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# Realistic initiation and dynamics of the Madden-Julian Oscillation in a coarse resolution aquaplanet GCM

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The main mechanisms for the initiation and propagation of the Madden-Julian Oscillation (MJO) are still widely debated. The capacity of operational global climate models (GCMs) to correctly simulate the MJO is hindered by the inadequacy of the underlying cumulus parameterizations. Here, we show that a coarse resolution GCM, coupled to a simple multicloud model parameterization mimicking the observed dynamics and physical structure of organized tropical convection, simulates the MJO in an idealized setting of an aquaplanet without ocean dynamics. We impose a fixed non-homogeneous sea surface temperature replicating the Indian Ocean/Western Pacific warm pool. This results in a succession of MJOs with realistic phase speed, amplitude, and physical structure. Each MJO event is initiated at a somewhat random location over the warm pool and dies sometimes near the eastern boundary of the warm pool, and sometimes at a random location way beyond the warm pool. Also occasionally the MJO events stall at the center of maximum heating. This is reminiscent of the fact that in nature some MJOs stall over the maritime continent while others reach the central Pacific Ocean and beyond. The initiation mechanism in the model is believed to be a combination of persistent intermittent convective events interacting with observed large scale flow patterns and internal tropical dynamics. The large scale flow patterns are associated with planetary scale dry Kelvin waves that are triggered by preceding MJO events and circle the globe while congestus cloud

decks on the flanks of the warm pool are believed to force Rossby gyres which then funnel moisture towards the equatorial region.

## 1. Introduction

The Madden-Julian Oscillation [*Madden and Julian*, 1971] is the dominant feature of the intraseasonal (20-100 days) variability in the tropical atmosphere. The MJO is an eastward propagating large-scale planetary scale disturbance in atmospheric winds and precipitation with coherent signals in many other variables. The MJO waves originate over the warm waters of the Indian Ocean (IO) and propagate eastward towards the maritime continent and Pacific Ocean with a speed of $\approx 5\text{ms}^{-1}$. The MJO interacts with the underlying oceans and influences the global weather and climate system [*Zhang*, 2005].

In spite of recent intensive research efforts [*Zhang*, 2005; *Lau and Waliser*, 2005], accurately simulating and predicting the MJO using state-of-the-art GCMs remains challenging. Several missing links in understanding the physics and dynamics of the MJO have motivated co-ordinated efforts in observational and diagnostic studies in the last few years [*Zhang*, 2005; *Zhang et al.*, 2013]. Realistic simulation of the observed phase and amplitude of the MJO is the most common bias seen in the climate model simulations. When eastward propagating MJOs are simulated, they are either too weak, or their spatial distributions and seasonal cycles are unrealistic [*Slingo et al.*, 1996; *Lin et al.*, 2006; *Straub et al.*, 2010; *Kim et al.*, 2009]. It is also noted that marked improvements have been made by few GCMs in simulating a realistic MJO [*Subramanian et al.*, 2011; *Del Genio et al.*, 2012; *Benedict et al.*, 2013; *Crueger et al.*, 2013].

Here, we use an aquaplanet model with a prescribed warm pool to simulate realistic MJOs. This model is designed without land or topography, without ocean-atmospheric coupling and without extratropical dynamics. In particular, a mask restricting heating and cooling to the tropical belt between 30°S and 30°N is applied [see *Khouider et al.*, 2011]. Here, we show that without boundary forcings and independent of initial conditions, a realistic simulation of MJO can be achieved. The main ingredient is the use of a simple-prototype multicloud model parameterization that is designed to capture the observed cloud morphology and dynamics of organized convection using three cloud types, congestus, deep, and stratiform, as the underlying building block [*Khouider and Majda*, 2006a; *Khouider et al.*, 2011]. As opposed to traditional plume-based and large-scale forcing type parameterizations, the multicloud cloud model aims at representing the unresolved mesoscale dynamics associated with organized convection which, by design captures the transition from shallow to deep convection through the progressive moistening due to congestus activity [*Khouider and Majda*, 2006a; *Mapes and Neale*, 2011; *Del Genio et al.*, 2012].

The present study emphasizes primary mechanisms for the initiation and propagation of the MJO that are distinct from some other mechanisms presented in the literature. MJO initiation can be triggered due to a variety of mechanisms including chaotic reorganization of intermittent convective events by pre-existing large scale circulation patterns and/or the intrusion of extra-tropical disturbances in winds, temperature, and/or moisture. This interpretation is in essence compatible with the DYNAMO/CINDY [*Zhang et al.*, 2013] field campaign working hypothesis, stipulating the existence of both a dynamical (external) and a convective (local) initiation of the MJO, which classifies MJO events into primary and successive categories [*Ling et al.*, 2013].

The paper is organized as follows. The diagnostics used in analyzing the results are described in Section 2. Discussion of the results and conclusions are outlined in Section 3. The description of the model and the experiment setup is outlined in the auxiliary material.

## 2. MJO Diagnostics

MJO-like characteristics are obtained from the numerical simulation of the Multicloud_HOMME Model (MHM; details of model configuration and set up outlined in the auxiliary material). A Hovmöller (longitude-time) plot of the 200hPa zonal wind (U200; shaded) and precipitation (vertically averaged heating; PCP; contours) averaged over the equatorial belt 10°S-10°N is shown in Fig. 1. A succession of MJO-like events are clearly seen in both zonal winds and precipitation. They are formed over the warm pool and propagate slowly eastward at roughly $5ms^{-1}$. Before they die as they exit the warm pool region, these MJO-like signals trigger fast moving streaks of wind disturbances that continue to move eastward but at a much faster speed of roughly $25ms^{-1}$, a second-baroclinic dry Kelvin wave. Dry Kelvin waves are believed to play an important role in the dynamics and initiation of the MJO [*Matthews et al.*, 1999]. As they propagate and circle the globe, these waves act as a precursor for MJO initiation in MHM. They do so via the associated planetary scale divergence field that organizes the otherwise chaotic and intermittent mesoscale convective systems, represented by the multicloud model. This cause-and-effect interaction is confirmed by the magnified picture in Fig. 2.

To illustrate the characteristics of the simulated MJO, we carry out more diagnostics like wave-frequency spectra on the three variables U850, U200 and PCP [*Wheeler and*

*Kiladis*, 1999]. The wave-frequency spectra show peak variance in the MJO band in the period between 30 and 80 days and zonal wave number 1-2 (Fig. 3). Elevated variance over the Kelvin wave regime is also evident in Fig. 3. Another prominent MJO diagnostic is based on the coherency between these three variables by computing the Combined Empirical Orthogonal Function [CEOF; *Madden-Julian Oscillation Working Group*, 2009]. An average of 20-100 day band pass filtered anomalies of PCP, U850 and U200 in tropics (15°S-15°N) is calculated. After normalizing each of these three fields separately by the square-root of the zonal mean of their temporal variance at each longitudinal point, a combined EOF of these three fields is computed. Based on a two dimensional phase diagram of first and second principal components (PC1 & PC2), eight different phases of the MJO are identified. The spatial composites of the selected points according to these phases show steady eastward propagation of MJO and associated spatial pattern in each phase (Fig. 4). The initiation of MJO over the warm pool (phase 4), slow eastward propagation over the warm pool region (phases 5-7), triggering of Kelvin waves and its propagation from the dateline (phases 8-3) is clearly evident in the composite spatial structure (Fig. 4), consistent with observations [*Madden-Julian Oscillation Working Group*, 2009].

In addition to the diagnostics presented here, the MJO-like wave simulated by the MHM has many other, if not all, the, principal features of the MJO as observed in nature, including the tilted baroclinic structure in zonal winds and temperature and a quadruple vortex structure (see auxiliary Fig.1) in the upper and lower troposphere surrounding the active convection [*Kiladis et al.*, 2009]. Another important feature of the MHM, is the ability of congestus cloud decks on the flanks of the convective core to reinforce these Rossby gyres which, in turn, funnel moisture along the equator [*Khouider et al.*, 2011].

## 3. Summary and Discussion

Several theories for the genesis of the MJO have been proposed in the past [*Wang*, 2005]. By the design of the multicloud model parameterization [e.g. *Khouider and Majda*, 2006a] none of the following mechanisms are present in the simulation; Wind Induced Surface Heat Exchange (WISHE), wave-CISK (Convective Instability of the Second Kind), boundary layer friction (FCI), cloud radiation forcing (CRF), ocean/sea-surface dynamics. Nevertheless, the MHM produces MJO-like events with dynamical and physical features that resemble observed MJOs, including stochastic initiation over the warm pool and sudden demise after propagating the length of the warm pool and sometimes beyond.

The multicloud heating acts on high-frequency disturbances to produce instability, through across-scale interactions, adequate for the genesis and propagation of the MJO [*Khouider and Majda*, 2006a]. This concept is rooted on the observational evidence that the MJO and embedded disturbances involve the multicloud structure: a deep convective core preceded by shallow convection or congestus clouds and trailed by upper-tropospheric stratus clouds [*Johnson et al.*, 1999; *Mapes et al.*, 2006]. When properly coupled to moisture, a two vertical mode model, the first and second baroclinic modes, can generate instability sufficient to drive tropical waves [*Khouider and Majda*, 2006a, b]. The convective activity coupled with large-scale circulation takes the form of an envelope of mesoscale and synoptic scale systems involving multiple cloud types [*Johnson et al.*, 1999; *Nakazawa*, 1988].

Several studies accentuate the role of land in stalling the MJO to attain its slow phase speed [*Matthews et al.*, 1999]. The fact that the aquaplanet MHM simulates MJO-like events indicate the secondary influence of land on the MJO genesis. An important role of air-sea interaction and related ocean dynamics in simulating realistic phase and amplitude of an MJO is highlighted in the ECHAM family of models [*Crueger et al.*, 2013]. Moreover, baroclinic instability and extratropical connection are not present in the MHM simulations. The MHM results suggests that realistic MJOs in a GCM is possible without land, ocean dynamics, baroclinic instability and extratropical interaction. Our results advocate that the primary factors responsible for the initiation of MJO differ entirely from most existing theories.

Our aquaplanet results show that MJO initiation can occur internally via the organization of chaotic organized convective events above the warm pool involving a moisture-coupled mode of the tropical troposphere internal variability represented by the MJO-skeleton model [*Majda and Stechmann*, 2009, 2011; *Kim et al.*, 2013]. An opposing school of thought advocates a Kelvin-Rossby Gill-type coupling in lieu of the MJO-mode, involving no moisture coupling [*Wang and Rui*, 1990]. However, a drawback is that such a structure can not produce the observed quadruple vortex structure of the MJO. Earlier MJO theories rely on mechanisms such as WISHE, CRF, wave-CISK, and FCI to produce instability. Moreover, the moisture mode instability advocated by *Kim et al.* [2013] has no scale selection property–all scales are unstable. The MJO acts as an envelope for mesoscale and synoptic scale convective systems, which in return, provide the necessary heating and upscale transport of momentum to sustain the MJO [*Biello and Majda*, 2005;

*Majda and Stechmann*, 2009]. In essence, across scale interactions and the existence of the embedded mesoscale and synoptic scale systems ensure the coupling between moisture and MJO dynamics. This is guaranteed by introducing a synoptic scale envelope of wave-activity in the neutrally stable MJO skeleton model [*Majda and Stechmann*, 2009].

The success of the multicloud model is rooted in its systematic use of mesoscale convective system (MCS) dynamics as the building block for the dynamical coupling of congestus, deep, and stratiform heating profiles based on the first two baroclinic modes of vertical structure. In this fashion, unlike traditional cumulus parameterizations, parameterized convection is not confined into a single grid column and single time step but distributed over the length and time scales of the MCSs and synoptic scale systems embedded in the MJO, as demonstrated by linear theory [*Khouider and Majda*, 2006a; *Khouider et al.*, 2012]. This is consistent with *Moncrieff* [2004], who successfully used a systematic representation of the MCS circulation patterns to overcome the vertical column pitfall of the underlying parameterization to drive convective momentum transport also addressed in the multiscale context by *Biello et al.* [2007].

## References

Benedict, J. J., E. D. Maloney, A. H. Sobel, D. M. Frierson, and L. J. Donner (2013), Tropical intraseasonal variability in version 3 of the GFDL atmosphere model, *J. Climate*, *26*, 426–449.

Biello, J., and A. J. Majda (2005), A multi-scale model for the Madden-Julian oscillation, *J. Atmos. Sci.*, *62*, 1694–1721.

Biello, J., A. J. Majda, and M. W. Moncrieff (2007), Meridional momentum flux in the multiscale IPESD MJO model, *J. Atmos. Sci.*, *64*, 1636–1651.

Crueger, T., B. Stevens, and R. Brokopf (2013), The Madden-Julian Oscillation in ECHAM6 and the introduction of an objective MJO metric, *J. Climate*, *26*, 3241–3256, doi:10.1175/JCLI-D-12-00413.1.

Del Genio, A. D., Y. Chen, D. Kim, and M.-S. Yao (2012), The MJO transition from shallow to deep convection in CLOUDSAT/CALIPSO data and GISS GCM simulations, *J. Climate*, *25*, 3755–3770, doi:10.1175/JCLI-D-11-00384.1.

Johnson, R. H., T. M. Rickenbach, S. A. Rutledge, P. E. Ciesielski, and W. H. Schubert (1999), Trimodal characteristics of tropical convection, *J. Climate*, *12*(8), 2397–2418.

Khouider, B., and A. J. Majda (2006a), A simple multicloud parameterization for convectively coupled tropical waves. Part I: Linear analysis, *J. Atmos. Sci.*, *63*, 1308–1323.

Khouider, B., and A. J. Majda (2006b), Model multi-cloud parameterizations for convectively coupled tropical waves: Detailed nonlinear wave evolution, *Dynam. Atmos. Oceans*, *42*, 59–80.

Khouider, B., A. St-Cyr, A. J. Majda, and J. Tribbia (2011), The MJO and convectively coupled waves in a coarse resolution GCM with a simple multicloud parameterization, *J. Atmos. Sci.*, *68*, 240–264, doi:101.1175/2010JAS3443.1.

Khouider, B., Y. Han, A. J Majda, S. N Stechmann (2012), Multiscale waves in an MJO background and convective momentum transport feedback, *J. Atmos. Sci.*, *69*, 915–933, doi:10.1175/JAS-D-11-0152.1.

Kiladis, G. N., M. C. Wheeler, P. T. Haertel, K. H. Straub, and P. E. Roundy (2009), Convectively coupled equatorial waves, *Rev. Geophys.*, *47*, RG2003, doi: 10.1029/2008RG000266.

Kim, D., et al. (2009), Application of MJO simulation diagnostics to climate models, *J. Climate*, *22*(23), 6413–6436, doi:10.1175/2009JCLI3063.1.

Kim, D., J.-S. Kug, and A. H. Sobel (2013), Propagating vs. non-propagating Madden-Julian oscillation events, *J. Climate*, p. in press, doi:JCLI-D-13-00084.1.

Lau, W. K. M., and D. E. Waliser (Eds.) (2005), *Intraseasonal Variability in the Atmosphere-Ocean Climate System*, 474 pp., Springer, Heidelberg, Germany.

Lin, J.-L., et al. (2006), Tropical intraseasonal variability in 14 IPCC AR4 climate models. Part I: Convective signals, *J. Climate*, *19*(12), 2665–2690.

Ling, J., C. Zhang, and P. Bechtold (2013), Large-scale distinctions between MJO and non-MJO convective initiation over the tropical Indian ocean, *J. Atmos. Sci.*, *70*, 2696–2712, doi:JAS-D-13-029.1.

Madden, R. A., and P. R. Julian (1971), Detection of a 40-50 day oscillation in the zonal wind in the tropical Pacific, *J. Atmos. Sci.*, *28*, 702–708.

Madden-Julian Oscillation Working Group, C. (2009), MJO simulation diagnostics, *J. Climate*, *22*, 3006–3030, doi:10.1175/2008JCLI2731.1.

Majda, A. J., and S. N. Stechmann (2009), The skeleton of tropical intraseasonal oscillations, *Proc. Nat. Acad. Sci. USA*, *106*(21), 8417–8422.

Majda, A. J., and S. N. Stechmann (2011), Nonlinear dynamics and regional variations in the mjo skeleton, *J. Atmos. Sci.*, *68*(12), 3053–3071, doi:10.1175/JAS-D-11-053.1.

Mapes, B., S. Tulich, J. Lin, and P. Zuidema (2006), The mesoscale convection life cycle: Building block or prototype for large-scale tropical waves?, *Dynam. Atmos. Oceans*, *42*, 3–29, doi:10.1016/dynatmoce.2006.03.003.

Mapes, B. E., and R. B. Neale (2011), Parameterizing convective organization to escape the entrainment dilemma, *J. Adv. Model. Earth Sys.*, *3*, M06,004.

Matthews, A. J., J. M. Slingo, B. J. Hoskins, and P. M. Inness (1999), Fast and slow kelvin waves in the Madden-Julian oscillation of a GCM, *Quart. J. Roy. Meteorol. Soc.*, *125*, 1473–1498.

Moncrieff, M. W. (2004), Analytic representation of the large-scale organization of tropical convection, *J. Atmos. Sci.*, *61*(13), 1521–1538, doi:10.1175/1520-0469(2004)061⟨1521:AROTLO⟩2.0.CO;2.

Nakazawa, T. (1988), Tropical super clusters within intraseasonal variations over the western Pacific, *J. Meteorol. Soc. Japan*, *66*(6), 823–839.

Slingo, J. M., et al. (1996), Intraseasonal oscillation in 15 atmospheric general circulation models: Results from an AMIP diagnostic subproject, *Clim. Dynam.*, *12*, 325–357.

Sobel, A., and E. Maloney (2012), An Idealized Semi-Empirical Framework for Modeling the Madden-Julian Oscillation, *J. Atmos. Sci.*, *69*, 1691–1705, doi:10.1175/JAS-D-11-0118.1.

Straub, K. H., P. T. Haertel, and G. N. Kiladis (2010), An analysis of convectively coupled Kelvin waves in 20 WCRP CMIP3 global coupled climate models, *J. Climate*, *23*, 3031–3056, doi:10.1175/2009JCLI3422.1.

Subramanian, A. C., M. Jochum, A. J. Miller, R. Murtugudde, R. B. Neale, and D. E. Waliser (2011), The Madden-Julian oscillation in CCSM4, *J. Climate*, *24*, 6262–6282, doi:10.1175/JCLI-D-11-00031.1.

Wang, B. (2005), Theory, in *Intraseasonal Variability in the Atmosphere-Ocean Climate System*, edited by W. K. M. Lau and D. E. Waliser, chap. 10, pp. 307–360, Praxis Springer, Berlin.

Wang, B., and H. Rui (1990), Dynamics of the coupled moist Kelvin-Rossby wave on an equatorial beta-plane, *J. Atmos. Sci.*, *47*, 397–413.

Wheeler, M., and G. N. Kiladis (1999), Convectively coupled equatorial waves: Analysis of clouds and temperature in the wavenumber-frequency domain, *J. Atmos. Sci.*, *56*, 374–399.

Zhang, C. (2005), Madden-Julian Oscillation, *Rev. Geophys.*, *43*, RG2003, doi:10.1029/2004RG000158.

Zhang, C., J. Gottschalck, E. Maloney, M. Moncrieff, F.Vitart, D. Waliser, B. Wang, and M. Wheeler (2013), Cracking the MJO nut, *Geophys. Res. Lett.*, doi:10.1002/grl.50244.

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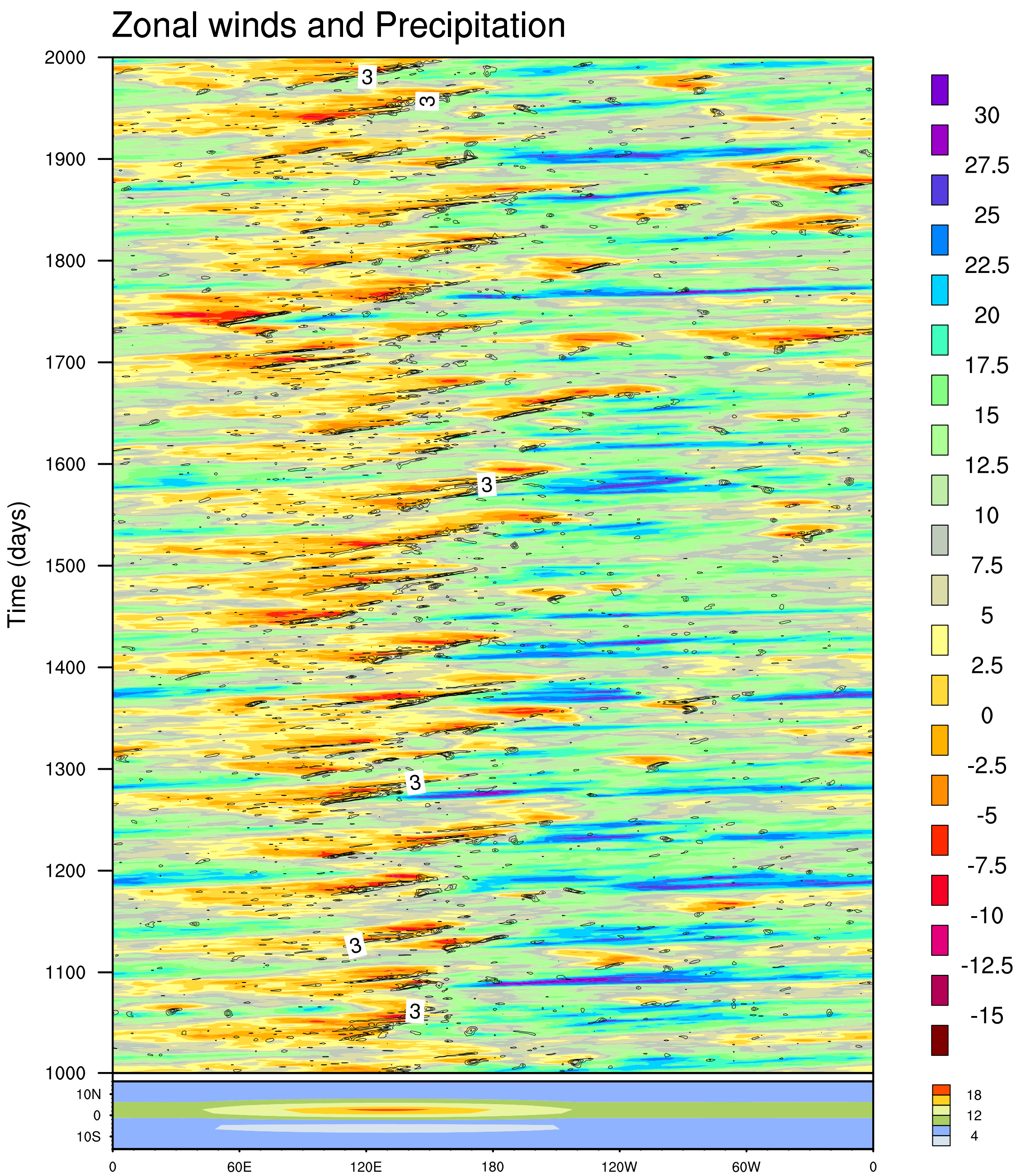


**Figure 1. Propagation of zonal winds and precipitation:** Hovmöuller plot of upper level zonal winds (shaded, ms$^{-1}$) and precipitation (contour, K.day$^{-1}$) averaged over the equatorial belt (10°S-10°N). Structure of the warm pool (°C) used in the simulations is shown in the bottom panel.

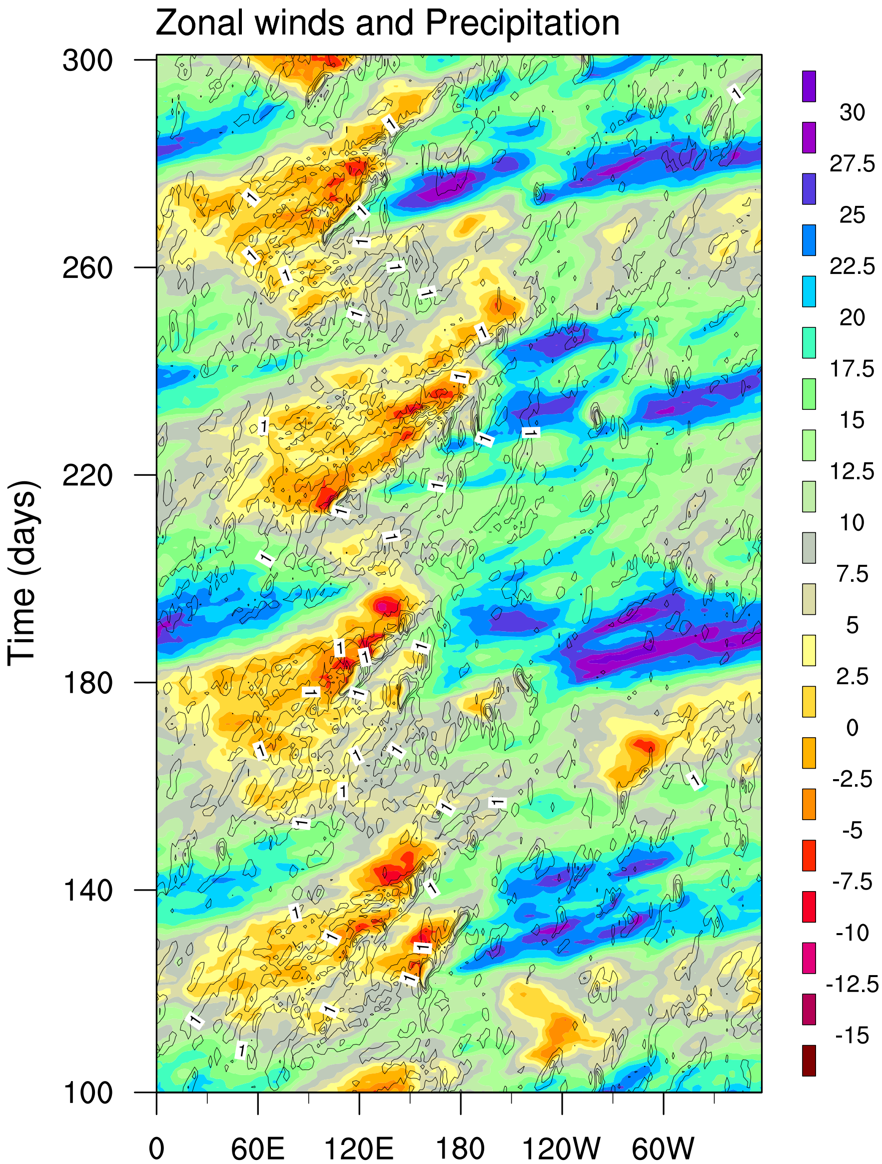


**Figure 2.** **Propagation of zonal winds and precipitation:** Same as Fig. 1 but zoomed during a short period. Starting contour is 1 $K.day^{-1}$ with an interval of 3 $K.day^{-1}$.

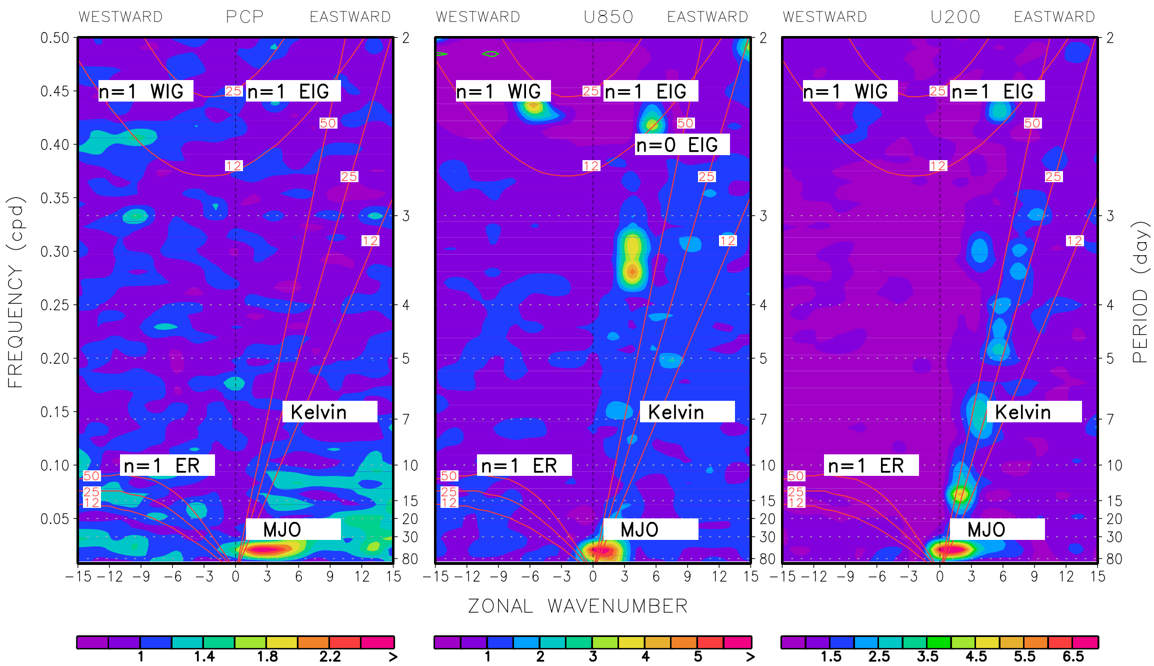


**Figure 3. Wave-Frequency spectra** of the symmetric component of precipitation, 850hpa winds and 200hPa zonal winds calculated for the last 1000 days from a 2000 days simulation. Time series is split into thirty 96 segments with a 65-day overlapping for smoothing.

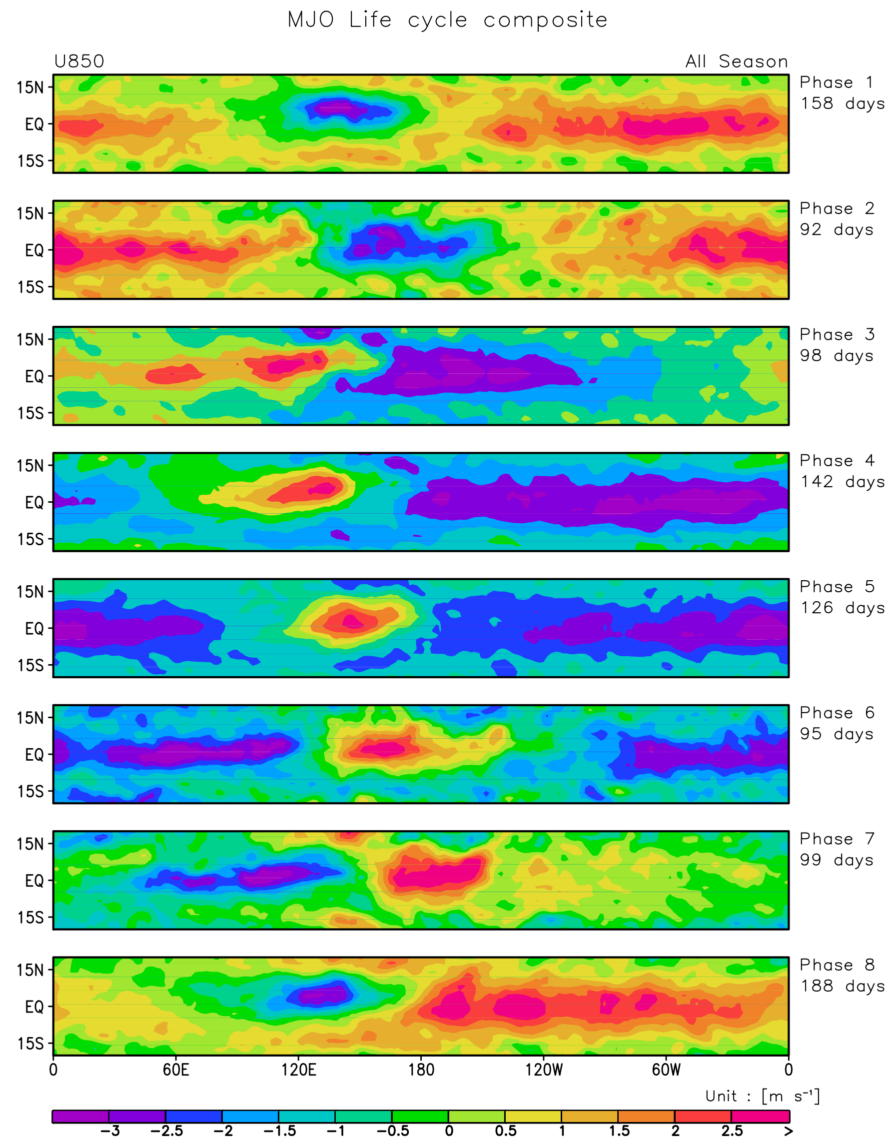


**Figure 4.** **Life-Cycle composites** of 850hPa zonal winds of the simulated MJO. (a) Identify MJO events through plots of PC-1 vs. PC-2 from the combined EOFs. Specifically, select points exceeding a root-mean-square exceeding 1 [i.e. sqrt(PC-$1^2$ + PC-$2^2$) > 1]. (b) Based on a two dimensional phase diagram of PC-1 and PC-2, define eight different phases of the MJO and generate spatial composites of the selected points according to these phases.

# Auxiliary Material

## Model and Setup

The High-Order Methods Modelling Environment (HOMME) is a highly parallelized code based on spectral element discretization of the hydrostatic primitive equations developed by the National Center for Atmospheric Research (NCAR), USA [*Dennis et al.*, 2005; *Nair and Tufo*, 2007]. HOMME relies on a cubed-sphere grid, where the earth is tiled with quasi-uniform quadrilateral elements, free from polar singularities. Here, we run the HOMME model in coarse resolution as a dry dynamical core coupled to the multicloud parameterization [*Khouider et al.*, 2011]. The mulicloud model assumes three heating profiles associated with the three cloud types, congestus, deep, and stratiform, that characterize tropical convective systems. These heating profiles force directly the first and second baroclinic modes of vertical structure. Mid-level moisture is used as a proxy to switch between congestus and deep convection regimes. When the midtroposhere is dry congestus clouds are favored and when it is moist deep convection is preferred. Stratiform heating trails deep convection by a prescribed time lag of 3 hours [*Khouider and Majda*, 2006]. Congestus clouds serve to moisten the mid-troposphere via the induced second baroclinic low-level convergence and precondition the environment for deep convection. The multicloud model is implemented in the full resolution Atmospheric General Circulation Model (AGCM) by invoking the vertical structure normal modes [*Khouider et al.*, 2011]. An asymmetric warm pool (Fig. 1; bottom panel) is forced over 60°E-180°E (roughly above Indo-W.Pacific region in a model with land) in this model setup. The AGCM is allowed to run freely for 2000 days;

outputs were collected for every six hours and the results of the last 1000 days were analyzed to avoid model spin-up.

## References

Dennis, J., A. Fournier, W. F. Spotz, A. St-Cyr, M. A. Taylor, S. J. Thomas, and H. M. Tufo (2005), High-resolution mesh convergence properties and parallel efficiency of a spectral element atmospheric dynamical core, *International Journal of High Performance Computing Applications*, *19*(3), 225–235, doi:10.1177/1094342005056108.

Khouider, B., and A. J. Majda (2006), A simple multicloud parameterization for convectively coupled tropical waves. Part I: Linear analysis, *J. Atmos. Sci.*, *63*, 1308–1323.

Khouider, B., A. St-Cyr, A. J. Majda, and J. Tribbia (2011), The MJO and convectively coupled waves in a coarse resolution GCM with a simple multicloud parameterization, *J. Atmos. Sci.*, *68*, 240–264, doi:101.1175/2010JAS3443.1.

Nair, R., and H. M. Tufo (2007), Petascale atmospheric general circulation models, in *Journal of Physics: Conference Series*, vol. 78, p. 012078, IOP Publishing, doi:10.1088/1742-6596/78/1/012078.

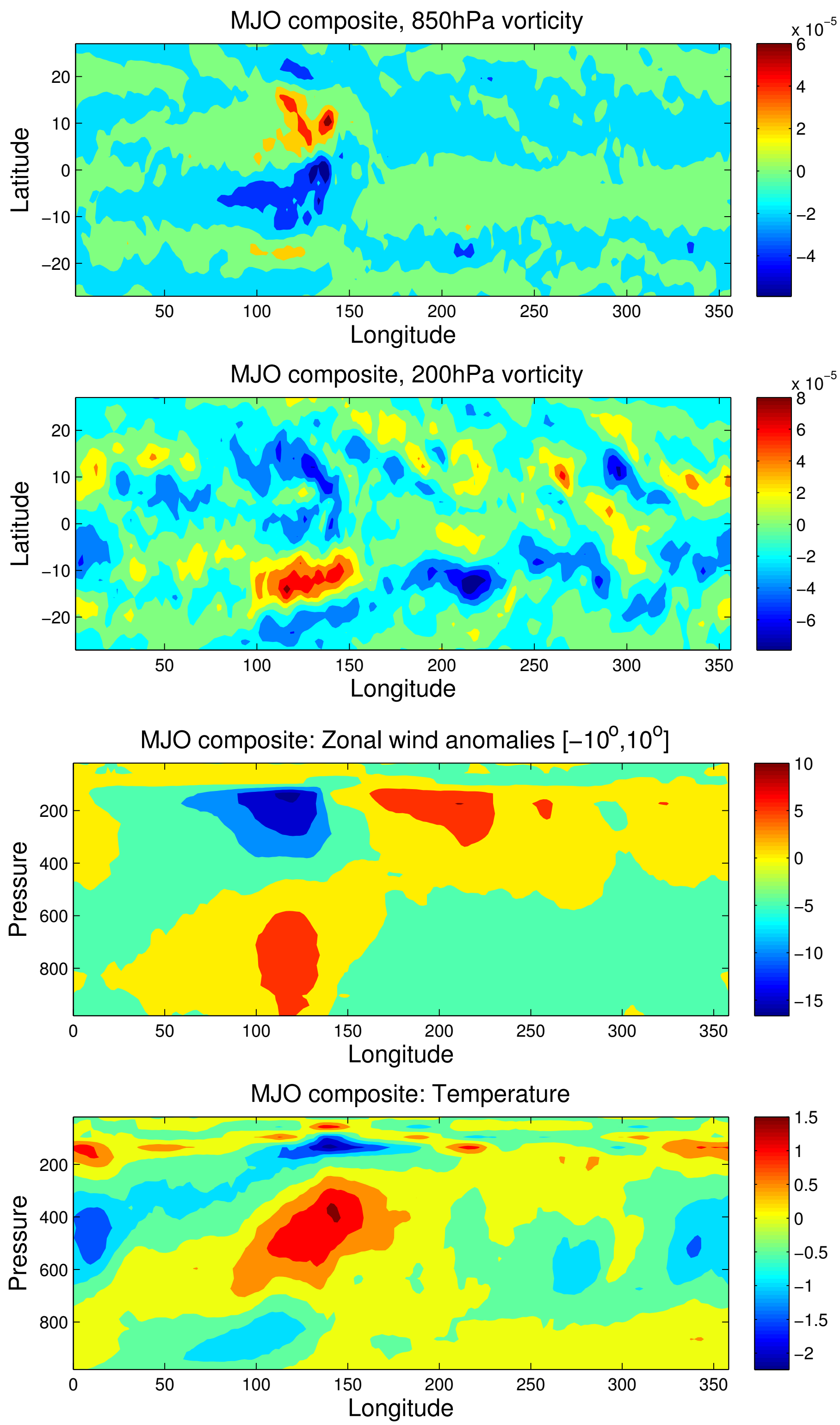


**Figure 1. Horizontal and vertical structure of the MJO in MHM simulations.** MJO-filtered vorticity ($s^{-1}$), zonal winds ($ms^{-1}$) and temperature (K) anomalies are shown.