Realistic MJO Dynamics and Initiation in a coarse resolution aquaplanet GCM

Ajaya Mohan Ravindran  
*Center for Prototype Climate Modelling, New York University Abu Dhabi*

Boualem Khouider  
*Department of Mathematics and Statistics, University of Victoria, Canada*

Andrew Majda  
*Department of Mathematics and Center for Atmosphere and Ocean sciences  
Courant Institute for Mathematical Sciences, New York University  
Center for Prototype Climate Modelling, New York University Abu Dhabi*

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OUTLINE

• Motivation
• The multicloud model parameterization
• Model set up
• Realistic simulation of MJO initiation and propagation
• Sensitivity to off-equatorial heat source (Northward propagation)
• Conclusion


Motivation

• Simulation of Convection in a GCM, one of the most challenging task.

• Despite continued effort and enormous progress in climate modelling capabilities, MJO remains major problem: poorly simulated by coarse resolution GCMs

• Search for convective parameterization that better mimic organized convection and new strategies for MJO simulations is major focus for improving climate models

• Widely recognized that large scale moisture/convective coupling plays key role

• Multicloud model (Khouider and Majda 2006, 2008,...) relies on the trimodal paradigm of organized tropical convection (Johnson et al. 1999)

• HERE: Introduce warm pool forcing to learn more about MJO dynamics and initiation

• Influence of slow variation in SST-- El Nino/La Nina, seasonal migration of ITCZ, warm pool width, etc.

• Earlier Talks here: Andrew Majda (SC1-PS222), Qiang Deng (SC1-PS172)
Based on three cloud types, congestus, deep, and stratiform.

Moisture Switch: Dry mid-troposphere favours congestus clouds while moist lower troposphere favours deep convection.

Stratiform clouds lag deep convection.

Associated heating profiles force the first two baroclinic modes of vertical structure.

MC Model is coupled to the boundary layer and to a vertically averaged moisture equation through downdrafts and precipitation.

Khouider and Majda 2006, 2008
**Multicloud in Aquaplanet GCM (HOMME)**

- *The* High-Order Method Modeling Environment (HOMME) uses fully unstructured quadrilateral based finite element meshes on the sphere, such as the cubed-sphere mesh for quasi-uniform resolution.

- Employing Spectral Element (SE) and Discontinuous Galerkin (DG) methods to solve the shallow water or the dry/moist primitive equations, HOMME is an extremely scalable and efficient dynamical core.

- HOMME is the default dynamical core of the [Community Atmosphere Model](#) (CAM) and the [Community Earth System Model](#) (CESM).

- Here, dry dynamical core coupled to multicloud parameterization

- 26 Vertical levels, 20 elements, time step 30s, tropical mask (30S-30N), temperature and moisture background from GATE sounding
Imposed Heating and Moisture background profiles: Based on GATE sounding (Grabowski et al. 2001)

Multicloud model is coupled to HOMME-GCM by applying the parameterized cloud heating and a prescribed cooling as a tendency in the temperature equation.

Khoudier, St-Cyr, Majda, Tribbia (JAS, 2011)
MJO key features:

- ~5 m/s prop. speed
- Baroclinic structure with westerly wind lagging convection
- Quadruple vortex striding the equator
- Progressive moistening prior to convection
- Boundary layer moisture lead

Khouri, St-Cyr, Majda, Tribbia (JAS, 2011)
Sensitivity Experiments with MC-HOMME

- Aquaplanet with fixed Non-Uniform SST--mimicking Indian Ocean/Western Pacific WP
- An asymmetric heat source mimicking the observations
Realistic MJO initiation and propagation

Succession of MJO with a phase speed of ~5m/s

MJOs trigger dry Kelvin waves with a speed of about 25m/s

Each MJO is initiated at some random location over the WP

Dies near the eastern boundary of the WP

Some MJOs stall at the center of maximum heating

Ajayamohan, Khouider, Majda (GRL, 2013)
Spectral Analysis (Asymmetric WP Run)
Composite Spatial Structure (Asymmetric WP Run)

MJO Life cycle composite

Dry KW propagation

Initiation of another MJO

Initiation

Slow EP over WP

Triggering of dry KW

Ajayamohan, Khouider, Majda (GRL, 2013)
The model uses a simple multicloud parameterization scheme (Khouider and Majda, 2006, Khouider et al. 2012, Majda and Stechmann, 2009, Majda and Stechmann, review in Lau and Waliser book)

- Systematic use of mesoscale convective systems dynamics as the building block for the dynamical coupling of congestus, deep and stratiform heating profiles based on the first two baroclinic modes of the vertical structure.

- Parameterized convection is not confined to a single grid but distributed over the length and time scales of MCS.

- Multicloud Model successfully represents CC waves as a natural synoptic scale instability.

- Primary factors responsible for initiation of MJO differ from most existing theories.

Ajayamohan, Khouider, Majda (GRL, 2013)
Boreal summer ISO (monsoon) precipitation propagates northward at ~2 m/s. Monsoon breaks when IO convection is at the Equator. Eastward propagation is also observed at the same time.

Can MC-HOMME aquaplanet model reproduce this northward propagation when the WP is shifted north?
Observations

Low level cross-equatorial flow, south westerlies

Deep baroclinic vertical structure

Upper level Easterlies
Summer ISO characteristics

Note Northward and Eastward propagation

Most ISOs (78%) exhibit northward and eastward movement (Lawrence and Webster, 2002)

Ajayamohan and Goswami, 2007, JAS
Simulation of mean circulation

Summer Mean vertical motion from Obs

Regional Hadley Cell
850hP  200hP  Mean Winds & RHC

WP_5N  WP_10N  WP_15N

Ajayamohan, Khouider, Majda (GRL, 2014)
Mean and variance of precipitation

15N

10N

5N
Lon-Time Plots

- Successive MJOs
- 5N similar to summer MJOs
- Northward and Eastward movement for 10N
- Westward movement for 15N

Ajayamohan, Khouider, Majda (GRL, 2014)
Filtered (20-100 days, wavenumbers -4 to +4 precipitation and winds)

Shaded; Precip and Vectors: 850hPa winds 4 times daily
WP_10N
Filtered (20-100 days, wavenumbers -4 to +4 precipitation and winds)
Shaded; Precip and Vectors: 850hPa winds 4 times daily
850 hpa zonal winds (Northward Propagation)

Lag-Lat Plots

EOF 1

Power Spectra of PC1

Ajayamohan, Khouider, Majda (GRL, 2014)
Conclusions

• Multicloud-HOMME model is used as a virtual lab to understand MJO dynamics and climate variability

• Based on building block paradigm of key three cloud types and their interaction with/through mid-level moisture:
  ▸ Congestus clouds precondition mid-troposphere prior to deep convection via second-baroclinic convergence
  ▸ Stratiform clouds lagging deep convection induce downdrafts play role of cold pools

• Eastward and northward propagation of ISO-like waves successfully simulated, for various surface-flux configurations, as in observations--->
importance of multicloud paradigm in dynamics of tropical convective systems through interactions across scales.
Significance of this simulation (Asymmetric WP Run)

Several theories are proposed to explain MJO initiation and propagation
(Wang, 2005 review in Lau and Waliser book)
- **Wave-CISK mechanism**
  (as closure not based on moisture convergence)
- **Cloud-Radiative forcing**
  (as no active radiation scheme in the model)
- **Wind Induced surface heating Exchange**
  (as surface flux not dependent on easterly winds)
- **Extra-tropical interaction**
  (due to the mask that limits convective heating to the tropics)

None of these mechanisms are present in these simulations !!!

Primary factors responsible for initiation of MJO differ from most existing theories.

The model use a simple multicloud parameterization scheme
(Khouider and Majda, 2006, Majda and Stechmann, 2009, Majda and Stechmann,
review in Lau and Waliser book)

Ajayamohan, Khouider, Majda (GRL, 2013)
Conclusions (II)

• In WP simulation: second baroclinic dry Kelvin waves circling the globe seem to help organize convection to effectively project onto a planetary-scale MJO skeleton/moisture mode.

• Northward propagation of ISO is captured under “summer monsoon conditions”, suggesting same multicloud and multiscale mechanism as for MJO.

• Absence of mechanisms reported in literature as being important for MJO initiation and/or maintenance: Wave-CISK, WISHE, cloud radiative forcing, extra-tropical influence…
5N
Filtered (20-100 days, wavenumbers -4 to +4 precipitation and winds)

Shaded; Precip and Vectors: wind
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of elements for HOMME</td>
<td>20</td>
</tr>
<tr>
<td>Time step</td>
<td>30s</td>
</tr>
<tr>
<td>Vertical levels</td>
<td>26</td>
</tr>
<tr>
<td>Tropical mask</td>
<td>Smoothed Heaviside function with slope k=10 and $y_0 = \pm \pi/6$ or $\pm 30^\circ$</td>
</tr>
<tr>
<td>Surface forcing</td>
<td>Uniform SST</td>
</tr>
<tr>
<td>Temperature background</td>
<td>GATE</td>
</tr>
<tr>
<td>Background moisture gradient</td>
<td>GATE</td>
</tr>
<tr>
<td>$\bar{Q}_1$</td>
<td>38.47(6.15)K</td>
</tr>
<tr>
<td>$\bar{Q}_2$</td>
<td>38.35(3.1)K</td>
</tr>
<tr>
<td>$Q_{R,1}^0$</td>
<td>1K/day</td>
</tr>
<tr>
<td>$\theta_{eb} - \bar{\theta}_{em}$</td>
<td>11.00K</td>
</tr>
<tr>
<td>$\theta^*<em>{eb} - \bar{\theta}</em>{eb}$</td>
<td>10.00K</td>
</tr>
<tr>
<td>$a_1/a_2$</td>
<td>0.1 / 0.9</td>
</tr>
<tr>
<td>$a_0/a'_0$</td>
<td>0.5 / 5.0</td>
</tr>
<tr>
<td>$\gamma_2/\gamma'_2$</td>
<td>0.25 / 0.6</td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.2</td>
</tr>
<tr>
<td>$\alpha_c/\alpha_s$</td>
<td>0.25 / 0.5</td>
</tr>
<tr>
<td>$\tau_s/\tau_c$</td>
<td>3h / 1h</td>
</tr>
<tr>
<td>$\tau_{conv}$</td>
<td>2h</td>
</tr>
</tbody>
</table>
Horizontal & Vertical (Asymmetric WP Run)

MJO composite, 850hPa vorticity

MJO composite, 200hPa vorticity

MJO composite: Zonal wind anomalies [−10°, 10°]

MJO composite: Temperature
Multicloud Model

The imposed total heating profile:

\[ Q_c = H_d \cdot \tilde{\psi}_1(p) + (H_c - H_s) \cdot \tilde{\psi}_2(p) \]
A tendency in the actual temperature equation:

\[
\frac{DT}{Dt} = \frac{1}{1 - \kappa} M(y) \left( \frac{p}{p_B} \right)^\kappa (Q_c - Q_R) + \frac{1}{\tau_R} (T_0 - T)
\]

The vertically averaged moisture:

\[
\frac{\partial q}{\partial t} + \nabla \cdot (q(\tilde{u} + u_1 + 0.1u_2)) + \tilde{Q}_1 \nabla \cdot u_1 + \tilde{Q}_2 \nabla \cdot u_2 = -P + \langle E \rangle
\]

\[
\tilde{Q}_j = \int_{p_T}^{p_B} \frac{dQ}{dp} \psi_j(p) dp, \ j = 1, 2.
\]

The boundary layer equivalent potential temperature:

\[
\frac{\partial \theta_{eb}}{\partial t} + u(x, y, p_1, t) \nabla \theta_{eb} = \frac{1}{h_b} E_s - \frac{1}{h} D
\]
**Convective heating closures:**

<table>
<thead>
<tr>
<th>Stochastic</th>
<th>Deterministic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_c = \frac{\alpha_c \bar{Q}}{H_m} \sqrt{CAPE_l^+}$</td>
<td>$\frac{\partial H_c}{\partial t} = \frac{1}{\tau_c} (\Lambda \alpha_c Q_c^+ - H_c)$</td>
</tr>
<tr>
<td>$H_d = \left{ \sigma_d \bar{Q} + \frac{1}{\tau_c(\sigma_d)} [a_1 \theta_{eb} + a_2 q - a_0 (\theta_1 + \gamma_2 \theta_2)] \right}^+$</td>
<td>$H_d = (1 - \Lambda) Q_d^+$</td>
</tr>
<tr>
<td>$H_s = \alpha_s \left{ \sigma_s \bar{Q} + \frac{1}{\tau_c(\sigma_s)} [a_1 \theta_{eb} + a_2 q - a_0 (\theta_1 + \gamma_2 \theta_2)] \right}^+$</td>
<td>$\frac{\partial H_s}{\partial t} = \frac{1}{\tau_s} (\alpha_s H_d - H_s)$</td>
</tr>
<tr>
<td>$\tau_c(\sigma_d) = \frac{\tilde{\sigma}_d}{\sigma_d} \tau_c^0$</td>
<td>$Q_c = \bar{Q} + \frac{1}{\tau_{conv}} [\theta_{eb} - a'_0 (\theta_1 + \gamma'_2 \theta_2)]$</td>
</tr>
<tr>
<td>$\tau_c(\sigma_s) = \frac{\tilde{\sigma}_s}{\sigma_s} \tau_c^0$</td>
<td>$Q_d = \bar{Q} + \frac{1}{\tau_{conv}} [a_1 \theta_{eb} + a_2 q - a_0 (\theta_1 + \gamma_2 \theta_2)]$</td>
</tr>
<tr>
<td>$\Lambda = \left{ \begin{array}{ll} 0, &amp; \text{if } \theta_{eb} - \theta_{em} \leq \theta^- \ 1, &amp; \text{if } \theta_{eb} - \theta_{em} \geq \theta^+ \ \text{Linear continuous}, &amp; \text{otherwise} \end{array} \right.$</td>
<td></td>
</tr>
</tbody>
</table>
Stochastic Multicloud Model to inform cumulus parameterization: represent the missing sub-grid scale variability

GCM: Large Scale Dynamics

Cumulus Parameterization

Stochastic Multi-cloud Model (for cloud area fractions)
MC-HOMME with asymmetric Warm Pool

- MJO in Warm Pool
- Dry Kelvin Waves outside WP
- Kelvin Waves Circle the globe and coincide with initiation of succeeding MJO
- Helps organize otherwise chaotic convective mesoscale and synoptic waves on the planetary scale.
- Projects onto a hypothetical MJO skeleton /Moisture mode (Majda and Stechmann, Sobel and Maloney)