Observations of Convection Organization

at the planetary scale

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with slides from: Angel Adames — Adam Sobel — Da Yang
many more adapted from: George Kiladis — Chidong Zhang
“convection organization”

WHAT DO WE MEAN BY ORGANIZATION?

- organization by the boundary
- self - organization of the atmosphere
  - through (dry) dynamics
  - through moisture
“convection organization”

WHAT DO WE MEAN BY ORGANIZATION

- organization by the boundary
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by the boundary

- orography
  - barrier
  - lift
- patterns in enthalpy fluxes
  - SST
  - wind speed
- patterns in surface convergence
- diurnal circulations (rectified)
diurnal circulations
at seasonal to interannual (& longer) scales organization is from the boundary

The seasonal excursion of an Aquaplanet ITCZ follows the (Laplacian) of SST

Figure 7. Seasonal evolution of the zonal mean (a) moist static energy (K), (b) temperature (K), (c) meridional gradient of temperature ($10^{-6}$ K/m), and (d) Laplacian of temperature ($10^{-12}$ K/m$^2$) at the lowest model level ($u_1D70E = 0.989$) ins had in Aqua20m. The open circles are $EFE_{actual}$, the open triangles $EFE_{theoretical}$, and the asterisks $PITZ$. Solid thick black lines show their annual harmonic. Vertical black dashed lines indicate pentads 11–15 August and 6–10 December, respectively, shown in Figure 5, which have the same ITCZ location, shown by the horizontal blue dashed line but different EFE, denoted by the green $uni2297$ symbol. The horizontal thin black line indicates the equator. The cyan and purple dots represent location (equator) and times (11–15 August and 6–10 December, respectively) for the vertical cross sections shown in Figures 8c and 8d.

To understand how oppositely signed cross-equatorial energy transport is affected at these two pentads, the corresponding vertical profiles of $v$ and $h$ at the equator are shown in Figures 8c and 8d, for the August and December pentad, respectively. The MSE vertical profiles at both pentads are consistent with observed typical profiles in the tropical atmosphere, with a minimum in the middle-to-lower troposphere and values at upper levels being larger than those close to the surface. While largely similar, these profiles differ in the lower atmosphere, with slightly higher MSE values below the minimum being found over a deeper layer in the retreating phase. Vertical profiles of the meridional wind, however, feature more pronounced differences. More specifically, in the retreating phase, the cross-equatorial Hadley cell develops a shallow return flow at heights where the MSE minimum is located. This is also evident in the structure of the stream function (Figure 8b). That the differences in the circulation (or meridional wind) vertical structure are more important than the differences in the MSE vertical structure for the sign reversal of the GMS in the retreating phase of the winter Hadley cell can be more accurately quantified by decomposing the anomalous mean MSE flux according to $\left(\frac{\partial}{\partial z} E_{v} \right) = E_{v} - E_{v} + E_{h} - E_{h}$, where $E_{v}$ represents the difference between the December and August fields (6–10 December minus 11–15 August) and we neglect the quadratic term. The first term represents the contribution to the anomalous mean MSE flux due to changes in the MSE vertical profile, while the second term represents the contribution due to changes in the meridional wind vertical profile. As shown in Figure 9, in the tropics differences in the total MSE flux between the two pentads are almost entirely accounted for by differences in mean MSE flux, which in turn are primarily dominated by differences in the circulation vertical structure rather than differences in MSE profiles. In other words, it is the presence of the shallow return flow near the MSE minimum, rather than MSE increases at lower levels, that causes the vertically integrated energy transport to be in the direction of the lower-level mass transport in the retreating phase, resulting in a negative GMS. At other pentads, the retreating cell does not always feature a shallow return flow as well defined as that seen around 6–10 December. Nonetheless, the structure of the associated stream function is very different from that of the winter cell in its expanding phase, with the upper- and lower-level meridional flow being confined in very thin layers, which also favors negative GMS (not shown). This means that while the EFE evolves seasonally almost in phase with the insolation, the surface temperature, the Hadley cell, and its ascending branch cannot change as rapidly.
at seasonal to interannual (& longer) scales organization is from the boundary
WHAT DO WE MEAN BY ORGANIZATION

- organization by the boundary
- self-organization of the atmosphere
  - through (dry) dynamics
  - through moisture
self-organization of the atmosphere

• through (dry) dynamics: Equatorial Waves
• through (maybe) moisture: The MJO

• (mostly) away from land
• sub-seasonal
A diversity of convectively-coupled waves and modes

Cloud Brightness 2005-03-22 09:00:00

MJO  Eq. Rossby  Kelvin  MRG

Ángel F. Adames
University of Michigan
How to diagnose tropical waves: the Wheeler and Kiladis diagram

1. Decompose (IR) into components that are symmetric and anti-symmetric about the equator. (This takes care of the y-direction)
2. Take 2-D Fourier transformation of $a(x, t) \rightarrow A(k, n)$
3. Plot $A^2(k, n)$: Power spectrum


How to diagnose tropical waves: the Wheeler and Kiladis diagram (2/5)
How to diagnose tropical waves: the Wheeler and Kiladis diagram (3/5)

Larger frequency == faster time scale

Larger wavenumber == smaller zonal scale

30 days

Westward Eastward

Smaller

Faster

Smaller
4. Determine “background” spectrum by smoothing raw spectra
5. Divide raw spectra by background spectra to determine signals standing above the background.
Enhanced power in the Wheeler and Kiladis diagram corresponds to known tropical waves. There is a good match to the dispersion relation of dry equatorially trapped waves found by Matsuno (1966).
Equatorial Shallow Water (unforced, undamped)

\[ \frac{\partial u}{\partial t} - \beta y v + \frac{\partial \phi}{\partial x} = 0 \]

\[ \frac{\partial v}{\partial t} + \beta y u + \frac{\partial \phi}{\partial y} = 0 \]

\[ \frac{\partial \phi}{\partial t} + gh \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) = 0 \]

SW:
incompressible
and \( L_z \gg L_{x,y} \)

Linearized around a basic state at rest

Two restoring forces:
Gravity and Rotation
=> wave solution
To the board:
let’s sketch how we get to the wave solutions
The dispersion relation of SW Equatorially Trapped Waves

\[
\frac{\sqrt{gh_e}}{\beta} \left( \frac{\omega^2}{gh_e} - k^2 - \frac{k}{\omega} \beta \right) = 2n + 1 \quad n = 0, 1, 2, \ldots
\]
Horizontal Structure of the Kelvin Wave

\( v = 0 \) everywhere
\( u = \phi \) (contours)

symmetric, decaying
divergent
Horizontal Structure of the Equatorial Rossby Wave

symmetric, rotational
Horizontal Structure of Inertio-Gravity Waves

n=1 Westward Inertio-gravity Wave Theoretical Structure

Wind, Pressure (contours), Divergence, blue positive

Horizontal Structure of Inertio-Gravity Waves

symmetric,

divergent
Mixed Rossby-Gravity Wave Theoretical Structure

Horizontal Structure of Mixed Rossby-Gravity Waves

anti-symmetric, rotational
Gravity Wave Speed

$$ c = \sqrt{gh} $$

Rossby Radius of Deformation:

$$ R_e = \sqrt{\frac{c}{\beta}} $$

**what is h?**

<table>
<thead>
<tr>
<th>$h_e$</th>
<th>$L_z$ (km)</th>
<th>$\sqrt{gh_e}$ (m s$^{-1}$)</th>
<th>$R_e$ (Degrees Latitude)</th>
</tr>
</thead>
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<tr>
<td>10</td>
<td>6.0</td>
<td>9.9</td>
<td>6.0</td>
</tr>
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<td>8.5</td>
<td>14.0</td>
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<td>13.4</td>
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<td>31.3</td>
<td>10.7</td>
</tr>
<tr>
<td>200</td>
<td>27.9</td>
<td>44.3</td>
<td>12.7</td>
</tr>
<tr>
<td>500</td>
<td>47.5</td>
<td>70.0</td>
<td>15.9</td>
</tr>
</tbody>
</table>

$H = 7.3$ km, $dT_0/dz = -7.0$ K km$^{-1}$ (Troposphere)
Back to the board: we relax the shallow water assumption
There is a continuum of equivalent depths $h_e$ in the observed CCEW.
One more type of “wave”: Tropical Depressions (and Easterly Waves)

JJA Tb

Symmetric

Antisymmetric
since this retains the full signal of the wave in those regions where convection is confined to one hemisphere and thus projects equally onto each component [see Straub and Kiladis, 2002].

The filters shown in Figure 1 are based on more expanded space-time domains than used by WK99 (except for the EIG wave), which better match the spectral peaks in Figure 1. The "TD-type" filter used to isolate EWs is not shown but is identical to that used by Kiladis et al. [2006] to encompass the prominent 2–6 day westward spectral peak found during northern summer (WK99).

Figure 5 shows the distribution of $T_b$ variance for the various CCEWs, along with some information on their propagation and impacts, to be discussed further in sections 4–8. These patterns compare well with those estimated using OLR by WK99, Wheeler et al. [2000] (hereinafter referred to as WKW00), and Roundy and Frank [2004a].

The space-time filtered $T_b$ of a particular CCEW at a given grid point is correlated and regressed against unfiltered dynamical and $T_b$ fields to obtain a "composite" picture of the wave's evolution. This technique is similar to that used by WKW00 except that we do not window by wave activity amplitude but instead use the entire period available regardless of season. General features of the results are not sensitive to the details of this approach.

For all of the plots in this article, the perturbations are scaled to a –20 K $T_b$ anomaly at the chosen base grid point, a typical minimum value seen during the convective phase of a moderate to strong event. Positive/negative lags refer to Figure 5.
A superposition of criss-crossing CCEW

CLAUS Brightness Temperature (2.5S–7.5N), April-May 1987

WIG: 23 m s\(^{-1}\)

Kelvin: 15 m s\(^{-1}\)
Horizontal Structure of the observed moist Kelvin Wave(s)

Regression against Kelvin filtered Tb anomalies
(DAY 0 at 2.5N, 0E, March-May)

200 hPa Streamfunction (contours $5 \times 10^5 \text{ m}^2 \text{s}^{-1}$)
Wind (vectors, largest around 2 m s$^{-1}$)
Tb (shading starts at +/- 4°K), negative blue
Day-4

Tb and 200 hPa Flow Regressed against Kelvin filtered Tb anomalies at 2.5N, 0E, for March-May

Streamfunction (contours 5 X 10^5 m^2 s^-1)

Wind (vectors, largest around 2 m s^-1)

Tb (shading starts at +/- 4 °K), negative blue
Day-3

Streamfunction (contours $5 \times 10^{-5}$ m$^2$ s$^{-1}$)

Wind (vectors, largest around 2 m s$^{-1}$)

$T_b$ (shading starts at $\pm 4$°K), negative blue

$T_b$ and 200 hPa Flow Regressed against Kelvin filtered $T_b$ anomalies at 2.5N, 0E, for March - May
Day-2

Streamfunction (contours 5 x 10^{-5} m^2 s^{-1})

Wind (vectors, largest around 2 m s^{-1})

Tb (shading starts at +/- 4°K), negative blue

Tb and 200 hPa Flow Regressed against Kelvin filtered Tb anomalies at 2.5N, 0E, for March-May
Day-1

Streamfunction (contours \(5 \times 10^5\) m\(^2\) s\(^{-1}\))

Wind (vectors, largest around 2 m\(s^{-1}\))

\(T_b\) (shading starts at +/-4\(^\circ\)K), negative blue

\(T_b\) and 200 hPa Flow Regressed against Kelvin filtered \(T_b\) anomalies at 2.5N, 0E, for March-May
Day 0

Streamfunction (contours $5 \times 10^{-5}$ m$^2$s$^{-1}$)

Wind (vectors, largest around 2 m$s^{-1}$)

$T_b$ (shading starts at +/- 4$°$K), negative blue

$T_b$ and 200 hPa Flow Regressed against Kelvin filtered $T_b$ anomalies at 2.5N, 0E, for March-May
Day+1

Streamfunction (contours $5 \times 10^{-5} m^2 s^{-1}$)

Wind (vectors, largest around 2 m s$^{-1}$)

$T_b$ (shading starts at +/- 4°K), negative blue

$T_b$ and 200 hPa Flow Regressed against Kelvin filtered $T_b$ anomalies at 2.5N, 0E, for March-May
Regression against Kelvin filtered Tb anomalies
(DAY 0 at 2.5N, 0E, March-May)

200 hPa Streamfunction (contours $5 \times 10^5$ m$^2$ s$^{-1}$)

Wind (vectors, largest around 2 m s$^{-1}$)

Tb (shading starts at +/- 4°K), negative blue
Vertical Structure of the observed moist Kelvin Wave(s)

Temperature
(contours, .1 °C), red positive

Zonal wind
(contours .25 m s⁻¹), red positive

at Majuro (7N, 171E) Regressed against Kelvin-filtered OLR (1979-1999)
Vertical Structure of the observed moist Kelvin Wave(s)

Specific humidity (contours, $1 \times 10^{-1} \text{ g kg}^{-1}$), red positive

Generalized Evolution of a Convectively Coupled Equatorial Wave (self similar organization?)
The main mode of intraseasonal variability: the Madden-Julian Oscillation (MJO)

Time–longitude diagram of CLAUS Tb (2.5°S–7.5°N), January–April 1987

MJO: 5 m s⁻¹

Madden and Julian
The MJO is slower, hence not a Kelvin Wave

Symmetric

Antisymmetric
Phenomenology of the MJO

- Organized planetary scale system
- Characterized by convectively active and inactive phases
- Convective signal strongest in Indian Ocean and West/Central Pacific.
- Phases connected by deep overturning zonal circulations
- Zonal winds reverse between lower and upper-level
- Dynamic signal seen throughout the tropics.
- Moves eastwards at about 5m/s
- Intraseasonal time scale (30-60 days)
MJO signal in rainfall

MJO CYCLE
Precipitation rate (TRMM)

RMM Phase 1 of 8
Day 0 of 48

mm day$^{-1}$

Less rain More rain

envam1.env.uea.ac.uk/mjo.html
Let’s go back to the equations to seek a steady-state (damped, forced) solution

\[-\beta y v = -\frac{\partial p}{\partial x} - \epsilon u\]
\[\beta y u = -\frac{\partial p}{\partial x} - \epsilon v\]
\[\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = Q - \epsilon_T p\]

\(Q = \text{single equatorial heating}\)

Gill 1980
Let’s go back to the equations to seek a steady-state (damped, forced) solution

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Q = single equatorial heating

Rossby Gyres: 5 m s\(^{-1}\)

Kelvin: 15 m s\(^{-1}\)

Gill 1980
We can superimpose linearly the solutions for different forcings

\[- \beta y v = -\frac{\partial p}{\partial x} - \epsilon u\]

\[\beta y u = -\frac{\partial p}{\partial x} - \epsilon v\]

\[\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = Q - \epsilon T p\]

\[Q = \text{wavenumber 2 equatorial heating}\]

**Figure:**
Horizontal structure of a wavenumber 2, linear moist wave. \(P'\) contoured, \(\phi\) shaded.
Let’s go back to the equations to seek a steady-state (damped, forced) solution.

\[-\beta y v = -\frac{\partial p}{\partial x} - \epsilon u\]

\[\beta y u = -\frac{\partial p}{\partial x} - \epsilon v\]

\[\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = Q - \epsilon_T p\]

Q = single equatorial heating

deep overturning in the meridional plane

Gill 1980
Observed Vertical Structure of the MJO

Temperature consistent with the Gill model

BUT the MJO PROPAGATES!

Zonal wind
Building a Theory of the MJO:

- Why does it propagate eastward?
- What sets the propagation speed?
- the spatial scale?
- the intra-seasonal time scale?
- Why is it much stronger over the Indo-Pacific?
- What is its energy source?
- What is the connection to the embedded fast waves?

A recent review of 4 modern MJO theories

The MJO as a moisture mode. Rationale:

The slow propagation speed is limited to the Warm Pool, where the MJO has a strong convective component.

Intraseasonal rainfall variance is greater over warm SST and greater over ocean than land, which suggests a role for net surface heat flux (likely dominated by latent heat flux).
The MJO as a moisture mode. Basic Idea:

A large-scale moist instability. Hence, the timescale is slower than the speed of gravity waves, so that we are in the WTG and CQE regime.

\[
\frac{\partial q'}{\partial t} + U \frac{\partial q'}{\partial x} = -MP' + E' - (1 - M)R'
\]

Energy Fluxes are the sources of energy

Precipitation is a restoring force

Adames

Sobel and Maloney (2012, 2013)
Radiation is the main destabilizing process.

High cirrus in deep convection reduce OLR and causes a net warming, which is balanced by upward motion and moisture import into the free troposphere.

Adames

Arnold and Randall 2015 JAMES
Need a better representation of moisture advection for Eastward propagation.

**Horizontal Advection:** meridional advection by the MJO wind of the background moisture gradient.

(during DYNAMO, zonal advection did the moistening to the east of the main convection)
vertical moisture advection: Frictional convergence and a shallow circulation to the East create a positive moisture (and MSE) tendency.

Hsu, P., & Li, T. (2012)
WISHE enhances surface fluxes when $u'$ reinforces the mean wind.

Assumptions and issues with a pure moisture mode:

- negative GMS needed for circulation to import energy and lead to amplification
- precipitation only a function of moisture
- radiative feedbacks need to be scale dependent for the unstable modes to select planetary scale
- depends on background moisture gradients for eastward propagation
Spatial scale remains unchanged when radiative feedbacks are switched off

Amplitudes become smaller
The “MJO” eastward propagation is not always sensitive to horizontal moisture advection.

Anti-Hadley circulation emerged

Two tropical rainfall peaks
Tropics is dry; subtropics is humid

The MJO still propagates to the east

Pritchard and Yang 2016, J. Climate
The MJO as a moisture mode. Summary:

- Distinct (but can co-exist) with buoyancy-driven (gravity) modes. Flow dominated by rotational component.
- Destabilized (at least partly) by moisture mode instability. Instability can occur from: cloud radiation feedbacks, negative gross moist stability, and air-sea interaction.
- Exhibit slow or no propagation.
- The processes that change column moisture determine propagation of the disturbance.

Adames; Yang et al 2019
Another kind of self organization: The MJO as an envelope of interfering WIGs and EIGs
A multi-scale theory: The MJO is a large-scale envelope of small-scale high-frequency eastward and westward inertia-gravity (IG) waves.

Convection excites a quasi standing IG wave, which triggers more convection events in the vicinity of recent convection events. Because of the non-linearity of the trigger mechanism, convection excites a range of frequencies.

\[
\lambda \sim \frac{c}{S}
\]

\[
c_W = c_E \Rightarrow c_{\text{MJO}} = 0
\]

\[
c_W < c_E \Rightarrow c_{\text{MJO}} > 0
\]
The zonal asymmetry of IG waves set the propagation speed of the MJO:

\[ c = 0.5(c_E - c_W) \]

This figure presented 60 simulations with a wide range of parameter values. Each marker represents a simulation. The curves correspond to the theoretical MJO speed. The lower one is associated with the lowest meridional structure.
The zonal scale is set by the mean free path (MFP) of gravity waves.

Fewer, stronger storms (large MFP) lead to large zonal scale of the MJO.

Faster gravity waves (small MFP) lead to small zonal scale of the MJO.

\[ \text{Speed (m/s)} = \frac{0.5 \times (\text{c}_E - \text{c}_W)}{0.5} \]
Results from a one-layer atmosphere model (shallow water model)

Yang and Ingersoll 2013, JAS

Dynamic Field (U)

convection

Yang and Ingersoll 2013, JAS
Validating the gravity-wave model:

Observation supports the multi-scale theory (in spectral — but not physical — space)

**Strong MJO**
Eastward & westward waves

**Weak MJO**
No eastward waves

Kikuchi 2010
Conclusions:

• The tropical atmosphere self-organizes at sub-seasonal and intraseasonal time scales.
• All CCEWs have dry-atmosphere counterparts (gravity, and rotation are their restoring forces), but are slowed down by moist convection.
• The MJO is (probably, partly) a moisture mode: convection in near-balance with the L-S flow destabilized by radiation, surface fluxes, and GMS propagating because of moisture advection.
• The MJO could be lots of other things… (combining Equatorial Waves, Convection, Radiation, and Boundary Layer Processes)
• Tropical Cyclones are a whole other ball of wax…
CAVEAT: What about the background?
“convection organization”

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WHAT DO WE MEAN BY CONVECTION?

• deep clouds? rainfall? PW?
We have assumed that $<q>$ and $P$ are tightly linked:

is that so over land?

Probability of $\text{sign}(\partial P/\partial t) = \text{sign}(\partial <q>/\partial t)$ with TRMM3B42

Kuni Inoue (in prep)
Active MJO convection

$RH = \frac{\langle q \rangle}{\langle q_s \rangle}$

Suppressed MJO

Adames (2017)
Basic Structure

Adames and Wallace (2015)
Radiation and GMS in the MJO

(a) Bottom-heavy System

(b) Top-heavy System

(c) Cloud-Rad Feedback

(d) Cloud-Rad Feedback
A current theory of tropical cyclogenesis, known as "marsupial" (Dunkerton et al. 2009, Atmos. Chem. Phys) holds that the incipient cyclone is essentially a blob of moist air that needs to be protected by closed streamlines against dry air advection.