MJO Initiation in the Real-Time Multivariate MJO Index

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ABSTRACT

Madden–Julian oscillation (MJO) initiation in the real-time multivariate MJO (RMM) index is explored through an analysis of observed case studies and composite events. Specific examples illustrate that both the dates of MJO initiation and the existence of the MJO itself can vary substantially among several well-known MJO indices, depending on whether the focus is on convection or circulation. Composites of “primary” MJO initiation events in which the RMM index rapidly increases in amplitude from a non-MJO state to an MJO state are presented and are supplemented by two case studies from the 1985/86 winter season. Results illustrate that, for primary MJO initiation events in the Indian Ocean (RMM phase 1), slowly eastward-propagating 850-hPa (200 hPa) easterly (westerly) anomalies over the Indian Ocean precede the amplification of the RMM index by at least 10 days, while suppressed convection over the western Pacific Ocean precedes the amplification by 5 days. These “local” Eastern Hemispheric predecessor signals are similar to those found in successive (well established) MJO events but are not captured by the global-scale RMM index because of their smaller zonal scale. The development of a primary MJO event is thus often transparent in the RMM index, since it occurs on scales smaller than zonal wavenumber 1, particularly in convection. Even when the RMM index is altered to respond to convection only, the same local precursor signals are found. Both composites and case studies suggest that, for primary MJO initiation events in the Indian Ocean, the development of global-scale circulation anomalies typically precedes the onset of large-scale deep convection.

1. Introduction

Since Madden and Julian’s pioneering studies in the early 1970s (Madden and Julian 1971, 1972), the Madden–Julian oscillation (MJO) has been analyzed via a dizzying array of unique methods, resulting in a seemingly countless number of MJO indices. The fact that new indices are still being developed 40 years later suggests that we as a community have not yet agreed on the defining characteristics of the MJO. Should the MJO be defined by its cloudiness signal? Or is its dynamical signal more important? Or does a combined measure of convection and circulation, like the real-time multivariate MJO (RMM) index (Wheeler and Hendon 2004, hereafter WH04), most effectively capture the “true” MJO?

Thankfully, most of the MJO indices developed over the past 40 years provide a fairly consistent picture of the mature MJO’s large-scale features, particularly when applied in an average sense over multiple years of data. However, as will be shown, event-by-event comparisons illustrate that the details, as well as the identification of events themselves, can differ dramatically among methods.

Not knowing whether a particular convective or dynamical sequence truly represents the MJO makes identifying MJO initiation even more difficult. Perhaps for this reason, few observational studies of MJO initiation exist. Of these studies, Hsu et al. (1990), Ray and Zhang (2010), and Wang et al. (2012) implicate the extratropics in MJO initiation, while Matthews (2008) finds no statistically significant extratropical precursors, instead concluding that midtropospheric destabilization is an important precursor signal in “primary” MJO events (with no immediately preceding event). Seo and Song (2012) show that a positive midtropospheric potential vorticity (PV) anomaly arising from the suppressed convective phase of a prior MJO event induces new MJO convection in the western Indian Ocean, Webber et al. (2012) demonstrate that primary MJO initiation is strongly influenced by equatorial ocean wave dynamics, and Seo and Kumar (2008) conclude...
that the strength of low-level moisture convergence plays a key role in MJO initiation. Clearly, a unified mechanism for MJO initiation has not yet been identified. At present, the most prominent MJO initiation theories are local discharge–recharge, extratropical influences, stochastic forcing, and circumnavigating waves, as thoroughly described in Zhang (2005).

Since the publication of WH04, the RMM index has become the leading method for identifying the state of the MJO, as evidenced by its widespread use in observations (e.g., Jiang et al. 2011; Riley et al. 2011; Wang et al. 2012), model analysis (e.g., Kim et al. 2009; Waliser et al. 2009; Gottschalck et al. 2010), and the 2011–12 Dynamics of the MJO (DYNAMO) field campaign (see the MJO discussion summary reports in the DYNAMO field catalog at www.eol.ucar.edu/projects/dynamo). Occasionally, the RMM index undergoes a rapid transition from a non-MJO state to a high-amplitude, long-lasting MJO state, suggesting that MJO initiation has occurred. Interestingly, these transitions often occur at times not identified as MJO initiation periods in other MJO indices. The fact that the RMM index is multivariate, taking into account both cloudiness and two measures of circulation, means that one variable could potentially dominate this transitional phase. It is, therefore, of interest to investigate these rapid amplitude increases to determine the processes responsible for MJO “initiation” in the RMM index.

This study focuses on two aspects of MJO initiation. First, addressed in section 3, are the difficulties encountered in defining consistent dates of MJO initiation using multiple MJO indices, which become critical when choosing initiation events to analyze. Second, in sections 4 and 5, the precursor signals to RMM-index MJO initiation in outgoing longwave radiation (OLR) and zonal wind—the components of the index—are examined in composites and case studies.

2. Data and methodology

Two datasets are utilized: 1) National Centers for Environmental Prediction (NCEP)–U.S. Department of Energy (DOE) Reanalysis 2 dynamical fields and 2) Advanced Very High Resolution Radiometer (AVHRR) OLR (Liebmann and Smith 1996). Both have a 2.5° spatial resolution and a daily temporal resolution from 1 January 1979 to 31 December 2010. All data have been deseasonalized by removing the smoothed (three harmonics) mean annual cycle. In addition, a 100-day Lanczos high-pass filter has been applied to remove interannual variability.

The RMM index empirical orthogonal functions (EOFs) and principal component (PC) time series are calculated via the methodology described in WH04. The deseasonalized data from 1979–2010 are used in the computation of the EOFs, while the deseasonalized and high-pass-filtered data are used as raw data in the calculation of the PC time series.

3. Defining the MJO

It is helpful to categorize the vast number of existing MJO indices into three types, based on their input data:

1) Cloudiness-based indices, which typically utilize OLR or precipitation data to isolate an MJO signal (e.g., Rui and Wang 1990; Kiladis and Weickmann 1992; Hendon and Salby 1994; Hendon et al. 1999; Matthews and Kiladis 1999; Matthews and Kiladis 2000; Wheeler et al. 2000; Kemball-Cook and Weare 2001; Kessler 2001; Myers and Waliser 2003; Kiladis et al. 2005; Benedict and Randall 2007; Matthews 2008; Kiladis et al. 2009);
2) Dynamical- or circulation-based indices, which typically measure the upper tropospheric circulation (e.g., Knutson and Weickmann 1987; Poehl and Matthews 2007; Chen and Del Genio 2009; Jones 2009; Tromeur and Rossow 2010); and
3) Combined cloudiness- and circulation-based indices (e.g., Weare 2003; WH04).

Until recently, one of the most frequently utilized MJO indices has been wavenumber–frequency-filtered OLR or precipitation, based on the procedure outlined in Wheeler et al. (2000). This method falls into category 1 above, Figure 1a is a longitude–time diagram of 100-day high-pass-filtered OLR, averaged from 15°S to 15°N, from 1 October 1992 to 31 March 1993, covering the Tropical Ocean and Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE). OLR filtered to eastward-propagating wave-numbers 0–6 and periods of 30–96 days, representing the MJO (Kiladis et al. 2005), is superimposed. Three active and three suppressed MJO events occur during this period (e.g., Chen et al. 1996). Although this MJO identification method is useful for isolating the OLR and/or precipitation signals associated with well-defined, high-amplitude MJO events, as illustrated here, and can be effectively used to extract the large-scale structure of MJO high-cloudiness fields in an average sense, it is less useful in examining details of individual events, as it relies on highly smoothed, filtered data. For example, it is unclear in Fig. 1a, based only on OLR, whether MJO convective initiation in the second MJO event begins with the westward-propagating OLR anomaly in late November in the Indian Ocean or in early December over the Maritime Continent, as the filtered OLR suggests. To
understand MJO initiation, we must first identify specifically when and where this process occurs.

Another index through which to analyze the MJO is the RMM index, which falls into the third category above (combined OLR and circulation). The RMM index is derived from a multivariate EOF analysis of 15°S–15°N averaged OLR and 200- and 850-hPa zonal winds (U200 and U850, respectively). The first two combined EOFs represent the eastward-propagating MJO cycle, and are shown in Fig. 2 as calculated for the period 1979–2010. The projection of the raw data onto these EOFs is typically represented by the PC time series of EOFs 1 and 2 as plotted in the style of Fig. 3. Counterclockwise rotation of the RMM index with amplitude greater than 1 represents a coherent MJO event. Figure 3 illustrates the RMM index for the TOGA COARE period: a weak MJO event occurs during October and early November 1992 (Fig. 3a), and is followed by a much-higher-amplitude event that begins around 20 December 1992 and rapidly dissipates by 15 February 1993 (Fig. 3b).

A comparison of the onset of the high-amplitude MJO event in the RMM time series in late December 1992 (Fig. 3b) with the wavenumber–frequency-filtered OLR in Fig. 1a illustrates a mismatch between the two MJO indices. The wavenumber–frequency-filtered OLR clearly indicates a strong, active MJO event beginning in early December, whereas the RMM index indicates unambiguous, high-amplitude, eastward-propagating MJO-like behavior beginning weeks later, in late December. Complicating this picture is a convectively coupled $n = 1$ equatorial Rossby wave in the Indian Ocean in early December, which may significantly project onto the RMM index (Roundy et al. 2009).

Examples of this mismatch between the OLR-only and OLR–circulation MJO indices abound. Two
additional examples are illustrated in Fig. 4. Figure 4a is a longitude–time plot for January–June 1987, in which the wavenumber–frequency-filtered OLR indicates a strong active MJO event throughout January and February. Figure 4b is a plot of the RMM index from 1 January to 15 March 1987. This MJO index does not indicate the presence of an MJO event until 20 February 1987. Thus these two MJO identification methods disagree as to whether or not an MJO event even occurs during January 1987. One might surmise that the broad latitude band over which the RMM index and longitude–time plots are calculated could mask the true, more latitudinally localized MJO signal during January, which could be remedied through the use of a more localized MJO index, as in Kikuchi and Wang (2010); however, in this case, using the RMM methodology, the zonal wind features during January are simply not broad enough in zonal scale to project strongly onto the RMM EOFs (not shown).

The opposite case, in which the RMM index indicates a strong MJO while the wavenumber–frequency-filtered OLR does not, is illustrated in Figs. 4c and 4d. Figure 4c is a longitude–time diagram of OLR anomalies from 1 January to 30 June 1998, covering the South China Sea Monsoon Experiment (SCSMEX) in May–June 1998. A weak active MJO event, constrained to the Indian Ocean, is indicated by the wavenumber–frequency-filtered OLR, and is followed by an intense smaller-scale eastward-propagating convectively coupled Kelvin wave in mid-May (Straub et al. 2006). Figure 4d shows the RMM index from 19 April to 1 June 1998, which indicates a strong, globally coherent MJO event from late April through the end of May.

Why are there such discrepancies between these two MJO identification methods? Although the RMM index is generated from standardized anomalies in OLR and zonal wind, such that each of the three input components is equally weighted, the OLR data actually contribute very little new information to the index. If the OLR data are withheld in the creation of the RMM PC time series, by projecting only the zonal wind data onto the zonal wind components of the EOF structures, the bivariate correlation between the original PC time series and the “no OLR” PC time series for the period 1979–2010 is 0.99 [see Gottschalck et al. (2010) for a description of the bivariate correlation methodology]. Table 1 lists additional correlations based on removing the zonal wind components individually, as well as retaining only one input variable. Clearly, the three components of the index are highly correlated, and the OLR is the least significant contributor to the full index.

To further illustrate this point, the RMM PC time series for the SCSMEX period with various input components withheld are shown in Fig. 5. In Fig. 5a, OLR data are withheld, such that the PC time series is based on U200 and U850 only. Note that Fig. 5a is nearly identical to Fig. 4d, which includes OLR in addition to the zonal winds. Figures 5b–d contain input data from
U850, U200, and OLR only. The U850-only and U200-only indices (Figs. 5b,c) show some resemblance to the full index, while the OLR-only index (Fig. 5d) has a high-amplitude, smooth, and coherent MJO-like quality only from 12–18 May 1998 in phases 3–5. Based on these results, it is clear that the full RMM index should be understood to rely very heavily on circulation data, rather than OLR.

Several MJO identification methods that incorporate only circulation data have also recently been developed. Poehl and Matthews (2007) and Jones (2009) construct MJO indices in the same manner as the RMM index, but use only the 15°S–15°N averaged 850- and 200-hPa zonal winds. The PC time series generated using this method has a bivariate correlation with the full RMM index of 0.92 for the 1979–2010 period. Again, the high

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**Fig. 4.** (a) OLR anomalies (shading) and MJO-filtered OLR (contours), averaged from 15°S to 15°N, for 1 Jan–30 Jun 1987. (b) RMM plot for 1 Jan–15 Mar 1987. (c) As in (a), but for 1 Jan–30 Jun 1998. (d) As in (b), but for 19 Apr–1 Jun 1998. Primary MJO initiation in (d) occurs on 21 Apr 1998 in RMM phase 7 (see Table 3). For (b) and (d), the large black dot represents the start date, and each symbol thereafter represents the next consecutive day. Dates divisible by 5 are labeled, and the last day is represented by the large gray dot. Months are differentiated by their symbols: January by open squares, February by asterisks, March by open circles, April by plus signs, and May by open stars.
correlation between the PC time series generated with and without the inclusion of OLR confirms that the circulation anomalies are the primary drivers of the full RMM index.

Chen and Del Genio (2009) develop an MJO circulation-only index based on an extended EOF analysis of 200-hPa velocity potential anomalies. This MJO index is contoured over 100-day high-pass-filtered OLR in Fig. 1b, for the same period as Fig. 1a, such that negative (positive) values represent enhanced (suppressed) convection. Although this method provides a more longitudinally continuous measure of the MJO than the wavenumber–frequency-filtered OLR in Fig. 1a, it is by no means always a close proxy for high cloudiness, particularly during December 1992. Interestingly, the fact that this circulation-based MJO index and the RMM index (which is also heavily circulation based) both show little coherent MJO activity until late December 1992, despite the enhanced eastward-propagating convective envelope beginning much earlier in the month, suggests that there is not always a direct correspondence between MJO-like OLR and circulation anomalies, at least averaged over this broad latitude band.

Ambiguous cases similar to these abound in the data record. The ambiguity of MJO events themselves as well as their dates of initiation would not be nearly so problematic if only the composite structure of the fully developed MJO was of interest. However, real-time forecasting of the MJO is currently being implemented (e.g., Wheeler and Weickmann 2001; WH04; Gottschalck et al. 2008; Jiang et al. 2008; Lin et al. 2008; Gottschalck et al. 2010; Vitart and Jung 2010) to provide insight into upcoming flood, drought, tropical cyclogenesis, and high-amplitude extratropical weather probabilities (e.g., Higgins et al. 2000; Jones 2000; Maloney and Hartmann 2000; Hall et al. 2001; Bond and Vecchi 2003; Bessafi and Wheeler 2006; Cassou 2008; Lin and Brunet 2009; Jones et al. 2011). Knowing when and where the next MJO will initiate, and when and where the current MJO will dissipate, is more than an academic exercise. The known local influences and remote teleconnection patterns associated with the MJO provide forecasters with critical insight at the 10–20-day time scale (e.g., Jones and Schemm 2000; Leroy and Wheeler 2008; Jones et al. 2011).

The sheer number of MJO indices developed and applied over the past 40 years, combined with the lack of agreement as to the appropriate input data, suggests that our definition of the MJO itself is far from crystallized. Can the MJO be defined locally, or must it be longitudinally continuous across the entire tropics, as in the RMM EOFs? Must MJO initiation be slowly varying, or can a rapid intensification occur? Are dynamics or convection more important in defining the MJO? Our choice of an index by which to identify the MJO should be informed by our answers to these questions.

4. MJO initiation

If defining the MJO itself is difficult, defining MJO initiation is even more problematic. MJO initiation is typically defined as the onset of a large-scale, prolonged, and eventually eastward-moving envelope of deep cloudiness in the Indian Ocean (e.g., Hsu et al. 1990; Matthews and Kiladis 1999; Kemball-Cook and Weare 2001; Hsu and Lee 2005; Zhang 2005; Seo and Kumar 2008; Zhang and Ling 2012). However, not all MJO events begin with convection in the Indian Ocean (Matthews 2008), and it is unclear how a previous MJO cycle might impact this definition. Does it matter whether the onset of deep convection, wherever it occurs, is primary (i.e., not preceded by significant MJO activity) or successive (i.e., following a well-established MJO event) (Matthews 2008)?

MJO initiation can also be defined without reference to OLR or precipitation, as the spinup of deep, planetary-scale, zonally oriented circulation cells. Circulation-based MJO indices implicitly favor this definition. Observations provide some evidence for this type of MJO initiation: for example, Lin et al. (2009) show that the positive phase of the North Atlantic Oscillation (NAO) often precedes development of the MJO in RMM phases 6 and 7, through a meridional convergence of the 200-hPa transient momentum flux. Hoskins and Yang (2000), Lin et al. (2007), and Wedi and Smolarkiewicz (2010) show that equatorial waves can be generated in dry atmospheric models by forcing initiated in the extratropics.

As a third alternative, MJO initiation can be defined as the simultaneous development of significant convective anomalies and planetary-scale circulation cells, as might be measured by a combined cloudiness and circulation index such as the RMM index. An important additional distinction to include within any of these three definitions is whether MJO initiation is primary or successive.
These three definitions of MJO initiation—the growth of cloudiness, circulation, and combined cloudiness-circulation fields on MJO space and time scales—will be explored in the remainder of this section. For simplicity, the RMM methodology will be utilized throughout. Although the RMM index was not designed to capture MJO initiation, but rather the well-developed, mature MJO, there do exist numerous cases of rapid amplification of the RMM signal after a period of relative quiescence, followed by a period of high-amplitude MJO activity. These periods represent rapid transitions on the global scale between non-MJO and MJO states. It is of interest to determine the precursor signals to these amplification periods. While other more localized MJO indices (e.g., Kikuchi and Wang 2010) may capture the smaller-scale features of MJO initiation more accurately, the RMM index is used in this study to investigate the growth of planetary-scale MJO anomalies.

The RMM index is used here in a manner that allows a deconstruction of the index into its individual components. Since the longitudinal structure of the OLR EOF derived via the RMM methodology is very similar to that derived from a univariate EOF analysis of OLR alone (the bivariate correlation of the longitudinal structures of EOFs 1 and 2 derived from the two methodologies is 0.83) and the 850- and 200-hPa zonal
wind RMM EOF structures are nearly identical to those derived from a multivariate EOF analysis of 850- and 200-hPa winds only (bivariate correlation of 0.99), the RMM OLR and combined U850/U200 EOF structures can be utilized independently of one another to investigate MJO initiation.

The composites in this section include data from October through May only, to focus on the Northern Hemisphere winter MJO. The RMM index typically includes smoothly propagating, high-amplitude events during these months, whereas during June through September the evolution of the index is quite different, with lower amplitudes, noisier day-to-day variability, and slower phase speeds.

a. Full RMM index

The first definition of MJO initiation to be analyzed is based on the full RMM index, as described in detail in WH04, and representing the third type of initiation detailed above. Deseasonalized and 100-day high-pass-filtered OLR, U850, and U200 data, averaged over latitudes 15°S–15°N, are projected onto RMM EOFs 1 and 2 for the years 1979–2010 to generate the “full RMM” PC time series. Primary MJO initiation is defined as a period when 1) the PC amplitude shows no counterclockwise rotation for at least 7 days at an average amplitude less than 1.0 and 2) the amplitude then increases above 1.0, where 3) it remains for at least 7 days and subsequently progresses through at least four subsequent phases, or half of a complete MJO cycle, in the counterclockwise direction. The date of primary MJO initiation is the first date on which the PC amplitude is greater than or equal to 1.0, and the phase of initiation is defined on this same date. The choice of amplitude 1.0 as the crossover point for MJO initiation is arbitrary, but represents a one standard-deviation anomaly in the RMM index and is typically used as a threshold for significant MJO events (e.g., WH04). One could argue that by the time the RMM index reaches an amplitude of 1.0, the MJO has in fact already initiated, because it is global in scale and projects significantly onto the zonal wavenumber-1 RMM components. This is true; however, the underlying motivation is to then look backward in time at the precursor signals to this large-scale development. With this in mind, “MJO initiation” in this study refers to the onset of a global-scale MJO signal. In any case, the results presented in this section are in fact robust, and are not overly sensitive to the exact amplitude at which MJO initiation is defined, since initiation in the RMM index is often a rapid process.

Often, an increase in the amplitude of the RMM index above 1.0 and subsequent high-amplitude MJO activity is preceded by counterclockwise movement of the RMM index inside the unit circle, representing weak prior MJO activity. These cases are not considered to be primary initiation events, since they evolve from a preexisting lower-amplitude MJO signal; rather, they are termed MJO “intensification” events. Intensification events differ from primary events only in criterion 1 above.

The numbers of primary MJO initiation and intensification events by RMM starting phase are listed in Table 2, and the primary and intensification event dates are listed in Table 3. Primary events are rare, with only 8 events in phase 1, fewer in phases 2–8, and 28 total events during the 1979–2010 period. Consistent with Matthews (2008), who used an OLR-only index to identify primary MJO events, initiation can occur in any MJO phase, and is not limited to the Indian Ocean. Intensification events are also quite rare, with a maximum of 7 events in phase 4 and a total of 32 events. For the 31 October–May periods analyzed, an average of one primary initiation and one intensification event occurs per year. Primary and intensification events each represent the beginning of a separate MJO; there is no double counting.

To contrast with primary MJO initiation and intensification events, successive MJO events are also analyzed. A successive MJO event is defined by the date on which the RMM index enters a particular phase with an amplitude greater than 1.0, having propagated through at least two prior phases with an amplitude greater than 1.0, and subsequently propagating through two successive phases with an amplitude greater than 1.0. For a typical strong MJO, which cycles through multiple RMM phases, a successive “event” is counted once in each phase, such that one MJO contributes numerous
events to the successive composites. Because of this double counting, successive events are much more common than primary initiation or intensification events, as shown in Table 2, with an average of 47 cases per phase.

Examples of the RMM index evolution from day \(-14\) to day \(+14\) in individual cases of primary initiation, intensification, and successive MJO events in starting phase 1 are illustrated in Figs. 6a–c, respectively. All primary initiation, intensification, and successive RMM cases in starting phase 1 from the 1979–2010 data record are illustrated in Figs. 6d–f, respectively. RMM index plots for primary initiation, intensification, and successive events for phases 2–8 are similar to these, but each occurs in its respective octant of the RMM plot.

Primary MJO initiation events, in which no prior MJO signal is present, are very rare (7% of cases) relative to successive and intensification events (93%), which both evolve from a preexisting MJO state. This
result, coupled with the 0.99 correlation between the full RMM index and the “no OLR” RMM index (Table 1), suggests that at least the dynamical signal of the MJO is fairly ubiquitous. In fact, of the 248 months in the October–May 1979–2010 period, only 28 months (11%) clearly contain no MJO signal in the RMM index (i.e., no periods during which the RMM amplitude is greater than 1.0 and progresses counterclockwise through multiple RMM phases). If a dynamical MJO state is the norm, then it is of interest to investigate the conditions under which primary initiation events occur and to contrast these changes with the conditions under which an existing MJO event transitions from one phase to the next.

The composite evolution of OLR anomalies from day −20 to day +20, relative to the RMM index entering phase 1 on day 0, is shown in Fig. 7 for (a) primary MJO initiation and (b) successive events. Composite results for intensification cases are not shown because of the low sample size (two). All composites in Figs. 7–9 are based on 10–100-day bandpass-filtered data; these results are very similar to 100-day high-pass-filtered data, but the statistical significance is increased due to less high-frequency noise. Statistical significance at the 95% level is marked by the contours; field significance was calculated via a 500-sample bootstrap resampling test for each lag, as described in Matthews (2008), and is shown by the solid bars at the right of the primary composites. All successive composites are field significant for their entire evolution. All signals are also robust in terms of the latitudes over which the averages are calculated; inspection of the horizontal structures of the composites (not shown) reveals that both the OLR and wind signals typically maximize on or near the equator, and contain significant anomalies in both hemispheres.

**FIG. 6.** RMM plot from day −14 to day +14, with initiation in phase 1 occurring on day 0, for a representative (a) primary, (b) intensification, and (c) successive event; and for all (d) primary, (e) intensification, and (f) successive events. Day 0 occurs on 26 Apr 1994 for the primary MJO initiation event in (a), on 12 Jan 2002 for the intensification event in (b), and on 7 Jan 1993 for the successive event in (c). The large black dot represents the start date, and each symbol thereafter represents the next consecutive day. Dates divisible by 5 are labeled, and the last day is represented by the large gray dot. Months are differentiated by their symbols: December by solid triangles, January by open squares, April by plus signs, and May by open stars.
The OLR anomalies after day 0 in Fig. 7 are similar between the primary and successive composites, with a weak negative OLR signal over Africa (0°–60°E) moving rapidly eastward from days 0 to 10, intensifying over the Indian Ocean (60°–120°E) at a reduced phase speed, and continuing its eastward movement into the western Pacific Ocean (120°E–180°) by day +20, in a similar manner to the MJO case study of Straub et al.
In addition, a nearly stationary positive OLR anomaly is present in both cases over the western Pacific from at least day −5 to +5. The similarities between the OLR composites after day 0 are expected, since the RMM index moves through successive RMM phases in both primary and successive events. An interesting difference occurs in the western Indian Ocean between day +4 and day +10, however: no statistically significant negative OLR anomaly occurs in the primary composite, suggesting that deep convection does not consistently organize and propagate eastward in primary cases until at least the eastern Indian Ocean.
Prior to day 0, the OLR anomalies evolve quite differently, particularly over the Indian Ocean. In the successive composite (Fig. 7b), a nearly stationary positive OLR anomaly exists over the Indian Ocean for nearly 20 days prior to day 0. In the primary composite (Fig. 7a), on the other hand, there is little coherent OLR activity over the Indian Ocean prior to day 0; instead, positive OLR anomalies develop in the western Pacific around day −5, in a similar location to the successive composite. Suppressed convection over the Indian Ocean may not necessarily be a precursor signal to primary MJO initiation events in that region, then, in contrast to
Matthews (2008); rather, suppressed convection over the western Pacific is consistently found in both primary and successive events, consistent with Seo and Song (2012).

Composites of U850 and U200 for primary and successive events are shown in Figs. 7c–f. Although the statistical significance of the anomalies is spotty in the primary composites because of the small sample size, clear patterns do emerge. As for OLR, the U850 and U200 primary and successive composites are more alike after day 0, when their RMM trajectories are similar. Between day −4 and day 0 in the primary composites, the wind signal in both U850 and U200 transitions to a lower zonal wavenumber state, in both cases through the development of more intense easterly anomalies, then moves eastward at 5–10 m s
−1 in the Eastern Hemisphere and 30–40 m s
−1 in the Western Hemisphere. In the successive composites, which represent the structure of the mature MJO, the zonal wavenumber-1 signal exists throughout the 40-day evolution. In both composites, the lower and upper tropospheric wind signals are almost exactly out of phase for the entire 40-day evolution.

It is important to recall that the RMM zonal wind EOF structures in Fig. 2 are zonal wavenumber 1 in scale. When the observed zonal wind signal transitions to a lower zonal wavenumber state, it more effectively projects onto the RMM EOFs, and therefore the amplitude of the RMM index increases. Whether or not the OLR signal also projects strongly onto the RMM OLR EOF is somewhat irrelevant, since the circulation signals dominate the projection.

Prior to day 0, the primary and successive U850 and U200 composites diverge, but remain consistent with one another in many of their large-scale features. Easterly U850 anomalies develop in both cases by day −10 or earlier over the Indian Ocean (Figs. 7c,d); however, the primary composite shows a slight westward movement of these anomalies, while the successive composite shows eastward propagation. The Western Hemisphere signals differ greatly prior to day 0, with a clear eastward progression of easterly anomalies in the successive composite and weak westerlies in the primary composite. Similarly for U200, the signal prior to day 0 in the Eastern Hemisphere is fairly consistent between the composites (Figs. 7e,f). Although the statistical significance of the primary results is low, there is a clear eastward propagation of the significant westerly U200 anomalies that extends back to day −10. The signals in the Western Hemisphere prior to day 0 also greatly diverge, as in U850.

It is remarkable that, despite the nonexistent or weak projection onto the RMM EOFs prior to day 0 in the primary cases, the primary composites retain a degree of similarity to the successive composites, at least in the Eastern Hemisphere, back to at least day −10. The lack of global-scale zonal wavenumber-1 U850 and U200 signals prior to day 0 in the primary composites, with the main differences in the Western Hemisphere, appears to explain the low projection onto the RMM EOFs.

Composites of other variables (e.g., temperature, specific humidity, and surface pressure) also show pre-existing signals in the Eastern Hemisphere that may contribute to MJO initiation (not shown). Warm and moist low pressure anomalies at low levels move slowly eastward into the Indian Ocean between days −20 and 0, concurrent with the 850-hPa easterly anomalies in Fig. 7c, while a cool and dry high pressure anomaly builds over the western Pacific around day −4, concurrent with the positive OLR anomaly in Fig. 7a, and then propagates eastward at a faster phase speed. Coincident with these faster-propagating low-level anomalies are statistically significant cold anomalies at 300 hPa, which reach Africa by day +6, several days after the development of the negative OLR anomalies in Fig. 7a. This suggests that upper tropospheric destabilization is not necessarily a key factor in the development of deep convective anomalies over the Indian Ocean, as in Matthews (2008). The additional signals described here are all consistent with previous studies of the precursor signals to MJO initiation and, while not all highly statistically significant, are certainly suggestive that slowly evolving MJO initiation processes occur well prior to the abrupt onset of a strong MJO in the RMM index.

If the RMM index is unable to detect the early stages of primary MJO initiation because of its global scale, can a more local index succeed? Based on the spatial and temporal evolution of the composite results, a local index was developed that does capture five of the eight primary MJO events in RMM phase 1. Using 10–100-day bandpass-filtered OLR and wind anomalies, primary MJO initiation in RMM phase 1 takes place near day 0 when the following conditions are met:

1) the amplitude of the RMM index from days −11 to −9 is <1.0 (no significant MJO signal in the RMM index),
2) U850 averaged from 15°S to 15°N and from 45° to 120°E is <0.0 m s
−1 on day −10 (low-level easterly anomalies over the Indian Ocean),
3) U200 averaged from 15°S to 15°N and from 30° to 70°E is >+3.0 m s
−1 on day −10 (moderate upper-level westerly anomalies over the western Indian Ocean), and
4) OLR averaged from 10°S to 10°N and from 130°E to 170°W is >+10.0 W m
−2 on day −3 (suppressed
convection over the equatorial western Pacific a week after the previous signals).

The averaging boxes and times for this method were chosen based on the horizontal structure of the composite RMM phase 1 primary initiation evolution. They are very robust, and are rather insensitive to the exact boxes or dates. This method produces 16 events (1–5-day periods when all criteria are met, with 14 of 16 events lasting only 1 or 2 days) during the October–May 1979–2010 period. Five of these event dates (19821012, 19861014, 19940420, 19981228, and 20041212; the format of dates in the table is year–month–day, where 19821012 corresponds to 12 October 1982) precede the RMM phase 1 initiation dates in Table 3 (19821024, 19861024, 19940426, 19990110, and 20041223) by an average of 10 days. Of the remaining 11 events, five are intensification events, five are successive or low-amplitude MJO events in which the RMM index dropped below 1.0 for a significant period, and one is an aborted MJO event in phase 2. In other words, all identified events were either actual incipient events or low-amplitude preexisting events, the difference between which would be obvious in a real-time forecast setting by a quick inspection of the daily RMM index. The success of this method in hindcasting primary initiation events in RMM phase 1 confirms that zonal wind precursor signals to primary MJO initiation do exist in the Indian Ocean 10+ days prior to initiation. Broad-scale easterly (westerly) zonal wind anomalies at 850 (200) hPa over the entire (western) Indian Ocean, followed about a week later by positive OLR anomalies over the equatorial western Pacific, are good indicators of a transition from a non-MJO state to a developing MJO in the Indian Ocean.

OLR and zonal wind composites similar to Fig. 7 have also been calculated for primary and successive MJO events starting in RMM phases 2–8, with the results for phase 6 shown in Fig. 8. Composites of MJO events that initiate in phases 7, 8, 1, and 2 are all quite similar to those shown in Fig. 7 (phase 1), with the OLR and wind signals shifting upward toward negative lags by approximately 5 days per phase from phase 7 to phase 2. In phase 7, the dominant convective signal prior to day 0 is a positive OLR anomaly over the Indian Ocean; by phase 8, this anomaly is flanked to its west by a negative OLR anomaly, and disappears altogether by phase 1 (Fig. 7a). In all four cases, predecessor dynamical signals similar to those in Figs. 7c and 7e are present, with evidence of eastward-propagating zonal wind anomalies well prior to day 0 coupled with in situ or eastward-moving convective anomalies.

Phases 3–7 continue with the same 5-day shift per phase toward negative lags in all fields, but the eastward-propagating convective signal prior to day 0 is typically much more prominent, extending at high amplitude back to day –20 in phases 5 and 6 (e.g., Fig. 8a). The accompanying zonal wind signal is present but weak until at least day –5 on average (e.g., day –2 for phase 6 in Figs. 8c and 8e), when it intensifies and broadens in zonal scale (e.g., Figs. 7c,e and 8c,e).

These composites suggest that the precursor signals to primary MJO initiation can be quite similar to those in successive events, but on a more “local” or subhemispheric scale. The precursor signals do not project strongly onto zonal wavenumber 1, and therefore do not project strongly onto the RMM EOFs, thus providing a low-amplitude RMM signal despite their MJO-like structures.

b. OLR-only index

The second definition of MJO initiation to be explored involves the onset of deep convection. Many previous studies presume that MJO initiation begins with the onset of deep convective heating, which is then followed by a response in the large-scale circulation (e.g., Lau and Peng 1987; Salby et al. 1994; Park et al. 1995; Hendon and Salby 1996; Li and Zhou 2009).

Primary and successive “OLR only” cases are isolated in a similar manner to those derived from the full RMM index, except that only the OLR data are projected onto RMM OLR EOFs 1 and 2. This methodology is similar to that used in Matthews (2008) to define primary and successive MJO events. Primary, intensification, and successive OLR-only MJO initiation are defined in the same manner as in the full RMM index.

Table 2 also lists the numbers of OLR-based MJO cases. The corresponding dates of primary and intensification events are listed in Table 3. The number of primary cases (27) is nearly identical to the full RMM, while the number of intensification (12) and successive (194) cases is much less, by at least a factor of 2. The OLR-only index is much noisier than the full RMM index (c.f. Fig. 5d with Fig. 4d) and includes many fewer continuous, long-lasting, high-amplitude events. Presumably this is a function of the generally noisier observed OLR field, which only very rarely attains the approximately wavenumber-1 state required for a high projection onto the RMM OLR EOFs. The TOGA COARE period (Figs. 1 and 3) was unusual in this respect, retaining an OLR-only RMM amplitude above 2.0 for 22 consecutive days and maximizing at an amplitude of 4.7 on 15 January 1993, the third highest OLR-only RMM amplitude in the 1979–2010 record.

Of the 27 primary OLR-only MJO initiation cases, 12 (44%) overlap with the primary or intensification cases identified using the full RMM index (Table 3, boldface...
dates; note that overlapping dates are not necessarily in the same phase). Eight of these 12 cases overlap as primary cases, with three in which the OLR-only initiation precedes the full RMM initiation (convection leads dynamics), three in which the full RMM leads the OLR-only initiation (dynamics lead convection), and two simultaneously developing. The other four cases are classified as intensification events in the full RMM index and primary initiation events in the OLR-only index, indicating that a preexisting low-amplitude MJO signal was already present before initiation in the OLR-only RMM index. This is confirmed by noting that in all four cases, the intensification onset date in the full RMM index precedes the primary OLR-only initiation date. Of the remaining 15 nonoverlapping primary OLR-only initiation cases, the majority (9) develop a high-amplitude OLR-only RMM index only after a preexisting full RMM index is already in existence. This suggests that the broad-scale zonal wind structure of the MJO typically exists well before convection attains a significant zonal scale. Only in a select few cases does the large-scale OLR signal clearly precede the dynamical signal.

Figure 9 shows the OLR, U850, and U200 composites for OLR-only primary and successive events that enter RMM phase 1 on day 0. The OLR composite derived from the primary OLR-only index (Fig. 9a) is similar in structure to that derived from the primary full RMM index (Fig. 7a), but is dominated by a positive OLR anomaly in the western Pacific between days ~2 and +8. This stronger OLR signal near day 0 is consistent with OLR being the sole MJO identifier in the OLR-only cases.

The successive composites are very similar between the full RMM and OLR-only RMM cases (cf. the right-hand columns of Figs. 7 and 9), with pattern correlations of 0.94, 0.96, and 0.96 for OLR, U850, and U200, respectively. Results for phases 2–8 are consistent, with high (>0.9) pattern correlations between composites calculated with the full RMM and OLR-only indices. These results confirm that the structure of the mature MJO is nearly identical whether it is identified through a combined cloudiness-circulation index or an OLR-only index.

The U850 OLR-only based composites (Figs. 9c,d) are very similar to those based on the full RMM index (Figs. 7c,d), despite the fact that the OLR-only RMM index contains no information about the dynamical fields. In the primary OLR-only U850 composite (Fig. 9c), easterlies develop in the Eastern Hemisphere prior to day 0, and are accompanied by westerly anomalies over the western Pacific around day ~12, similar to the successive OLR-only case (Fig. 9d). It is remarkable that a consistent eastward-moving U850 signal occurs for 10+ days prior to MJO initiation in a composite based on events captured with an OLR-only index having no MJO signal prior to day 0; this suggests that there is indeed a dynamical precursor to even primary MJO convective initiation in the Indian Ocean.

The same conclusions are reached using the U200 fields. In the primary OLR-only U200 composite (Fig. 9e), the dynamical signal moves eastward at a phase speed more akin to the successive composites (Figs. 7f and 9f) than the primary full RMM composite (Fig. 7e), which moves eastward at 5 m s\(^{-1}\) prior to day +6 and 25 m s\(^{-1}\) after day +6. Thus, what looks like a fully developed (successive) dynamical MJO signal exists in multievent composites prior to the initiation of a primary OLR-based MJO event in the Indian Ocean. Consistent with this finding is the fact that, in the September 1992 primary MJO initiation case study in Matthews (2008), a weak MJO signal is seen in the full RMM index for at least 18 days prior to the OLR-based primary MJO initiation date (not shown). Identifying MJO initiation events based on cloudiness-only indices, then, may confuse truly primary initiation, with no preexisting cloudiness or circulation signal, with the initiation of an MJO-like cloudiness signal in the context of a preexisting event.

The primary OLR-only composites for other RMM starting phases with more than one event are similar in nature to those illustrated for phase 1: an eastward-propagating dynamical signal extends back to at least day ~10, with a strong resemblance to both the primary and successive full RMM composites. The phase speed of U850 and U200 in the OLR-only primary composites is typically slower than in the full RMM composites.

c. Circulation-only index

The third definition of MJO initiation to be analyzed is the onset of a planetary-scale, zonally oriented, first-baroclinic-mode tropical circulation, such as is illustrated in Fig. 16 of Madden and Julian (1972). Since the tropical atmosphere is baroclinic to first order, MJO indices depend upon upper-tropospheric divergence or velocity potential measure this circulation. Here, a circulation-only RMM index is used, which represents a zonal wavenumber-1, first baroclinic mode zonal wind structure. The circulation-only RMM index is calculated as in the full RMM index, except that the OLR data are excluded. Primary initiation, intensification, and successive MJO events are defined as in the full RMM and OLR-only cases. The numbers of primary, intensification, and successive events are listed in Table 2, and the initiation dates are listed in Table 3.

There is a significant overlap between circulation-only and full RMM primary and intensification events, as identified by the italicized dates in Table 3. Of the 23
circulation-only primary cases, 17 (74%) overlap within 3 days of full RMM primary cases; 15 of 34 (44%) of the intensification cases overlap. Since there is a 0.99 correlation between the full RMM PC time series and the circulation-only time series (Table 1), it is not surprising that so much overlap exists between cases. In fact, the longitude–lag composites of OLR, U850, and U200 for the circulation-only cases in phase 1 are so similar to those derived from the full RMM index that they are not shown here. Pattern correlations between the RMM starting phase 1 circulation-only and full RMM composites for OLR, U850, and U200 are >0.94 for primary cases and >0.98 for successive cases. Phases 1 and 8 have the highest pattern correlations averaged across fields between the circulation-only and full RMM primary composites (>0.94), while the correlations are >0.65 for phases 6–7 and >0.75 for phase 4. For the successive cases in phases 2–8, pattern correlations for OLR, U850, and U200 are always >0.98 when averaged across fields, again demonstrating the similarity between indices when centered on the mature MJO.

5. Case studies

Figures 10 and 11 illustrate two examples of primary MJO initiation from the 1985/86 Northern Hemisphere winter season. Figure 10 includes longitude–time diagrams of the 100-day high-pass-filtered, 15°S–15°N averaged OLR, U850, and U200 for the period 1 September 1985–28 February 1986. This period includes the December 1985–January 1986 MJO initiation case study analyzed in Hsu et al. (1990). MJO-filtered OLR, as in Fig. 1a, is superimposed. Based on this MJO identification methodology, the first MJO event initiates in the Indian Ocean around 1 November 1985, moves eastward to the Maritime Continent in early November, and dissipates. A suppressed MJO event follows in November, and a strong active MJO event initiates in the Indian Ocean in late December.

RMM plots for this period are shown for the full (Fig. 11a,d), OLR-only (Fig. 11b,e), and circulation-only (Fig. 11c,f) RMM indices for 1 September–15 November 1985 (top) and 15 November 1985–15 January 1986 (bottom). Perhaps surprisingly, the full RMM time series in Fig. 11a shows a clear MJO initiation event in phase 3 around 5 October 1985, while the wavenumber–frequency-filtered OLR shows no MJO activity during this period. The circulation-only PC time series (Fig. 11c) is nearly identical to the full RMM; clearly, OLR does not contribute significantly to the full RMM index. The OLR-only index (Fig. 11b) suggests that “convective” MJO initiation does not take place until 23 October 1985, between phases 8 and 1; eastward propagation does not begin until 31 October. Note that this convective MJO initiation is preceded by a strong positive OLR anomaly in the western Pacific, consistent with Fig. 9a, whereas the 5 October MJO initiation based on the full RMM index has no strong precursor OLR signal. The date and location of OLR-only MJO initiation in this case is also consistent with the wavenumber–frequency-filtered OLR in Fig. 10a, which is not surprising given that both indices are based on low-zonal-wavenumber OLR signals.

During October, while the OLR index shows no MJO activity, the circulation index shows significant MJO activity. Figures 10b and 10c illustrate the corresponding U850 and U200 fields; clear eastward-propagating anomalies are seen beginning in early October. These anomalies propagate eastward at approximately 13 m s\(^{-1}\), are out of phase between the upper and lower troposphere, and have zonal wavenumber-1 spatial scales, such that they project strongly onto the RMM circulation EOFs. October 1985, then, is a period of strong dynamical MJO activity and weak MJO OLR activity, at least at the latitudes incorporated into the RMM index. When the OLR and circulation are viewed in daily map form, it is apparent that the OLR activity in early October is primarily constrained to the Northern Hemisphere in westward-propagating tropical depression-like vortices, which do form successively eastward in time, such that the 5°–15°N averaged OLR does project onto the MJO (not shown). In this case, then, the strong dynamical signal beginning in early October may be the result of processes not traditionally defined as the MJO, but which still produce circulation anomalies that project strongly onto the RMM index.

Figures 11d–f show the full, OLR-only, and circulation-only RMM plots for 15 November 1985–15 January 1986. In the full RMM (Fig. 11d), it appears that the October–November MJO event dissipates by 22 November, a period of inactivity follows, and a new MJO event initiates in phase 8 on 20 December. Again, the full RMM (Fig. 11d) and circulation-only (Fig. 11f) plots are nearly identical; the OLR-only index (Fig. 11e), however, shows MJO initiation on 25 December in phase 1, 5 days later and 1 phase ahead of the circulation-based index but still consistent with the wavenumber–frequency-filtered OLR in Fig. 10a. Clearly, the large-scale OLR and circulation fields evolve differently from one another, particularly around the time of MJO initiation, suggesting that the MJO initiation process does not necessarily rely upon the spatially and temporally simultaneous growth of large-scale convection and circulation. In the first half of the analyzed period, the global-scale circulation signal precedes the development of large-scale equatorial convection by several weeks; in the second half,
circulation precedes convection by several days. These examples are consistent with the conclusion of Wedi and Smolarkiewicz (2010) that “the process of convection is important but chronologically secondary” in MJO initiation. In general, global-scale MJO dynamical processes appear to occur well before the development of large-scale convection, even in primary cases, and thus MJO initiation dates based on OLR or another measure of convection may miss the true “beginning” of the MJO. While it is certainly plausible that these dynamical precursor signals are correlated but not fundamentally causal to the process of MJO initiation, which likely relies on thermodynamic parameters such as low-level moisture (Seo and Kumar 2008) and upper tropospheric instability (Matthews 2008), their existence is intriguing, and suggests the need for further investigation.

6. Discussion and conclusions

Although the MJO has been studied for 40 years, terms such as “MJO initiation” remain mysterious.
Traditionally, the MJO itself has been identified based on some measure of cloudiness or convective heating and, less frequently, on the upper tropospheric divergent circulation. More recently, the WH04 RMM index, which takes into account both convection and circulation, has become the standard MJO index. While the structure of the mature MJO is consistent among indices, a clear definition of MJO initiation has remained elusive.

In this study, MJO initiation is explored in the context of the WH04 RMM index. Initiation is defined as a period when the index rapidly transitions from a non-MJO state to an MJO state, which is shown to occur in any RMM phase, consistent with Matthews (2008). Because the large-scale zonal circulation dominates the RMM index, however, MJO initiation in this index is not an appropriate measure of convective MJO initiation, and users of the RMM index are cautioned against treating the index as such. A rapid increase in RMM amplitude may not in fact be accompanied by convective MJO initiation, but rather represents the growth of global-scale tropical circulation anomalies.

Both the composites in section 4 and the case studies in section 5 show that a large-scale dynamical signal can precede primary MJO initiation by at least 10 days, in a similar manner to successive events. This is surprising, considering the common perception that primary MJO initiation begins with an outbreak of deep convection in the Indian Ocean. Rather, local easterly (westerly) zonal wind anomalies at 850 (200) hPa build up over the western Indian Ocean in the absence of a significant convective anomaly for at least 10 days, then move eastward into the western Pacific and rapidly grow in zonal scale well prior to the onset of active convection in the Indian Ocean. The growth in zonal scale allows the wind anomalies to effectively project onto the RMM index, and thus the index rapidly increases in amplitude.

The RMM index, although not suitable for specifically identifying MJO convective onset, could potentially
provide insight into the processes by which the large-scale circulation anomalies rapidly develop. The role of the extratropics is particularly tantalizing, given recent research by Ray et al. (2009), Vitart and Jung (2010), Wedi and Smolarkiewicz (2010), and Ray et al. (2011), among others. Ray et al. (2009) show that MJO initiation in a tropical channel model is controlled almost entirely by the temporal variability of the extratropical boundary conditions, while Vitart and Jung (2010) document an increase in the skill of the ECMWF forecast system in predicting the MJO, as measured by the RMM index, when the Northern Hemisphere extratropics are relaxed to analysis fields. These results suggest that the difficulty of simulating the MJO in models may not be entirely due to their convective parameterizations, which are often blamed. On the other hand, it is possible that adequate extratropical forcing may still not give rise to a realistic MJO if the convective parameterization is unable to couple with the large-scale circulation to promote growth of anomalies on planetary scales (Ray et al. 2009), or if the basic state is erroneous (Ray et al. 2011).

The fact that the RMM index is dominated by its circulation components raises the question of its suitability for the assessment of the MJO in models and model forecasts. If the RMM index most effectively measures the strength of the zonal wavenumber-1 tropical baroclinic circulation, models that capture and/or forecast this feature most accurately will appear to have the best MJOs. This measure, then, may not be representative of the coupling between circulation and convection that is known to exist in the observed MJO. Perhaps a better strategy would be to employ the RMM index alongside other measures of the MJO for the most comprehensive assessment.

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REFERENCES


