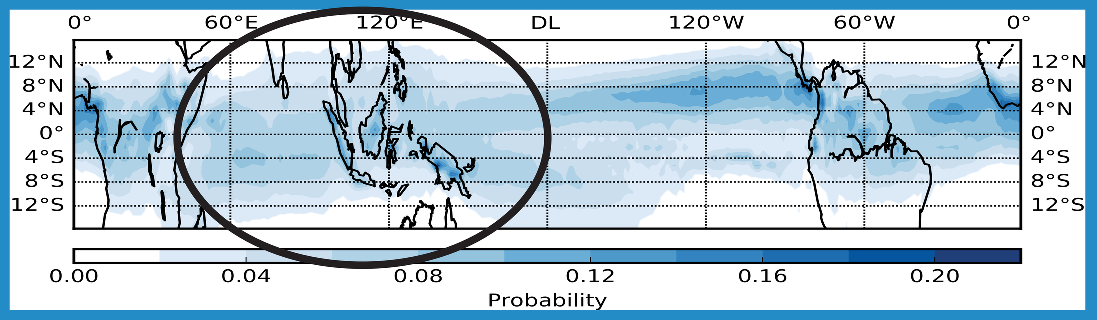
- Predicted propagation speed is 20-30 m s^{-1} over Western Hemisphere, up to 35 m s^{-1} over Atlantic and Africa, and generally < 20 m s^{-1} over warm pool.

5. Tracking the composite MJO Circumnavigation

- Problem: The phase speeds predicted by the offset between Q' vs. $S\omega'$ yield a phase speed that is often much larger than that observed over the warm pool by many previous studies.

- MJO shown to propagate as moisture wave over the warm pool[17], where WTG applies, and latent heating is spread out meridionally yet centered near the equator.

Like this:



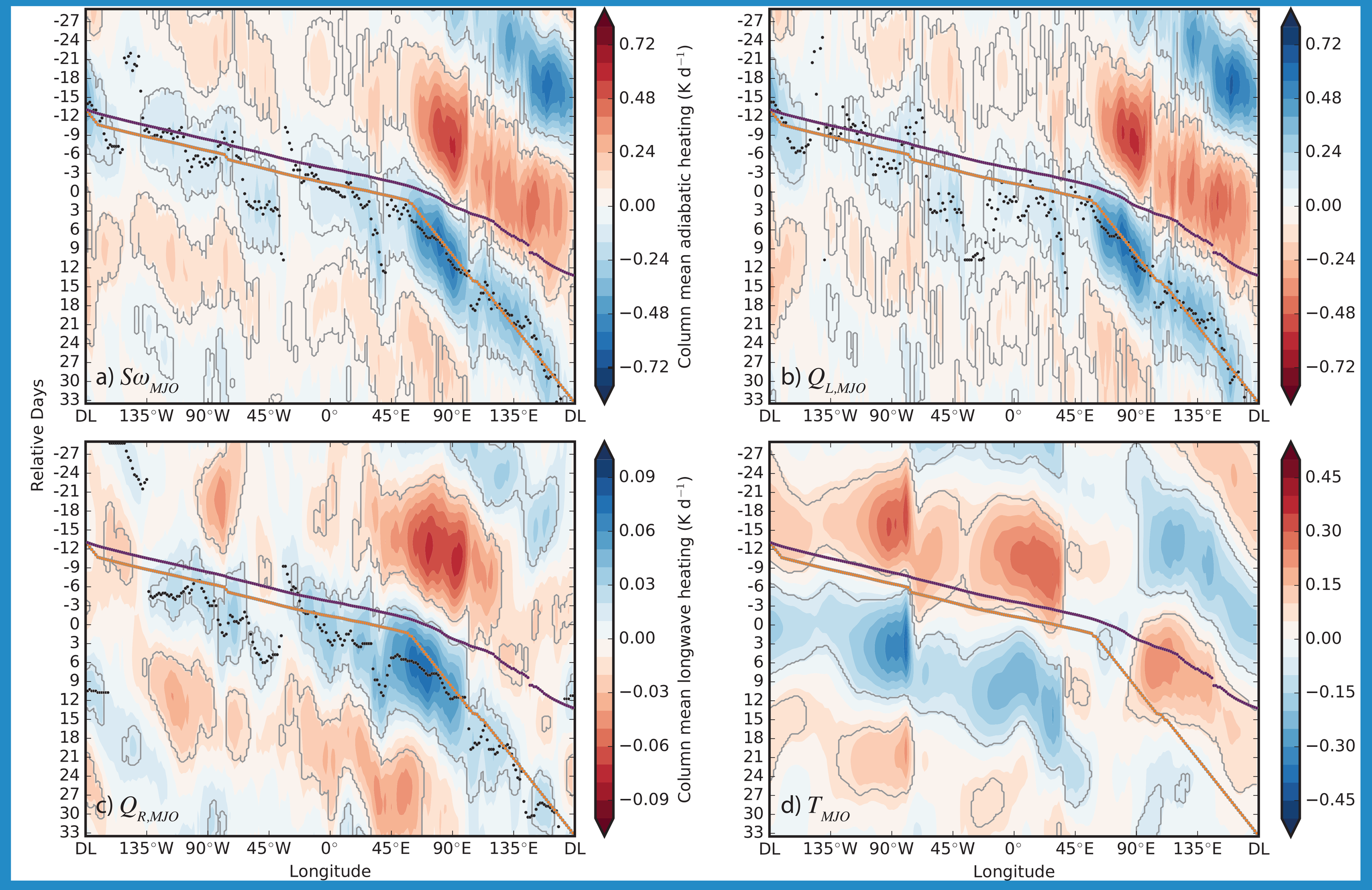
Above: Normalized histogram for location of maximum column mean latent heating as a function of longitude. Not surprisingly, it looks a lot like the distribution of precipitation in the tropics.

In such locations, the phase speed of a moisture wave can be approximated as

$$c_{p,moisture} = \frac{\tilde{p} A_{KR}}{\tau_c k^2}$$

Below: Composites of a) $S\omega_{MJO}$, b) $Q_{L,MJO}$, c) $Q_{R,MJO}$, d) T_{MJO} relative to 00 UTC on the first day in which the successive MJO enters Category D (Atlantic/Africa). In panels a, b, and c, blue represents anomalous heating/upward motion.

- **Black dots: time of minimum or maximum value of each field as function of longitude**
- **Magenta dots: Expected location of MJO if it propagates only as a coupled buoyancy wave.**
- **Orange dots: Expected location if MJO propagates as coupled wave where μ<0.875, but as moisture wave (with k = 2) if μ≥0.875.**



Conclusions: See title.

[1]Powell, S.W., *GRL*, in review. [2]Knutson and Weickmann 1987, *MWR* [3]Seo and Kim 2003, *JGR*
[4]Matthews 2008, *QJRMS* [5]Xu and Rutledge 2016, *GRL* [6]Powell and Houze 2015, *JGR*
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[13]Haertel et al. 2008, *JAS* [14]Kiladis et al. 2009, *Rev. Geophys.* [15]Molod et al. 2015, *Geosci. Model Dev.*
[16]Kiladis et al. 2014, *MWR* [17]Adames and Kim 2016, *JAS*

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