Upscale Impact of Mesoscale Convective Systems on the CCEWs and MJO and Its Parameterization in an Idealized GCM

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Infrared data for 2013 global weather pattern

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Yang, Majda, and Brenowitz, 2019: Effects of Rotation on the Multi-Scale Organization of Convection in a Global 2-D Cloud-Resolving Model, in revision.
A typical example for multi-scale organization of tropical convection
How to characterize multi-scale interactions?
(a) time tendency  
(b) horizontal advection  
(c) vertical advection  

\[ \text{CMT} = - \frac{1}{\rho} \left< \rho w' u' \right>_z \]

(Units: m/s/day, from Tung and Yanai, 2002)
CMT from unorganized convection $\rightarrow$ Dissipation

VS.

CMT from organized convection (e.g., MCS) $\rightarrow$ Upscale
Why is CMT \((-\frac{1}{\rho} \langle \rho w' u' \rangle_z)\) from MCSs important?

(Moncrieff, et al., 2017)
Is there a general framework to describe multi-scale organization of tropical convection?

Is CMT the only upscale effects induced by MCSs?

What exactly is the relationship between large and small scales?
Multi-Scale Models for the Tropics

"Systematic Multi-Scale Models for the Tropics” (Majda and Klein, 2003)
"New Multiscale Models and Self-Similarity in Tropical Convection” (Majda 2007)
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- Microscale: \(O(10 \text{ km})\)
- Mesoscale: \(O(150 \text{ km})\)
- Synopticscale: \(O(1500 \text{ km})\)
- Planetary-scale: \(O(15000 \text{ km})\)

- Micro-time scale: \(O(15 \text{ min})\)
- Meso-time scale: \(O(1 \text{ hr})\)
- Synoptic-time scale: \(O(8 \text{ hr})\)
- Intraseasonal scale: \(O(3.5 \text{ days})\)

- Hot Tower
- MCS (e.g., Hurricane Embryo, squall line)
- MJO
- CCEW (e.g., CCKW, 2-day wave)
- Diurnal Cycle

Upscale Impact from smaller-scale fluctuations
Modulation effects by larger-scale envelope

Other Applications:
- ITCZ breakdown (Yang, Khouider and Majda 2017)
- Synoptic-mesoscale interactions in the ocean (Grooms et. al., 2012)
- Superparameterization (Majda 2007)
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Is there a general framework to describe multi-scale organization of tropical convection? Yes, it is multi-scale models.

Is CMT the only upscale effects induced by MCSs? No, there should be eddy transfer of momentum, temperature and moisture.

What exactly is the relationship between large and small scales? The main nonlinear interactions across scales are quasi-linear. Eddy flux divergences of momentum and temperature from the smaller-scale spatiotemporal flows accumulate in time and drive larger spatiotemporal scales. Meanwhile, larger scales set the environment through mean advection of small scales. (Majda 2007)
Example:

Using the multi-scale model to study the upscale impact of MCSs on convectively coupled Kelvin waves
Upscale impact of MCSs on CCKWs
**Mesoscale Equatorial Synoptic Dynamics (MESD) model**

<table>
<thead>
<tr>
<th>Variation</th>
<th>Distance</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>~ 150 km</td>
<td>~ 1500 km</td>
<td>~ 8 hrs</td>
</tr>
<tr>
<td>~ 50 min</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Mesoscale fluctuations

\[
\begin{align*}
  u'_T &= -p'_x, \\
  v'_T &= -p'_y, \\
  \theta'_T + w' &= s'_\theta, \\
  p'_z &= \theta', \\
  u'_x + v'_y + w'_z &= 0
\end{align*}
\]

### Synoptic-scale circulation

\[
\begin{align*}
  U_t - yV &= -P_x - dU - \left\langle \overline{w'u'} \right\rangle_z, \\
  V_t + yU &= -P_y - dV - \left\langle \overline{w'v'} \right\rangle_z, \\
  \Theta_t + W &= -d_\theta \Theta - \left\langle \overline{w'\theta'} \right\rangle_z + S_\theta, \\
  P_z &= \Theta, \\
  U_x + V_y + W_z &= 0
\end{align*}
\]

(Majda, 2007)
MESD model

Mesoscale fluctuations

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Synoptic-scale circulation

\[
\begin{align*}
    U_t - yV &= -P_x - dU - \langle w'u' \rangle_z, \\
    V_t + yU &= -P_y - dV - \langle w'v' \rangle_z
\end{align*}
\]

Yang and Majda, 2018: Upscale impact of mesoscale disturbances of tropical convection on convectively coupled Kelvin waves. JAS 75(1), 85-111.
How do $-\langle w'u' \rangle_z$ and $-\langle w'\theta' \rangle_z$ look like?
Low-level potential temperature anomalies (2.6 km)

(Yang and Majda, 2018a)
Comparison with Cloud-Resolving Simulations

Convective momentum transport – $\left\langle w' u' \right\rangle_z$

The MESD model

Cloud-resolving simulation by Khouider and Han (2013)

(Yang and Majda, 2018a)
Synoptic-Scale Potential Temperature

The MESD model

Cloud-resolving simulation

(Yang and Majda, 2018a)
The MESD model was also used to study the upscale impact of MCSs on 2-day waves.

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Next, we proposed a basic parameterization for the upscale impact of MCSs
The GCMs have too coarse resolutions to resolve organized tropical convection (e.g., MCSs), so their upscale impact is missing.
An idealized testbed: the multicloud model

(Khouider and Majda, 2006...)
Theoretical Prediction about Eddy Terms

Eddy momentum transfer

\[
\left(-\langle w'u' \rangle_z, -\langle w'v' \rangle_z \right) = \kappa^u \left[-\frac{3}{2} \cos(z) + \frac{3}{2} \cos(3z) \right] \begin{pmatrix} \cos(\gamma) \\ \sin(\gamma) \end{pmatrix}
\]

Eddy heat transfer

\[
-\langle w'\theta' \rangle_z = \kappa^\theta \left[\frac{3}{2} \sin(z) - \frac{9}{2} \sin(3z) \right]
\]

They’re useful for developing a basic parameterization for upscale impact of MCSs in coarse-resolution GCMs.

Yang and Majda, 2018: Upscale impact of mesoscale disturbances of tropical convection on convectively coupled Kelvin waves. JAS 75(1), 85-111.
Here we proposed a basic parameterization for the upscale impact of MCSs,

\[
F^u = \kappa^u \left( \alpha \frac{P_0}{Q} + (1 - \alpha) \frac{\triangle U}{U_{\text{ref}}} \right) \text{sign} (\triangle U) \left[ -\frac{3}{2} \cos (z) \right]
\]

\[
F^\theta = \kappa^\theta \left( \alpha \frac{P_0}{Q} + (1 - \alpha) \frac{\triangle U}{U_{\text{ref}}} \right) \left[ \frac{3}{2} \sin (z) \right]
\]

Three large-scale modulation effects are considered,

- \(P_0\), similar concept as CAPE.
- \(\triangle U\), vertical shear of zonal winds.
- \(\text{sign} (\triangle U)\) guarantees an upshear scenario.

Effect of this parameterization in the idealized GCM

(left) Hovmöller diagrams for precip, wheeler-Kiladis diagrams for (right upper) precip and (right bottom) surface winds

Without this basic parameterization

With this basic parameterization

(Yang, Majda and Moncrieff, 2019)
Three-way interaction between MJO analog, parameterized upscale impact of MCSs, and background vertical shear on longer time scales

(Yang, Majda and Moncrieff, 2019)
Current Research Project

The goal is to implement this basic parameterization in a full coarse-resolution GCM and improve the MJO simulation.
Conclusion

1. Tropical convection is organized in a hierarchical structure across multiple spatio-temporal scales.

2. The MESD model theoretically predicts the upscale impact of MCSs through eddy transfer of momentum and temperature.

3. Westward-moving MCSs provide favorable conditions for eastward propagation of CCKWs.

4. The basic parameterization for upscale impact of MCSs improves the idealized GCM. The simulations reveals an appealing three-way interaction mechanism with a QBO-like oscillatory pattern.


“It’s easier to make simple things complex, it is more difficult to make complex things simple.”

Happy Birthday, Prof. Majda!