Rencontres des Jeunes Physicien·ne·s 2021

A new born hypothesis for the Madden-Julian Oscillation (MJO)

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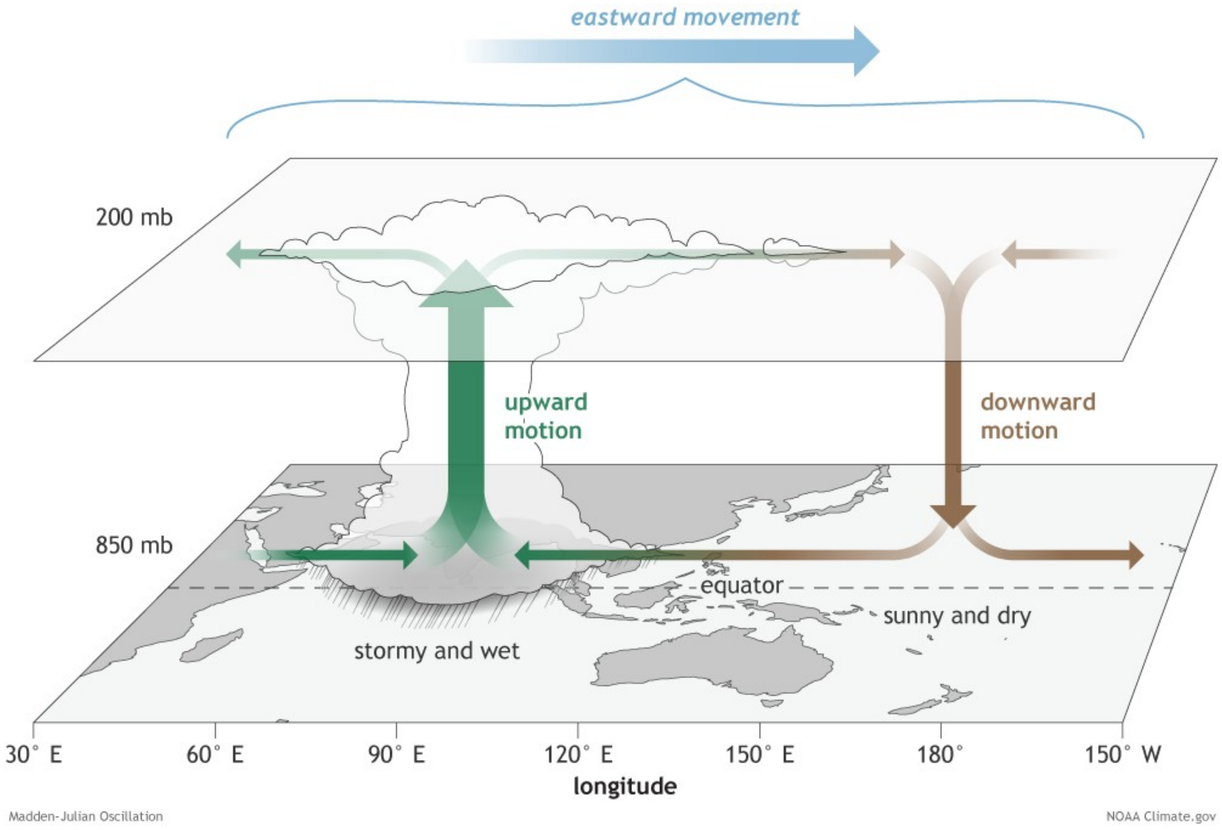
16 March 2021

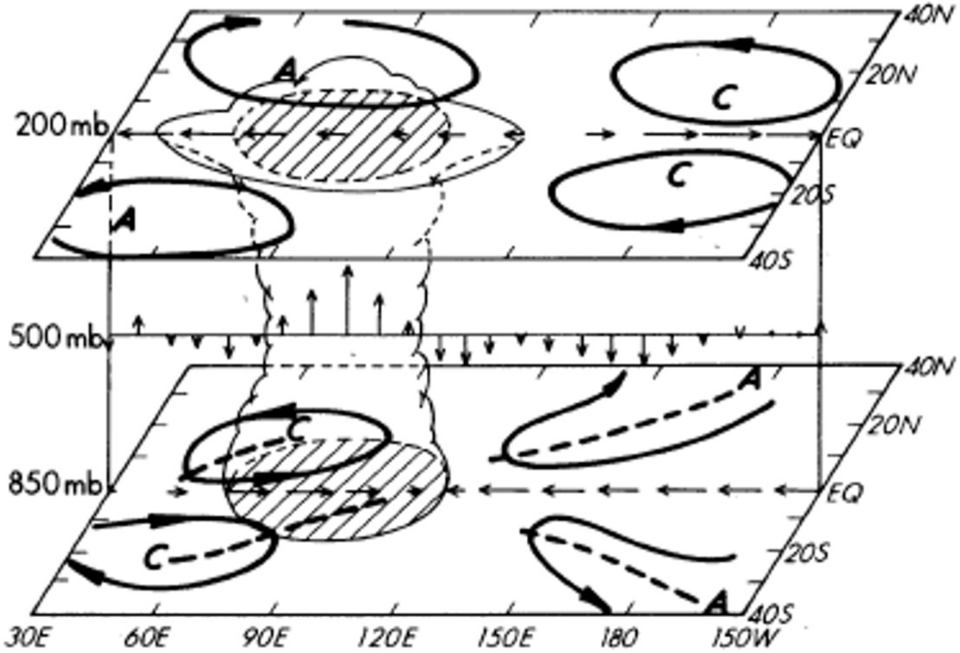
What is MJO?

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



What is MJO?

Quadrupolar structure with opposite-sign vorticity anomaly in the upper layer.

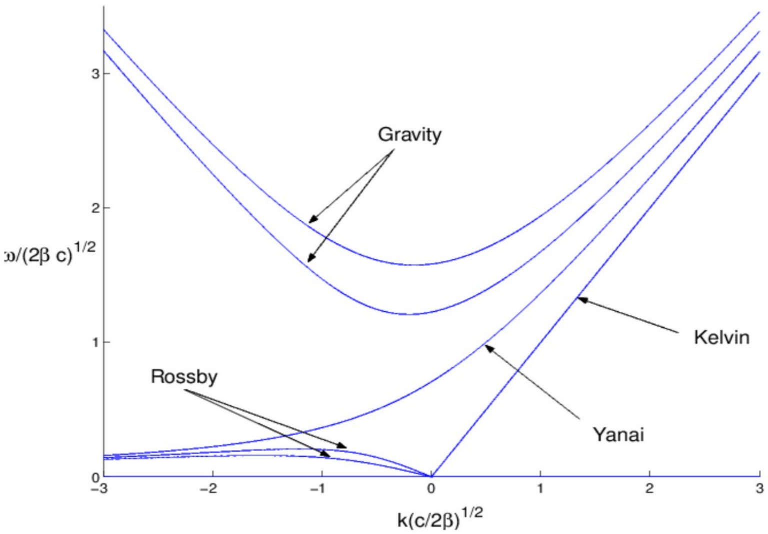


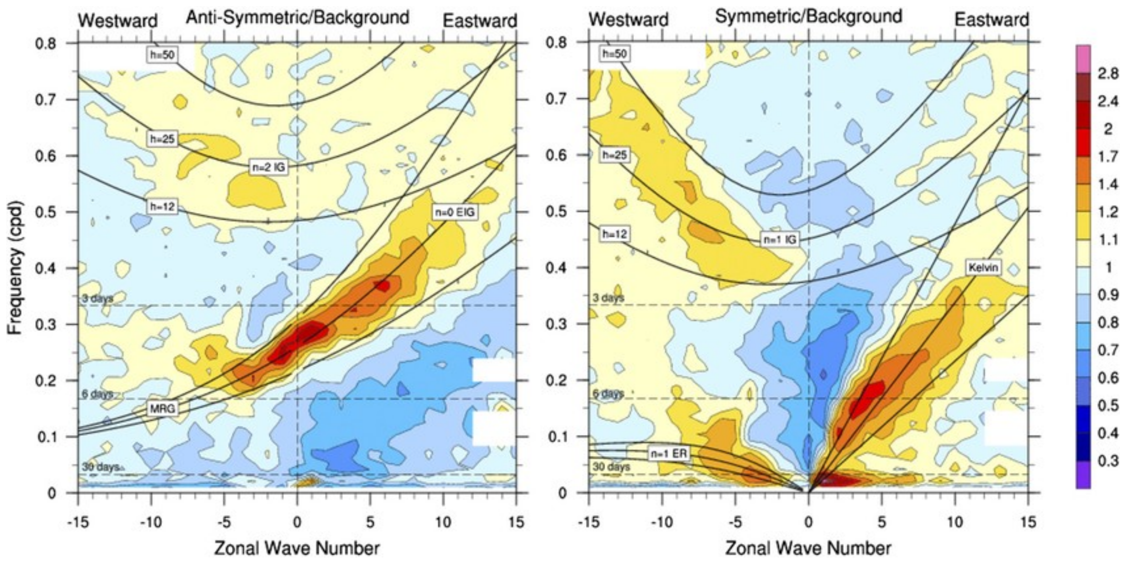
Kiladis et al., 2005

Dispersion diagram for equatorial waves

Enigmatic slow eastward-propagating motions of the Madden-Julian Oscillation (MJO).

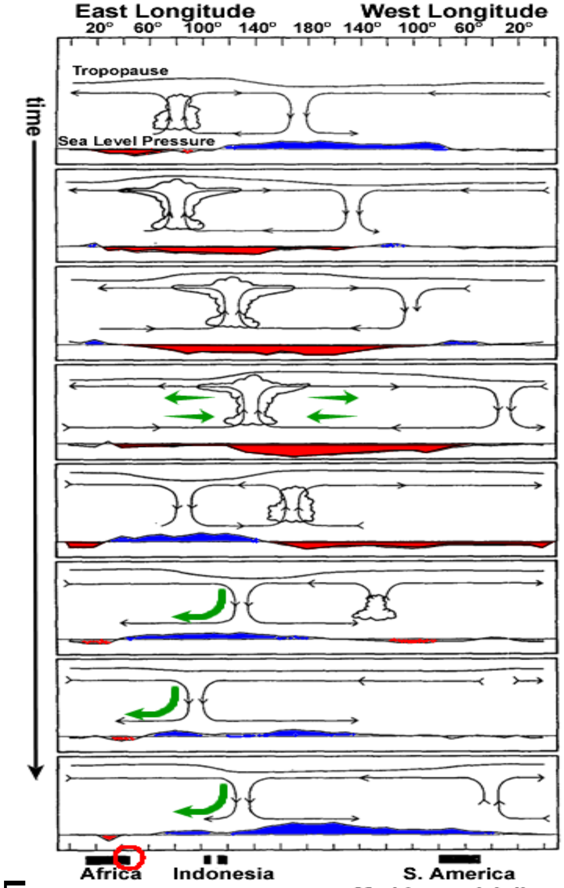
OLR data superimposed onto dispersion diagram of equatorial waves (Wheeler & Kiladis, 1999)



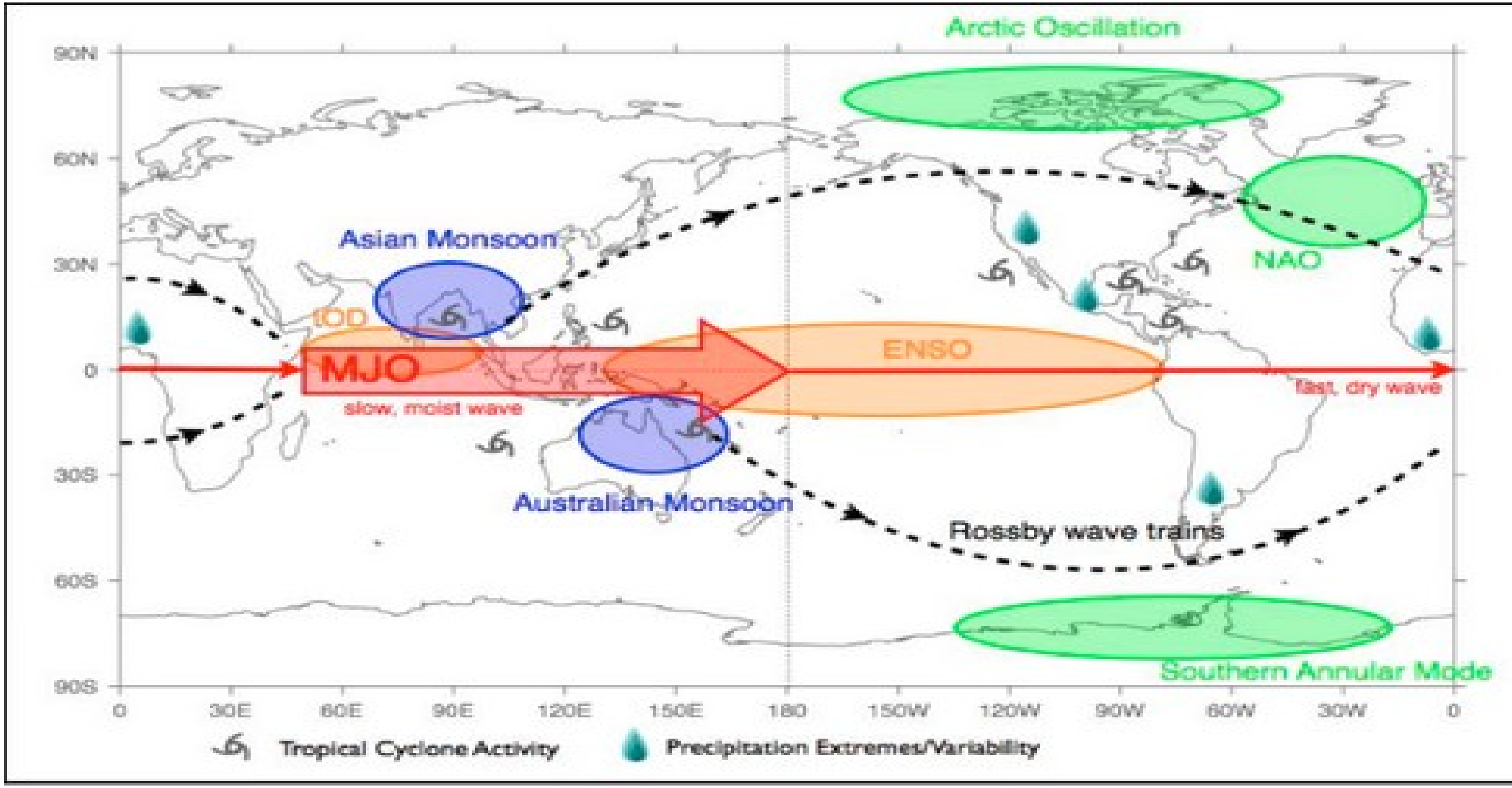


What Is MJO:

The periodically arising ***large-scale*** patterns of enhanced ***deep convection*** which are ***slowly moving eastward*** from the Indian Ocean over the maritime continent and are ***dying out*** in the Pacific



Madden and Julian, 1972



Proposed Theories

1) Hayashi (1970), Lindzen (1974), Yano and Emanuel (1991): *fail to identify the MJO as a separate mode from a faster eastward-propagating Kelvin mode.*

2) Fuchs and Raymond (2007), Raymond and Fuchs (2007, 2009): predicts the phase velocity of about 6 m/s. However, *it fails to explain the preferred scale of the MJO (i.e., wavenumber 2) with the growth rate approximately constant independent of the wavenumber.*

3) The skeleton model (Majda and Stechmann 2009; Thual and Majda 2016): *There is a careful tuning of their free parameter Q*, which controls the gross moist stability (GMS: effective moist stability of the atmosphere): making the GMS sufficiently small but positive. This choice is rather limited, because observations suggest that GMS could often be negative (López Carrillo and Raymond 2005).

4) Convectively coupled wave theories (e.g., Yang and Ingersoll 2011, 2013; Adames and Kim 2016): *these theories hardly suggest any tendency for converging*.

5) Equatorial Modon of Yano & Tribbia 2017 and Rostami & Zeitlin 2019: The former is a spherical modon in "dry" environment, the latter in both dry and moist-convection which captures the crudest features of the MJO. These findings do not explain the vertical structure and generation of the MJO.

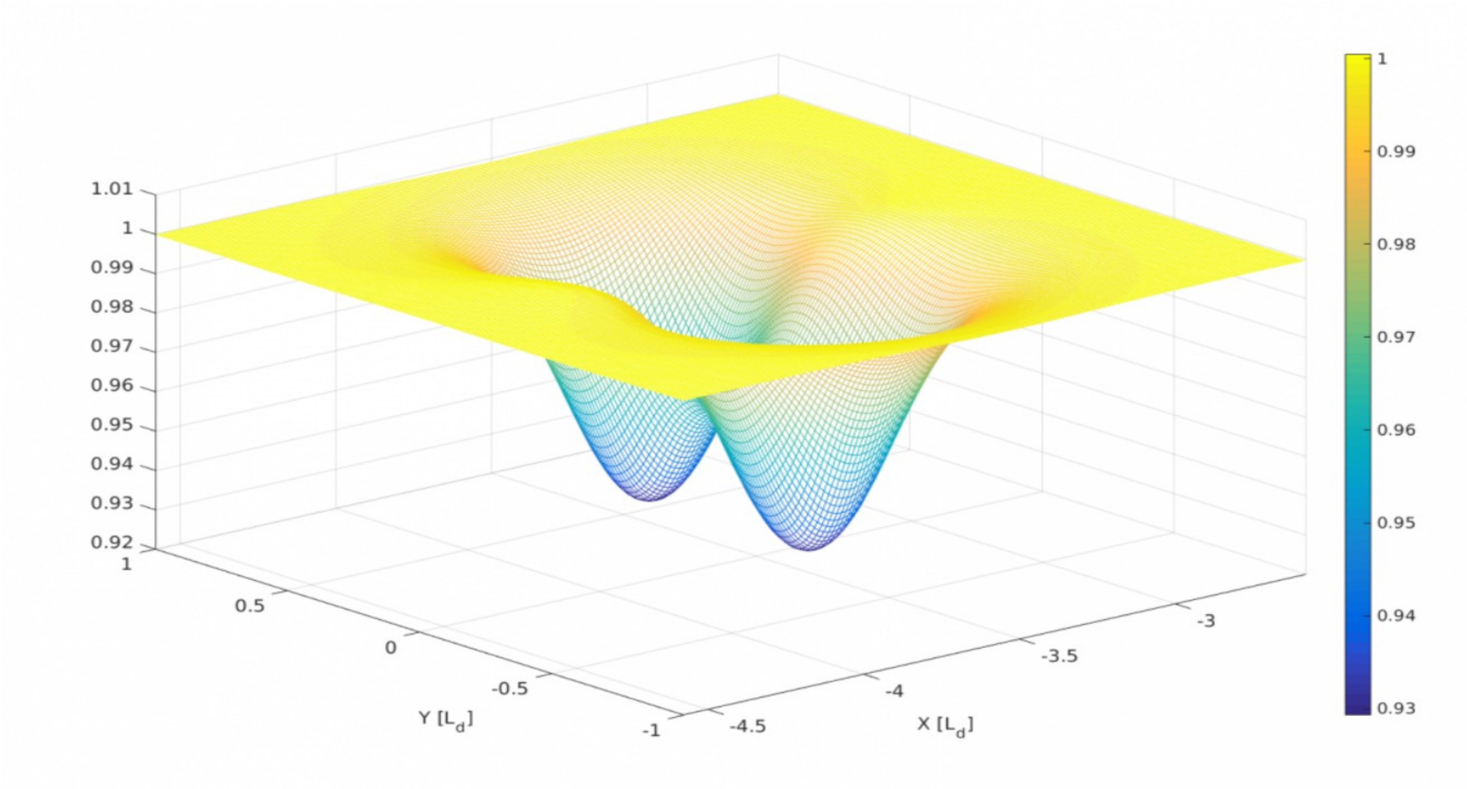
6) MJO has a hybrid baroclinic Rossby-Kelvin mode structure: Equatorial Modon which looses its coherency, and convectively coupled Baroclinic Kelvin Waves, generated from equatorial adjustment over the warm pool (Rostami & Zeitlin, 2020): It captures all the crudest dynamical features of the MJO.

New hybrid Rossby-Kelvin mode structure hypothesis

(Rostami & Zeitlin, 2020)

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”, which looses its coherency due to baroclinicity, and convectively coupled detaching baroclinic Kelvin wave that lasts for an interseasonal scale.

Discovery Of A New Eastward-Propagating Coherent Atmospheric Structure in RSW model: Equatorial Modon (Rostami & Zeitlin, 2019a)



Theory: Charney regime in Equatorial RSW

RSW equations

$$\begin{cases} \partial_t \mathbf{v} + \mathbf{v} \cdot \nabla \mathbf{v} + \beta\, y\, \hat{\mathbf{z}} \wedge \mathbf{v} + g \nabla h = 0\,, \\ \partial_t h + \nabla \cdot (\mathbf{v} h) = 0\,, \end{cases} \tag{1}$$

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 $gH\lambda/V^2 = \mathcal{O}(1) \Rightarrow V << \sqrt{gH}$:

$$\partial_t \mathbf{v} + \mathbf{v} \cdot \nabla \mathbf{v} + \overline{\beta}\, y\, \hat{\mathbf{z}} \wedge \mathbf{v} + \nabla \eta = 0\,, \tag{2}$$

$$\lambda(\partial_t \eta + \mathbf{v} \cdot \nabla \eta) + (1 + \lambda\eta)\, \nabla \cdot \mathbf{v} = 0, \tag{3}$$

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

$$\nabla^2 \psi_t + \mathcal{J}(\psi, \nabla^2 \psi) + \overline{\beta} \psi_x = 0, \quad \mathcal{J} - \text{Jacobian.} \tag{4}$$

Asymptotic solutions

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

$$\begin{cases} \psi_{ext} = -\frac{Ua}{K_1(pa)} K_1(pr)\sin\theta, \; p^2 = \overline{\beta}/U, \; U > 0, \quad r > a, \\ \\ \psi_{int} = \left[\frac{Up^2}{k^2 J_1(ka)} J_1(kr) - \frac{r}{k^2}(1 + U + Uk^2)\right]\sin\theta, \quad r < a, \end{cases} \tag{5}$$

– 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.

Asymptotic solutions

Pressure distribution at a given ψ:

$$\nabla^2\eta = Hess[\psi] + \overline{\beta}(\psi_y + y\nabla^2\psi) \qquad (6)$$

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).

"Improved" 2-layer mcRSW with dry upper and moist,vclose to saturation, lower layers

$$\begin{cases} \dfrac{d_1 \boldsymbol{v}_1}{dt} + f\hat{z} \times \boldsymbol{v}_1 = -g\boldsymbol{\nabla}(h_1 + h_2) + \dfrac{\beta C - \beta^* V}{h_1}\left(\dfrac{\boldsymbol{v}_1 - \boldsymbol{v}_2}{2}\right), \\ \dfrac{d_2 \boldsymbol{v}_2}{dt} + f\hat{z} \times \boldsymbol{v}_2 = -g\boldsymbol{\nabla}(h_1 + sh_2) + \dfrac{\beta C - \beta^* V}{h_2}\left(\dfrac{\boldsymbol{v}_1 - \boldsymbol{v}_2}{2}\right), \\ \partial_t h_1 + \boldsymbol{\nabla}.(h_1 \boldsymbol{v}_1) = -\beta C + \beta^* V, \\ \partial_t h_2 + \boldsymbol{\nabla}.(h_2 \boldsymbol{v}_2) = +\beta C - \beta^* V, \\ \partial_t W_1 + \boldsymbol{\nabla}.(W_1 \boldsymbol{v}_1) = +(1-\gamma)\, C - P, \\ \partial_t W_2 + \boldsymbol{\nabla}.(W_2 \boldsymbol{v}_2) = +\gamma\, C - V, \\ \partial_t Q_1 + \boldsymbol{\nabla}.(Q_1 \boldsymbol{v}_1) = -C + E, \\ \partial_t Q_2 + \boldsymbol{\nabla}.(Q_2 \boldsymbol{v}_2) = V. \end{cases}$$

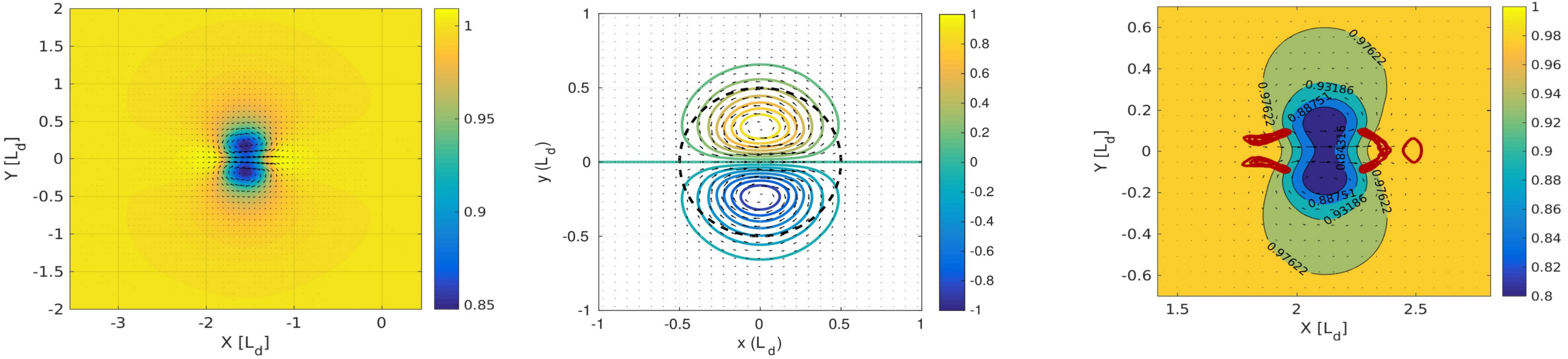
Moist vs dry characteristic velocities

c^m is real for positive moist enthalpy of the lower layer in the state of rest : $M_1 = H_1 - \beta Q^s > 0$, and

$$C_-^m < C_- < \frac{g(H_1 + \alpha H_2)}{2} < C_+ < C_+^m,$$

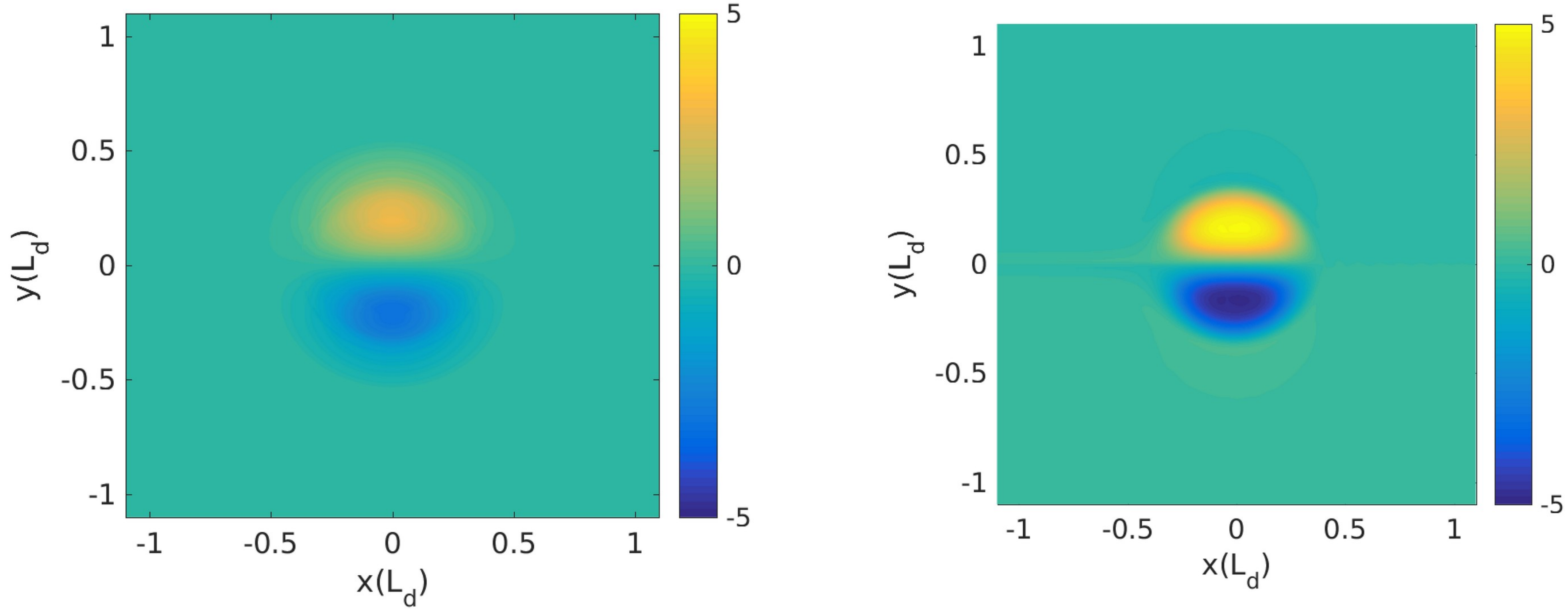
for $0 < M_1 < H_1 \Rightarrow$ moist internal (mainly baroclinic) mode propagates slower than the dry one, consistent with observations.

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



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



Relative vorticity of the asymptotic (left) vs “exact” (right) modons.

Conversion of asymptotic modon to “adjusted modon” in a self sustained manner

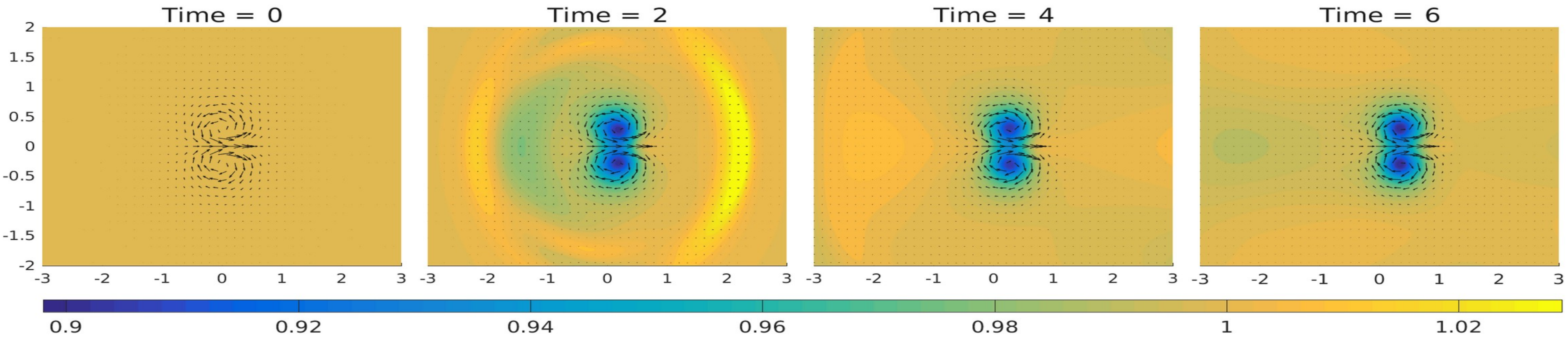


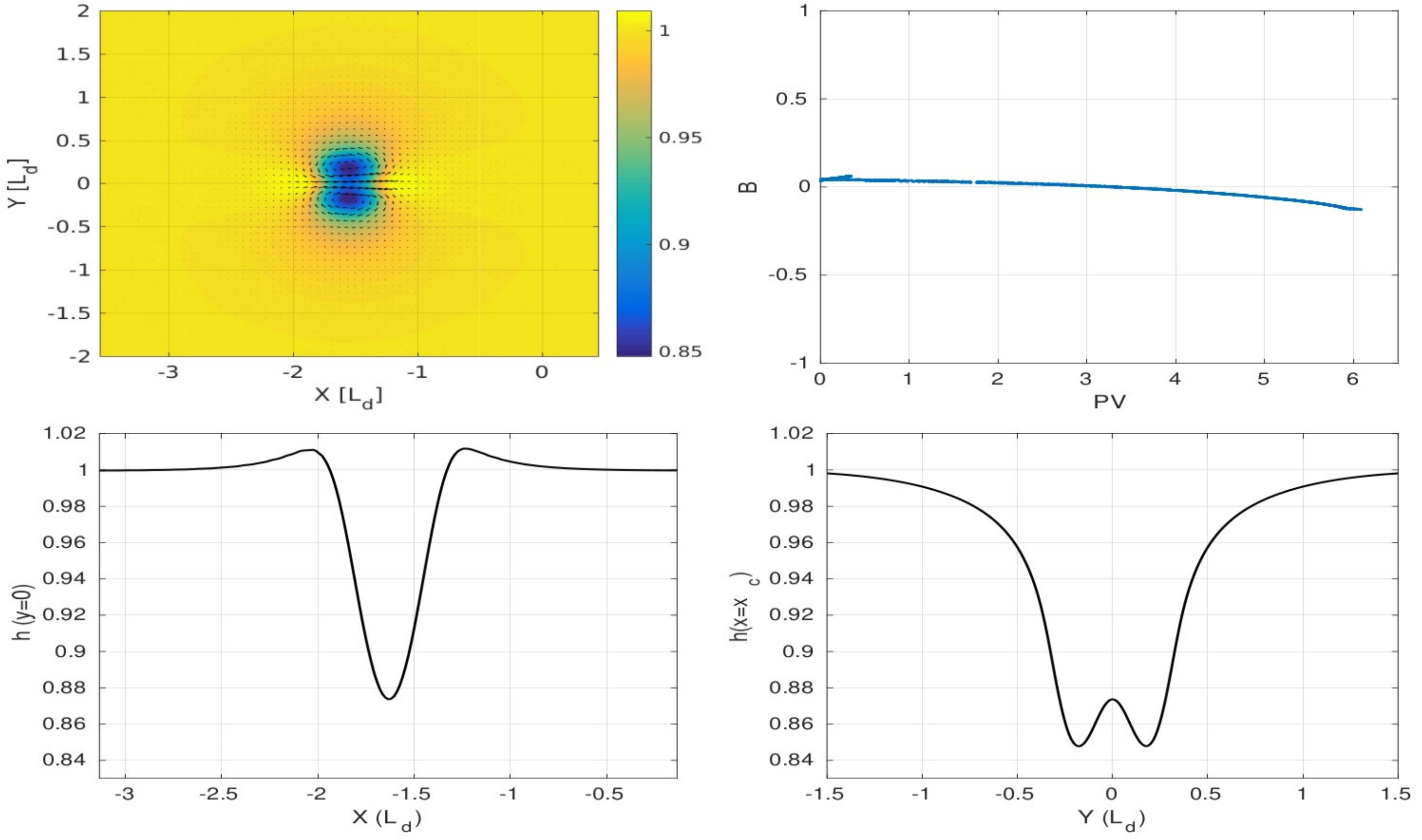
Fig. 2. Emerging of “adjusted” EM from asymptotic modon under Charney regime.

Asymptotic solution of EM:

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

J_1 and K_1 are ordinary and modified Bessel functions of order one.

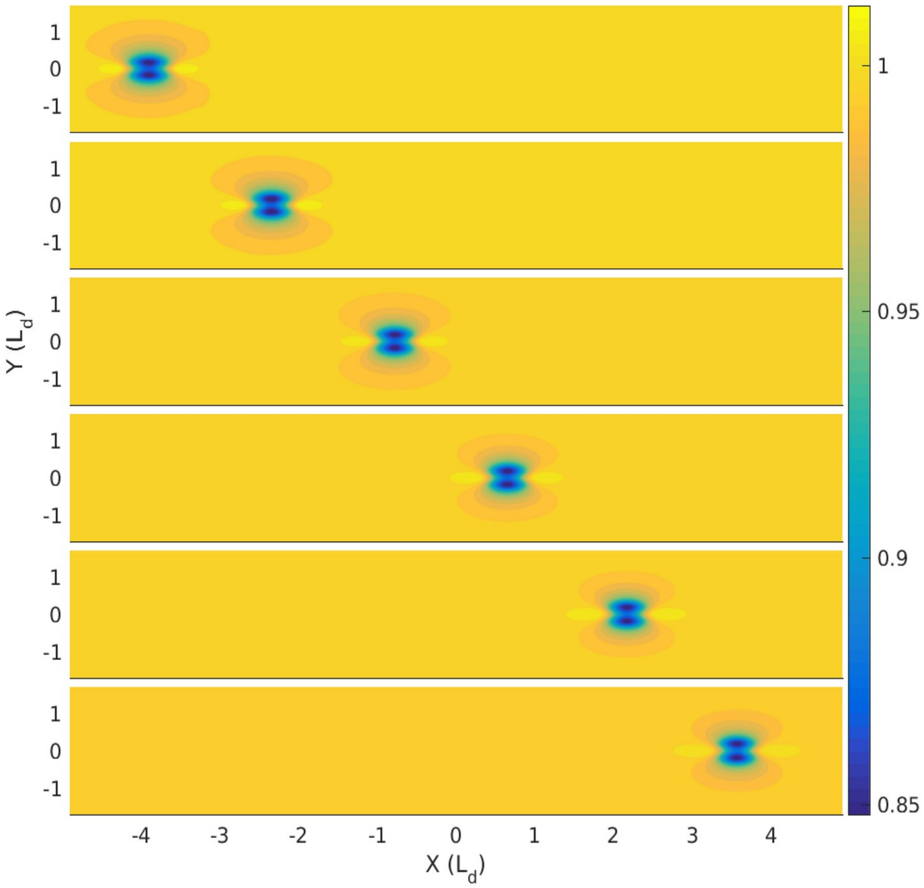
Coherence of the adjusted “true” modon

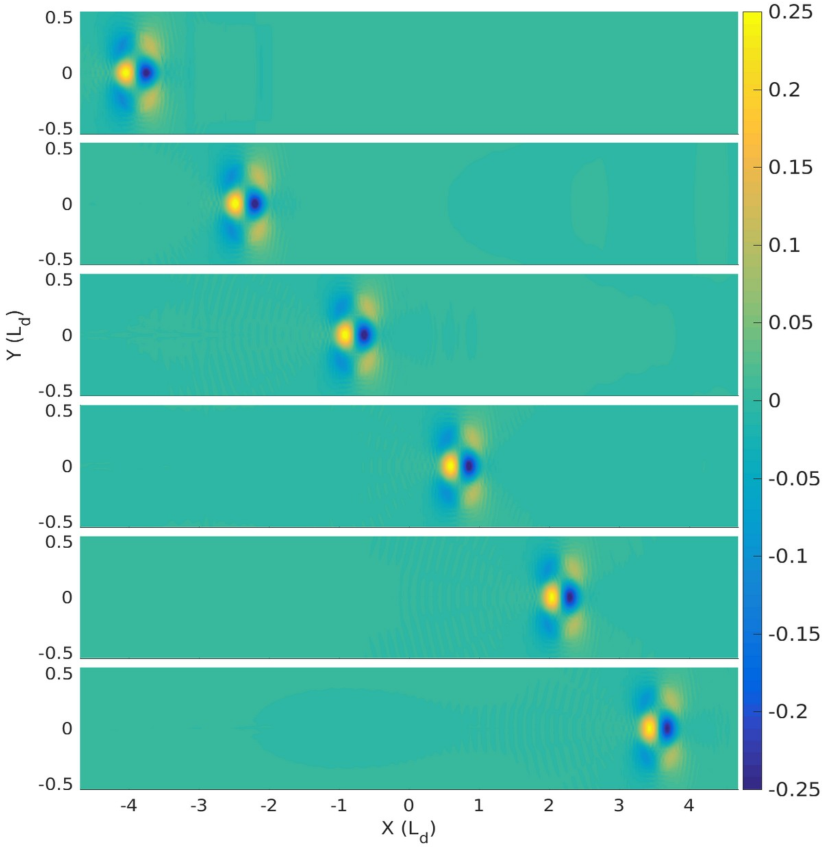


Thickness, Bernoulli function vs potential vorticity in the co-moving frame, zonal and meridional sections of the modon at t = 15 [1/βL d].

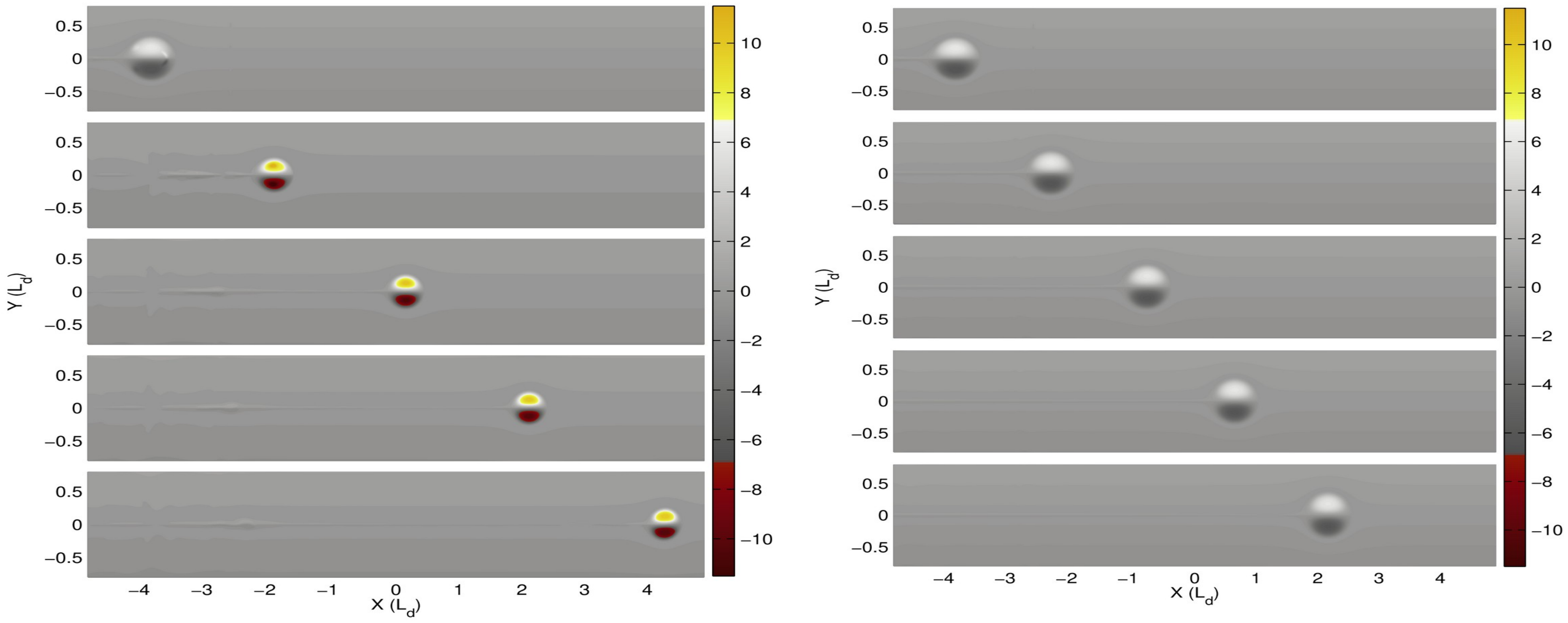
Evolution of the “true” modon

(pressure and div. fields)

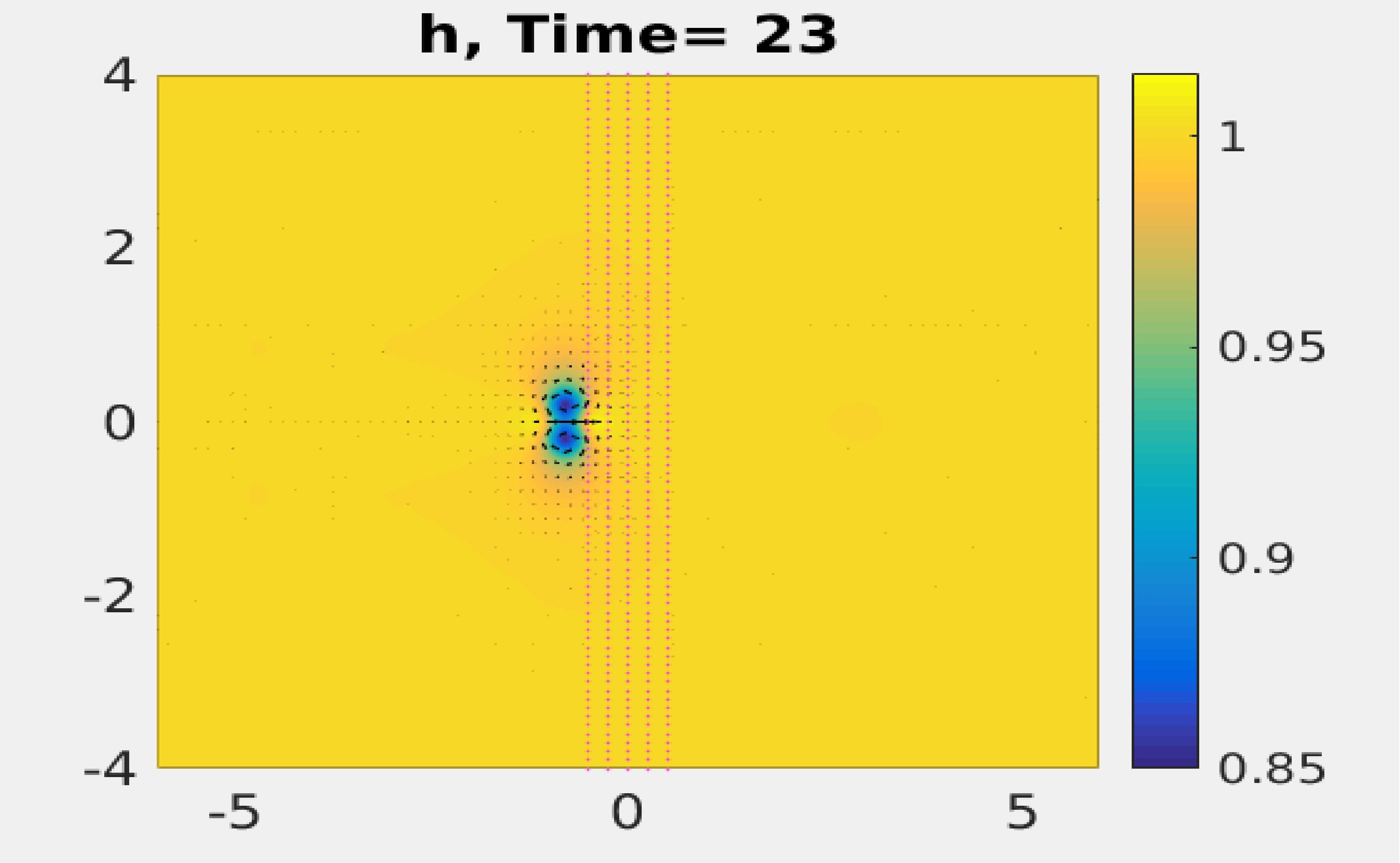




Eastward Propagation of Equatorial Modon in “dry” and its intensification in moist-convective environment



Steady eastward propagation of the equatorial modon, as seen in PV field in moist-convective (left) and adiabatic (right) environments.


h, Time= 23
4
2
0
-2
-4
-5
0
5
1
0.95
0.9
0.85

Generation of Equatorial Modon from *Equatorial Excitable Systems* (EES)

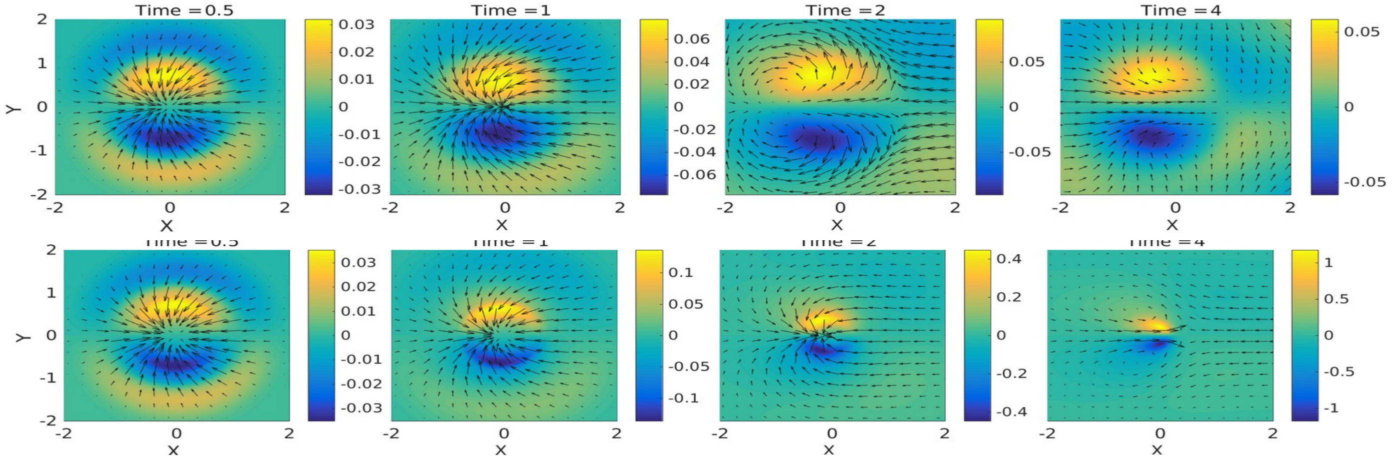


Fig. Snapshots of vorticity (colors) and velocity (arrows) of the initial stages of “dry” (top) and moist-convective, bottom) adjustments of a circular negative pressure anomaly with max$|\Delta H/H|$ = 0.1. Note a pronounced convergence at t = 2 $[1/\beta L_d]$ due to condensation in the bottom panel.

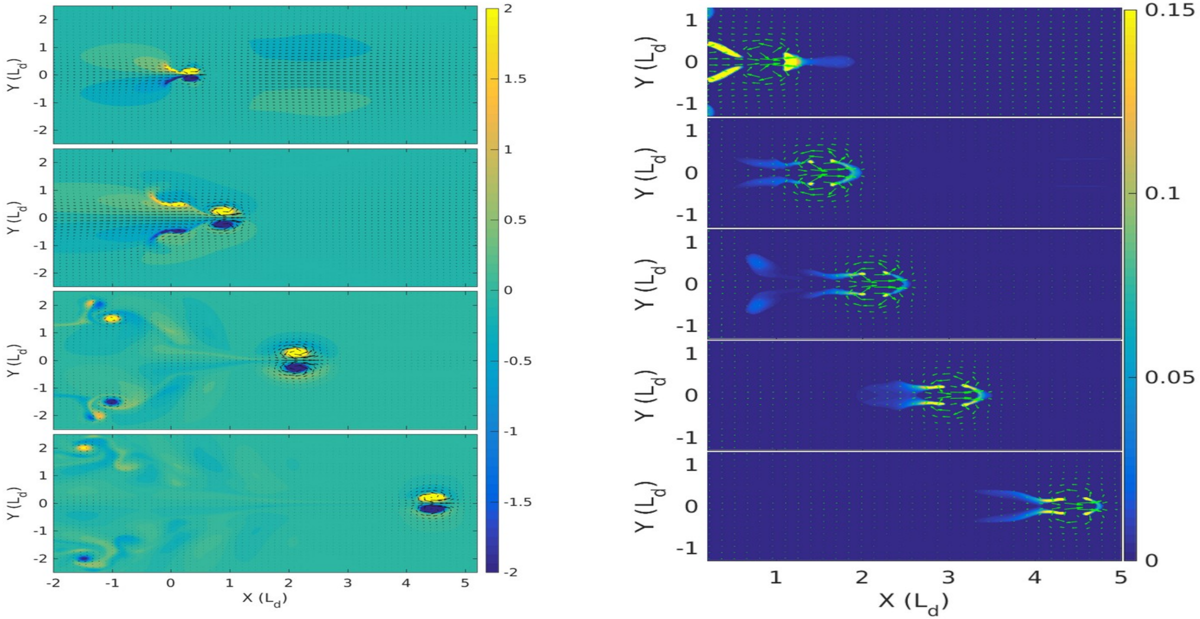
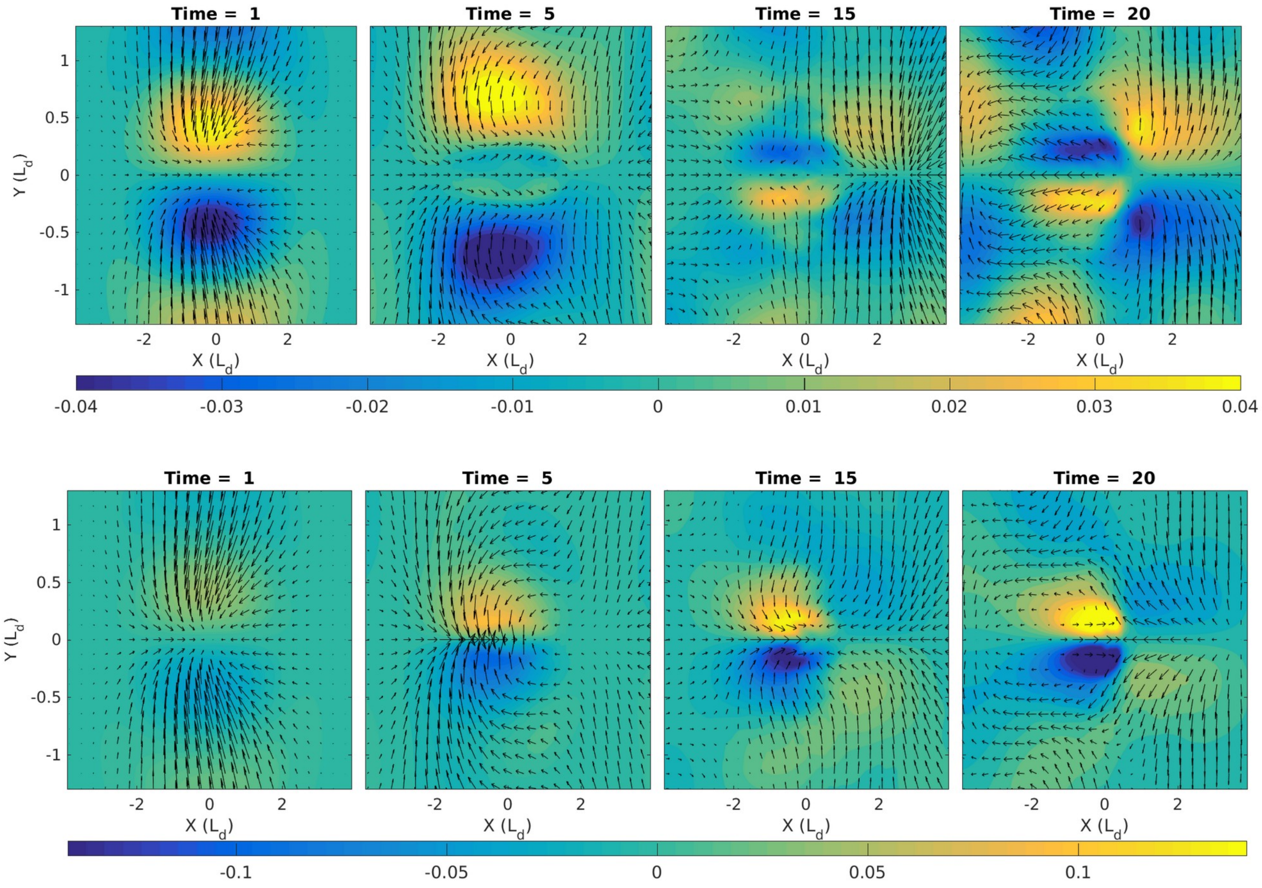


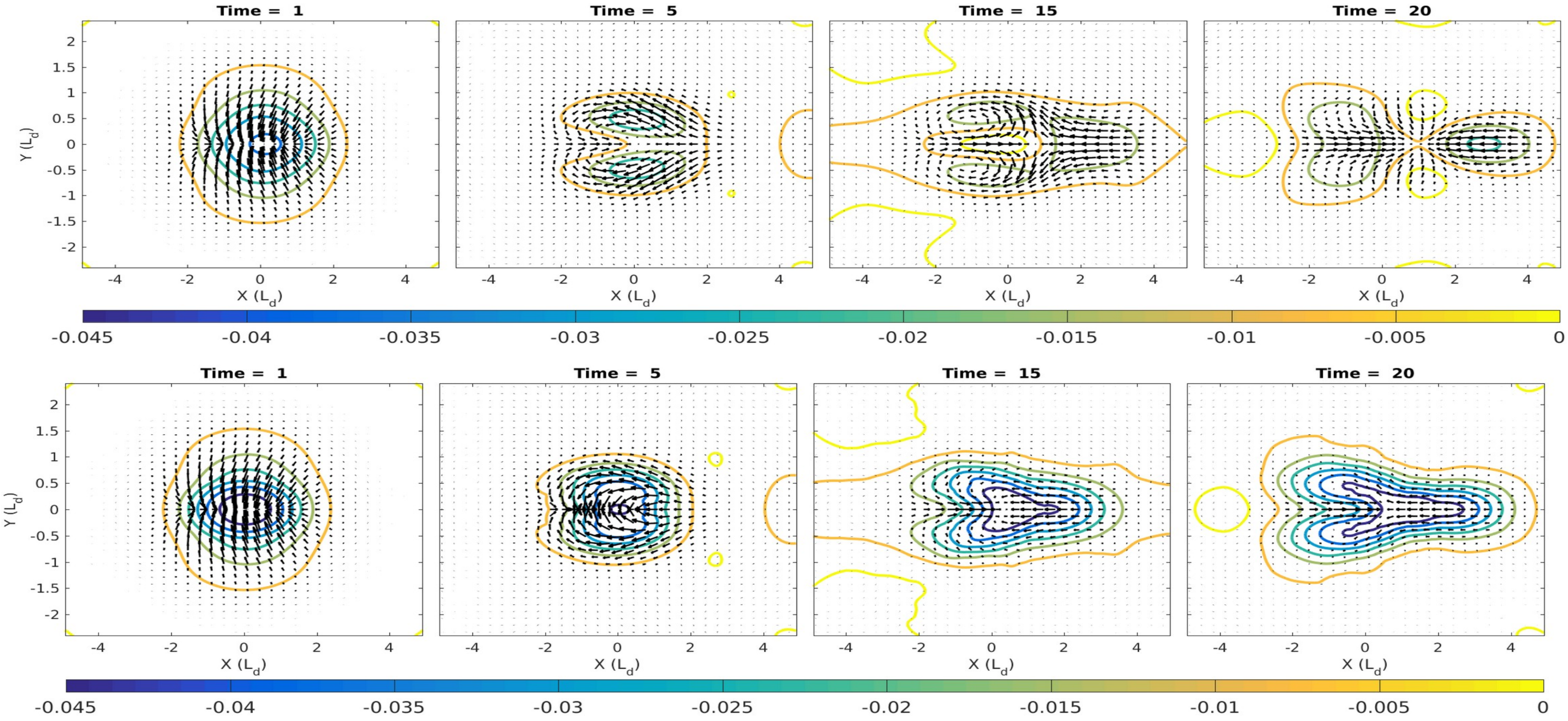
Fig. Evolution at later times t = 5, 30, 45, 75 $[1/\beta L_d]$ of relative vorticity during the moist-convective adjustment of circular negative pressure anomalies with max$|\Delta H/H|$ = 0.18 (left panel) and corresponding precipitation pattern.

Generation of MJO-like structure from geostrophic adjustment of baroclinic disturbances in tropical atmosphere (Rostami & Zeitlin, 2020)



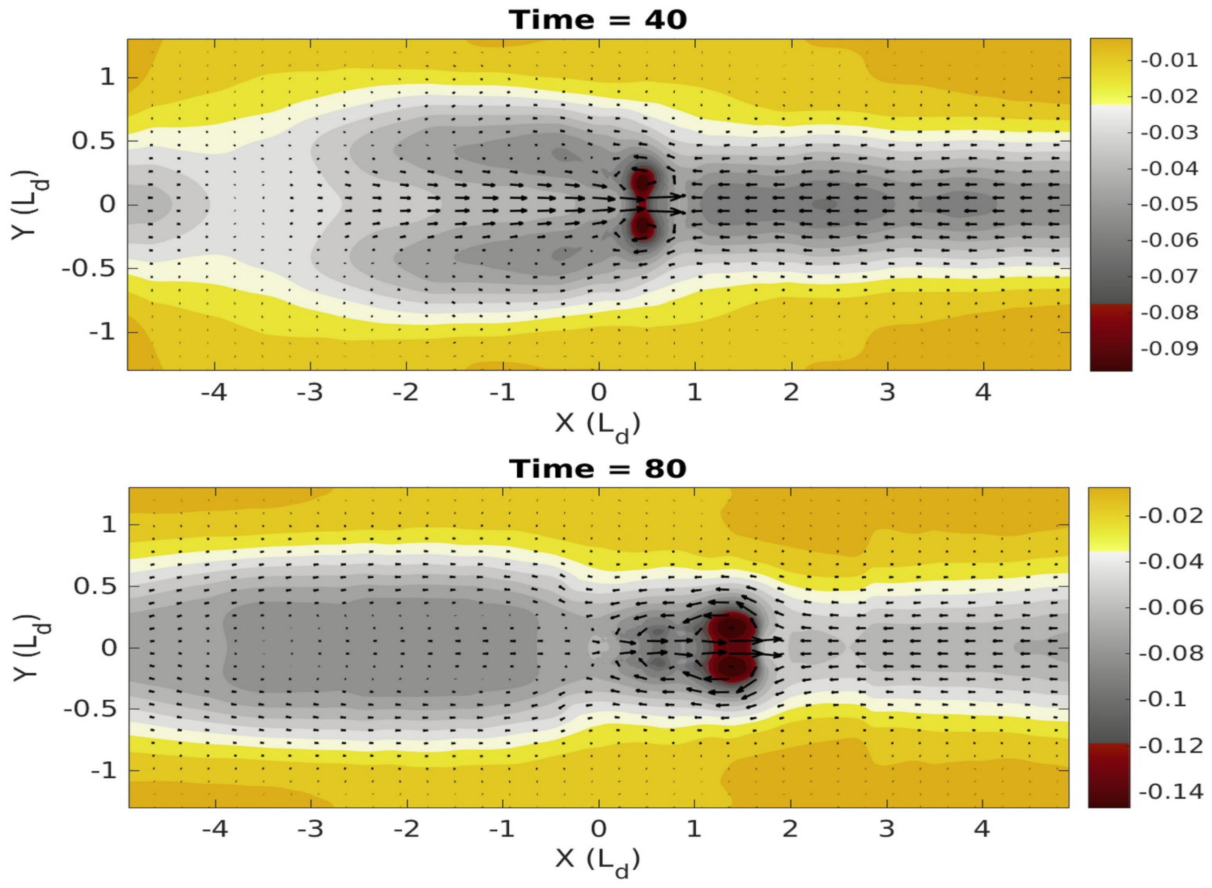
The initial evolution of velocity (arrows) and relative vorticity (colors) fields that correspond to the upper-layer and lower-layer components, respectively from top to bottom.

Hybrid structure: Baroclinic Modon-Kelvin Wave (initial stages)



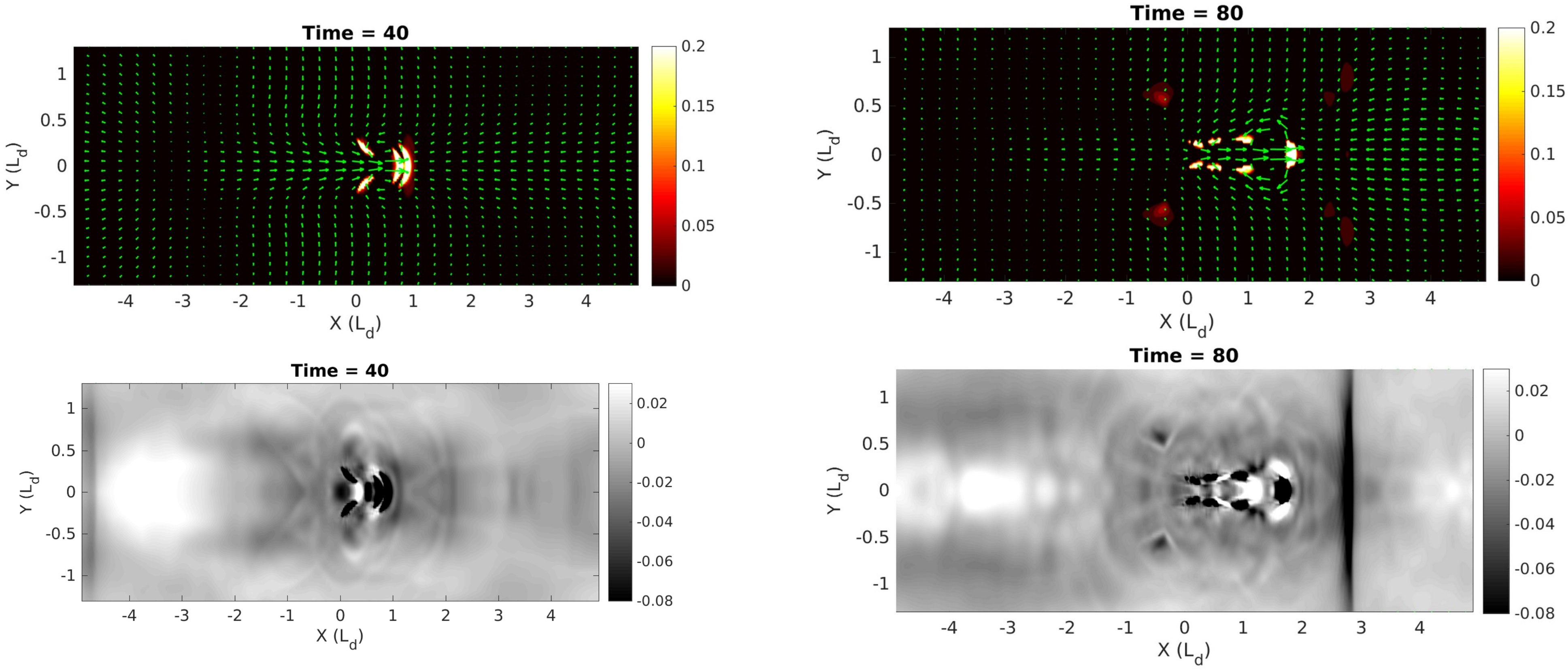
Initial stages of equatorial adjustment of a negative pressure anomaly in the lower layer as seen in evolution of the baroclinic velocity (arrows) and pressure anomaly (contours) in “dry” (upper panel) and moist-convective (lower panel) environments.

Hybrid structure: Baroclinic Modon-Kelvin Wave (late stages)



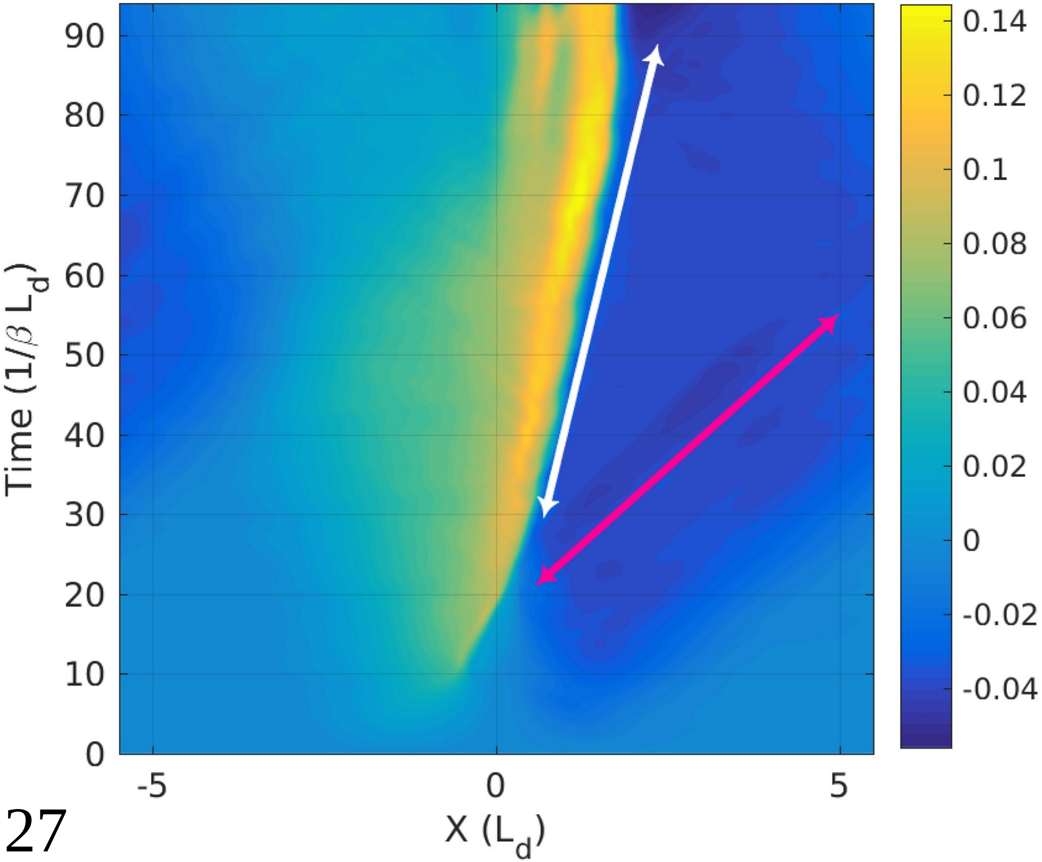
Eastward-propagating intense baroclinic dipole as seen in the baroclinic pressure anomaly (colors) and baroclinic velocity (arrows) at times t = 40, 80 $(L_d/\sqrt{gH_s})$.

Divergence and condensation patterns of hybrid structure

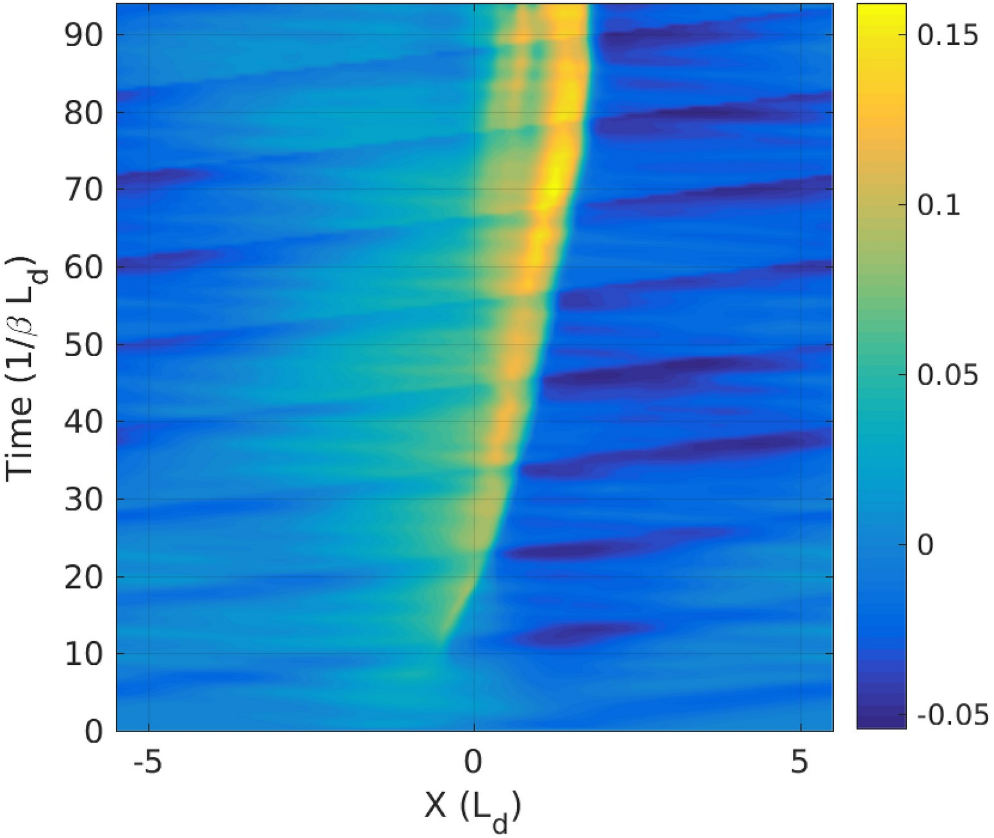


Hovmöller diagram of the ”hybrid structure”

Left panel: baroclinic zonal velocity



Right panel: zonal velocity in the lower layer



Conclusion

Our experiments on ***adjustment of lower-troposphere pressure anomalies*** show a genesis of structures combining Rossby- and Kelvin- wave responses and reproducing many of the observed features of the MJO events crudely, but surprisingly well. Some similarities with the key observational facts on the MJO events are listed below.

I. Quadrupolar structure with opposite-sign vorticity anomaly in the upper layer

II. Enhanced dipolar structure in the lower layer, Kelvin wave detachment, and zonal spreading

III. Westerly and easterly inflows, moisture distribution, and precipitation

IV. The offered hypothesis gives explanation for existing difference between propagation speed of the MJO with Kelvin-waves phase velocity.

V. The response to the localized depression we observe is a combination of the ***modon-like structure***, similar to Yano & Tribbia (2017) & Rostami & Zeitlin (2019) ***but attached to a baroclinic Kelvin wave***.

Thank you for your attention

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