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The effects of climate change upon tipping points of tropical extreme events such as MJO

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Summary / Abstract

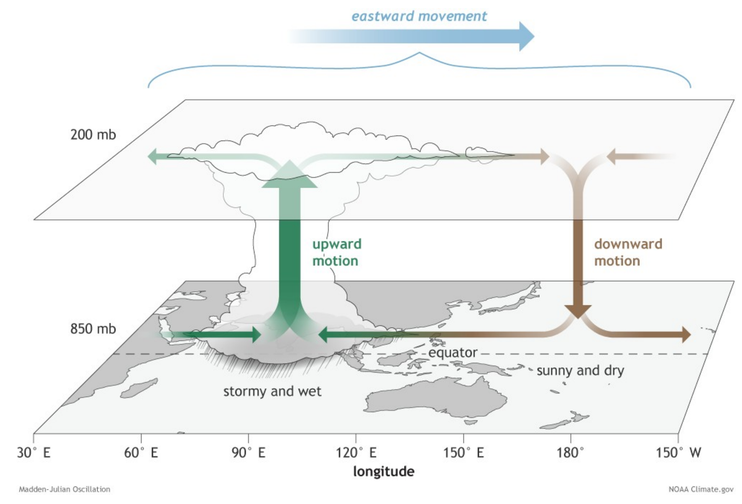
More than half of the globe is occupied by the tropical zones, thus a proper understanding of the tropical atmosphere and it extreme events are crucial for the projections of the global climate change. The tropical atmosphere is traditionally considered dominated by moist cumulus convection associated with strongly divergent horizontal flows. The Madden-Julian Oscillation (MJO) is the dominant slowly eastward propagating mode of intra-seasonal planetary scale variability in the tropical atmosphere that is known as one of global extreme events that not only affects Maritime continent, but also has influences on mid-latitude atmospheric jets. Previous theoretical studies, modeling, and field observations have contributed positively to our understanding of MJO; nevertheless, there is no robust theory for a few aspects of the dynamics of MJO such as its initiation, role of moist-convection on propagation speed, role of global warming upon its genesis and evolution, the barrier effect of the Maritime Continent on MJO propagation, and its slowly eastward propagation mechanism, which are poorly understood. Understanding response of the MJO to climate change is vital for estimating the natural hazards.

By using a hierarchy of models and theoretical studies, we have raised this theory that MJO-like skeleton can be generated in a self-sustained manner from a large-scale localized heating in the lower troposphere, over the warm pool, as a "hybrid structure". The latter is constituted by combination of an "equatorial modon" that is convectively coupled by detaching baroclinic Kelvin wave. The hybrid structure can last for an interseasonal scale. Indeed, augmentation of temperature and humidity could intensify the genesis and consequently the precipitation pattern of the MJO. The presentation includes a summary recently findings in relevant to MJO genesis and its evolution. Some of the preliminary results have already been published in some ISI journals by the authors (see references). Firstly, we show the construction of new improved moist-convective Thermal Rotating Shallow Water (mcTRSW) model with pseudo-spectral based method on spin-weighted coordinate and previous version of the model so called mcRSW [1, 2], which is well-balanced, shock capturing, front resolving, with finite volume scheme. Secondly, we explain one of the main observations of the authors that was discovery of a nonlinear dynamical regime in the Rotating Shallow Water (RSW) model which arises in the limit of small pressure variations and gives a slow propagating coherent dipolar structure so called "Equatorial Modon" [3]. Thirdly, we demonstrate that in the pioneering work by authors [4] the Equatorial Modon's structure can also be emerged from the process of geostrophic adjustment of localized large-scale depression-type disturbance in the mcRSW model on the equatorial beta-plane. Other dynamical features of equatorial modons, such as loss of coherency, eastward propagating phase speed, role of bottom topography, etc have been investigated too [5]. Finally, after reproducing "generation" of MJO-like structure from geostrophic adjustment of baroclinic disturbances in tropical atmosphere, we propose the aforementioned theory as the backbone structure of the MJO [6] and present the effect of climate change upon its genesis and tipping point by recently improved mcTRSW conceptual model.

MJO: Dominant extreme event in the tropical Indo-Pacific region

What is the MJO?

The Madden-Julian Oscillation (MJO) is the dominant slowly eastward propagating mode of intra-seasonal planetary scale variability in the tropical atmosphere.



Theory	Essence (Jiang et al., 2020)
1. WTG moisture mode Sobel and Maloney (2012, 2013) and Adames and Kim (2016)	Moisture-convection coupling is key. Moisture advection important for propagation. Cloud-radiative feedbacks cause growth and determine horizontal scale.
2. WISHE moisture mode Fuchs and Raymond (2005, 2007, 2017)	Moisture-convection coupling is key. WISHE (wind-induced surface heat exchange) determines propagation, growth, and scale selection. Cloud-radiative feedbacks provide additional growth.
3. BLQE model Khairoutdinov and Emanuel (2018) and Emanue, (2019)	Convection adjusts to maintain BL quasi-equilibrium (BLQE). MSE evolution is key. Cloud-radiation feedback determines growth, and WISHE propagation.
4. Trio-interaction B. Wang and Rui (1990) and B. Wang, Liu, and Chen (2016)	BL frictional moisture convergence to the east of MJO convection center determines propagation and growth. Moisture-convection coupling slows down the MJO.
5. Skeleton Majda and Stechmann (2009, 2011) and Thual et al. (2014)	MJO is an envelope of synoptic waves and mesoscale systems. MJO propagation due to interaction between low-level moisture and synoptic-scale wave activity.
6. Gravity wave D. Yang and Ingersoll (2013, 2014)	MJO is an envelope of eastward and westward propagating inertio-gravity waves. Horizontal scale is determined by interaction of waves and convection. Asymmetry between waves due to beta effect determines propagation.
7. Large-scale convective vortex Hayashi and Itoh (2017)	MJO is an eastward propagating pair of Rossby gyres. Propagation is due to strong low-level vortex stretching from deep convection to the east of the cyclones.
8. Nonlinear solitary wave Yano and Tribbia (2017) and Rostami and Zeitlin (2019)	MJO is a strongly nonlinear solitary Rossby wave. MJO is explained by dry dynamics to first order. Nonlinear vorticity advection explains propagation. Large-scale modons exhibit the longest duration.

Proposed mechanism for MJO

MJO-like skeleton can be generated in a self-sustained manner from a large-scale localized heating in the lower troposphere, over the warm pool, as a "hybrid structure". The latter is constituted by combination of an "quasi-equatorial modon", which looses its coherency due to baroclinicity, and convectively coupled detaching baroclinic Kelvin wave that lasts for an interseasonal scale.

Results

Effect of equatorial heating upon MJO

Large-scale localized heating over the equator when reaches to critical tipping point can lead to slowly eastward propagating in a self-sustained and self-propelling manner due to its geostrophic adjustment in moist-convective environment. This statement indicates that the well-known Gill's mechanism is not universal.

Discovery of Equatorial Modon

One of the basic concepts of the proposed mechanism is based on generation of a robust eastward propagating structure that is called Equatorial Modon that is an exact, form-preserving, eastward uniformly translating, horizontally localized, nonlinear solution to the inviscid quasi-geostrophic equations (Rostami & Zeitlin, 2019a).

Theory: Charney regime in Equatorial RSW

RSW equations

$$\begin{cases} \partial_t \mathbf{v} + \mathbf{v}\cdot\nabla\mathbf{v} + \beta\, y\, \hat{\mathbf{z}}\wedge\mathbf{v} + g\nabla h = 0\,, \\ \partial_t h + \nabla\cdot(\mathbf{v}h) = 0\,, \end{cases}$$

Scaling $h = H(1+\lambda\eta)$, $(x,y)\sim L$, $(u,v)\sim V$, $t\sim L/V$, $\overline{\beta} = \beta L^2/V$. If $gH\lambda/V^2 = \mathcal{O}(1) \Rightarrow V << \sqrt{gH}$:

$$\begin{aligned} \partial_t \mathbf{v} + \mathbf{v}\cdot\nabla\mathbf{v} + \overline{\beta}\, y\, \hat{\mathbf{z}}\wedge\mathbf{v} + \nabla\eta &= 0\,, \\ \lambda(\partial_t\eta + \mathbf{v}\cdot\nabla\eta) + (1+\lambda\eta)\,\nabla\cdot\mathbf{v} &= 0, \end{aligned}$$

Leading order in $\lambda \Rightarrow \nabla\cdot\mathbf{v}_0 = 0 \Rightarrow u_0 = -\partial_y\psi,\ v_0 = \partial_x\psi$,

$$\nabla^2\psi_t + \mathcal{J}(\psi,\nabla^2\psi) + \overline{\beta}\psi_x = 0, \quad \mathcal{J} - \text{Jacobian}.$$

Asymptotic solutions

Steady modon (Rostami & Zeitlin, 2019) with zonal velocity U:

$$\begin{cases} \psi_{ext} = -\frac{Ua}{K_1(pa)} K_1(pr)\sin\theta,\ p^2 = \overline{\beta}/U,\ U>0,\ \ r>a, \\ \\ \psi_{int} = \left[\frac{Up^2}{k^2 J_1(ka)} J_1(kr) - \frac{r}{k^2}(1+U+Uk^2)\right]\sin\theta,\ \ r<a, \end{cases}$$

– J_1 and K_1 are ordinary and modified Bessel functions of order one.
– p is real, and $p^2 = \overline{\beta}/U$, so $U>0$, and the motion is eastward.
– Each pair $(a,p) \rightarrow$ series of eigenvalues k arising from matching conditions, the lowest corresponds to a dipole.

Pressure distribution at a given ψ:

$$\nabla^2\eta = Hess[\psi] + \overline{\beta}(\psi_y + y\nabla^2\psi)$$

where $Hess[\psi] = \partial^2_{xx}\psi\partial^2_{yy}\psi - (\partial^2_{xy}\psi)^2$ is the Hessian operator. Note that equations 4 and 6 are shallow-water counterparts of the non-divergent model for large-scale tropical motions Charney (1963).

Asymptotic solutions

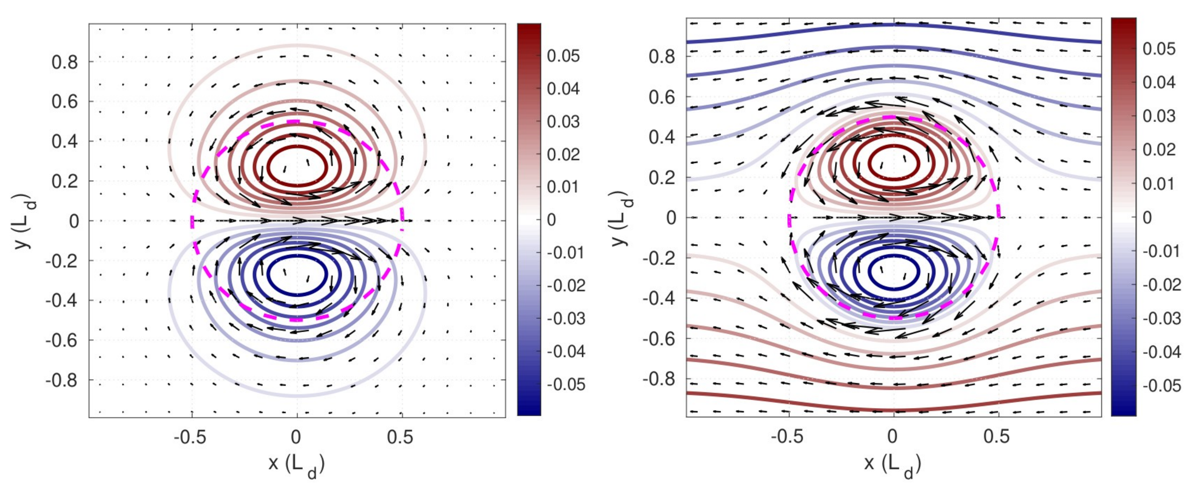


Fig. 1. Streamlines and velocity field of an asymptotic modon in stationary (left) and comoving (right) frames with U = 0.1 . Dashed circle: separatrix of radius a = 0.5 .

Phase portrait of "*asymptotic*" and "*adjusted*" Equatorial Modon (EM)

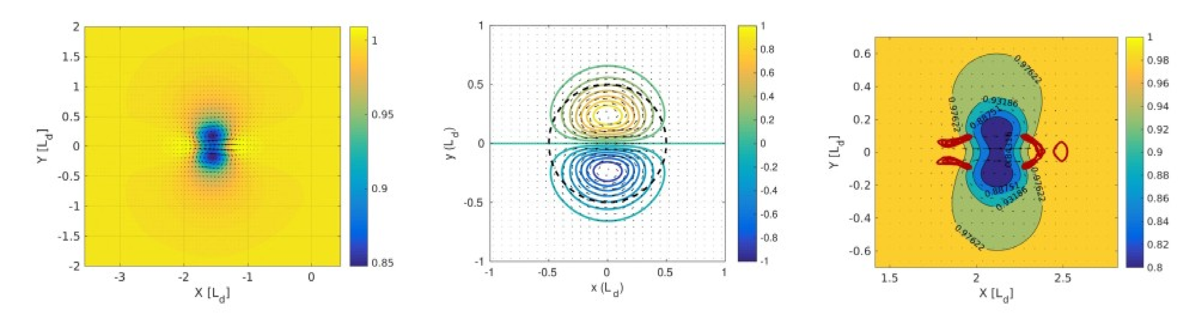


Fig. 2. Left panel: Structure of the equatorial modon. Middle panel: Stream-function of the barotropic equatorial modon (asymptotic modon). Right panel: Convectively coupled equatorial modon showing the condensation regions. Dashed : separatrix r = a.

"Exact" vs asymptotic modon

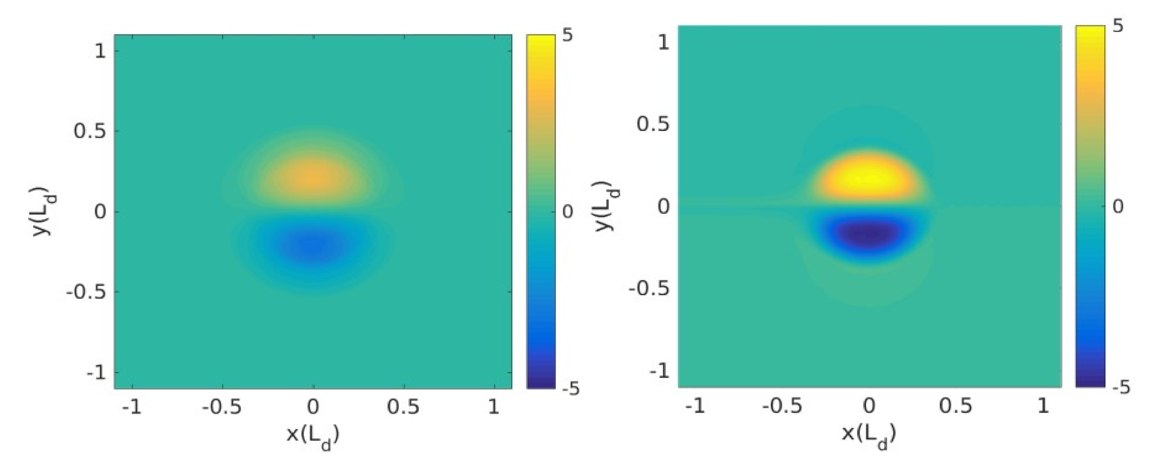


Fig. 3. Relative vorticity of the asymptotic (left) vs "exact" (right) modons.

Conversion of asymptotic modon to "adjusted modon" in a self sustained manner

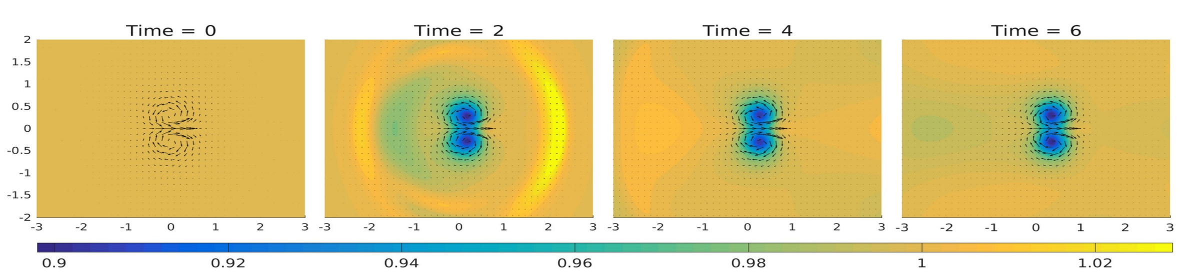


Fig. 4. Emerging of "adjusted" EM from asymptotic modon under Charney regime.

Adjustment of positive buoyancy anomaly via mcTRSW

Fig. 5. Evolution of the buoyancy, vorticity, and precipitation in the l

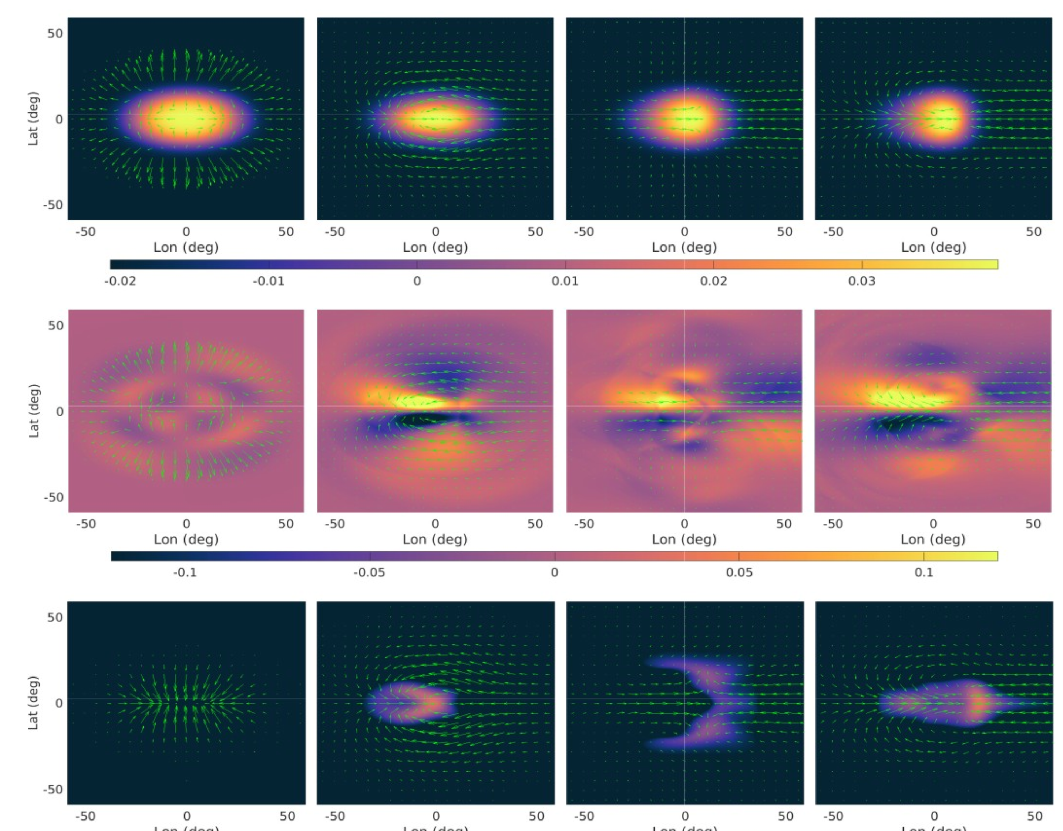
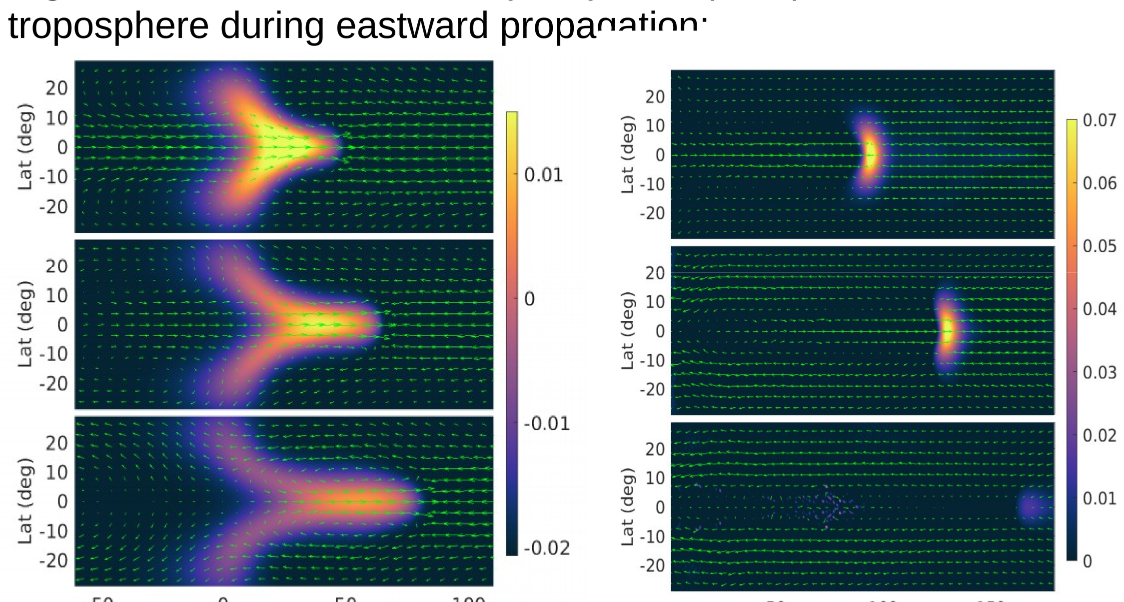


Fig. 6. Evolution of the buoyancy and precipitation in the lower troposphere during eastward propagation:



Dynamical core of moist-convective Thermal Rotating Shallow Water (mcTRSW) model

$$\frac{d\boldsymbol{v}_1}{dt} + f\hat{\boldsymbol{z}}\times\boldsymbol{v}_1 = -\frac{1}{2}h_1\boldsymbol{\nabla}b_1 - b_1\boldsymbol{\nabla}(h_1+h_2),$$

$$\frac{d\boldsymbol{v}_2}{dt} + f\hat{\boldsymbol{z}}\times\boldsymbol{v}_2 = \frac{1}{2}h_2\boldsymbol{\nabla}b_2 - \boldsymbol{\nabla}(h_1b_1+h_2b_2) - \frac{1-\gamma}{b_2h_2}(\boldsymbol{v}_2-\boldsymbol{v}_1)(\mathcal{C}-\mathcal{D}),$$

$$\partial_t h_1 + \boldsymbol{\nabla}.(h_1\boldsymbol{v}_1) = \frac{1-\gamma}{b_1}(-\mathcal{C}+\mathcal{D}) + (1-\gamma^*)\frac{h_1-(B_1/b_1)H_1}{\tau_r},$$

$$\partial_t h_2 + \boldsymbol{\nabla}.(h_2\boldsymbol{v}_2) = -\frac{1}{b_2}(-\mathcal{C}+\mathcal{D}) + (1-\gamma^*)\frac{h_2-(B_2/b_2)H_2}{\tau_r},$$

$$\partial_t b_1 + \boldsymbol{v}_1.\boldsymbol{\nabla}b_1 = \frac{1}{h_1}(\mathcal{C}-\mathcal{D}) - \frac{b_1-(H1/h_1)B_1}{\tau_r},$$

$$\partial_t b_2 + \boldsymbol{v}_2.\boldsymbol{\nabla}b_2 = \frac{1}{h_2}(-\mathcal{C}+\mathcal{D}) - \frac{b_2-(H2/h_2)B_2}{\tau_r},$$

$$\partial_t q + \boldsymbol{\nabla}.(q\boldsymbol{v}_1) = E_s - \mathcal{C} + \mathcal{D},$$

References and Acknowledgement

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PS: The new introduced pseudo-spectral based moist-convective Thermal Rotating Shallow Water (mcTRSW) model is also dynamical core of Aeolus2, which is one of atmospheric components of POEM model.