Conditional Nonlinear Optimal Perturbations of Moisture Triggering Primary MJO Initiation

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Abstract The Madden-Julian Oscillation (MJO) is a dominant intraseasonal variability originating in the tropics and influencing global weather and climate. Despite this dominance, we still lack reliable precursor signals triggering nonlinear initiation of primary MJO events. Here for the first time, we deal with this question from the point of view of nonlinearity, with successful implementation of conditional nonlinear optimal perturbation (CNOP). Our results show that relative to random perturbations, CNOPs of moisture have the most potential to trigger the strongest primary MJO events more than 15–20 days in advance from the given non-MJO reference states. The CNOPs manifest as a moist equator and aggregate in the lower troposphere, with stronger signals over the western Indian Ocean than over the eastern one. These CNOPs can also capture the observational moist precursor conditions of primary MJO events. This work also implies the necessity of utilizing nonlinear optimal moist initialization in subseasonal predictions.

Plain Language Summary As a dominant intraseasonal (20–90 days) variability prevailing in the tropics, the Madden-Julian Oscillation (MJO) casts significant impacts on global weather and climate. However, we still lack reliable precursor signals for MJOs initiating over the western Indian Ocean, especially for primary events, that is, those without an immediately preceding MJO event. Here for the first time, we deal with this topic from the point of view of nonlinearity, with the successful implementation of conditional nonlinear optimal perturbation (CNOP). In particular, we find that our CNOPs can identify the optimal precursors of primary MJO initiation. We examined four non-MJO reference states, selected based on both circulation- and convection-based MJO indices. Although different reference states produce different CNOPs, all tend to manifest as a moist equator and aggregate in the lower troposphere, with stronger signals over the western Indian Ocean than over the eastern Indian Ocean. These CNOP-type moist precursor conditions are also found preceding the onset of observed primary events. We find that, relative to random perturbations, CNOPs of moisture have the most potential to trigger the strongest MJO event more than 15–20 days in advance. This work implies the necessity of utilizing nonlinear optimal moist initialization to improve subseasonal (15–60 days) predictions.

1. Introduction

A remarkable feature of tropical mesoscale cloud clusters is their tendency to be organized as slowly eastward propagating (~5 m/s) convective envelopes at a planetary scale (Nakazawa, 1988). This phenomenon is known as the Madden-Julian Oscillation (MJO; Madden & Julian, 1971, 1972). Widely recognized as the dominant intraseasonal (20–90 days) variability prevailing over the tropics (Zhang, 2005), the MJO can cast significant impacts not only on tropical systems but also on a variety of climate phenomena across different spatial and temporal scales. These phenomena include (1) modulating the occurrence of extreme weather (Ren et al., 2018; Ren & Ren, 2017; Xavier et al., 2014), (2) affecting the onsets and breaks of global monsoon systems (Wang, Liu, et al., 2017; Zhou & Chan, 2010), (3) interacting with the extratropics by exciting Rossby wave train and teleconnection (Henderson et al., 2017; Jones et al., 2004), and (4) contributing to the life cycle of El Niño events (McPhaden, 1999). The successful prediction of the MJO, which bridges weather and climate (Zhang, 2013), is thus invaluable for saving and improving human lives around the world.

The MJO has intrigued scientific communities since it was first documented. Over the past four decades of scientific pursuit, the MJO has become well understood as an equatorially trapped, unstably initiating,
planetary-scale circulation system (Li & Zhou, 2009; Wei et al., 2017), coupled with a multiscale convective complex (Majda & Biello, 2004), moving eastward slowly with a rearward-tilted (Kiladis et al., 2009), mixed Kelvin-Rossby wave structure (Chen & Wang, 2018a; Wang et al., 2018; Wang & Chen, 2016). In spite of significant progress in simulating and predicting the MJO, there are still numerous long-standing, fundamental, yet unresolved scientific questions about the MJO. One of the most challenging and least studied among these is the identification of the optimal precursors that trigger the initiation of large-scale, organized, eastward propagating, deep convection of the MJO over the western Indian Ocean (Ling et al., 2017). Building on previous works, two major schools of thought have developed as follows. The first school considers the triggering of MJO initiation to arise exclusively from tropical dynamic and thermodynamic processes, including regeneration from upstream circumnavigating Kelvin waves (Lau & Peng, 1987; Sakaeda & Roundy, 2015, 2016; Zhang et al., 2017); the recharge of moist static energy through localized nonlinear interaction among radiation, convection, and evaporation (Bladé & Hartmann, 1993; Kembel-Cook & Weare, 2001; Maloney & Wolding, 2015); air-sea interactions (Fu & Wang, 2004; Li et al., 2008; Rydbeck & Jensen, 2017; Rydbeck et al., 2017; Webber et al., 2010, 2012); and downstream Rossby wave dynamic effects (Li et al., 2015; Wang et al., 2005; Zhao et al., 2013). The second school emphasizes the critical role of tropical-extratropical interaction (Hsu et al., 1990; Ray et al., 2009; Ray & Zhang, 2010).

A consensus on the essential mechanisms for MJO initiation has not yet been reached. One possible reason for the lack of agreement is the intrinsic diversity and sporadic nature of the MJO. Each MJO event can be classified as either primary, that is, with no immediately preceding MJO event, or successive, that is, immediately following a preceding event (Matthews, 2008). Unlike the smooth variation of the real-time multivariate MJO (RMM) index (Wheeler & Hendon, 2004) throughout both the initiation and development in successive MJO events, a fast, localized growth of the composite RMM index always occurs prior to the eastward propagation of primary events (e.g., Figure 4 in Ling et al., 2013, and Figure 6 in Straub, 2013). A new MJO is then triggered after sufficient predestabilization, possibly by the advective moistening processes associated with equatorial wave dynamics (Zhao et al., 2013) and/or three-way interaction among radiation, evaporation, and convection (Bladé & Hartmann, 1993). This kind of sudden initiation from non-MJO states strongly suggests that some nonlinear processes play important roles. Thus, the linearized theoretical framework has previously experienced difficulty in simulating MJO initiation that occurs without a strong predecessor signal (e.g., Adames & Kim, 2016; Wang & Chen, 2016; Wang, Wei, et al., 2017; Wei et al., 2017). This may be a result of linear models’ omission of key components of MJO initiation and amplification that have not yet been identified. However, nonlinear processes are perhaps critical to primary MJO initiation and linear models should not be expected to perform well under these circumstances. Consequently, a new nonlinear framework methodology is urgently needed to study the initiation of MJO events, especially that of primary MJO events.

This study aims to demonstrate that primary MJO events can be triggered in a process of nonlinear optimal moist initialization. Roles of moist processes have been shown to be essential in initiating (e.g., Li et al., 2015; Zhao et al., 2013) and maintaining the MJO (e.g., Adames & Kim, 2016; Hsu & Li, 2012; Sobel & Maloney, 2012, 2013) and also in improving subseasonal to seasonal prediction (e.g., Ham et al., 2012; Ren et al., 2016). Our efforts will be devoted to mathematically identifying moist optimal precursors that trigger primary MJO initiation in a coupled global climate model (CGCM). Benefiting from this advanced CGCM, we have developed a new nonlinear framework methodology to study the initiation of the MJO. In this work, the key accomplishment is the successful implementation and application of “conditional nonlinear optimal perturbation” (CNOP), a technique proposed by Mu et al. (2003).

In section 2, we introduce the data and model used in this paper. Section 3 describes a new nonlinear methodological framework for studying primary MJO initiation. The results are provided in section 4, and the final section gives a brief summary and discussion of this research.

2. Data and Model

2.1. Data

To measure convective activity, we use the daily mean outgoing longwave radiation (OLR) interpolated from the National Oceanic and Atmospheric Administration’s Advanced Very High Resolution Radiometer satellite (Liebmann & Smith, 1996). The daily mean winds and specific humidity are from the reanalysis project of the National Centers for Environmental Prediction/the National Center for Atmospheric Research.
(Kalnay et al., 1996). The time period analyzed herein is from 1979 to 2013. All data sets have been interpolated to horizontal resolution of 2.5° × 2.5° before analysis. For simplicity, we refer to them as “observations” throughout this paper.

2.2. The Hybrid CGCM

The model used in this study is a hybrid CGCM (Fu & Wang, 2004). The atmospheric component is the standard T42 version of the ECHAM-4 model (Roeckner et al., 1996), which resolves 19 vertical layers extending from the surface to 10 hPa. The oceanic component is a tropical upper ocean model of intermediate complexity (Fu & Wang, 2001). The ECHAM-4 model was coupled with the ocean model once per day by exchanging surface heat fluxes, surface wind stress, and sea surface temperature over the tropical global ocean without heat flux corrections. A 30-year free run was carried out and is analyzed below. The CGCM shows substantial capability in simulating the ocean without heat flux corrections. A 30-year free run was carried out and is analyzed below. The CGCM shows substantial capability in simulating the ocean without heat flux corrections.

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3. A New Methodological Framework for Studying Primary MJO Initiation

After some unsuccessful attempts to derive suitable linear solutions, we have directly chosen the nonlinear method, that is, CNOP (Appendix A). Using a CNOP framework, we constructed MJO initiation as a unified nonlinear optimization problem. We first identified eight non-MJO reference states (NMRSs; Appendix B), half of which were randomly chosen for examination in this study. Each NMRS has a 42-day duration, with very weak (<1) index values for both the OLR-based MJO index (OMI; Kiladis et al., 2014) and the RMM index. Neither convection nor circulation displays an organized, large-scale, eastward-propagating MJO signal. It is noteworthy that this kind of convective initiation from non-MJO to MJO event, if any, must be primary (Ling et al., 2013; Straub, 2013).

To find optimal precursors mathematically, an indicator must be constructed in advance to (i) clearly distinguish non-MJO and MJO events and (ii) measure the strength of the triggered MJO events. Taking advantage of the 42-day power spectra of convection and circulation, an indicator can be formulated as follows:

\[ I = \sum_{i=1}^{4} \rho_i \iint_{\Omega_{MJO}} P_i(\omega, k) \, dk \, d\omega, \]

where \( i = 1, 2, 3 \) denotes OLR, 850-hPa zonal wind (U850) and coherence square between them, respectively. \( \rho_i \in [0, 1] \) is the weight coefficient. Here we take \( \rho_1 = \rho_2 = \rho_3 = 1/3 \), which guarantees a more precise definition of MJO initiation that further considers the tight coupling between circulation and convection. \( P_i(\omega, k) \) is power variance at frequency \( \omega \) and wavenumber \( k \). \( (\omega, k) \in \Omega_{MJO} = [1/100, 1/20] \times [0, 3] \), which outlines the spatiotemporal range of the eastward propagating MJO signal. To satisfy the additivity requirement, prenormalization is necessary. \( \pi_i \) is the standard deviation of the total power spectrum in \( \Omega_{MJO} \). Remarkably, under the “perfect model” assumption, \( I \) is totally controlled by the initial conditions of each individual NMRS.

To identify the optimal moist precursors, we let \( q_0 \) be the initial specific humidity of the prechosen reference state and \( q_0 \) a finite-amplitude disturbance of \( q_0 \), that is, \( \|q_0\| \leq \delta \). We term “ctr” and “per” as the respective numerical integrations initiated from \( q_0 \) and from \( q_0 + q_0 \). Contributions of initial moist perturbations to the MJO can be derived as follows:

\[ J = J(q_0) = I_{\text{per}}(q_0 + q_0) - I_{\text{ctr}}(q_0) \]

From equation (2), a stronger MJO event must correspond to a larger value of \( J \). Thus, searching for the optimal moist precursors \( q_0 \) that triggers the strongest primary MJO initiation can be generalized as the following unified nonlinear optimization problem:
Equation (3) tells us that the moist optimal precursor should be the global optimal point in the feasible region \( \{ q_0^\prime \mid \| q_0^\prime \| \leq \delta \} \), that is, CNOP.

Upon obtaining the CNOP of each given NMRS, we performed three reforecasts: The first run (“Control run”) began with unperturbed initial conditions, the second run (“CNOP run”) had CNOP-perturbed initial conditions, and the third run (“RP run”) was initialized with random perturbations. To facilitate comparison, we scale any random perturbations to have the same norm as the CNOPs. The role of CNOP in triggering primary MJO initiation was then revealed by comparing the three runs.

### 4. Results

#### 4.1. CNOPs and Observational Evidence

In this section, we first discuss the three-dimensional (3-D) structures of the CNOPs in all four cases. To demonstrate the ability of CNOPs to capture the “true” precursor conditions of primary MJO initiation, we then search for these signals in observational data.

In general, the 3-D distributions of CNOPs (Figure 1) show that different NMRSs produced different CNOPs, which implies that different MJO events should have distinctive preceding optimal initial perturbations. Despite the different patterns overall, all CNOPs tend to be wet along the equatorial Indian Ocean but dry away from the equator. The strongest signals aggregate over the lower troposphere, with stronger perturbations in the equatorial western Indian Ocean (WIO) than in eastern Indian Ocean (EIO). To search for these signals from observations, we calculated the Hovmöller diagrams of the equatorially averaged (10°S...
to 10°N), 20- to 90-day bandpass-filtered OLR (contour in watts per square meter) and 850-hPa specific humidity (shading in grams per kilogram) anomalies using the 23 observed primary MJO events. The solid (dashed) contour is from 5 (−5) W/m² at intervals of 5 W/m². The thin black contour denotes the zero values. The two magenta lines outline the zonal region for calculating the conditional nonlinear optimal perturbations. The dotted area and contours represent results passing Student’s t test at the 95% confidence level. The x axis is longitude (in degrees), while the y axis is lead time (in days). (b) Composite RMM2 index of observed primary Madden-Julian Oscillation events. The x axis is RMM2, while the y axis is lead time (in days). OLR = outgoing longwave radiation; RMM = real-time multivariate MJO; SHUM = specific humidity.

Figure 2. (a) Composite Hovmöller diagrams of equatorially averaged (10°S to 10°N), 20- to 90-day bandpass-filtered OLR (contour in watts per square meter) and 850-hPa specific humidity (shading in grams per kilogram) anomalies using the 23 observed primary MJO events. The solid (dashed) contour is from 5 (−5) W/m² at intervals of 5 W/m². The thin black contour denotes the zero values. The two magenta lines outline the zonal region for calculating the conditional nonlinear optimal perturbations. The dotted area and contours represent results passing Student’s t test at the 95% confidence level. The x axis is longitude (in degrees), while the y axis is lead time (in days). (b) Composite RMM2 index of observed primary Madden-Julian Oscillation events. The x axis is RMM2, while the y axis is lead time (in days). OLR = outgoing longwave radiation; RMM = real-time multivariate MJO; SHUM = specific humidity.

The results showed that 23 of 49 events are clearly preconditioned by a moisture anomaly. The composite of these 23 events (Figure 2) shows that preceding the onset of large-scale, eastward propagating, deep convection, a significant moisture signal originates from the EIO and moves toward the WIO. Since day −10, this moisture signal tends to be reflected near eastern Africa. Then it continuously moves eastward and triggers primary MJO initiation at day −5. In addition, there also exists a small, localized, narrow, and suppressed convection over the EIO at day −15, which may also play a role in initiating the MJO through a midtropospheric, cooling-induced, predestabilization effect (Matthews, 2008). The horizontal structure of q850 and the vertical distribution of specific humidity have been also diagnosed (Figures S4 and S5). Together, the above findings demonstrate the existence, well captured by the CNOPs, of significant moisture anomalies aggregating in the lower troposphere over eastern Africa and the WIO.

4.2. CNOPs Triggering Primary MJO Initiation

Despite displaying distinctive 3-D structures, all the CNOPs tend to trigger a similar spatiotemporal variance pattern, especially over Ω_{MJO}. This pattern is illustrated by the composite zonal wavenumber-frequency spectra of both convection (OLR) and circulation (U850) in Figure 3. As expected, both the Control run
and RP run show very weak power spectral variance, and the westward signal is comparable with the eastward one. However, when the nonlinear optimal moist initialization with the CNOPs is included, the variances of convection and circulation associated with the eastward propagating MJO increase intensely, leaving a largely reduced westward signal. In a further difference from the Control and RP runs, the CNOP run’s $\Omega_{MJO}$ shows a strong variance of the coherence square between OLR and U850, which implies that strong coupling between convection and circulation has been also triggered by the CNOPs.

To demonstrate the triggering of primary MJO initiation, we also investigated the phase diagram of the RMM index (Figure S6). The results show that, in contrast to the RMM index’s small growth in the Control and RP runs, the CNOP run’s RMM index increased quickly and crossed the unit circle after 15–20 days of development, which is a typical initiation of primary MJO events (Ling et al., 2013; Straub, 2013).

The triggering of primary MJO initiation can be observed more clearly from the time-longitude sections of OLR and U850 (Figures 4a–4c). During the first 10 days, the perturbations in the three runs show very weak power spectral variance, and the westward signal is comparable with the eastward one. However, when the nonlinear optimal moist initialization with the CNOPs is included, the variances of convection and circulation associated with the eastward propagating MJO increase intensely, leaving a largely reduced westward signal. In a further difference from the Control and RP runs, the CNOP run’s $\Omega_{MJO}$ shows a strong variance of the coherence square between OLR and U850, which implies that strong coupling between convection and circulation has been also triggered by the CNOPs.

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similar patterns. After days 10 to 15, the results start to diverge. The differences increase with lead time. After days 25 to 30, an organized, large-scale, slowly eastward propagating, convectively coupled, primary MJO event is triggered only in the CNOP run. In contrast, for the Control run and RP run, as implicated by their small index evolutions, there are only very weak and unorganized anomalies. This distinction with respect to random perturbations demonstrates the power of nonlinear fast growth of the CNOPs in triggering the strongest primary MJO event from a given NMRS. A strong, new, primary MJO event is also triggered by the CNOPs in other NMRSs (Figures 4d–4l), although the initiation time, strength, duration, and phase speed are somewhat different, reflecting MJO diversity and dependence on basic flow (Lorenz, 1965).

5. Conclusions and Discussion
A newly developed nonlinear methodological framework was applied to identify the optimal precursors triggering primary MJO initiation. This framework mathematically identified optimal precursors from the four prechosen NMRSs using a hybrid CGCM that can accurately simulate observed primary MJO events and a novel concept of CNOP. In this new framework, searching for the optimal precursors of primary MJO initiation can be generalized as solving for optimal solutions, that is, CNOPs, of a unified constraint nonlinear optimization problem.

Our results show that although different CNOPs have been found in different NMRSs, they tended to manifest as a moist equator and aggregate over the lower troposphere, with stronger signals in the WIO than in the EIO. Preceding the initiation of observed primary MJO events, we found significant lower-tropospheric moisture signals moving toward the equatorial WIO, implying the key role of moisture-convection feedback while demonstrating the true-to-life quality of the CNOPs. The GCM reforecast experiments show that CNOPs have the most potential to initiate the strongest primary MJO events from any given NMRSs, while random perturbations only induce a non-MJO or weak-MJO initiation.

CNOPs trigger a new primary MJO event after a development of more than 15–20 days, which may imply that we can predict the onset of primary MJO initiation more than 15–20 days in advance, if the CNOPs are implemented in the initial conditions. Comparing the linear and nonlinear evolutions of CNOPs, we found that nonlinear growth is always dominant on the 20- to 90-day intraseasonal timescale (see Text S2, Figure S7, and Table S1). This finding may suggest the necessity of utilizing nonlinear optimal moisture initialization in subseasonal (15- to 60-day timescale) prediction.

Under the conditions of limited computational resources and as a preliminary application of this new methodological framework, we examined only humidity field with limited vertical levels and four NMRSs. In addition, we eschewed the problem of identifying the dominant physical processes that control the nonlinear growth of CNOPs. These issues deserve in-depth study, which will be part of our future work.

Appendix A

We write the evolution equations for the state vector $U$, which may represent wind, specific humidity, temperature, etc., as follows

\[
\begin{align*}
\frac{\partial U}{\partial t} &= F(U, P) \\
U|_{t=0} &= U_0
\end{align*}
\]  

(A1)

where $U_0$ is the initial state, $P$ is model parameter that is independent with time $t$, and $F$ is a nonlinear differential operator. Assuming that equation (A1) is well defined, the solution to equation (A1) for the state vector $U$ at time $\tau$ is given by

$$U(\tau) = M_\tau(P)(U_0).$$  

(A2)

Here $M_\tau(P)$ is the propagator of equation (A1) with the parameter $P$ and “propagates” the initial value $U_0$ to the time $\tau$ in the future. Now we consider the situation in which there exist both initial perturbation $u_0$ and parameter perturbation $p'$ in equation (A2). Then we have
where \( u(u_0, p' ; \tau) \) is the departure from the reference state \( U(\tau) \) caused by the combined error mode \((u_0, p')\). A nonlinear optimization problem is defined as follows.

\[
J(u_0; p' \in C_0/C_1) = \max_{u_0 \in C_0, p' \in C_1} \left| M_1(P + p')(U_0 + u_0) - M_1(P)(U_0) \right|, \tag{A4}
\]

and

\[
J(u_{05}; p' \in C_2) = \max_{u_0 \in C_1, p' \in C_2} J(u_0; p'). \tag{A5}
\]

Here \( u_0 \in C_\delta \) and \( p' \in C_\sigma \) are, respectively, the constraint conditions of the initial perturbation and parameter perturbations, where \( C_\delta \) and \( C_\sigma \) are closed and \( \delta \) and \( \sigma \) distinguish the constraints of initial perturbation and parameter perturbation. The optimal combination mode of initial perturbation and parameter perturbation, that is, \((u_{05}; p'_{\sigma})\), of the constrained maximization problem (A5) is called the CNOP (Mu et al., 2010).

In this work, we consider the perfect model assumption, that is, \( p' = 0 \). In this case, the optimization problem is reduced to

\[
J_{u_0}(u_{05}) = \max_{u_0 \in C_1} \left| M_1(P)(U_0 + u_0) - M_1(P)(U_0) \right|. \tag{A6}
\]

The initial perturbation \( u_{05}^I \) satisfying equation (A6) is just the CNOP defined in Mu et al. (2003).

Appendix B

The NMRSSs have been selected based on both the RMM and OMI indices. First, the RMM amplitude is calculated. To facilitate selection, we use a 5-day running mean to remove high-frequency variability. Second, we identify day 0 when the amplitude reaches its minimum. Third, the amplitudes from day 0 to day 31 should be smaller than a prescribed threshold of one standard deviation. In some scenarios, however, the convection may be still active, albeit with a weak RMM index (Straub, 2013). Thus, the 5-day running mean OMI is also examined to adjust the weak event selected by the RMM index. To be specific, we have removed those events that continuously maintain a high-amplitude (>1) OMI lasting for more than 10 days. In the present article, we focus solely on the extended boreal winter from 15 October to 15 May.

Appendix C

To improve computational efficiency, an EOF-based strategy is carried out to reduce the model dimensionality. We assume that the role of low-frequency basic state (> 90 days) is minor in triggering the large-scale, deep convection initiation on intraseasonal time scales (20 to 90 days). The variance of the 90-day highpass-filtered specific humidity prefers the Indo-Pacific region and aggregates over the lower atmosphere (500–1,000 hPa). Considering that MJO events are often initiated over the equatorial Indian Ocean (Matthews, 2008), we choose that precise region for the extraction of possible precursor signals, in particular the lower-level, equatorially symmetric Indian Ocean from 15°S to 15°N, from 40°E to 110°E, tiered vertically at 1,000, 925, 850, 700, 600, and 500 hPa. The EOF results demonstrate that the first 50 PCs can explain more than 80% of the total variance. Most of them can pass the North test (North et al., 1982) and thus are well separated. Any initial perturbation can be expanded orthogonally by the first 50 EOF modes

\[
q'_0 \approx \sum_{i=1}^{50} \lambda_0^i e_i, \tag{C1}
\]

where \( \lambda_0^i \) is the initial time coefficient disturbance corresponding to the \( i \)th EOF mode \( e_i \).
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References
Chen, G., & Wang, B. (2018b). Does the MJO have a westward group velocity? Journal of Climate, 31(6), 2435–2443. https://doi.org/10.1175/JCLI-D-17-0446.1


