Precursor Environmental Conditions Associated with the Termination of Madden–Julian Oscillation Events

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(Manuscript received 30 August 2014, in final form 8 December 2014)

ABSTRACT

This study presents an analysis of the precursor environmental conditions related to the termination of Madden–Julian oscillation (MJO) events. A simple climatology is created using a real-time MJO monitoring index, documenting the locations and frequencies of MJO decay. Lead–lag composites of several atmospheric variables including temperature, moisture, and intraseasonal wind anomalies are generated from three re-analyses. There is remarkable agreement among the datasets with long-term, lower-tropospheric moisture deficits over the local domain best identifying termination events over the Indian Ocean. MJO termination in the Indian Ocean is also linked to a northward shift of the intertropical convergence zone (ITCZ) with possible lead times as much as 20 days prior to MJO decay.

Statistically significant differences in the low-level vertical velocity and specific humidity are also identified more than 10 days in advance of MJO termination events in the western Pacific, though the differences here are more symmetric about the equator. Unlike the Indian Ocean and western Pacific, MJOs that terminate over the Maritime Continent appear to be related to their own intensity rather than the downstream conditions. As such, only the strongest MJOs tend to propagate into the warm pool region.

Finally, a budget analysis is performed on the three-dimensional moisture advection equation in order to better elucidate what time scales and physical mechanisms are most important for MJO termination. The combination of intraseasonal vertical circulation anomalies coupled with the mean-state specific humidity best explain the anomalous moisture patterns associated with MJO termination, suggesting that the downstream influence of the MJO circulation can eventually lead to its future demise.

1. Introduction

The Madden–Julian oscillation (MJO) is the leading mode of intraseasonal climate variability in the tropical atmosphere (Madden and Julian 1971, 1972, 1994) and represents a broad envelop of eastward-moving cloud and precipitation anomalies that occur on the planetary scale. The MJO most frequently initiates over the western Indian Ocean before propagating into the central and western Pacific at roughly 5 m s$^{-1}$ (e.g., Zhang 2005), though at least 50% of MJO events tend to initiate in different basins (Matthews 2008). The MJO has a direct influence on tropical precipitation anomalies and can affect the intensity and variability of global monsoons (Lau and Chan 1986; Goswami and Ajaya Mohan 2001; Matthews 2004; Wheeler and Hendon 2004), tropical cyclone formation (e.g., Maloney and Hartmann 2000; Jiang et al. 2012), midlatitude weather anomalies (e.g., Higgins et al. 2000; Bond and Vecchi 2003; Guan et al. 2012), and the development of the El Niño–Southern Oscillation (ENSO; Lau and Waliser 2005). Despite its importance in determining large-scale variability at both low latitudes and the extratropics, previous (e.g., Slingo et al. 1996; Waliser et al. 1999; Lin et al. 2006; Zhang et al. 2006; Li et al. 2009) and current (Hung et al. 2013; Jiang et al. 2014, manuscript submitted to J. Geophys. Res. Atmos.) generations of weather forecast and global climate models (GCMs)
continue to struggle with simulating many of the observed features of the MJO and often suffer from low skill regarding initiation forecasts.

A number of theories regarding MJO initiation have been developed including boundary layer frictional convergence (Wang and Rui 1990), surface wind–evaporation feedbacks (Emanuel 1987; Neelin et al. 1987), stochastic linearized convection and deep convective heating (e.g., Salby et al. 1994), and influences from higher latitudes such as Rossby wave trains and cold-air outbreaks (Hsu et al. 1990; Matthews and Kiladis 1999; Ray and Zhang 2010; Wang et al. 2012). Topographic effects may be important for MJO initiation (e.g., Hsu and Lee 2005) and mean sea level pressure (MSLP) anomalies associated with dry Kelvin waves from previous MJO disturbances may help initiate a successive event (Matthews 2000). In short, there are a large number of theories and possibilities for MJO initiation.

Recent observational work has focused on the analysis of case studies or long-term composites in order to examine the precursor conditions associated with the start of an MJO event. These studies differ over the relative importance of the environmental conditions and various mechanisms for MJO initiation, including suppressed convection and midlevel temperature destabilization (Matthews 2008), the organization of planetary-scale wind anomalies into a wavenumber-1 pattern (Straub 2013), diabatic heating and precipitation anomalies generating low-level cyclonic potential vorticity (Ling et al. 2014), and decreased stability from positive temperature and moisture anomalies in the lower troposphere (Seo and Kumar 2008; Zhao et al. 2013). Of these, the concept of low-level moisture preconditioning seems particularly promising with observations often showing frictional moisture convergence and positive moistening upstream and to the east of the MJO and areas of deep convective heating (e.g., Hendon and Salby 1994; Myers and Waliser 2003). These moisture anomalies can enhance the local cumulus and congestus cloud population, producing low-level heating anomalies that are critical for the initial strengthening of the MJO in GCM experiments (e.g., Lappen and Schumacher 2014). Nevertheless, uncertainty remains regarding the role of low-level heating (and moisture) anomalies for the initiation and maintenance of the MJO as recent work has indicated discrepancies in the magnitude and structures of vertical heating profiles derived from observations and reanalyses (e.g., Jiang et al. 2011; Stachnik et al. 2013).

Theoretical and modeling studies continue to reinforce the importance of low-level heating and moisture anomalies as being critical toward improving simulations of the MJO. For example, the multicloud model parameterization of Khouider and Majda (2006, 2007), which accounts for lower-tropospheric heating from moisture anomalies and congestus clouds, successfully produces MJO-like waves in simplified model experiments. Furthermore, embedding the multicloud model within higher-order models has been shown to improve MJO simulations in simplified aquaplanet and coarse-resolution GCMs (e.g., Khouider et al. 2011; Ajayamohan et al. 2013). Superparameterization simulations, which better account for the redistribution of moisture and explicit convection, also often contain improved MJOs (e.g., Grabowski 2003; Benedict and Randall 2009; Pritchard and Bretherton 2014). Low-level moisture anomalies have similarly been shown to produce MJO-like waves in recent experiments using the MJO “skeleton model” (Majda and Stechmann 2009, 2011) with more realistic MJO simulations when including a stochastic convective parameterization (Thual et al. 2014).

Despite the progress made toward understanding MJO initiation, far fewer studies have examined the large-scale conditions associated with quiescent periods of the MJO and the decay of existing events. In particular, we are interested in the role of low-level moisture anomalies during MJO termination, though our analysis includes a complete investigation of the thermodynamic and dynamical variables that may be associated with MJO decay. Understanding these conditions and potential mechanisms may provide a valuable context toward improving simulations of MJO initiation and propagation in climate and operational weather forecast models.

This study presents an analysis of the precursor environmental conditions related to the termination of MJO events. As such, we first determine a climatology of MJO termination events using a popular MJO index and composite the dates with three atmospheric reanalyses. A review of the MJO index, in addition to the algorithms used to identify MJO termination, are described in section 2. Results pertaining to the 34-yr climatology are presented in section 3, with section 4 focusing on the conditions associated with MJO decay over the Indian Ocean. Section 5 examines the similarities and differences of MJO termination over the western Pacific and Maritime Continent. Finally, section 6 closes with a summary of key results from the composite analysis and identifies avenues for continued work.

2. Data and methods

a. Defining MJO events

This study uses the real-time multivariate MJO (RMM) index developed Wheeler and Hendon (2004) as the principal measure of MJO activity. As implied by its name,
the RMM index relies upon a multivariate empirical orthogonal function (EOF) analysis of upper- and lower-tropospheric zonal winds from reanalysis and outgoing longwave radiation (OLR) datasets as proxies for the intraseasonal circulation and convection anomalies from 15°S to 15°N, respectively. The leading two modes are used to define the MJO and the projection of the original data yields corresponding time series (i.e., principal components) that are referred to as RMM1 and RMM2. Additional details regarding the sensitivity and development of the index are summarized in Wheeler and Hendon (2004).

While the RMM index normalizes the circulation and cloudiness fields by their global variance in order to ensure equal contributions for the variance of the combined analysis, Straub (2013) documented that the RMM index was most sensitive to and primarily determined by the circulation component. As such, the RMM index may not accurately depict the development of an initial or “primary” MJO event (i.e., intraseasonal variability preceded by quiescent conditions) over local regions, particularly when occurring at scales smaller than the zonal wavenumber-1 depiction in the RMM index (Straub 2013). It should be noted that other convectively coupled equatorial waves can project onto the RMM index (Roundy et al. 2009) and different MJO identification methods have been used including wavenumber–frequency filtering (Wheeler et al. 2000) or indices that are entirely dependent on the upper-tropospheric divergence or wind alone (e.g., Pohl and Matthews 2007; Chen and Del Genio 2009). Nevertheless, we feel that the choice of RMM index is appropriate for this study as our main focus is on the termination of well-developed and preexisting MJOs—a situation in which one might expect less variation among the MJO indices than otherwise exhibited during initiation (e.g., Straub 2013). Moreover, we also choose to evaluate the RMM index owing to its widespread use and popularity in addition to providing a more meaningful comparison with previous work examining planetary-scale MJO anomalies.

To identify MJO termination, we must first determine what constitutes an MJO “event.” In the RMM1–RMM2 phase space defined by Wheeler and Hendon (2004), MJO activity is depicted as a counterclockwise rotation (i.e., eastward propagation) of the daily RMM values with the corresponding amplitudes normalized by their standard deviation. As such, a combined amplitude greater than or equal to unity represents intraseasonal anomalies of at least one standard deviation and is a common threshold value for defining the MJO.

Examples of two periods with active MJOs are shown in Fig. 1. In both cases, the RMM index starts with weak amplitude (i.e., inside the unit circle) and grows in magnitude until exceeding values greater than 1.0 in phase 7 and phase 2 for the cases in Figs. 1a and 1b, respectively. The first days with a combined amplitude greater than unity are marked with a large, gray point in each panel and are referred to as the initiation of a primary event, following the terminology used in Matthews (2008), who defined similar events using an RMM-like index based solely on OLR datasets. Matthews (2008) required that an MJO event travel through all four quadrants of the corresponding principal components phase space (i.e., analogous to propagating through all eight phases of the RMM index); we use a more relaxed definition following Straub (2013) where an MJO event must complete four phases, or a half-cycle in the RMM phase space. As such, an MJO event is defined herein by an RMM segment with a path history that demonstrates continuous eastward propagation and a combined amplitude above the common threshold of 1.0.

To contrast with those MJO events that arise from relatively quiescent conditions (i.e., primary events), we define a “continuing” event [referred to as a “successive” MJO by Matthews (2008) and Straub (2013)] as instances where the RMM index has already maintained a strong amplitude and propagated through at least two previous phases. These events represent situations with a preexisting MJO signal that continues to propagate through four additional phases, thereby meeting the event criterion as previously defined. A continuing event for phase 1 is shown in Fig. 1a, with the first day of the event indicated with a large marker and the subsequent four phases highlighted in blue. Long-lasting MJOs can thus contain multiple continuing events for a single primary initiation and are highlighted in light and dark green for phase-2 and phase-3 continuing events (embedded within the previous blue primary path) in Fig. 1a, respectively. For simplicity, only the first day of the continuing events are highlighted in Fig. 1b, with a special wave-train or “circumnavigating” event highlighted in gold. In these cases, the MJO has successfully traversed the entire globe (e.g., Yoneyama et al. 2013) from its original initiation location (phase 2 for Fig. 1b) and continues to propagate for an additional four phases. Finally, a “termination” event occurs whenever the RMM signal falls below unity for an extended period of time or begins to show significant westward propagation. Example termination events are highlighted in red for phase 6 and phase 5 in Figs. 1a and 1b, respectively.

Figure 1 also illustrates two examples of where the event identification algorithm is considered forgiving. The search algorithm allows an event to occasionally have an amplitude less than unity, provided that it always remain above some lower buffer (in this case, RMM ≥ 0.9) and
reaches the 1.0 threshold within the following 3 days (e.g., between phase 4 and phase 5 in Fig. 1a). Overall, the results were not sensitive to the choice of buffer strength nor the length of consecutive weak days in the search algorithm. Noncontinuous eastward progression is also permitted as the phase cycle may occasionally retrograde along the western boundary when entering a new phase. The westward propagation is limited to a single phase, however, and additional westward propagation beyond one phase results in a termination event identified at the start of where the RMM index began to retrograde. An example of an accepted westward propagation is shown in Fig. 1b, where the RMM index depicts an MJO moving from phase 7 to phase 6, with subsequent eastward propagation to phase 7. Generally, these conditions were less important to the climatology results, as the vast majority of MJO events terminated via a weak amplitude cutoff rather than excessive westward propagation.

b. Reanalyses

Three sets of atmospheric reanalyses are used in this study including the National Aeronautics and Space Administration (NASA) Modern-Era Retrospective Analysis for Research and Applications (MERRA; Rienecker et al. 2011), the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim; Dee et al. 2011), and the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR), versions 1 and 2 (Saha et al. 2010). Daily output files were either downloaded directly from the data servers or calculated from 6-hourly data. The MERRA and CFSR data were regridded to 1.25° horizontal resolution while the surface and upper-air variables from the ERA-Interim use a 1.5° fixed grid. The output data also include 31 (MERRA) or 32 (ERA-Interim and CFSR) pressure levels. Additional details regarding the specifics of the datasets can be found in the above references.

To investigate the intraseasonal variability and precursor conditions associated with MJO decay, we composite the reanalyses using methods similar to Matthews (2008) and Straub (2013). Daily anomalies were first created by removing the smoothed annual cycle and first three harmonics. The daily anomalies were then time filtered using a 20–100-day Lanczos filter with 201 weights. Lead–lag composites for each of the different MJO event types (primary, continuing, circumnavigating, and terminating) were generated based on the day-0 definitions above, though we focus here on differences between the

![Fig. 1. Examples of different MJO event classifications in the two-dimensional phase space defined by the Wheeler and Hendon (2004) RMM index. Daily values of RMM1 and RMM2 are shown as small dots for (a) 13 May–3 Jul 2007 and (b) 1 Dec 2003–18 Feb 2004. The start and end of the MJO events are denoted with a circumscribed ×. Gray (red) points indicate a primary initiation (termination) event in each case. Blue and green points indicate the start of continuing events in (a), with the subsequent RMM path history (i.e., time evolution through the following four phases) highlighted for each event. Continuing events are shown in blue in (b), with the beginning of a circumnavigating (i.e., wave train) MJO event and subsequent evolution highlighted in gold. See the text for the allowances provided by the search algorithm and the definitions used for each event type.](image-url)
continuing and terminating events. While the analysis mostly considers composites of the anomalous 20–100-day variability, we also briefly mention event-to-event variability in the summary and discussion.

Finally, it should be noted that this study uses 34 years (1979–2012) of data for all seasons. Although the characteristics of the MJO are different for boreal summer and winter, we find strong agreement in our results when considering year-round or boreal-winter-only MJO events. A brief comparison regarding the year-round and boreal winter MJO climatology is provided for reference in section 3 with the remainder of the analysis focusing on the yearly data.

### 3. Climatology of MJO events

Table 1 identifies the number and frequency of MJOs by RMM phase for primary, continuing, circumnavigating, and terminating events. Overall, there were 154 MJO initiation and termination events during the 1979–2012 period (approximately 4.5 MJOs per year) with 91 of these events occurring during the boreal winter (November–April; Table 2). Continuing events are more common by definition (recall that long-lasting MJOs will contain multiple continuing events) with 330 events summed across all RMM phases. Circumnavigating events, in which the MJO signal can be traced around the entire globe, are much rarer. Only 15 events were observed during the entire period (Table 1).

Figure 2 shows the frequency of primary, continuing, and termination events by RMM phase for year-round and boreal winter data. Although the figure is similar to the phase-space diagrams of Wheeler and Hendon (2004), the plot indicates the frequency of occurrence for each event type in a radial–frequency domain (i.e., MJOs are more common for a given phase if plotted farther from the origin). Consequently, the lines drawn between the individual data points are merely to

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**Table 2.** As in Table 1, but for the 1979–2012 Northern Hemisphere winter (November–April).
assist with identifying the skew of the distribution and overall likelihood for an event to occur within a given region of the RMM phase space.

Primary MJOs occur most frequently in phases 1–3 (i.e., immediately west of or directly over the Indian Ocean) for the year-round data (Fig. 2a), consistent with Matthews (2008). Nevertheless, more than 50% of the MJO events initiate outside these regions—again consistent with previous work. The curve for continuing events is mostly symmetric, despite a slight skew toward the Maritime Continent, with each RMM phase containing approximately 10%–15% of the total continuing MJOs. The boreal winter climatology (Fig. 2b) for primary and continuing MJO events is similar to the all-season data with differences generally less than 1%–2% for each RMM phase (cf. Tables 1 and 2, Figs. 2a and 2b).

Of particular interest to this study are the termination events that are most likely to occur over the phase-8 (Western Hemisphere) domain (20.1% of all termination events; Table 1). There is also a secondary termination maximum (16.9%) located within the RMM phase-6 domain as the MJO exits the Maritime Continent region and begins to enter the western Pacific (Fig. 2a). Once again, the termination climatology for boreal winter events is similar to the yearly amounts, although the secondary peak in the RMM phase-6 domain for the all-season data is more broadly distributed over the combined western Pacific domains (RMM phase 6 and phase 7; Fig. 2b). These maxima are somewhat different from the decay climatology performed by Klingaman and Woolnough (2014a,b) in which the RMM index most frequently weakened over the phase-5 and phase-1 domains. Their analysis was focused on individual days with strong RMM amplitudes, however, and did not consider the entire history of MJO events as done here.

Termination composites of the RMM1 and RMM2 indices are shown for all phases in Fig. 3a and alternatively as a time series for the combined amplitude in Fig. 3b. Day 0 for each phase is indicated with a circumscribed cross in Fig. 3a and occurs 3–4 days (for the composite) after propagating into the new region from the previous phase. Curiously, 3–4 days also seems to be the relevant time scale for MJO termination, as most phases contain relatively constant values (or small growth) in the combined RMM amplitude prior to day 2 when the signal begins to experience rapid decay (Fig. 3b). Only RMM phase-2 termination events appear to experience gradual decay, with the composite amplitude beginning to weaken at day ~7. In other words, the forecast skill of the RMM index alone (i.e., as a predictor to whether an event will terminate) appears to have a relatively limited range for MJO decay. As such, we now examine the precursor conditions for termination events in order to see if differences in the large-scale

![Fig. 2. Radial–frequency plots indicating the percentage occurrence of MJO events subset by RMM phase for (a) year-round and (b) boreal winter data. Occurrence frequencies are indicated using black dots at the center angle of each phase. The individual dots are only connected for the ease of viewing primary, continuing, and terminal events (gray, blue, and red lines, respectively). Circumnavigating event frequencies are not shown because of their low overall occurrence and are instead listed in Tables 1 and 2. Range rings are for the 1%, 5%, 10%, 15%, and 20% occurrence frequencies from the center to the edge of the diagram, respectively.](image-url)
environmental conditions can provide additional lead time and forecast skill beyond this initial range.

4. Composites for Indian Ocean termination events

Although RMM phase 2 only contains 11.0% of all termination events (Table 1, Fig. 2), we begin by focusing on MJO decay and termination here given that MJO events are most likely to initiate in this region. In particular, we focus on the differences in the precursor conditions (i.e., negative lag) in the days leading up to an MJO 1) entering and continuing through or 2) terminating in the phase-2 domain.

Because the day-0 definitions for continuing and terminating events permit additional eastward propagation for the latter (e.g., see Fig. 1 where the termination events are not restricted to the first day of entering a new phase), we employ a first-order correction by equally subtracting 3 days from the termination composites before calculating the difference panels. While the composite panels for continuing and termination events use their own definitions for day 0, the difference panels rely on the time-shifted termination composites and thus contain missing data for the final 3 days of the calculation. A Student’s t test is then used to evaluate the presence of a statistically significant different mean at each point in the longitude–time domain, using a 40° averaging window and a test value of 95% (p = 0.05).

**a. Lead–lag composites**

We first examine differences in the low-level circulation given the well-known dependence of the RMM index on zonal wind and the fact that primary MJOs are often preceded by the development of a wavenumber-1 circulation anomaly (Straub 2013). Figure 4 shows lead–lag composites of the 850–700-hPa anomalous zonal wind from the three reanalyses averaged from 10°S to 10°N for continuing and terminal MJO events (and their associated differences) in the phase-2 region. Data from the MERRA, ERA-Interim, and CFSR are shown in Figs. 4a–c, 4d–f, and 4g–i, respectively. The stippling in the difference panels (terminal minus continuing) indicates the presence of a statistically significant different mean for continuing and terminating events.

To begin, it is surprising to note the incredible degree of similarity among the reanalyses, particularly for mostly oceanic and tropical domains where the number of observations available for data assimilation are scarce relative to land and higher latitudes. Each of the datasets shows a strong and well-developed wavenumber-1 wind anomaly of approximately 2–3 m s⁻¹ approaching the Indian Ocean near day 0, with the MJO signal continuing through the local domain for continuing events (Figs. 4a, 4d, and 4g). Conversely, the MJO wind anomalies are sharply divided by the day-0 line for the
termination cases with only weak (~1 m s⁻¹) anomalies remaining (Figs. 4b, 4e, and 4h) and statistically significantly differences after day 0 (Figs. 4c, 4f, and 4i). Statistically significant and positive wind differences of about 1 m s⁻¹ are identified over the Indian Ocean (60°–90°E) for all three reanalyses up to 9 days prior to the eventual MJO decay (i.e., stronger westerlies or weaker easterlies for termination events), providing some minor improvement over the decay time scales noted in Fig. 3b.

Peculiarly, there also appears to be a statistically significant wave train in the zonal wind difference over parts of the Maritime Continent and western Pacific (i.e., 120°–150°E) that starts nearly 30 days before the eventual MJO decay. The source of this difference remains elusive, however, as lead–lag composites of the daily anomalies (in lieu of the 20–100-day-filtered anomalies as shown here) provided no evidence of higher-frequency or westward-traveling synoptic waves interfering with the large-scale environment as the MJO approached the Indian Ocean near day 0 (not shown). Nevertheless, additional work is needed before it can be successfully concluded whether or not these wave trains and downstream differences are a potential cause of future MJO termination.

Figure 5 shows the same composite analysis as for zonal wind but for the intraseasonal MSLP anomalies. Once again, the reanalyses demonstrate remarkable agreement with each other and all of the significant differences (in excess of 1 hPa) between continuing and terminating events occur after day 0 or in areas well downstream (i.e., east of 150°E) in the days leading up to MJO decay (Figs. 5c, 5f, and 5i). The MSLP discontinuities at 40°E and 75°W in Fig. 5 (and similar figures) are an artifact of the major land–ocean boundaries in the tropics and equally affect the composites for both continuing and terminating MJO events. Whereas Matthews (2000) found that MSLP anomalies associated with the propagation of dry Kelvin waves across the equatorial
Atlantic Ocean and African continent from previous MJOs could initiate a successive event, the differences in sea level pressure here appear less important for influencing MJO termination.

Composite anomalies of midlevel (600–400 hPa) temperature and their associated differences are shown in Fig. 6 for continuing and terminating MJOs. Matthews (2008) found that midlevel cooling and destabilization occurred prior to the onset of primary MJOs over the Indian Ocean. The opposite is not necessarily true for termination events; that is, midlevel warm anomalies and enhanced stability in the inactive region of the MJO are not detected here as an immediate precursor for MJO decay. Although the reanalyses do identify statistically significant midlevel warming differences of 0.1–0.2 K for termination events over eastern Africa and the Indian Ocean (spanning 30°–90°E) during the inactive period (i.e., when the MJO convection is far away), the anomalies are isolated to 20 days prior to the event termination and appear to have smaller and near-zero differences from day –15 to day 0 as the MJO convection propagates back into the region (Figs. 6c, 6f, and 6i). Significant cooling differences are noticeable for termination events in the Indian Ocean after day 0, as the continuing MJO composite produces enhanced midlevel warm anomalies owing to latent heat release and moist processes occurring in cloud.

Figure 7 furthers the composite analysis and documents the midlevel vertical pressure velocity (i.e., omega) anomalies for Indian Ocean continuing and terminating MJOs. As before, the reanalyses are largely in agreement with one another, though differences in the vertical velocity patterns over the Indian Ocean can be identified as much as 20–30 days prior to MJO decay. There is ascent (i.e., negative values) over the 60°–90°E region in the days immediately prior to day 0 for both continuing and termination events, though the ascent is stronger by 10–20 hPa day$^{-1}$ for the continuing composite (cf. Figs. 7a, 7d, and 7g with Figs. 7b, 7e, and 7h). Likewise, there is evidence of stronger subsidence 20 days prior to the eventual MJO decay, though these differences are not statistically significant since the data are averaged symmetrically about the equator. As will be shown in the following subsection, the vertical velocity anomalies contain significant asymmetries about the equator and these differences are in fact a more

![Fig. 5. As in Fig. 4, but for the 20–100-day-filtered MSLP anomalies.](image-url)
robust indicator of the precursor environmental conditions associated with MJO termination over the Indian Ocean.

Finally, Fig. 8 shows the composite anomalies of continuing and terminating MJO events for the low-level specific humidity. As with the midlevel vertical velocity, positive moisture anomalies are seen over the Indian Ocean from day $-10$ to day $0$ as the active area of MJO and deep convection returns to the region for both continuing and termination events. The peak specific humidity anomalies reach $0.6$–$0.7 \text{ g kg}^{-1}$ for the continuing events (Figs. 8a, 8d, and 8g), while the termination events have a slightly weaker positive anomaly of $0.4$–$0.5 \text{ g kg}^{-1}$ that peaks over a much smaller domain (Figs. 8b, 8e, and 8h). It should be noted that the peak moistening appears to shift toward the east for the termination cases (cf. Figs. 8a and 8b); this again is an artifact of the additional eastward propagation allowed in the definition of day $0$ for termination events and has been corrected in the difference panels. As such, there are generally negative moisture anomaly differences of $0.1$–$0.3 \text{ g kg}^{-1}$ over the $60^\circ$–$90^\circ$E domain during the 20 days prior to MJO decay for the termination events.

The previous suggests that long-term deficits of lower-tropospheric moisture over the local region may help predict whether an MJO event will continue or terminate once entering the RMM phase-2 domain. The statistical significance of this conclusion is again limited using the current framework (i.e., absence of stippling at day $-20$ in Figs. 8c, 8f, and 8i), as maps of the intra-seasonal moisture anomalies reveal significant off-equatorial structures that appear to be unique to this domain.

**b. Patterns of spatial variability**

Snapshots of the low-level specific humidity and pressure vertical velocity are shown at day $-10$ and day $-5$ in Fig. 9 for continuing and terminating MJO events. Given the similarity among reanalyses, the remainder of the analysis only presents those results from the MERRA data. As expected, positive moisture anomalies are apparent to the east of Africa and over the western Indian Ocean at day $-10$ for continuing events (Fig. 9a). These anomalies extend slightly eastward and intensify by day $-5$ (up to and exceeding $1 \text{ g kg}^{-1}$ along the equator) as the active
phase of the MJO and deep convection approaches the region (Fig. 9b). Overall, the specific humidity anomalies appear to be well correlated with the patterns of low-level vertical velocity with the region of anomalous ascent also expanding and growing in magnitude from day −10 to day −5 for the continuing events (Figs. 9c and 9d).

There is a marked contrast, however, with the corresponding day −10 and day −5 patterns of specific humidity and vertical velocity for the termination events. Terminating MJOs have similar peak moisture anomalies as documented for continuing events, though the moisture is displaced almost entirely north of the equator by day −5 (Fig. 9f). Furthermore, there is a band of negative (dry) anomalies south of the equator that is most noticeable at day −10 (Fig. 9e), resulting in the weaker equatorial average values identified in Fig. 8 for termination events. These dry zones are best explained by the presence of anomalous subsidence (positive anomalies) over the region and can be seen in the corresponding vertical velocity plots (Figs. 9g and 9h). The east–west dipole bands of specific humidity and vertical velocity anomalies suggest that there is a northward displacement of the MJO and/or intertropical convergence zone (ITCZ) over the Indian Ocean for termination events.

Curiously, the negative moisture anomalies and low-level subsidence occur over the regions just south of the equator that contain the greatest intraseasonal variability in Indian Ocean sea surface temperatures (SSTs; e.g., Han et al. 2007). As will be shown, these drying anomalies can be explained by vertical advection anomalies within the atmosphere—namely, the combination of the intraseasonal-scale (i.e., MJO) circulation anomalies interacting with the mean-state and background moisture. While it remains possible that cold SST anomalies over the Indian Ocean could result in weaker atmospheric uplift and moistening, the previous result is also true for those regions with reduced intraseasonal SST variability (see section 5). We therefore choose to focus on the atmospheric component for the remainder of this study, though future work may investigate the possible role of SST anomalies and ocean dynamics associated with MJO decay.

Finally, it should be noted that the above analysis is for year-round data. Under these circumstances, the termination signal could be dominated by boreal
summer MJO events in which the ITCZ and MJO migrate north of the equator in conjunction with the Indian summer monsoon. This was not the case, however, as repeating the above analysis on the subset of events occurring in boreal winter (November–April) revealed identical patterns for termination events (not shown). In fact, the magnitude of the dry-air and subsidence anomalies was greater for winter-only events when compared to the year-round data.

c. Moisture budget analysis

To determine the potential source of the moisture deficit and structures identified in Fig. 9, we now examine the three-dimensional moisture transport associated with MJO termination events in the MERRA data. The time tendency for the total advection of specific humidity $q$ can be expanded as

$$ \left( \frac{\partial q}{\partial t} \right)_{\text{adv}} = u \frac{\partial q}{\partial x} + v \frac{\partial q}{\partial y} + \omega \frac{\partial q}{\partial p}, $$

where $u$ and $v$ represent the zonal and meridional winds and $\omega$ indicates the pressure vertical velocity. As such, the three terms on the right-hand side of Eq. (1) specify the zonal, meridional, and vertical moisture transport, respectively.

Likewise, the above quantities can be separated into a constant and time-varying component using a Reynolds average such that $u = \bar{u} + u'$, where the overbar and prime quantities in this case represent the climatological mean and anomalous intraseasonal varying components, respectively. The individual terms on the right-hand side of Eq. (1) can thus be expanded in order to focus on the anomalous intraseasonal variability and are rewritten as

$$ \left( \frac{\partial q}{\partial t} \right)_{\text{adv}} = \bar{u} \frac{\partial q}{\partial x} + u \frac{\partial q}{\partial x} + \omega \frac{\partial q}{\partial p}. $$

The first and third terms on the right-hand side of Eq. (2) represent the anomalous intraseasonal zonal moisture transport due to nonlinear advection by the mean and intraseasonal flow, respectively. The second term on the right-hand side represents the mean moisture transport due to nonlinear advection by the intraseasonal zonal wind anomalies. Similar expansions can be done for the
meridional and vertical transport terms in Eq. (1). Although the change is small across the tropical band, a cosine latitude correction has been applied to the zonal transport term in order to account for the varying $\delta x$ at each latitude.

Figure 9 presents a conceptual reference for the subsequent moisture advection analysis. The composite specific humidity anomalies $q'$ are shown at day −20 and day −5 for continuing and terminating events with the corresponding wind vectors indicating the anomalous

![Figure 9](image1)

**Fig. 9.** Spatial patterns of the 20–100-day-filtered (a),(b) low-level (850–700 hPa) moisture and (c),(d) low-level vertical velocity anomalies for continuing RMM phase-2 MJO events from MERRA data. Composite snapshots are provided for lags at (a),(c) day −10 and (b),(d) day −5 prior to the start of a continuing event. The equator is plotted as a thin, gray line in all panels for reference. (c)–(h) As in (a)–(d), but for terminating events.

Figure 10 presents a conceptual reference for the moisture advection analysis. The composite specific humidity anomalies $q'$ are shown at day −20 and day −5 for continuing and terminating events with the corresponding wind vectors indicating the anomalous

![Figure 10](image2)

**Fig. 10.** Conceptual reference for the moisture advection analysis. Color shading indicates the composite, 20–100-day-filtered low-level specific humidity anomalies for RMM phase-2 MJO (a),(b) continuing and (d),(e) terminal events. (c),(f) Color shading represents the background (mean state), low-level specific humidity. The wind vectors indicate the anomalous low-level horizontal wind at (a),(d) day −20, (b),(e) day −5, and (c) for the mean flow. Dashed (solid) contours in (f) indicate mean ascent (subsidence) with a contour interval of 10 hPa day$^{-1}$. Vertical velocity anomalies for continuing and terminating events are not shown for the sake of clarity and generally overlap the moisture anomalies. All panels use MERRA data.
The instantaneous values of the total anomalous zonal, meridional, and vertical moisture transport are shown at day $-10$ in Fig. 11. While the differences in zonal flow appear somewhat large for the continuing and terminating cases in Fig. 10, the vertical advection is the dominant term within the Indian Ocean (magnitudes approaching $0.5 \text{ g kg}^{-1} \text{day}^{-1}$) and best match the anomalous moisture patterns at day $-10$ (cf. Figs. 9e and 11e). Further decomposition of the vertical advection term following Eq. (2) revealed that the total vertical transport almost entirely comprises the interaction between the anomalous intraseasonal flow and the climatological specific humidity (i.e., $\omega' \partial q/\partial p$; not shown). As such, the above finding suggests the downstream influences of the MJO circulation may eventually lead to its own future demise.

The combination of these time scales (i.e., intraseasonal circulation anomalies and mean specific humidity) was previously found by Zhao et al. (2013) as the dominant term responsible for the lower-tropospheric moisture anomalies that serve as a precursor for MJO initiation in the Indian Ocean. Even so, Zhao et al. (2013) reported that it was in fact the horizontal transport terms that contributed most to the moisture anomalies and MJO initiation, thus making our finding of vertical transport a unique result for the termination events.

5. Termination in other regions

As previously mentioned, only 11.0% of MJO termination events occur in the western Indian Ocean. While the previous analysis is useful for comparing potential
termination mechanisms against those that might initiate the MJO in the RMM phase-2 domain, we now extend the above techniques to other regions in order to investigate MJO termination processes in different domains. Likewise, we once again restrict the presentation to the MERRA data given the similarities among the reanalyses.

a. Western Pacific MJOs

The decay of MJO events is common in the western Pacific, with 16.9% of all termination events occurring within the RMM phase-6 domain (Table 1, Fig. 2). As before, we examine the different precursor conditions associated with continuing and terminal MJO events in this region. For brevity, only the difference panels and statistical significance calculations for the 10°S–10°N equatorial average are discussed.

Figure 12 shows the composite differences for low-level zonal wind, low-level divergence, MSLP, midlevel temperature, midlevel vertical velocity, and low-level specific humidity. Unlike with RMM phase-2 events, differences in the low-level zonal wind occur well in advance of the RMM phase-6 local domain (120°E–160°E; Table 3), with statistically significant and enhanced easterlies (negative values) over the central Indian Ocean between day −10 and day −5 (Fig. 12a). Meanwhile, weaker easterlies (positive values) are located downstream near the warm pool at this time (150°E–180°) and propagate eastward along with the negative anomalies. These wind shifts result in statistically significant differences for the low-level divergence between day −10 and day −5, with enhanced convergence (negative values) and divergence (positive values) for MJO termination events to the west and east of the expected convection center, respectively (Fig. 12b). These areas correspond to the differences in MSLP (Fig. 12c), with positive pressure anomalies of 0.5–0.8 hPa identified at approximately day −10 over the RMM phase-6 domain (120°–160°E) and overlapping the region of enhanced low-level divergence (Fig. 12b). Interestingly, there are statistically significant areas of negative pressure anomalies along the eastern edge of the Maritime Continent.
and warm pool region (130°–160°E) that are first detected at day −20, though it remains unclear whether these affect the future MJO termination event.

Differences in the midlevel heating for continuing and terminating MJOs occur mostly after day 0, though there is enhanced cooling (i.e., decreasing warming) beginning near day −10 in the RMM phase-6 domain (Fig. 12d). There is also stronger midlevel subsidence (i.e., weaker ascent) in Fig. 12e for the termination cases that starts before day −10 over the Maritime Continent (90°–120°E). Consequently, the termination composite has negative moisture anomalies when compared to the continuing events over the RMM phase-6 region near day −10 (Fig. 12f).

While it might be easy to presume that these large-scale conditions (enhanced low-level divergence, positive pressure anomalies, weaker midlevel warming, etc.) are precursors for MJO termination events, we believe these are more likely effects (rather than causes) of a weakening MJO. Nonetheless, these observations yield significant improvements on the noticeable lead times (up to 10 days) for potential MJO termination events compared to that of the RMM index (Fig. 3) for phase 6.

The spatial variability of the low-level specific humidity and vertical velocity anomalies are shown in Fig. 13 for continuing and terminating RMM phase-6 MJO events. It is obvious by day −5 that the MJO anomalies for the terminal events have all but disappeared over the local domain (Figs. 13f and 13h), especially when compared to the composites for continuing events (Figs. 13b and 13d). Positive moisture anomalies and large-scale ascent are present over the western Pacific for termination events at day −10 (Figs. 13e and 13g), yet these are again of weaker magnitude than those for continuing MJOs (Figs. 13a and 13c). There is also no evidence of a northward displacement as was identified for MJO termination in the Indian Ocean, with the moisture deficit being mostly symmetric about the equator for RMM phase-6 events.

Although a single precursor condition was not as easily identifiable for MJO termination in the western Pacific, it is interesting to note that differences in the moisture anomalies were once again dominated by the vertical advection. Figure 14 shows the time series of the total anomalous zonal, meridional, and vertical moisture tendencies for continuing and terminating western Pacific MJOs averaged over the RMM phase-6 domain (Table 3). In both cases, the three-dimensional sum of the advection terms most closely follows the vertical advection, which principally comprises the intraseasonal circulation anomalies and background specific humidity (i.e., $\omega' \delta q / \delta p$) as shown in Fig. 15. While the mechanisms for the different intraseasonal vertical velocity anomalies remain unknown for termination events, the overall finding is consistent in that the far-reaching and downstream influences of the MJO circulation appear to be capable of altering its own upstream environmental conditions that result in its eventual demise.

b. Maritime Continent MJOs

MJO events are often susceptible to decay over the Maritime Continent as the convective envelop experiences discontinuities with stronger diurnal cycles,
topographic effects, and enhanced boundary layer friction over land. While the MJOs that weaken in this region may ultimately terminate elsewhere (such as the in the western Pacific), 9.1% of all termination events occur within the RMM phase-4 domain (90°–130°E; Table 3).

**Figure 16** shows the usual set of atmospheric variables in an attempt to identify the precursor conditions associated with MJO termination over the Maritime Continent. Of these, the most robust signals are found for low-level divergence, midlevel vertical velocity, and low-level specific humidity (Figs. 16b, 16e, and 16f, respectively).

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**FIG. 14.** Time series of the total, zonal, meridional, and vertical anomalous low-level specific humidity tendencies for (a) continuing and (b) terminating RMM phase-6 MJO events using MERRA data.

**FIG. 15.** Time series of the anomalous budget tendency terms for the vertical advection of low-level specific humidity using MERRA data. Composites for (a) continuing and (b) terminating RMM phase-6 MJO events.
Rather than associate termination conditions with the local environment, the likelihood of an MJO event to decay over the Maritime Continent seems linked to its own strength and long-term intensity. For example, Fig. 16b shows positive low-level divergence (i.e., weaker convergence) for terminating MJOs relative to continuing events, with statistically significant differences located at 0° beginning at an incredible 30 days prior to the termination event. The weaker convergence anomalies travel within the MJO envelop as it propagates eastward, eventually terminating at day 0 near 110°E in the RMM phase-4 domain. Similar differences can be seen in the midlevel vertical velocity anomalies with statistically significant and weaker ascent beginning 30 days prior to decay (Fig. 16e). Negative moisture differences and dry anomalies of 0.5 g kg⁻¹ also track alongside terminating MJOs (Fig. 16f), albeit these differences only become statistically significant at day −18 over the central and eastern Indian Ocean (75°–115°E).

Composites of the anomalous moisture advection tendencies for RMM phase-4 continuing and terminating MJO events are shown in Fig. 17. Once more, the vertical advection term best captures the total three-dimensional moisture transport over the Maritime Continent domain. Furthermore, the time series also substantiate the previous claim that MJO strength is ultimately the deciding factor as to whether an event will propagate through or terminate in this region. Both of the total moisture tendencies have similar shapes from day −20 to day −7, with negative tendencies (i.e., drying) observed until approximately day −10 and moistening thereafter. The amplitude of the total moisture tendency is weaker throughout the entire period for the termination composite (Fig. 17b), reflective of the gradual weakening and noticeable differences in MJO low-level divergence and midlevel vertical velocity that begin at day −30 for the termination events (Fig. 16).

6. Summary and discussion

This study developed a climatology of MJO termination events and decay using 34 years of the observed Wheeler and Hendon (2004) RMM index. MJO events were found to terminate in all phases of the RMM index, with the greatest frequency of occurrence within the phase-8 and phase-6 domains (Western Hemisphere and western Pacific, respectively). The RMM index tends to be stationary or experience slight growth prior to event decay, with rapidly weakening amplitudes in the 3–4 days immediately preceding MJO event termination.

Lead–lag composites of several variables including temperature, moisture, MSLP, vertical velocity, divergence, and intraseasonal wind anomalies were generated from three atmospheric reanalyses. Overall, there was incredible agreement among the datasets, with long-term, lower-tropospheric moisture deficits over the local domain best discriminating between continuing and terminating MJO events over the Indian Ocean. Many of the precursor conditions that may be important for MJO initiation were not necessarily relevant for the termination of existing events, including
midlevel temperature destabilization (Matthews 2008), MSLP anomalies associated with dry Kelvin waves and previous MJOs (Matthews 2000), and the development of planetary-scale circulation anomalies at wavenumber 1 (Straub 2013), among others. Our results suggest that environmental conditions in the local domain are most important for MJO decay, though it should be noted that other recent studies continue to emphasize the importance of the downstream conditions for MJO propagation and initiation (e.g., Kim et al. 2014).

The anomalous moisture composites for the termination events matched those of the low-level vertical velocity. As such, MJO termination over the Indian Ocean appears to be linked to a northward shift of the intertropical convergence zone (ITCZ) with anomalous subsidence located south of the equator. Possible lead times may exceed 20 days prior to MJO decay, which embodies a significant improvement over the potential lead time gained (~3–4 days) when using the observed RMM index. The importance of the ITCZ was recently highlighted by Kerns and Chen (2014a), who found that dry-air intrusions from the subtropics helped focus convection and initiate MJO events during the recent Dynamics of the Madden–Julian Oscillation (DYNAMO; Yoneyama et al. 2013) field campaign. Kerns and Chen (2014a) explain that displacing convection equatorward from the ITCZ was critical for the convective organization and MJO initiation over the Indian Ocean. We find that the opposite is true (i.e., a poleward displacement of convection) for termination events in this domain. Furthermore, Kerns and Chen (2014b) found that those DYNAMO forecast models that did not capture the synopticscale disturbances and dry-air intrusions responsible for displacing the ITCZ convection toward the equator did a poorer job of forecasting the observed MJO initiation. These results, combined with our own, suggest that future work examining the wave power associated with the symmetric and asymmetric modes of convectively coupled equatorial waves may be invaluable for learning more about MJO initiation and termination events over the Indian Ocean.

Statistically significant differences were also identified more than 10 days in advance of MJO termination events in the western Pacific, though these differences were likely the effects of a weakening MJO rather than causes responsible for the actual decay. Unlike the Indian Ocean and western Pacific, MJOs that terminate over the Maritime Continent appear to be related to their own intensity rather than the downstream environmental conditions. Statistically significant differences in low-level divergence and midlevel vertical velocity were observed to propagate alongside the MJO convection up to 30 days prior to the termination event over the RMM phase-6 domain. As such, only the strongest MJOs tend to propagate into the warm pool region.

Table 4 summarizes the statistical significance tests at day −5 for all three reanalyses and seven of the eight RMM phases. Many of the reanalyses do not indicate the presence of statistically significant different means for MJOs that terminate near the Indian Ocean (e.g.,

![Figure 17](https://example.com/fig17.png)

**Fig. 17.** As in Fig. 14, but for RMM phase-4 MJO events.
phases 1–3) because of the asymmetric differences previously discussed (recall that the statistical test is symmetric about the equator). The later phases show almost unanimous agreement for all variables at day −5, suggesting that the identification of decaying MJOs and their associated differences in the large-scale environmental conditions is robust.

Finally, a budget analysis was performed on the three-dimensional moisture advection equation in order to better elucidate what time scales and physical mechanisms were most important for MJO termination. The combination of intraseasonal vertical circulation anomalies coupled with the mean-state specific humidity best explained the anomalous moisture patterns associated with MJO termination for all phases, suggesting that the downstream influence of the MJO circulation can eventually lead to its future demise.

Despite containing the greatest frequency of termination events, the precursor conditions and termination mechanisms for RMM phase-8 (Western Hemisphere) MJOs were not discussed. The RMM phase-8 domain covers a very broad region with the negative phase of the leading EOF used to define it containing negative OLR anomalies from approximately 180° to 60°E (Wheeler and Hendon 2004). As such, selecting an appropriate longitudinal window for the significance calculations in Table 4 becomes imprecise. Furthermore, the difficulties associated with the decoupling of the MJO circulation and convection anomalies in this region make selecting a single narrow band less appropriate since different environmental variables may exhibit significant differences at separate lead times and varying longitudes. Therefore, it is nearly impossible to detect differences between continuing and terminating events using the present techniques. Initial attempts at determining the statistical significance using a narrow window over the tropical Atlantic Ocean (10°–50°W) proved largely inconclusive as any potential local signal was likely smoothed out as a result of including numerous events that decayed elsewhere in the domain. Future investigations of MJO termination in the RMM phase-8 domain would likely benefit from an index capable of better distinguishing the areas within this region (i.e., central Pacific, eastern Pacific, South America, and Atlantic Ocean).

The importance of low-level moisture for MJO termination underscores the necessity to incorporate observational results into theoretical and modeling studies. The MJO skeleton model (Majda and Stechmann 2009, 2011; Thual et al. 2014) effectively parameterizes the amplitude of the MJO envelop as a sole function of lower-tropospheric moisture anomalies. As such, this model may intrinsically outperform higher-order GCMs in regard to MJO termination, and future work will examine this hypothesis as part of larger set of model experiments.

In closing, it is worth noting that although the composites show great promise for improving statistical models of MJO termination and decay, there remains uncertainty among the continuing and terminating anomalies when considering individual events. Figure 18 shows the event-to-event variability of the previous variables at day −5 for RMM phase-6 MJO events. Although there are statistically significant different means for all of the variables with the exception of low-level zonal wind (Table 4), there is still appreciable overlap in the anomaly distributions. For example, some continuing events may have stronger negative moisture anomalies than seen in termination events (Fig. 18f). This event-to-event variability may also be different for different ocean basins (e.g., Bellenger and Duvel 2012). Future work may investigate new methods of generating moisture composites using observations taken with the Atmospheric Infrared Sounder (AIRS) on board the NASA Aqua satellite (e.g., Tian et al. 2006, 2010) as a way to reduce overlap and uncertainty.
FIG. 18. Box-and-whisker diagrams showing the distribution of (a) low-level zonal wind, (b) low-level divergence, (c) MSLP, (d) midlevel temperature, (e) midlevel pressure vertical velocity, and (f) low-level specific humidity anomalies for RMM phase-6 continuing and terminating MJO events at day −5. Box lines indicate the 25%, 50%, and 75% percentiles, with whiskers indicating the minimum and maximum for all events. Values are averaged from 10°S to 10°N using the longitude boundaries specified in Table 3. Mean quantities for each event type are shown using a black star and overlaid upon the markers that indicate local-domain average values for individual events.
Acknowledgments. Special thanks to Daria Halkides for helpful discussions related to this work and technical assistance with the moisture budget calculations. The RMM index was obtained from the Australian Bureau of Meteorology website. MERRA data were generated by the NASA Global Modeling and Assimilation Office (GMAO) and disseminated by the Goddard Earth Sciences (GES) Data and Information Services Center (DISC). ERA-Interim data have been obtained from the ECMWF data server. The CFSR data were developed by NOAA’s NCEP. The CFSR data used for this study are from NOAA’s National Operational Model Archive and Distribution System (NOMADS), which is maintained at NOAA’s National Climatic Data Center (NCDC). Additional CFSR data were obtained from the Research Data Archive (RDA) at the National Center for Atmospheric Research (NCAR) Computational and Information Systems Laboratory (CISL). Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. This study was funded by the Office of Naval Research (ONR) Award Number N00014-12-1-0912.

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