Interactions between Circulation and Convection in the MJO

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Intraseasonal 200hPa Zonal Wind and OLR
Madden-Julian Oscillation

**TIME SCALE**
- Tropical cyclones
- Regional extreme rainfall/temperature
- Westerly wind burst
  - Tornados
  - Equatorial waves
  - Storm track

**SPACE SCALE**
- SST, Ozone, Jets
- MJO
- Tropopause
- PNA, NAO

**CLIMATE**
- Monsoons
- ITCZ
- ENSO
- Artic Oscillation
- Atmospheric Angular Momentum

**WEATHER**
- Synoptic
- Planetary
Big Questions

- What mechanisms drive the MJO?
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  - Most specialists focus on the effects of deep convection interacting with moisture
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  • Dry dynamics, associated with Rossby wave breaking, play major roles in determining MJO structure
Big Questions

• What mechanisms drive the MJO?
  • Most specialists focus on the effects of deep convection interacting with moisture
  • Dry dynamics, associated with Rossby wave breaking play major roles in determining MJO structure
  • Good data in the upper troposphere from the middle latitudes to the equator is critical to understanding the momentum budget associated with the MJO
[RMM1, RMM2] Phase Space for 21-Jan-2016 to 29-Feb-2016

Western Pacific

Indian Ocean

Maritime Continent

West Hem. and Africa
Phase 3 – 250 hPa

Positive Height Anomalies (15 m):
Negative Height Anomalies (15 m):

OLR Anomalies:

RMM Amp: 1.85

RMM Amp: 1.27

Positive Height Anomalies (15 m):
Negative Height Anomalies (15 m):

OLR Anomalies: + -
Positive Height Anomalies (15 m):

Negative Height Anomalies (15 m):

OLR Anomalies:

RMM Amp: 1.89

RMM Amp: 1.47
Methods: MJO Events

- MJO Index: Leading 2 PCs of 20-100 day filtered OLR anomaly, rotated to best match the RMM index
- The Western Hemisphere 200 hPa Zonal Wind Index (WHZI): 20-100 days
Methods: MJO Events

- Select MJO Phase 1 events with amplitude greater than or equal to 0.5 during DJF

- WHZI<0: Easterly Wind Events (45 Events)

- WHZI>0: Westerly Wind Events (13 Events)
From Roundy (2014, J. Atmos. Sci)
Theoretical Kelvin Wave Structure

Horizontal Structure

Vertical Structure (Stratosphere)

\[ \frac{\partial u}{\partial t} = -g \frac{\partial \Phi}{\partial x} \] : Zonal Momentum Equation
Eastward-Moving OLR, 100hPa Wind, and Geopotential Height Anomalies
Methods:
Zonal Momentum Budget at 200 hPa

\[ \frac{\partial u}{\partial t} = -\vec{v} \cdot \nabla u - g \frac{\partial \Phi}{\partial x} + fv + X \]
10°S-5°N, 110°W-80°W Averaged Budget Terms

Intraseasonal Zonal Wind Tendency

Easterly Wind Events

\[ \partial u^* / \partial t \]
10°S-5°N, 110°W-80°W Averaged Budget Terms

Intraseasonal Zonal Wind Tendency

Easterly Wind Events

\[
\partial u^* / \partial t
\]

\[
u^*
\]
10°S-5°N, 110°W-80°W Averaged Budget Terms

Pressure Gradient Force and Coriolis Force

Easterly Wind Events

\[ \frac{\partial u^*}{\partial t} \quad -\frac{\partial \Phi^*}{\partial x} + f v^* \]
10°S-5°N, 110°W-80°W Averaged Budget Terms

Pressure Gradient Force and Coriolis Force

Easterly Wind Events

\[ \frac{\partial u^*}{\partial t} \]

\[ -\frac{\partial \Phi^*}{\partial x} + f v^* \]

\[ -\frac{\partial \Phi^*}{\partial x} \]
10°S-5°N, 110°W-80°W Averaged Budget Terms

Easterly Wind Events

Zonal Advection

- $\partial u^* / \partial t$
- $-\partial \Phi^* / \partial x + f v^*$
- $-u(\partial u / \partial x)^*$
10°S-5°N, 110°W-80°W Averaged Budget Terms

Easterly Wind Events

Meridional Advection

- $\partial u^*/\partial t$
- $-\partial \Phi^*/\partial x + fv^*$
- $-u(\partial u/\partial x)^*$
- $-v(\partial u/\partial y)^*$
10°S-5°N, 110°W-80°W Averaged Budget Terms

Easterly Wind Events

Vertical Advection

- $\partial u^*/\partial t$
- $-\partial \Phi^*/\partial x + fv^*$
- $-u(\partial u/\partial x)^*$
- $-v(\partial u/\partial y)^*$
- $-\omega(\partial u/\partial p)^*$
Easterly Wind Events

10°S-5°N, 110°W-80°W Averaged Budget Terms

Sum of All Terms

- $\frac{\partial u^*}{\partial t}$
- $-\frac{\partial \Phi^*}{\partial x} + f v^*$
- $- u (\frac{\partial u}{\partial x})^*$
- $- v (\frac{\partial u}{\partial y})^*$
- $- \left[ \omega (\frac{\partial u}{\partial \rho}) \right]^*$
- $- \left[ \nabla \cdot \vec{v} \right]^* - \frac{\partial \Phi^*}{\partial x} + f v^*$
Methods: Zonal Momentum Budget at 200 hPa

- Time linear decomposition of zonal momentum equation

\[ u = \bar{u} + u^* + u' \]

\( \bar{u} \): Background State (Seasonal Cycle + Periods longer than 100 days)
\( u^* \): Intraseasonal Timescale (20-100 days)
\( u' \): Transient Timescale (Periods shorter than 20 days)

\[ \frac{\partial u^*}{\partial t} \approx -\bar{v} \cdot \nabla u^* - \bar{v} \cdot \nabla \bar{u} - \bar{v} \cdot \nabla u^* - \nabla \bar{v}' u' - g \frac{\partial \Phi^*}{\partial x} + f v^* \]
10°S-10°N Averaged Longitude-Pressure Cross Sections

Day -6

Shading: intraseasonal zonal wind anomaly
Black contour: intraseasonal geopotential height anomaly at 2 m interval
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Black contour: intraseasonal geopotential height anomaly at 2 m interval
10°S-10°N Averaged Longitude-Pressure Cross Sections

Day -6

NOT Similar to Kelvin wave structure

Similar to Kelvin wave structure

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10°S-10°N Averaged Longitude-Pressure Cross Sections

Day -6

NOT Similar to Kelvin wave structure

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Black contour: intraseasonal geopotential height anomaly at 2 m interval
10°S-10°N Averaged Longitude-Pressure Cross Sections

Day −3

Shading: intraseasonal zonal wind anomaly
Black contour: intraseasonal geopotential height anomaly at 2 m interval

Sakaeda and Roundy (2015,a,b), Powell and Houze (2015)
10°S-10°N Averaged Longitude-Pressure Cross Sections

Day 0

Shading: intraseasonal zonal wind anomaly
Black contour: intraseasonal geopotential height anomaly at 2 m interval

Sakaeda and Roundy (2015,a,b), Powell and Houze (2015)
Summary

- Upper-tropospheric intraseasonal wind over the Western Hemisphere cannot simply be explained as a “free” Kelvin wave generated by MJO convection.
- Breaking waves couple the mid latitudes to the equator.
Additional Figures

Phase 1 Easterly Events (0 days)
  a) Zonally Asymmetric Component

Phase 1 Westerly Events (0 days)
  b) Zonally Asymmetric Component

  c) Eastward Moving Component

  d) Eastward Moving Component

  e) Westward Moving Component

  f) Westward Moving Component
Advection of Background Zonal Wind by Intraseasonal Wind

![Graph showing Easterly Wind Events](image)

- **Time Lags (days)**
- **Easterly Wind Events**
- **$\partial u^*/\partial t$**

**Legend:**
- Black line: $\partial u^*/\partial t$
Advection of Background Zonal Wind by Intraseasonal Wind

Easterly Wind Events

\[ \partial u^*/\partial t \]

\[ -u^*(\partial \bar{u}/\partial x) \]

Time Lags (days)
Advection of Background Zonal Wind by Intraseasonal Wind

**Day 0**

- **Intraseasonal Zonal Wind Tendency**
- **\( \partial u^*/\partial t \)**

- **\(-u^*(\partial \bar{u}/\partial x)\)**

- Black contour: Background zonal wind at 4 m s\(^{-1}\) interval

- **\( \partial \bar{u}/\partial x < 0 \)**
Advection of Background Zonal Wind by Intraseasonal Wind

Easterly Wind Events

- $\frac{\partial u^*}{\partial t}$
- $-u^*(\frac{\partial \tilde{u}}{\partial x})$
- $-v^*(\frac{\partial \tilde{u}}{\partial y})$

Time Lags (days)
Advection of Background Zonal Wind by Intraseasonal Wind
Advection of Background Zonal Wind by Intraseasonal Wind

Easterly Wind Events

- $\partial u^*/\partial t$
- $-u^*(\partial \bar{u}/\partial x)$
- $-v^*(\partial \bar{u}/\partial y)$
- $-\omega^*(\partial \bar{u}/\partial p)$
- $-\partial \Phi^*/\partial x$
Advection of Background Zonal Wind by Intraseasonal Wind

Easterly Wind Events

- $\partial u^* / \partial t$
- $-u^*(\partial \bar{u} / \partial x)$
- $-v^*(\partial \bar{u} / \partial y)$
- $-\omega^*(\partial \bar{u} / \partial p)$
- $-\partial \Phi^* / \partial x$
- $-v^* \cdot \nabla \bar{u} - \partial \Phi^* / \partial x$
Advection of Background Zonal Wind by Intraseasonal Wind

Maintains and amplifies the zonal wind

\[-u^* \frac{\partial \bar{u}}{\partial x}\]
Advection of Intraseasonal Zonal Wind by Background Wind

Easterly Wind Events

Time Lags (days)

m s⁻²

x 10⁻⁵

∂u*/∂t
Advection of Intraseasonal Zonal Wind by Background Wind

Easterly Wind Events

\[ \frac{\partial u^*}{\partial t} \quad \text{and} \quad -\bar{u} \left( \frac{\partial u^*}{\partial x} \right) \]

\( \text{Time Lags (days)} \)

\( \text{m}^2 s^{-2} \)

\( x \times 10^{-5} \)
Advection of Intraseasonal Zonal Wind by Background Wind

Easterly Wind Events

- $\partial u^*/\partial t$
- $-\bar{u}(\partial u^*/\partial x)$
- $-\bar{v}(\partial u^*/\partial y)$

Time Lags (days)

m s$^{-2}$

$\times 10^{-5}$
Advection of Intraseasonal Zonal Wind by Background Wind
Advection of Intraseasonal Zonal Wind by Background Wind

Easterly Wind Events

Only vertical advection is significant during the peak easterly acceleration

\[-\bar{\omega} \frac{\partial u^*}{\partial p}\]
Advection of Intraseasonal Zonal Wind by Background Wind

**Black contour:** Background vertical motion at $5 \times 10^{-3}$ Pa s$^{-1}$ interval

**Background subsidence advects zonal wind anomaly downward**

**Day 0**

**Intraseasonal Zonal Wind Tendency**

$$\partial u^* / \partial t$$

$$-\bar{\omega} (\partial u^*/\partial p)$$
Additional Figures

a) Easterly Wind Event
Eastward Propagating Component

Time Lag (days)
Longitude

b) Easterly Wind Event
Westward Propagating Component

Time Lag (days)
Longitude
OLR and 200hPa Wind and Geopotential Height Anomalies

Easterly Wind Events: Day −9

200-hPa Geopotential Height and Wind Anomaly

OLR Anomaly
OLR and 200hPa Wind and Geopotential Height Anomalies

Easterly Wind Events: Day −6

200-hPa Geopotential Height and Wind Anomaly

OLR Anomaly
OLR and 200hPa Wind and Geopotential Height Anomalies

Easterly Wind Events: Day −3
OLR and 200hPa Wind and Geopotential Height Anomalies

Easterly Wind Events: Day 0

200-hPa Geopotential Height and Wind Anomaly

OLR Anomaly
OLR and 200hPa Wind and Geopotential Height Anomalies

Easterly Wind Events: Day +3

200-hPa Geopotential Height and Wind Anomaly

OLR Anomaly
10°N-10°S Averaged OLR

Easterly Wind Events

Westerly Wind Events

Time Lag (days)

180°W 120°W 60°W 0°E 60°E 120°E 180°E

180°W 120°W 60°W 0°E 60°E 120°E 180°E
200-hPa Zonal Wind and OLR

Easterly Wind Events

Westerly Wind Events

Shading: Intraseasonal 200-hPa geopotential height anomaly
Black contour: Intraseasonal OLR anomaly at 5 Wm^{-2} interval
"They're digging in the wrong place...!"

"They're digging in the wrong place...!"
Amplification Mechanism from Kinetic Energy Perspectives

\[
C\left(\frac{1}{2} \frac{\partial \overline{u}^2}{\partial t}, \frac{1}{2} \frac{\partial \overline{u}^*^2}{\partial t}\right) = -\overline{u}^* \overline{v}^* \cdot \nabla \overline{u}
\]

\[
= -\overline{u}^* \frac{\partial \overline{u}}{\partial x} - \overline{u}^* v^* \frac{\partial \overline{u}}{\partial y} - \overline{u}^* \omega^* \frac{\partial \overline{u}}{\partial p}
\]

Energy Conversion
\[
\overline{u}^2 \rightarrow \overline{u}^*^2
\]
where \( \partial \overline{u} / \partial x < 0 \)

Shading: Variance of 200hPa Intraseasonal Zonal Wind
Black contour: Zonal Convergence of 200hPa Background Zonal Wind
(2 x 10^6 s^{-1} interval)