Further exploration of MJO initiation events and precursors as revealed by an MJO-like dynamical mode

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ABSTRACT

The Madden Julian Oscillation (MJO) is a tropical phenomenon that develops over the Indian Ocean as a large area of convection approximately 1000km across. This intraseasonal oscillation affects both weather and climate in extratropical regions, where most of the world’s population resides. However, computational models do not represent the MJO adequately, and the scientific community has turned its attention to the MJO’s initial stages. This research studies Primary MJO events (those arising in the absence of a pre-existing MJO signal) identified by four methods developed by previous researchers. Two of the methods focus mainly on precipitation while the other two focus on circulation. A multivariate MJO-like dynamical mode, obtained from unfiltered five-day-mean gridded data, was used to visualize the events during the 1998-2009 boreal winters. The contributions made to the MJO-like mode by the following variables were analyzed: outgoing long-wave radiation (OLR), sea level pressure (SLP), mid-tropospheric temperature ($T_{400}$), and upper- and lower-level zonal winds ($u_{200hPa}$ and $u_{850hPa}$). The mode was able to depict typical eastward-propagating events, and it was also able to show westward-propagating and non-propagating events seen by other researchers. In addition, the mode depicts extratropical interactions and the areas of suppressed convection preceding events, as noted by previous studies. However, the mode did not represent the convection of all of the selected events. The study shows that the multivariate MJO-like dynamical mode was able to capture the complexity of MJO events, making it a useful tool for future MJO studies.

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1. Introduction

The tropical phenomenon of the Madden-Julian Oscillation (MJO) is an intraseasonal oscillation with a frequency of 1/40 to 1/50 days\(^{-1}\) that develops over the equatorial Indian Ocean between \(\sim 10^\circ\)N and 10\(^\circ\)S (Madden and Julian 1971, 1972). The MJO’s initial stages consist of a large area of deep convection (\(\sim 1000\)km across) that propagates slowly eastward at a rate of \(\sim 5\) m/s (Yoneyama et al. 2013; Zhang 2005, 2013). The large region of deep convection releases latent heat in the mid troposphere; this in turn can force planetary-scale Rossby waves that travel in the upper atmosphere and in that manner alter weather and climate in the extra-tropics (Zhang 2013). As the MJO convection propagates eastward over the Maritime Continent, it begins to dissipate and disappears as it leaves the warm waters of the west Pacific Ocean (Zhang 2005).

Although the MJO’s initial stages include a convective phase, after dissipation, its circulation continues to travel in the upper atmosphere, sometimes circumequatorially. Furthermore, it is only possible for one fully developed MJO to exist in the tropics at a time.

Since its discovery by Madden and Julian (1971), many efforts have been underway to study and understand this phenomenon (e.g. Madden and Julian 1972; Wheeler and Hendon 2004). Most of the existing computational models do not do a good job at simulating the MJO (Feng et al. 2015; Haertel et al. 2015), therefore limiting the possibility for scientists to generate accurate forecasts, and limiting our understanding of both climate and weather associated with the MJO. Researchers have recently focused on the initiation phase of the oscillation to better understand what atmospheric processes are more preferable for MJO formation (e.g. the Dynamics of the Madden-Julian Oscillation (DYNAMO) field campaign (Yoneyama et al. 2013; Ling et al. 2013, hereafter Lzb13; Straub 2013, hereafter S13). However, there is no concrete agreement among the scientific community regarding which factors are considered to be more
influential for MJO initiation. Knowing how the MJO works can help us improve our computational models, which in turn can aid the scientific community in improving their forecasts and their understanding of both weather and climate on a global scale (Zhang 2013).

Previous work has shown that not every MJO event is the same, but the atmospheric conditions present during its development and propagation over time create unique events (Feng et al. 2015, hereafter FLZ15; LZB13; S13). A complete understanding of how the different variables (such as outgoing long-wave radiation and upper- and lower-level zonal winds, among others) behave during each MJO event’s initial stages is needed. Several methods have been proposed to identify MJO initiation, and three categories for identifying different types of MJOs have been developed: Primary, Successive or Intensifying, and Non-MJO (LZB13; S13; Feng et al. 2015). Primary events don’t have a pre-existing MJO signal, while the Successive or Intensifying events do. The Non-MJO cases were identified by LZB13 as events that begin over the Indian Ocean (IO) but do not propagate out of it. LZB13 found three atmospheric signals showing consistent behavior 10-20 days before MJO connective initiation and identified them as precursors: in the low-level zonal winds ($u_{850hPa}$), easterly anomalies extended over the western IO; in sea-level pressure (SLP), negative anomalies covered all the longitudes from South America to Africa, while the rest of the equatorial belt was dominated by positive SLP anomalies; and in $T_{400}$, negative anomalies in the middle to upper atmosphere, starting at the 400 hPa, appeared over the IO and were mostly confined to the equator.

Vargas and Hartten (2015, hereafter VH15) used lists of MJO initiation events obtained via four methods from S13 and LZB13 that identified MJO initiation events. Two methods focused on the circulation aspect of the MJO and the other two focused on the convective aspect of the oscillation. VH15 focused on four events identified as Intensifying and Non-MJO events
by the methods. The current study uses the same lists to explore several MJO initiation events identified as Primary events. Following VH15, through the use of a multivariate MJO-like dynamical mode of Hartten and Penland (described in more detail in section 2.b of this paper), this study analyzes multiple atmospheric variables and their patterns over time, both before and after the identified initiation dates.

2. Data and Methodology

The Realtime Multivariate MJO-index (RMM) developed by Wheeler and Hendon (2004), combines the precipitation (via outgoing long-wave radiation, OLR) and the circulation (upper- and lower-level zonal wind, u200 and u850) aspects of the oscillation to identify its genesis and propagation over time. VH15 selected events to study using event lists based on four methods created by LZB13 and S13: Ling et al., which uses daily rainfall data; Straub-OLR, which uses OLR; Straub-Full, which uses OLR, u200 and u850; and Straub-Circulation, which uses u200 and u850. The first two focused mainly on the convective aspect of the oscillation while the latter two focused mainly on the circulation. Since the four methods use different criteria to identify the events, they do not identify the same events on every occasion. This study also analyses the events’ precursor variables previously identified by LZB13: low-level (850 hPa) zonal winds, mid-tropospheric temperature (T400hPa) and sea level pressure (SLP).

LZB13 used daily rainfall data from the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis to identify the events. S13 used two data sets extracted from the National Centers for Environmental Prediction (NCEP)-U.S. Department of Energy (DOE) Reanalysis 2 dynamical fields and from the Advanced Very High Resolution Radiometer (AVHRR) OLR (Liebman and Smith 1996). For further information about their methodology
and data, refer to LZB13 and S13. As in VH15, the study focuses on the Boreal wintertime period from 1998-2009 since LZB13 only studied this time range.

a) Event Selection

The list of events used throughout this study was obtained from C. Zhang (personal communication, 2015), and S13 (Table 1), following the work done by VH15. VH15 selected 12 events by comparing the events identified by the 4 methods. The criteria used in VH15 for the event selection was that the events could not be further apart than 10 days from the LZB13 identification date. For this study, only events whose identified initiation dates were no more than 10 days apart from the initiation of the convection, as seen with the MJO-like mode, were selected. This study focuses on the four events (out of the initial twelve selected by VH15) identified as Primary by the methods (Table 1).

b) MJO-like Dynamical Mode

The events are studied using the MJO-like dynamical mode presented in Hartten and Penland (2016; hereafter HP16). The data used to identify the dynamical mode came from gridded analyses, 30°N-30°S, with 2.5 degree latitude x 2.5 degree longitude, horizontal resolution (Liebmann and Smith 1996; Kalnay et al. 1996). The data were not band-pass-filtered; only the long-term mean and annual cycle were removed, thus all Fourier frequencies represented in the data were retained. HP16 did an EOF analysis on five variables that have been identified as influential to the MJO’s initiation and propagation: OLR, SLP, mid-tropospheric temperature (T_{400}) and upper- and lower-level zonal winds (u_{200} and u_{850}). They used the highest EOF values of each variable for a Principal Oscillation Pattern (POP; von Storch 1988) analysis. This yielded 15 dynamical modes, one of which was MJO-like. It has time characteristics similar to the MJO, consisting of a period of 11
pentads (55 days) and a 3-pentad decay period (15 days). With the mode, each variable’s contribution can be viewed and analyzed separately, and an example of the OLR contribution to the mode is presented in Figure 1. The figure shows an idealized example of an MJO event, with the modal amplitudes being pure sine waves in quadrature showing an eastward propagation over time.

Table 1. The 4 Primary events that were selected from VH15’s 12 initial cases. The method that was used for identification purposes appears on the upper row and the event identification type appears in the first column. The initiation date for each event appears in the boxes and the identification type appears in a parenthesis, with (P) for Primary and (I) for Intensifying. Some of the methods did identify an event close to the 10 days that were used as criteria for event selection. These events printed in red. The Ling et al. method and Straub-OLR are thermodynamic methods (the convective part of the MJO is more prevalent) and the Straub-Full and Straub-Circulation are dynamical methods (the circulation part of the MJO is more prevalent).

<table>
<thead>
<tr>
<th>Type</th>
<th>Ling et al.</th>
<th>Straub-OLR</th>
<th>Straub-Full</th>
<th>Straub-Circulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>17-Jan-1999 (P)</td>
<td>4-Jan-1999 (P)</td>
<td>10-Jan-1999 (P)</td>
<td>11-Jan-1999 (P)</td>
</tr>
<tr>
<td>Primary</td>
<td>30-Oct-2009 (P)</td>
<td>28-Oct-2009 (P)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary or Intensifying</td>
<td>9-Jan-2006 (P)</td>
<td>29-Dec-2005 (P)</td>
<td>30-Dec-2005 (P)</td>
<td>10-Jan-2006 (I)</td>
</tr>
<tr>
<td>Primary or Intensifying</td>
<td>15-Dec-2006 (P)</td>
<td>19-Dec-2006 (P)</td>
<td>18-Dec-2006 (I)</td>
<td>18-Dec-2006 (I)</td>
</tr>
</tbody>
</table>

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Figure 1. Evolution of the OLR contribution to the MJO-like mode (theoretical case example, modal amplitudes are pure sine waves in quadrature). Each panel shows the equatorial belt 30N-30S. The values are anomalies (deviation from the long-term mean OLR). (Taken from VH15, Figure 1). Negative values represent areas of enhanced convection while the positive values represent areas of suppressed convection.

3) Precursor Variables’ Patterns

Through the use of the MJO-like dynamical mode each of the variables’ contribution to the event can be studied over time. In the MJO-like mode, an unorganized area of suppressed convection occurs over the Indian Ocean (IO) and Maritime Continent (MC) 5-15 days before convective initiation in all the events presented in this work. This observation was also made by VH15 for their Intensifying and Non-MJO events. The suppressed convection preceding Primary events is stronger than what was observed for Intensifying and Non-MJO events in VH15. The
area of suppressed convection preceding events will be discussed in the sections 4.a.1, 4.b.1, 4.c.1 and 4.d.1 of this paper.

For the Primary event on November 2009 (Figures 2-4) $u_{850}$ easterly anomalies (Figure 2) are observed to cover the IO from its west to east side on 15-Oct-2009, 20 days before convective initiation (4-Nov-2009). These easterlies become weaker in the following pentad (20-Oct-2009) and do not appear on 25-Oct-2009. The anomalies re-intensify on 30-Oct-2009, 5 days before convective initiation, and go on to be part of the zonal circulation once convection starts on 4-Nov-2009. Negative mid-tropospheric temperature signals (Figure 3) are not observed 10-20 days before convective initiation. However, off-equatorial cold anomalies do appear across the longitudes extending over the IO on 30-Oct-2009, one pentad before convective initiation. In Figure 4, positive SLP anomalies extend over the longitudes from South America to Africa and negative anomalies cover the rest of the equatorial belt over the 10-20 day period preceding convection.

The observations in $u_{850}$ for the Primary event on November 2009 (Figure 2) agree with those proposed by LZB13. While there is not a $T_{400}$ signal for the event in the 10-20 day window (Figure 3) as seen in LZB13, cold anomalies still precede it. The SLP anomalies for this event (Figure 4) show opposite behavior from that observed by LZB13.
Figures 2 and 3. Five-day mean (pentad) precursor contribution of anomalous $u_{850}$ (Figure 2) and $T_{400}$ (Figure 3) to the MJO-like dynamical mode for the event on November 2009 (both figures show four pentads before convective initiation on 4-Nov-2009).

Figure 4. Five-day mean (pentad) precursor contribution of anomalous SLP to the MJO-like dynamical mode for the event on November 2009 (figure shows four pentads before convective initiation on 4-Nov-2009). Negative anomalies represent low pressure and positive anomalies represent high pressure.
The January 2006 event (Figures 5-7), identified by the methods as Primary or Intensifying, easterly \( u_{850} \) anomalies (Figure 5) appear over the IO on 29-Dec-2005, around 10 days before convective initiation (8-Jan-2006). These anomalies, however, are towards the center of the IO and do not extend completely into the western part of it. These easterly anomalies intensify the following pentad (3-Jan-2006) and extend over all the longitudes covering the IO and parts of the MC. The \( T_{400} \) contribution preceding MJO convection (Figure 6) remains quiet in the 10-20 day time range. However, strong cold temperature anomalies appear over the IO and part of the MC (off-equatorially) around 5 days before convective initiation. This event is peculiar in the SLP precursor contribution (Figure 7). On the fourth pentad preceding MJO convection (19-Dec-2005), an area of negative SLP anomalies extends over the longitudes from South America to Africa, and positive SLP anomalies cover the rest of the equatorial belt.

For the January 2006 event, identified by the methods as Primary or Intensifying, \( u_{850} \) anomalies (Figure 5) did appear over the area of interest within the time range indicated by LZB13. The observations in the negative \( T_{400} \) precursor (Figure 6) did not agree with LZB13, as they do not appear 10-20 days before convective initiation over the IO. The SLP precursor (Figure 7) for the January 2006 event is the only SLP precursor studied in this work that is consistent with LZB13’s observations. The OLR contribution for that specific pentad shows convection appearing over the MC. The negative SLP anomalies could be a product of this convective pop-up rather than a consistent precursor signal. There is also a small south-equatorial maximum anomaly over the MC in that pentad.
Figure 5 and 6. Same as Figures 2 and 3 but for the event that initiated on 8-Jan-2006.

Figure 7. Same as Figure 4 but for the event that initiated on 8-Jan-2006.
For the January 1999 Primary event (Figures 8-10), strong $u_{850}$ easterly anomalies (Figure 8) extend over the IO and parts of the MC on 13-Jan-1999, around 10 days before the small convective signal appears over the IO (23-Jan-1999). The anomalies for this event are stronger than those seen in most of the other studied events. These anomalies dissipate the following pentad and are not present on the day of convective initiation. Strong off-equatorial $T_{400}$ anomalies (Figure 9) appear around 10 days before the initial convective signal across the longitudes of the IO (13-Jan-1999). As with the $u_{850}$ anomalies, the negative temperature signals dissipate the next pentad and then do not show up on the pentad with the convective signal (23-Jan-1999). The equatorial belt is dominated by positive SLP anomalies extending from South America to Africa 10-20 days before the convective initiation over the IO (Figure 10). In the 13-Jan-1999 pentad, there is an area of strong positive anomalies extending over the longitudes of the IO, MC and WPO. These anomalies are not only located in the Southern Hemisphere, but extend into the Northern Hemisphere over the longitudes of the MC and WPO. These anomalies dissipate the next pentad and do not appear on the pentad of convective initiation.

The observations in $u_{850}$ (Figure 8) for the January 1999 Primary event are inconsistent with LZB13’s observations of zonal winds that went on to be part of the zonal circulation of the oscillation. The behavior in $T_{400}$ (Figure 9) agree with that observed by LZB13, but the observations in the SLP precursor (Figure 10) disagree with those made by LZB13.
Figures 8 and 9. Same as Figures 2 and 3 but for the event that initiated on 23-Jan-1999.

Figure 10. Same as Figure 4 but for the event that initiated on 23-Jan-1999.
The precursor signals for the December 2006 event (Figures 11-13), identified by the methods as Primary or Intensifying, will be discussed as an individual case whose convective initiation began on 9-Dec-2006. This event follows very closely in time the November 2006 event, more information about the event will be presented in Section 3.b.iv of this paper (for more information regarding the precursors for the November 2006 event refer to VH15). For the December 2006 event investigated here, easterly \( u_{850} \) anomalies (Figure 11) are observed over the eastern IO and the MC on 19-Nov-2006, 20 days before convective initiation (9-Dec-2006). The anomalies dissipate by the pentad before convective initiation (4-Dec-2006) and then re-intensify over a greater area of the IO, MC and south WPO. Cold \( T_{400} \) anomalies are observed over the IO, MC and WPO longitudes 20 days before convective initiation (Figure 12). These negative anomalies occur off-equatorially and dissipate before the event. On the pentad of convective initiation these anomalies re-appear over a broader latitude range, similar to that observed in the \( u_{850} \) contribution. The dominating SLP anomalies preceding the event are positive over most of the equatorial belt (Figure 13). The only pentad before the convective initiation where negative and positive anomalies are more balanced is 29-Nov-2006.

The \( u_{850} \) observations for the November 2006 event, identified by the methods as Primary or Intensifying, (Figure 11) did not agree with the behaviors observed by LZB13 for the \( u_{850} \). The observations in \( T_{400} \) (Figure 12) partially agree with those presented in LZB13, as they said that the anomalies are confined to the equator. The observations in SLP for this event (Figure 13) did not agree with those in LZB13.
Figure 11 and 12. Same as Figures 2 and 3 but for the event that initiated on 9-Dec-2006.

Figure 13. Same as Figure 4 but for the event that initiated on 9-Dec-2006.
4) Event Evolution

Through the MJO-like dynamical mode each variables’ contribution to the event will be traced and studied over time, analyzing the OLR, SLP, T\textsubscript{400} and u\textsubscript{200} and u\textsubscript{850} contributions. In the upcoming sub-sections, events will be studied individually. Two of the events show a classic eastward progression while the other two show more out-of-the-ordinary behavior.

a) November 2009 Event

The November 2009 event was identified by the two thermodynamic methods: by LZB13 as a Primary event starting on 30-Oct-2009, and by Straub-OLR as a Primary event with a start on 28-Oct-2009. The dynamical methods were unable to identify the event.

1) OLR Contribution

This event (Figure 14) shows a textbook-like convective evolution over time. An organized center of negative OLR anomalies appears over the IO on 4-Nov-2009. The event remains over the IO for the next two pentads and then begins to propagate eastward. As it moves over the Maritime Continent (MC), it re-intensifies. The convection then continues to propagate eastward, dissipates and has its eventual decay on 4-Dec-2009. An area of suppressed convection extends over the IO and MC appears on 30-Oct-2009, one pentad before convective initiation (4-Nov-2009). This area of suppressed convection has an eastward propagation similar to that of the convection.

2) SLP Contributions

Positive SLP anomalies appear over the IO, MC and West Pacific Ocean (WPO) on 30-Oct-2009 (Figure 15), one pentad before the convective initiation. The positive anomalies move eastward during the next pentad (4-Nov-2009) and intensify. on 9-Nov-2009, one pentad after convective initiation, the positive SLP anomalies are replaced by
an area of negative SLP anomalies. On 19-Nov-2009 the negative SLP anomalies intensify and extend closer to the equator. The maximum SLP anomalies appear to be mainly concentrated in the Southern and Eastern Hemisphere (rarely cross the date line).

3) $T_{400}$ Contributions

Negative temperature anomalies appear on 30-Oct-2009 over the IO and MC (Figure 16), one pentad before convective initiation (4-Nov-2009). The anomalies intensify and propagate eastward. $T_{400}$ anomalies are largest during the convective initiation with the cold anomalies extending over the IO, MC and WPO. Three pentads after the convective initiation, positive $T_{400}$ anomalies appear over the IO on 19-Nov-2009. These positive anomalies have a weak eastward propagation and dissipate before passing the MC. Most of the anomalies occur towards the Western Hemisphere. All the $T_{400}$ anomalies are off-equatorial.

4) $u_{200}$ and $u_{850}$ Contribution

The upper- and lower-level zonal winds ($u_{200}$, Figure 17; $u_{850}$, Figure 18) follow the OLR behavior throughout the event. The divergence (convergence) in $u_{200}$ ($u_{850}$) occurs where the enhanced negative OLR appears, and convergence (divergence) occurs around the suppressed OLR. The zonal winds show an eastward progression during the event, as expected after seeing the OLR contribution.
Figure 14. Five-day mean (pentad) contribution of anomalous OLR to the MJO-like dynamical mode for the November 2009 event. Each panel constitutes the equatorial belt from 30N-30S with negative anomalies representing enhanced convection and positive anomalies representing suppressed convection. The figure depicts a textbook-like example of the MJO propagation over time, with convection starting on 30-Oct-2009.
Figure 15. Five-day mean (pentad) contribution of anomalous SLP to the MJO-like dynamical mode for the November 2009 event. Each panel constitutes the equatorial belt from 30N-30S with negative anomalies representing low pressure and positive anomalies representing high pressure.
Figure 16. Five-day mean (pentad) contribution of anomalous $T_{400}$ to the MJO-like dynamical mode for the November 2009 event. Each panel constitutes the equatorial belt from 30N-30S with negative anomalies representing cold mid-tropospheric temperatures and positive anomalies representing warm mid-tropospheric temperatures.
Figures 17 and 18. Five-day mean (pentad) contribution of anomalous $u_{200}$ (Figure 17) and $u_{850}$ (Figure 18) to the MJO-like dynamical mode for the November 2009 event. Each panel constitutes the equatorial belt from 30N-30S with negative anomalies representing easterly zonal winds and positive anomalies representing westerly zonal winds.
b) January 2006 Event

This event also shows textbook-like convective evolution of the MJO-like dynamical mode. The two thermodynamic identification methods, LZB13 and S13 OLR, both identified the event as Primary, and identified it under the guidelines (within 10 days of convective initiation). The other two methods also identified a Primary event close to this time, but more than 10 days before or after the convective initiation.

1) OLR Contribution

This event (Figure 19) shows a similar behavior to that seen in the theoretical example presented in Section 2.b (Figure 1). The convective phase of the MJO initiates over the IO (8-Jan-2006), intensifies, and shows a clear eastward progression over the MC and then over the WPO. The only pentad that appears to be inactive is that on 18-Jan-2006, but then the event re-intensifies over the MC. The event has a life period of around 8 pentads (40 days) with its convective dissipation happening around 12-Feb-2006. An area of suppressed convection appears on the mode 10 days before convective initiation, mostly distributed over the IO but also covering some areas of the MC. The positive OLR anomalies intensify the next pentad with its major organization over both the IO and MC. Such an area of suppressed convection was previously observed by LZB13, VH15, Haertel et al. (2015), and Sakeda and Roundy (2015).

2) SLP Contribution

SLP anomalies have a similar behavior to that observed in VH15, with most of the SLP anomalies occurring off-equatorially (Figure 20). In this event, positive SLP anomalies appear south of the equator over parts of the IO, MC and WPO, a pentad before convective initiation (just as did the T_{400}) on 3-Jan-2006. Negative SLP anomalies
appear over the IO, MC and WPO as the convection begins to propagate eastward. Strong positive SLP anomalies appear over the majority of the IO and central WPO at the time of decay on 2-Feb-2006.

3) T_{400} Contribution

The T_{400} behavior (Figure 21) is similar to that observed in VH15, with maximum temperature anomalies appearing off-equatorially. Larger T_{400} are (mostly) over the IO and MC. As convection initiates on 8-Jan-2006 these anomalies move eastward and an area of large positive (warm) anomalies appear over the IO and MC. Positive T_{400} anomalies dominate the equatorial belt as the convective center begins to move eastward and is over the MC.

4) u_{200} and lower-level u_{850} Zonal Wind Contribution

The upper- (Figure 22) and lower-level (Figure 23) zonal winds follow the behavior of the OLR contribution to the mode for this event, with divergence (convergence) occurring where the enhanced OLR are and convergence (divergence) occurring around the suppressed OLR for the u_{200} (u_{850}). Anomalies for the zonal winds intensify with larger OLR anomalies, as expected. Unlike the SLP and T_{400} anomalies, the anomalous winds are not off-equatorial, but rather extend across the equator.
Figure 19. Same as Figure 14 but for the January 2006 event. The figure depicts a textbook-like example of the MJO propagation over time, with convection starting on 9-Jan-2006, Intensifying over the IO the following pentad.
Figure 20. Same as Figure 15 but for the event that initiated on 9-Jan-2006.
Figure 21: $T_{400}$ Contribution

Figure 21. Same as figure 16 but for the event that initiated on 9-January-2006.
Figures 22 and 23. Same as figure 17 and 18 but for the event that initiated on 9-January-2006.
c) January 1999 Event

This event shows unusual behavior for an MJO event, as a significant convective signal does not appear over the IO in the mode near the dates identified by the methods. This event was identified by LZB13 (17-Jan-1999), Straub-Full (10-Jan-1999) and Straub-Circulation (11-Jan-1999; Straub-OLR identified an event on 4-Jan-1999, but was more than 10 days apart from the convective appearance over the IO as Primary.

1) OLR Contribution

An area of enhanced convection did not appear over the IO around the dates identified by the four methods (Figure 24). The only convective signal appears over the IO on 23-Jan-1999 as a small and weak area of convection. There is no sign of eastward propagation for the small negative OLR signal appearing over the IO, as it dissipates by the next pentad. There is an unorganized area of suppressed convection appearing over the IO and MC three pentads before the small convective signal (which falls in the 10-20 day precursor window, although it was not identified by LZB13 as a precursor variable). The suppressed convection is strong during the pentads after the convective signal. The areas of suppressed convection in this event show the largest anomalies seen among all events, including those studied in VH15. This behavior show that the suppressed phase is as important as the convective phase to the MJO-like dynamical mode.

2) SLP Contribution

There are not any significant SLP anomalies during the date of convective initiation (23-Jan-1999; Figure 25). Strong positive SLP anomalies, however, appear over broader latitudes two pentads before convective initiation on 13-Jan-1999. These anomalies are somewhat out of the ordinary because, on contrary to previous cases, they...
are not confined to the southern hemisphere, but they extend into the equator and into the northern hemisphere. These positive SLP anomalies appear once again on 17-Feb-1999 with the same unusual behavior. The signals extend over some longitudes past the date line and happen in the same pentads where the strongest OLR anomalies are observed.

3) $T_{400}$ Contributions

$T_{400}$ anomalies appear to be very quiet on the pentad of convective initiation (23-Jan-1999; Figure 26). Two pentads before the convective signal over the IO on 13-Jan-1999, strong negative $T_{400}$ anomalies appear over the IO and propagate and dissipate eastward in the next pentad. On 13-Jan-1999 positive $T_{400}$ anomalies appear (mostly) to the east of the dateline, therefore spreading further into the western hemisphere. The same anomalous regions appear on 17-Feb-1999 (the pentad with the highest values in $T_{400}$ out of the eight studied events). For the rest of the pentads shown, the temperature anomalies remain fairly quiet along the equatorial belt.

4) $u_{200}$ and $u_{850}$ Contribution

This event does not show any strong zonal circulation (Figures 27 and 28). In the pentads with stronger suppressed convection (13-Jan-1999 and 17-Feb-1999) low easterlies and upper westerlies appear over the IO and part of the MC. The area of suppressed convection also moves eastward and the zonal circulation follows. This behavior is expected, as this is how the theoretical behavior of the OLR and the wind fields appear in the MJO-like dynamical mode.
Figure 24. Same as Figure 14 but for the event on January 1999. Event shows an unusual evolution over time from that seen in other events, its convective phase initiates and dissipates on 23-January-1999.
Figure 25. Same as Figure 15 but for the event that initiates and dissipates on 23-January-1999.
Figure 26. Same as Figure 16 but for the event that initiates and dissipates on 23-January-1999.
Figure 27 and 28. Same as Figures 17 and 18 but for the event that initiates and dissipates on 23-January-1999.
d) December 2006 Event

This event also shows an unusual behavior. The methods all identified it at very similar times (Table 1). In the MJO-like mode, it seems to follow the convection of an event on November 2006 identified by LŽB13 as Non-MJO convection and by Straub-Full as Intensifying (Studied by VH15, Figure 3). There is only one quiet pentad (4-Dec-2006) between the end of the November 2006 event and the initiation of this one. Yet, the event was identified by LŽB13 and Straub-OLR as Primary and by Straub-Full and Straub-Circulation as Intensifying. When looking at both events in sequence, there is one pentad in between that has the lowest convective signal over the IO (4-Dec-2006) and then the following pentad (9-Dec-2006) the convection re-intensifies over the IO. It is not completely clear from the MJO-like mode’s OLR contribution whether the event succeeds a preexisting event (such as is the definition for Intensifying events) or if it is part of the event studied in VH15. Because of this uncertainty, figures include pentads from the November 2006 event studied in VH15, although discussion will focus on the initiation of 9-Dec-2006.

1) OLR Contribution

Looking at this as an isolated event (Figure 29), convection appears over the IO on 9-Dec-2006 and intensifies over the same region on the next two pentads. On 29-Dec-2006, the event starts progressing eastward, and then decays the next two pentads over the MC. On 13-Jan-2007 the event shows a slight westward propagation, a behavior that has been observed by other researchers (Jiang et al. 2015) and which is even clearer in the following pentad (18-Jan-2007). The following pentads are fairly quiet and show minimal negative OLR anomalies. The event appears to dissipate completely around 7-Feb-2007.
2) SLP Contribution

Positive SLP anomalies appear over the south IO, MC and WPO on the pentad of convective initiation (9-Dec-2006; Figure 30) and propagate eastward in time. On 19-Dec-2006 the positive anomalies are replaced by negative anomalies over the IO. On the pentads that show the westward propagation, the anomalies remain stationary. The anomalies in this event stay (mostly) concentrated in the eastern hemisphere.

3) T\textsubscript{400} Contribution

Negative T\textsubscript{400} anomalies appear over the IO, MC and WPO on the pentad of convective initiation (9-Dec-2006; Figure 31). These anomalies are off-equatorial in the MJO-like dynamical mode (this behavior was also observed in VH15). They have a slight eastward progression over time over the next three pentads following the convection startup over the IO. Positive T\textsubscript{400} anomalies appear on 29-Dec-2006 over the IO and remain over the region with different intensity until 13-Jan-2007.

4) u\textsubscript{200} and u\textsubscript{850} Contribution

When analyzing the zonal circulation (Figures 32,33) preceding the event, no significant eastward-progressing circulation is observed. Due to these observations, the event is more likely to be part of the same event that was studied in VH15.

Looking at this as an isolated event, the zonal circulation for this event gives insight into what might have happened in its initial stages, and also helps visualize some of the features of the event. The u\textsubscript{200} and u\textsubscript{850} show an eastward propagation consistent with the behavior observed in OLR anomalies for the life period of the event. The zonal circulation for this event also shows the slight westward propagation in the 13-Jan-2007
and 18-Jan-2007 pentads. However, the zonal circulation for the event in VH15 did not show any propagation (which agreed with the identification offered by LZB13, Non-MJO convection). This observation could support either hypothesis mentioned above about whether it is its own event or not. This event needs further exploration in able to reach a conclusion regarding its identification.
Figure 29. Same as Figure 14 but for the December 2006 event. The event follows the event studied in VH15 (Figure 3 in their paper) with a quiet pentad in between. The pentad of convective initiation is 9-Dec-2006.
Figure 30. Same as Figure 15 but for the event that initiated on 9-Dec-2006.
Figure 31: $T_{400}$ Contribution

Figure 31. Same as Figure 16 but for the event that initiated on 9-Dec-2006.
Figure 32 and 33. Same as Figures 17 and 18 but for the event that initiated on 9-Dec-2006.
5. Conclusion

Previous work (VH15) shows that the HP16 MJO-like dynamical mode can depict Intensifying and Non-MJO events. This work shows that the MJO-like mode can depict Primary events, and that it can show other phenomena occasionally seen with MJO’s (westward propagation; Jiang et al. 2015). Occasionally, phenomena attributed to the MJO are not represented in this mode, such as the convection that does not appear in the January 1999 event (Figure 20). This shows that the dry phase of the oscillation is just as important to the mode as its enhanced convection phase.

The events presented in this study had an area of suppressed convection that extended over parts of the IO and MC prior to MJO convective initiation. The areas of suppressed convection observed in the Primary events were very strong compared to that previously seen in VH15 for Non-MJO and Intensifying events. The MJO-like dynamical mode has off-equatorial T₄₀₀ and SLP signals that are concentrated for the most part in the Eastern Hemisphere, with occasional anomalies crossing the dateline. In events with strong anomalous signals (in all variables), the largest SLP values seem to deviate from the normally observed behavior (concentrated in the Southern Hemisphere) and extend north of the equator and across it.

The MJO-like dynamical mode does not completely show the precursor patterns proposed by LZB13. The u₈₅₀ anomalies are the most consistent of these signals as they appear in most of the events. The T₄₀₀ anomalies appear off-equatorially rather than being confined to the equator. The negative SLP signal only appeared once (which could be a product of convection appearing over the MC).

Further efforts could be made to use the MJO-like dynamical mode as an index for event identification over the studied period as a measure of comparison with the other methods. The
MJO-like dynamical mode should also be used to further explore other types of identified events such as those that propagate westward (Jiang et al. 2015) and those that do not propagate (Feng et al. 2015). Further study could explore the extra-tropical interactions with the MJO as the MJO-like dynamical mode depicted the anomalies as being off-equatorial rather than confined to the equatorial belt. The January 1999 and December 2006 events should be carefully studied as they might give valuable insight on the MJO-like dynamical mode and the methods studied in this research.

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