A 20-Year Climatology of Madden-Julian Oscillation Convection: Large-Scale Precipitation Tracking From TRMM-GPM Rainfall

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Abstract This study presents a 20-year climatology of the Madden-Julian Oscillation (MJO) convection based on Large-scale Precipitation Tracking (LPT) using TRMM-GPM Multisatellite Precipitation Analysis (TMPA) data from 1998–2018 over the global tropics. A total of 215 convective events are identified as MJO LPT systems over the 20 years, extending the results of Kerns and Chen (2016, https://doi.org/10.1002/2015JD024661). MJO LPT systems provide quantitative information regarding size, intensity, and location of the MJO convection in both the longitudinal and meridional directions. The MJO contributes up to 40–50% of the annual precipitation over the tropical Indo-Pacific warm pool. MJO LPT systems have distinct seasonal and interannual variability. While MJO LPT systems are generally confined over the equatorial tropics during boreal winter, some MJO LPT systems propagate northeast in the Bay of Bengal or from the south China Sea to the western North Pacific during boreal summer. MJO LPT systems are more than doubled over the Indian Ocean (IO) and Maritime Continent (MC) during La Nina compared to El Nino. The 63% of MJO LPT systems initiate over the tropical IO, 26% over the MC and western Pacific, and 11% from the central Pacific to South America. About 40% of the MJO LPT systems that initialized over the IO were unable to propagate through the MC, namely, the barrier effect. The MC barrier effect is most pronounced during the spring and autumn transitions. This 20-year MJO LPT climatology product will be provided as a supplement to this publication.

1. Introduction

The Madden-Julian Oscillation (MJO) is the predominant mode of intraseasonal variability in the tropics (Madden & Julian, 1972; Zhang, 2005). The MJO was identified using the time series of upper level winds at Canton island (2.8°S, 171.7°W) in the equatorial central Pacific Ocean, which is a reflection of the anomalous easterly (westerly) winds that are observed at low (upper) levels ahead of the MJO convection, and vice-versa behind it (Madden & Julian, 1972). It has previously been documented back in 1960s (Li et al., 2018; Xie et al., 1963). The MJO is characterized by a large-scale (e.g., thousands of kilometers), eastward propagating complex of deep convection that most often initiates in the equatorial Indian Ocean (IO). The MJO convection is mainly limited to the Indo-Pacific warm pool, where high SSTs and ample moisture can support large-scale tropical convection. The MJO convection is often disrupted over the Maritime Continent (MC), which is an active topic of study (DeMott et al., 2018; Feng et al., 2015; Hagos et al., 2016; Hendon & Salby, 1994; Kerns & Chen, 2016; Kim et al., 2017; Rui & Wang, 1990; Zhang & Ling, 2017, and many others). When the MJO convection is active, the MJO wind patterns can be viewed as a time integrated response to the convection (Chen et al., 1996; Houze et al., 2000; Kiladis et al., 2005; Salby & Hendon, 2002). Meanwhile, the MJO convection serves as a source of elevated latent heating for the MJO (Schumacher et al., 2004) and sets up distinct wind regimes over the IO (Kerns & Chen, 2018). The MJO convection generally does not propagate beyond the western Pacific warm pool; however, the MJO wind anomalies can circumnavigate the globe (Knutson & Weickmann, 1987; Krishnamurti et al., 1985).

MJO convection does not occur in isolation from other modes of variability. The multiscale nature of MJO convection has been pointed out by Chen et al. (1996) and others. Convectively coupled equatorial waves influence convection in the MJO on time scales from days to weeks (Kikuchi et al., 2017; Wheeler & Kiladis, 1999). Tropical cyclones and other cyclonic gyre disturbances may spin off of the MJO (Judt & Chen, 2014), affecting the MJO convection (Kerns & Chen, 2014; Sobel & Maloney, 2000; Zhao et al., 2015). Westward propagating waves with a periodicity of 2 days are often observed (Chen & Houze,
1997a; Haertel & Kiladis, 2004; Takayabu, 1994; Takayabu et al., 1996). Enhanced moisture buildup over the southern MC (15°S–5°S) relative to the central MC (5°S–5°N) is one factor that can enhance rainfall south of the Equator as the MJO crosses the MC (Kim et al., 2017). The diversity of convective evolution of individual MJO events is so pronounced that events closely resembling the “canonical” MJO are rare (Pohl & Camberlin, 2014). The highly variable nature of MJO convection and the diverse characteristics of individual MJO events make studying the MJO convective initiation, eastward propagation, and downstream influences a challenge.

The MJO influences weather patterns around the world including tropical cyclones, severe weather outbreaks, floods, droughts, and heat waves (Zhang, 2013). One prominent teleconnection mode is the Pacific/North American pattern, in which a Rossby wave train emanates from the tropical Pacific and affects weather over North America (Blackmon et al., 1984; Leathers et al., 1991). The heavy precipitation and westerly winds of the MJO also affect the upper ocean mixed layer on time scale of weeks to months (Jones et al., 1998; Shinoda et al., 2013). The MJO may also play a role in initiating and/or modulating El Nino Southern Oscillation (ENSO) (Kessler, 2001; Seiki & Takayabu, 2007; Zhang, 2013). Traditionally, these influences of the MJO have been elucidated based on composites of many events. However, with the large variability of the MJO events, especially its location and strength of large-scale heating associated with convection, the spatiotemporal evolution of MJO convection can have a significant effect on downstream influences. In particular, MJO convection has recently been linked to enhanced tropical-extratropical teleconnections as it crosses the MC (Adames & Wallace, 2014; Dole et al., 2014; Stan et al., 2017).

Most methods of identifying and tracking the MJO have used empirical orthogonal functions (EOFs), including the commonly used Realtime Multivariate MJO (RMM) index (Wheeler & Hendon, 2004) and the OLR MJO Index (Kiladis et al., 2014). The RMM index is most sensitive to the anomalous zonal winds associated with the MJO (e.g., Straub, 2013), while the OLR MJO Index uses only OLR. These EOF-based indices can be easily used in real time using readily available data sets; nevertheless, they do not directly track the MJO convection. Instead, the location of convection is implicit based on the multiyear composites. The spatiotemporal distribution of convection in individual MJO events may differ from the composite structures—especially during MJO initiation (Kiladis et al., 2014; Straub, 2013). The behavior of individual MJO events has been shown to vary significantly (Kim et al., 2014; Salby & Hendon, 2002; Slingo et al., 1999; Yoneyama et al., 2013; Zhang & Hendon, 1997). To better understand the physical processes associated with the MJO and predict its influences on global weather systems, it is useful to directly track the MJO convection in time and space, including its zonal and meridional variability. A climatology of MJO convection that represents initiation over the IO, eastward propagation, and meridional variability of the MJO convection is difficult to obtain using the EOF-based MJO indices.

Ling et al. (2014) developed an equatorial tracking method for MJO rainfall anomalies using the tropical mean time-longitude evolution of rain anomalies, which has been refined by Zhang and Ling (2017). This method can be used in near real time to track the longitude of the center of MJO convection. Nevertheless, it does not quantify whether the center of the MJO convection is near the equator or at higher latitudes, and it is less effective when the convection is centered off the equator.

Several studies have used Lagrangian object tracking to study intraseasonal variability and the MJO. For some strong MJO events, “super clusters” can be tracked using infrared satellite imagery (Nakazawa, 1988). Jones et al. (2004a, 2004b), Rui and Wang (1990), and Wang and Rui (1990) used 5-day OLR anomalies to track tropical intraseasonal convective anomalies. Kerns and Chen (2016, hereafter KC16) developed a systematic large-scale precipitation tracking (LPT) method using 3-hourly TRMM-GPM Multisatellite Precipitation Analysis (TMPA) data with grid resolution of 0.25°. LPT represents the spatiotemporal evolution of MJO convection in both zonal and meridional directions explicitly for individual events. It can be carried out in near real time using readily available satellite rain products, model analyses, and model forecast products. Nevertheless, KC16 was limited in several ways. The study was limited to October–March (the MJO peak season), and it only included the tropical Indo-Pacific warm pool region (15°S–15°N, 40°–180°E). This study uses the full 20-year TMPA data from 1998–2018, analyzing the MJO convection in the context of the global tropical-midlatitude (50°S–50°N) precipitation climatology. It also expands the analysis of the MJO convection to include the entire annual cycle with a number of improvements that capture more MJO events than the KC16 method. The remainder of this manuscript is organized as follows. Section 2...
describes the data and methods, focusing on several updates that have been made to the LPT method. Section 3 presents climatological properties based on the 20 years of MJO LPT systems as well as LPT and MJO contributions to global rainfall. The topic of section 4 is seasonal variability. Section 5 focuses on interannual variability. MJO strength is discussed in section 6. Section 7 focuses on the MC barrier effect from the perspective of LPT. Finally, conclusions are given in section 8.

2. Data and Methods

2.1. TRMM/GPM Precipitation Analysis

The TRMM TMPA uses passive-microwave retrievals of rain rate from TRMM TMI, AMSR-E, SSMI, and AMSU to estimate 3-hourly instantaneous rain rates on a regular 0.25° grid (Tropical Rainfall Measuring Mission (TRMM), 2011). Data are provided every 3 hr from 0000 to 2100 UTC each day. When passive microwave data are not available within 1.5 hr of the time stamp (approximately 10% of the time), infrared-based rain estimates are used to fill in the gap. This study uses the Version 7 research product, which incorporates rain gauge measurements over land. The time period is 0000 UTC 1 June 1998 to 2100 UTC 31 May 2018 (see Huffman et al., 2007, for further details regarding the TMPA).

2.2. LPT

Here we provide exceedingly detailed description of our tracking method so that readers can adapt the method to other observational data set and/or model output as they wish. The following terms are used throughout this article. LPT refers to the Lagrangian object tracking methodology for large-scale precipitation. Large-scale Precipitation Objects (LPOs) are contiguous areas of 3-day running mean large-scale precipitation. LPT systems are sets of LPOs which have spatial overlap in time for at least 7 days (as defined below). Finally, MJO LPT systems are LPT systems that exhibit eastward propagation for at least 7 days. The implementation of LPT in this study is an update to KC16, which addresses some limitations in the original method. The main differences from KC16 are as follows:

1. Tracking is carried out for the global tropics-midlatitudes (50°S to 50°N) instead of 15°S–15°N, 40°–180°E.
2. Overlapping LPT systems are allowed, instead of truncating the smaller LPT system.
3. The falling below the threshold allowance (section 2.2.2) is determined based on area overlap instead of centroid distance.
4. MJO identification is based on eastward propagating segments of the LPT system track rather than the entire LPT system.

2.2.1. LPOs

Identifying coherent precipitation systems is a challenge because rainfall is noisy. The criteria for identifying LPOs is the same as in KC16, which has been shown to be robust for tracking the MJO convection. Following KC16, the 3-day running mean rain is subjected to a two-dimensional Gaussian smoother with a standard deviation of 20 grid points (5°, approximately 550 km near the equator) extending out three standard deviations in each direction. LPOs are identified as contiguous features with greater than 12 mm day$^{-1}$ 3-day filtered rain and a minimum size of 400 contiguous grid cells (e.g., ~300,000 km$^2$, Figure 1). The rationale behind the 12 mm day$^{-1}$ threshold was presented in the appendix of KC16. Diagonal connectivity is not considered as contiguous. LPOs are identified every 3 hr. The centroids of the LPOs are the latitude and longitude of the center of mass, which represents the large-scale centers of convective activity. Note that smaller scale rain maxima may occur away from the center of mass, which reflects mesoscale and synoptic variability. The area of the LPO is the sum of the areas of each of the grid cells that encompass the LPO. The nominal time associated with each LPO is the end of the 3-day running mean period.

Using the 12 mm day$^{-1}$ threshold, the MJO convection is readily discerned. As shown in Figures 1a–1c, during 2–18 March 2012, a large area of rain spanning several thousand kilometers, marked as feature B, propagated eastward across the MC, with the LPO centroids tracking from 115°E on 0000 UTC 4 March 2011 to 145°E on 0000 UTC 20 March. The eastward propagation of this system is evident from late February to late March (Figure 2a). It was associated with a strong MJO event (Gottschalck et al., 2013; Yoneyama et al., 2013). Note that as the MJO crossed the MC, the heaviest 3-day rain occurred near 16°S, 115°E at 0000 UTC on 12 March and near 18°S, 145°E at 0000 UTC on 20 March; nevertheless, the area of rainfall associated with the MJO extended across the MC to 5–10°N. While the LPO centroid does not correspond
with the heaviest rain, it is representative of the large scale MJO. In addition to the MJO, several LPOs were identified which do not have as much continuity in time, which are labeled as A, C, D, and E in Figure 1. The next section describes how LP objects with continuity in time, such as B, were tracked.

2.2.2. LPT Systems

2.2.2.1. Connectivity in Time

The LPOs were connected in time as follows. Similar to KC16, two LPOs that occur at consecutive times (e.g., 3 hr apart) are connected in time if they overlap by the minimum of at least half of the grid points of either object. Most overlapping pairs of LPOs well exceed this criterion (e.g., Figures 2b and 3b).

In addition to the overlapping criterion for consecutive times, an allowance was made for situations where the filtered rain falls below the 12 mm day$^{-1}$ threshold for a short period (up to 3 days) and then recovers. For the LPT systems identified using the consecutive time overlap criteria, a search was carried out using the beginning and end times. If the beginning of one LPT system occurred up to 3 days after the end of another LPT system, and if the LPOs at those times overlapped by at least half of their area, the two LPT systems were combined into a single, longer lasting LPT system. This is referred to as the "falling below the threshold allowance." Sensitivity tests showed that the conclusions of this study were not sensitive to the choice of this threshold, for allowances of 6 hr up to 5 days, although some LPT systems had longer tracks with longer thresholds. (Previously, KC16 had used the distance between the centroids instead of the overlapping criterion for the falling below the threshold allowance).

LPT systems can be summarized by their tracks, areal extent, and duration. Their tracks consist of the centroid latitudes and longitudes of the relevant LPOs at each time. The LPT system area as a function of time is the area of the relevant LPO(s) at each time. For times when there are two or more LPOs, the weighted centroid of the LPOs is used, and the LPT system area is the sum of the LPO areas. The LPT system duration is

Figure 1. The 3-day mean rain rate ending at (a) 0000 UTC 4 March 2012; (b) 0000 UTC 12 March 2012; and (c) 0000 UTC 20 March 2012. The 3-day Gaussian filtered rain rate ending at (d) 0000 UTC 4 March 2012; (e) 0000 UTC 12 March 2012; and (f) 0000 UTC 20 March 2012. The contour represents the 12 mm day$^{-1}$ filtered rain contour. LPO centroids are indicated by the x markers.
the time period from the earliest LPO to the latest LPO for each LPT system. Figures 2a, 2b, 3a, and 3b illustrate the LPT system tracks and area evolution for two MJO events. Figure 2 is for the February–March 2012 event, which occurred during the DYNAMO year (Gottschalck et al., 2013). The LPOs marked B in Figure 1 were associated with this LPT system.

In order to focus on systems that exceed synoptic disturbance time scales, only the LPT systems with a minimum duration of at least 7 days were considered for the remainder of this study. This cutoff was applied after the falling below the threshold allowance. The 7 days minimum duration together with the 3 days mean rain period used for LPOs represents a minimum 10 days time scale for LPT systems in this study.

2.2.2. Splits and Mergers
Most long-lived LPT systems experience splits and mergers (e.g., Figures 2 and 3). Splits occur when an LPO at a particular time, denoted T1, overlaps with two or more LPOs at the subsequent analysis time T2 (e.g., 3 hr later). Mergers occur when two or more LPOs at T1 overlap with a single LPO at T2. (There were no instances of splits or mergers associated with the falling below the threshold allowance). In KC16, splits and mergers were handled by terminating the track with the smaller LPO at the time of split or merger. This resulted in some MJO cases being missed when the track that was terminated had eastward propagation. In this study, splits and mergers were handled as follows. LPOs are allowed to be associated with two or more overlapping LPT systems. In split cases, for each LPO at T2, the LPO was added to the entire previous history of the LPT system, resulting in two overlapping LPT systems. In merger cases, the separate LPOs at T1 were already part of separate LPT systems, and each of those LPT systems were continued using

Figure 2. (a) Time-longitude evolution of 15°S–15°N rainfall (color shading) and LPT system tracks. Black circles are drawn every 3 hr with sizes proportional to the area. The MJO eastward propagating segment is highlighted in red. The area spanned by the LPT system is indicated by the black dashed contour. (b) Spatiotemporal evolution of LPOs. Color shading indicates time. Initial (final) times are drawn in navy blue (magenta). (c) Time series of centroid longitudes with the MJO eastward propagation segment in red. (d) The 3-hourly zonal propagation speed. (e) East and west propagation segments from the divide and conquer algorithm. The time period is 28 February to 26 March 2012.
Some LPT system groups initially contained dozens of overlapping LPT systems! To simplify the analysis and to ensure that the multiple LPT systems in each group represent sufficiently distinct propagating large-scale systems, many LPT system tracks were eliminated and/or recombined into single LPT systems, as follows. First, when two LPT systems split and then merge back together, those LPT systems were recombined into a single LPT system. For the times between when the tracks split and when they merged back together, there are two LPOs associated with the LPT system. Second, for pairs of LPT systems that merge and/or split without recombining, the system with the shortest track before (after) the merger (split) was discarded if the tracking period before (after) the merger (split) was less than 3 days. After this step, 12 LPT system groups had more than four overlapping LPT systems, and the maximum number of overlapping LPT systems in a single group was 17. Note that when splits and mergers occur, there can be an abrupt change in the centroid longitude and/or latitude (e.g., during 23 December 2011 in Figure 3a), but the overall large-scale area of rainfall does not jump as dramatically. As an example of a split, an LPT system broke away of the dominant LPT system in Figure 2a on 9 March 2012, and it could be tracked as a separate system until 12 March. Both LPT systems were kept as separate overlapping systems. An example of a merger is an LPT system on 16–22 December 2015 which merged into the December 2015–January 2016 MJO event (Figure 3a).

### 2.2.2.3. Tracking by Years

While retaining the individual branches in split and merger cases has the advantage of being able to detect more MJO events, it increases the complexity and computational expense of the tracking compared with KC16. To reduce the computational demand, LPT was carried out separately for each year, with tracking years beginning at 0000 UTC 1 June of Year 1 and ending at 2100 UTC 30 June the subsequent year (Year 2). June was included at both the beginning and end of each tracking year. This is done to avoid breaking
up Boreal summer LPT systems which span May to June. In order to avoid duplication, the following rules were followed for the overlapping periods between tracking years. First, LPT systems that begin and end during 0000 UTC 1 June to 2100 UTC 30 June of Year 2 were discarded, as these systems were identified in the subsequent year. Next, LPT systems that begin at 0000 UTC 1 June on Year 1 (e.g., the beginning of the tracking year) and end before 0000 UTC 1 July of Year 1 were discarded. These LPT systems were more completely tracked in the preceding tracking year from May to June of Year 2. Finally, two LPT systems were tracked both from May–June in Year 2 and June–July of the subsequent Year 1. Since the tracking period in May was just a few days as opposed to several weeks in July, the tracks during June–July were retained and the May–June track from the prior year discarded. These cases occurred from May–July 2001 and May–August 2003. The late May portions of those two LPT systems were excluded from the database. For LPTs initiating in May 2018 and persisting to June 2018, they are counted as LPT systems, however, their associated rainfall in June 2018 was not included. Figures 4a and 4c show the LPT systems tracked during the study period.

2.3. Classification of MJO LPT Systems

This study focuses on the LPT systems with week-long segments of predominantly eastward propagation (e.g., MJO events), which are defined as MJO LPT systems. As shown in Figures 2 and 3, LPT systems associated with MJO events often have segments of both east and westward propagation of the centroid, though the overall motion is eastward. In both cases, there are westward propagating “tails” at the beginning and end of the MJO LPT systems. The identification of MJO events is based on the dominant eastward propagation segments of the LPT system centroid tracks, while allowing for tails at the beginning and end of the track and short segments of westward retreat. The approach is to use a minimal number of selection criteria, in order to not force specific MJO properties to emerge. For an MJO LPT system to be identified, there must be an eastward propagation segment that satisfies the following conditions:

1. It must have a zonal mean speed of $>0$ m s$^{-1}$.
2. The centroid must track eastward within 15°S–15°N for at least 7 days.

If two or more overlapping tracks in a group had overlapping eastward propagating segments, the track with the greatest integrated product of area and zonal propagation speed was chosen as the MJO LPT system. Note that a single LPT can be associated with two or more distinct eastward propagation periods. During the period of study, four MJO LPT systems had two eastward propagation periods associated with them. For MJO LPT statistics, these MJO LPT systems were counted only once as MJO LPT systems.

For identifying east and west propagation segments, the following method was used. First, the 3-hourly centroid zonal propagation speed was calculated from the longitude time series for each LPT system (Figures 2c, 2d, 3c, and 3d). This was done using centered differencing except for the first and last time which used forward and backward differencing, respectively. The time series of centroid zonal propagation speed is noisy and generally does not depict well the general motion of the LPT system as a whole. The following iterative divide-and-conquer algorithm was used to divide the LPT system track into eastward and westward segments. At each iteration, the remaining westward propagation segments (e.g., consecutive time periods with zonal propagation $<0$ m s$^{-1}$) were identified, and it was decided whether each westward propagation period (from shortest duration to longest duration) was to be absorbed in to the preceding and succeeding segments of eastward propagation (e.g., “conquered”). The westward propagation period was absorbed if both the time period of both the preceding and succeeding east propagation segments were longer than the westward propagation period and if the east most longitude of the succeeding period was further east than that of the preceding one. Using these criteria, some systems would be identified as MJO events despite having retrograded from the western Pacific to the IO, which is not expected behavior for the MJO. Therefore, the westward propagation segments were excluded from being conquered by the adjoining east propagation periods if they were longer than 7 days or if they traversed at least 20° of longitude. Similarly, at each iteration, it was considered whether eastward propagation segments should be “conquered” by the preceding and succeeding westward propagation segments. Beginning and ending westward propagation segments were not allowed to be “conquered” (e.g., beginning and ending west propagation periods in Figures 2d and 2e). Iteration ended when there were no more westward or eastward propagation periods to be conquered.
As an example of the identification of candidate east propagation periods for classifying MJO LPT systems, for the March 2012 MJO event, there was a westward propagation period of 3 days on 4–7 March and several shorter period of west propagation, all of which were “conquered” and are considered to be part of the predominant trend of eastward propagation (Figures 2d and 2e). Since the overall eastward propagation occurred for over 7 days within 15°S–15°N, it was classified as an MJO LPT system. In contrast, for the December 2015 to January 2016 MJO event, there was a period of slow westward propagation both before and after the dominant eastward propagation period (Figure 3). The divide and conquer algorithm identified the period of sustained dominant eastward propagation from 8 December to 2 January. Note that while the eastward propagation period is used to identify whether the LPT system is an MJO LPT system, the westward propagation periods (e.g., the tails) at the beginning and/or end of the LPT system (generally at higher latitudes) are considered as part of the MJO LPT.

Figure 4. LPT system tracks (tan lines), initiation points (blue dots), and dissipation points (red x markers) all LPT systems (a) and MJO LPT systems (b) during June 1998 to May 2018. Track density for all LPT systems (c) and MJO LPT systems (d).
Using the methodology described above, 215 MJO LPT systems were identified (Figures 4b and 4d). The thresholds and criteria used in this study are arbitrary to some degree. This is inevitable for a complex weather phenomenon such as the MJO. The greatest uncertainty in the 20-year count of MJO LPT systems is the threshold chosen for LPOs. The number of MJO LPT systems identified varies by ~10−15% for thresholds of 11−13 mm day$^{-1}$. While some sensitivity in MJO identification is inevitable in any algorithm, the choice of 12 mm day$^{-1}$ has previously been shown to be effective for TMPA data (see the appendix of KC16). The number of MJO events is also somewhat sensitive to the eastward propagation time cutoff of 7 days. Using shorter cutoffs caused many synoptic scale systems propagating eastward to be identified as MJO LPT systems. Sensitivity tests showed that using cutoffs of 8−10 days caused events crossing the MC with significant signals in the RMM index to be eliminated. Note that the number of MJO events identified using this method is larger than in some previous studies using the RMM index. This is because relatively permissive MJO identification criteria are being used, some MJO RMM events are expected to be associated with multiple MJO LPT systems, and some weak MJO LPT systems do not have a pronounced RMM index signature (e.g., amplitude >1 with propagation between multiple RMM phases).

3. Climatological Characteristics of LPT Systems and the MJO

3.1. Track Characteristics

LPT systems occur with a wide range of duration, area, and propagation characteristics. MJO LPT systems have some distinctive characteristics when compared to the population of non-MJO LPT systems (Figure 5). To effectively separate MJO LPT systems and non-MJO LPT systems, non-MJO LPT systems are defined as LPT systems occurring in groups which had no MJO LPT systems. Therefore, the non-MJO LPT systems were not associated with an MJO event in any way.

Both MJO LPT and non-MJO LPT systems tend to initiate near the Equator; however, many of them propagate to higher latitudes (e.g., poleward of 20°S or 20°N; Figures 4a and 4b). A total of 134 out of 215 MJO LPT systems tracked poleward of 15° latitude during the 20 years. In these cases, the entire LPO tracked away from the Equator not merely the centroid (e.g., Figures 2b and 3b). While the influence of the MJO at higher latitudes is well established, less is known about how it depends on the latitude to which the MJO convection propagates. LPT track density is maximized over the equatorial IO, western North Pacific, and Bay of Bengal (Figure 4c). There are secondary maxima over the eastern North Pacific and the Amazon. For MJO LPT systems, the maximum over the Bay of Bengal is not as pronounced, indicating that those LPT systems are likely westward propagating monsoon systems rather than associated with the MJO. Note that while Matthews (2008) found that MJO events based on the RMM index initiate with nearly equal probability in all eight phases, MJO LPT systems are limited to where widespread deep convection is favored.

There are several distinguishing characteristics of MJO LPT systems compared with non-MJO LPT systems. MJO events have a much greater proportion of cases lasting over 2 weeks, with several cases lasting over a month (Figures 5a and 5b). The eastward propagation portion of MJO LPT systems generally lasted 1−2 weeks with some cases up to a month (Figure 5c). Non-MJO LPT size distribution (e.g., the square root of the LPT systems maximum areal extent) peaks at 1,500−2,200 km (Figure 5d). MJO LPT systems are associated with the larger end of the size spectrum, peaking at 2,200–3,500 km (Figure 5e), which these maximum areas occurring during the eastward propagation period (Figure 5f). Non-MJO LPT systems have a slight preference for westward zonal propagation (Figure 5g). In contrast, the eastward propagation periods associated with MJO LPT systems have a peak of 3−4 m s$^{-1}$ and are mostly 1−7 m s$^{-1}$ (Figure 5i). Due to the inclusion of some westward propagation periods, the net MJO LPT speeds are a few meters per second slower than the east propagation periods (Figure 5h). Note that 97 MJO LPT systems had net zonal propagation of <2 m s$^{-1}$ (Figure 5h) and hence would be excluded by KC16 despite having a distinct period of east propagation. The fastest events identified as MJO LPT systems are significantly slower than convectively coupled Kelvin waves (e.g., 15−17 m s$^{-1}$; Wheeler & Kiladis, 1999). These propagation speeds are not forced by the MJO selection criteria. Note that previous studies have indicated a propagation speed of ~5 m s$^{-1}$ for the MJO. Many events in this study propagate slower, which may be due to several reasons, including (1) the inclusion of higher latitudes and events that propagate relatively slowly northeastward in the IO and (2) some MJO convective events may not have a strong projection on to global MJO indices such as the RMM index. It should be pointed out the MJO LPT zonal propagation speed is based on the least squares fit of
the LPT systems centroid longitudes, which is representative of the LPT systems’ bulk motion. Nevertheless, these propagation speeds may be somewhat lower than an algorithm that explicitly emphasizes only the periods of eastward propagation, such as wavenumber-frequency decomposition (see Waliser et al., 2009).

3.2. Large-Scale Precipitation and MJO Rainfall

LPT is a rainfall object tracking method which focuses on rainfall organized on the large-scale (e.g., thousands of kilometers). In addition to rainfall within the 12 mm day\(^{-1}\) boundary of the constituent LPOs, some rainfall on the periphery, within the Gaussian filter width, also contributes to the LPO (e.g., Figures 1a–1c). Therefore, to determine the rainfall associated with LPOs (and hence, LPT systems) a peripheral zone of one filter standard deviation (e.g., 5° latitude/longitude) outside of the LPO, in addition to the rain occurring within the LPO, is used. Incorporating the peripheral Gaussian filter zone allows the rainfall associated with the MJO to be more completely identified (e.g., Figures 2a and 3a). Note that each LPO represents a time period of 3 days leading up to nominal time; therefore, all of the rain occurring within the 3 days period leading up to the nominal time of each constituent LPO (and within the footprint of the LPO plus the periphery zone) is considered to contribute to the LPT rainfall (e.g., Figures 2a and 3a). Since LPT directly tracks precipitation systems, it is not surprising that most LPT systems are associated with the climatological rainfall maxima over the Indo-Pacific warm pool and the western Hemisphere tropics (Figures 4 and 6). However, rainfall also occurs outside of large-scale systems. This non-LP rain occurs mainly over the intertropical convergence zones of the oceans, Africa, midlatitude storm tracks, and the large islands of the MC (Figure 6b).
In contrast, LPO precipitation mostly occurs over the Indo-Pacific warm pool with secondary maxima in the western Hemisphere tropics and off the east coasts of the United States, Japan, and Brazil/Argentina (Figure 6c). Not all LPO precipitation is sufficiently coherent in time to be considered as LPT systems. Similar to LPO rainfall, LPT system rainfall is concentrated over the Indo-Pacific warm pool (Figure 6d).

Rainfall from MJO LPT systems is a subset of LPT rain (Figure 6e). MJO LPT systems are ~20% of all LPT systems; however, they account for ~60% of the rainfall associated with LPT systems. Furthermore, MJO LPT systems account for 40–50% of the total annual mean rain over the Indo-Pacific warm pool (Figure 7). The largest rainfall fraction contributions from the MJO LPT systems occur over the eastern equatorial IO, the southern South China Sea, and the Indonesian seas. The MJO LPT systems contribute up to 60% (55%) of the rain in Boreal summer (winter), and they contribute up to 66% (61%) during El Nino (La Nina; not shown).

Figure 6. (a) June 1998 to May 2018 annual mean rainfall from TMPA; (b) annual mean rain not associated with LP objects; (c) annual mean rain from LP objects (LPO); (d) annual mean rain from LPT systems (LPT systems); and (e) annual mean rain from MJO LPT systems (MJO).
Notably, MJO LPT track density is over the central MC (Figure 4d), but MJO rainfall peaks over the seas both north and south of the large islands of the MC (Figure 7). The MJO LPT centroid tracks are more representative of the large-scale areal extent of the MJO rain, while the heaviest rain rates associated with the MJO occur to the north of the MC and in the southern MC. Additionally, MJO LPT rainfall over land masses including the large islands of the MC is significantly less than MJO LPT rainfall over the surrounding seas.

Previous studies using the RMM index have shown that the diurnal cycle amplitude is strongest during the active MJO and that MJO rainfall over the islands of the MC predominantly occurs with a pronounced diurnal cycle (Birch et al., 2016; Peatman et al., 2014). To the extent that diurnal rainfall occurs within the footprint of LPOs (with the Gaussian filter peripheral region), it would be identified as MJO LPT rainfall in this study. The relatively low MJO LPT land rainfall compared with adjacent oceanic rainfall is not due to filtering. One consideration is that the MC is not completely covered with convection at all times during active RMM phases. Nevertheless, there is a need to clarify the multiscale interactions from diurnal to intraseasonal scales from the perspective of Lagrangian object tracking.

The centroid tracks of the MJO LPT systems tend to emphasize the overall areal extent of the MJO large-scale convection, and they are less sensitive to where the heaviest rain occurs at a given time, which may be due to localized features at a much smaller scale than the MJO (e.g., Figures 1b–1c, 1e–1f). The remainder of this paper focuses on seasonal and interannual variability in the Indo-Pacific region.

4. Seasonal Variability of the MJO

Precipitation in the Indo-Pacific region has a pronounced seasonal cycle related to the Asian-Australian monsoon system (Chang et al., 2005, 2010; Sumi & Murakami, 1981). During Boreal summer the monsoon rainfall is concentrated over South and Southeast Asia. In contrast, during Boreal winter, the rain tends to be focused over Indonesia, Papua New Guinea, and northern Australia. Not surprisingly, MJO LPT systems are modulated by the seasonal march of deep convection (Figures 8 and 9). MJO LPT systems peak in January and have a minimum in July–September, the peak Asian monsoon season. Previous studies have shown that in terms of the RMM index, the Boreal winter MJO is generally stronger (e.g., Lu & Hsu, 2017). Indeed, during the period of study, the seasonal cycle of MJO events as determined by the RMM index peaks in Boreal winter and has a clear minimum in summer, similar to the seasonal cycle of MJO LPT systems (Figure 8). Here RMM MJO events are defined similar to Straub (2013): at least 7 days of counterclockwise (e.g., eastward) propagation with the RMM index amplitude at least 1.0. Due to the relatively short duration of many MJO LPT systems, episodes of RMM amplitude at least 1.0 were considered as events if they propagated through two (rather than four) phases. The official RMM index daily values from the
If four phase RMM events were used, the Boreal summer minimum was more pronounced (not shown).

While the MJO is generally considered to be strongest over the equatorial IO and Pacific in Boreal Winter, the seasonality of the MJO is a strong function of geographic location (Adames et al., 2016; Zhang & Dong, 2004). As discussed below, the Boreal winter MJO as diagnosed from LPT is generally more concentrated over the equator, propagates further east, is associated with somewhat greater rain volume, and tends to be somewhat larger, compared with Boreal summer.

4.1. Boreal Winter

The MJO during Boreal winter is considered to be closer to the “canonical” MJO since the convection tends to be closest to the Equator and eastward propagation is more pronounced. However, there is considerable latitudinal variability even within Boreal winter (Figure 9). During October–March, MJO LPT system centroids track mostly within 5° latitude of the equator from the IO (70°E) through the MC (140°E; Figure 9). However, east of the longitudes of the MC, most MJO LPT systems track south of the equator into the South Pacific convergence zone. Several tracks are also directed northward into the western North Pacific. MJO convective initiation is concentrated near the equator in the IO (Figure 9a). Nevertheless, there is a second initiation maximum east of the MC. Dissipation is most concentrated over the MC and in the South Pacific convergence zone region.

MJO rainfall is generally concentrated near the equator in the IO and MC and in the South Pacific convergence zone. However, the maximum rainfall (4–5 mm day⁻¹) occurs just to the west of Sumatra and Borneo.
not over the equatorial IO where the centroids are most concentrated (Figures 9e and 9g). Over the MC, a relative minimum of rain (with respect to longitude) occurs east of Borneo. This “rain shadow” is also evident in the background annual rainfall climatology and the MJO LPT rain climatology (Figure 6).

4.2. Boreal Summer

In April–September, while the Asian monsoon is dominant, the center of MJO convection is shifted to the north compared with Boreal winter (Figures 9b, 9d, and 9f). There are two dominant preferred tracks: one in the equatorial IO, and a second one from the Bay of Bengal and Southeast Asia east-southeastward into the western Pacific (Figure 9f). While some MJO events pass near the equator over the MC, this is not a preferred track. More tracks enter the western North Pacific in Boreal summer than in Boreal winter. Similar to Boreal winter, MJO convective initiation most commonly occurs over the equatorial IO, and there is a secondary peak over the equatorial western Pacific (Figure 9b). Additionally, MJO initiation occurs in the Bay of Bengal during Boreal summer. Dissipation most often occurs over India, the Bay of Bengal, Southeast Asia, and over the South China Sea (Figure 9d). This is likely related to the Boreal Summer Intraseasonal Oscillation (BSISO; Jiang et al., 2004; Murakami et al., 1984; Wang & Xie, 1997; Yasunari, 1979, 1980).

Similar to Boreal winter, MJO rainfall tends to be concentrated where the highest MJO LPT centroid track density is (Figure 9h). In contrast to Boreal winter, Boreal summer MJO rainfall over the western MC is relatively low, <2 mm day$$^{-1}$$. The MJO convection tends to pass to the north of the MC in Boreal summer, likely affected by the monsoon circulation.

5. Interannual Variability of the MJO

The MJO is known to be strongly affected by ENSO (see Zhang, 2005, and references therein). Chen and Houze (1997b) have shown that MJO convection has distinct interannual variability associated with ENSO. To determine the influence of ENSO on MJO LPT systems, the NINO 3.4 monthly SST anomaly was used (Figure 10). Following the historical El Nino identification criteria used by the Climate Prediction Center, El Nino (La Nina) periods are identified when the centered 3-month NINO 3.4 SST anomaly (5°S–5°N, 120°–170°W) is >0.5 °C (less than −0.5 °C) for at least 5 consecutive months, which is referred to as the Oceanic Niño Index. The ERSSTv5 data are used for this purpose (Huang et al., 2017).

Several differences can be discerned in MJO LPT systems between El Nino and La Nina conditions (Figure 11). Not surprisingly, El Nino tracks reach further east along the equatorial Pacific (Figures 11a, 11c, and 11e). La Nina tracks are more concentrated in the South Pacific convergence zone (Figures 11b, 11d, and 11f). During El Nino, there is a more distinct minimum in track density and rainfall over the MC than La Nina (Figures 11e and 11g). While several tracks dissipate over the MC (Figure 11e), the dominant track of the center of convection is to the north of the MC during El Nino (Figure 11f). This is like Boreal summer, in which most MJO convection centers pass to the north of the MC (Figure 9f). A pronounced maximum in MJO LPT systems initiation occurs over the MC and western Pacific during El Nino, which is less the case during La Nina (Figures 11a and 11b). During El Nino, the MJO rainfall over the western Pacific is significantly greater than over the equatorial IO (Figure 11e). In contrast, the preferred track during La Nina years is directly across the MC and into the South Pacific convergence zone, which is the most preferred dissipation location (Figures 11d and 11f). This is more like Boreal winter (Figures 9c and 9e) MJO LPT systems in which the center of convection passes directly over the MC.

6. MC Barrier

The MC is considered to be a barrier for the MJO because many events are diminished or dissipate there (Hendon & Salby, 1994; KC16; Kim et al., 2014; Ling et al., 2019; Rui & Wang, 1990; Zhang & Ling, 2017).
Vitart and Molteni (2010) showed that, based on the RMM index, around 30% of MJO events are unable to cross from the IO to the west Pacific. Based on the 20 years of LPT in this study, 136 MJO LPT systems initiated over IO, of which 78 (~60%) crossed the MC (MC-crossing), and 58 (~40%) did not (non-MC-crossing; Table 1, Figures 12a and 12c). Here MC-crossing events are defined as MJO LPT systems that have the west most centroid longitude west of 100°E and easternmost centroid longitude east of 130°E, same as in KC16. Note that in KC16, around 30% of MJO LPT systems were blocked by the MC, because it excluded some cases which tracked north of 15° and/or had average eastward propagation speed of <2 m s\(^{-1}\). There are no such restrictions in this study. The larger proportion of MJO events blocked by the MC in this study compared with Vitart and Molteni (2010) likely reflects that some MJO LPT systems are not associated with RMM MJO events.

![Figure 11](image1.png)

**Figure 11.** Same as Figure 9, except for El Nino in panels (a), (c), (e), and (g) and La Nina in panels (b), (d), (f), and (h).

<p>| Seasonal and Interannual Variability in the Number of MJO LPT Systems Starting in the IO, MC-Crossing Systems, non-MC-Crossing Systems, and the Fraction of IO Systems Blocked by the MC |</p>
<table>
<thead>
<tr>
<th>Starting in IO</th>
<th>MC-crossing</th>
<th>Non-MC-crossing</th>
<th>Blocked by MC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>136</td>
<td>78</td>
<td>58</td>
</tr>
<tr>
<td>DJF</td>
<td>39</td>
<td>29</td>
<td>10</td>
</tr>
<tr>
<td>MAM</td>
<td>27</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>JJA</td>
<td>31</td>
<td>18</td>
<td>13</td>
</tr>
<tr>
<td>SON</td>
<td>39</td>
<td>18</td>
<td>21</td>
</tr>
<tr>
<td>El Nino</td>
<td>26</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>La Nina</td>
<td>52</td>
<td>30</td>
<td>22</td>
</tr>
<tr>
<td>Neutral</td>
<td>58</td>
<td>33</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 1
On average, about 40% of MJO LPT systems tracked from west of 100°E do not make it to 130°E (Table 1). Given that many MJO events are blocked by the MC, it is reasonable to assume that MC-crossing events would be weakened as they cross the MC. However, in terms of the size of MJO LPT systems, there is little indication that the MJO LPT systems are diminished as they cross the MC. In fact, MC-crossing events tend to reach their maximum size (on average ~2,500 km) as they exit the MC (Figure 12b). The MJO convection tends to occur over the seas both north and south of the large islands over the MC, which may explain the expansion in size of some MJO LPT systems as they cross the MC. This result is consistent with the total MJO LPT precipitation map shown in Figure 7. Furthermore, there is no clear separation in sizes between MC-crossing and non-MC-crossing LPT systems prior to entering the MC (Figure 12d).

The MC barrier effect has a distinct seasonal variability. It peaks (>60%) during the spring (April) and autumn (October and November) transitions and weakens during Boreal winter (December–February) (Figure 13), which is also reflected in the 3-monthly seasonal blockage of the MC (Table 1). There was little variation in MC blockage of MJO LPT systems between El Nino, La Nina, and ENSO neutral cases (Table 1).

In addition to the MJO LPT systems initiating in the IO, 54 MJO LPT systems initiated east of 130°E (WPAC; Figure 12e). These MJO LPT systems over the western Pacific were disconnected from the non-MC-crossing cases. Only four of the western Pacific cases exhibited eastward propagation within 60° longitude and 30 days when a non-MC-crossing case ended its eastward propagation (not shown). Therefore, the western Pacific MJO LPT systems are largely independent from the non-MC-crossing cases initiating in the IO. WPAC cases are on average significantly smaller than MC-crossing cases at the same longitude (Figure 12f).

Figure 12. Tracks (a) and size (b) of MC-Crossing MJOs. Tracks (c) and size (d) of non-MC-Crossing MJOs. Tracks (e) and size (f) of WPAC MJOs. Blue and red triangles denote the west and east ends of the tracks, respectively. The blue dashed lines indicate 100°E and 130°E. Solid black curves in (b), (d), and (f) are the mean within each 2° longitude bin. The MC-crossing curve from (b) is repeated in (d) and (f) as a dashed black line.

Figure 13. The percentage of MJO LPT systems initiating over the IO (west of 100°W) in each month that are blocked by the MC. Green circles indicate December–February. Orange circles are for the spring and autumn transition months with strong MC blockage, April, October, November.
7. Strength of the MJO Convection

An important question is how the characteristics of MJO convection, such as size and intensity of precipitation, vary in relation to the variability of the MJO from seasonal to interannual time scales, and the MC barrier. To address this question, we define the strength of MJO LPT system as the maximum area and the integrated volume of rain throughout the life. The integrated volume of rain depends on the area, duration, and intensity of rain over the lifetimes of the LPT systems. The volumetric rain takes into account the 3-day running mean period and the area extending one filter standard deviation from the 12 mm day\(^{-1}\) contour, as described in section 3.2. MJO LPT systems are generally much larger and produce much more rain throughout their lifetime than non-MJO LPT systems (e.g., LPT systems not occurring within groups which had MJO LPT systems; Figure 14a). The median MJO LPT produced over three times the rain volume as the median non-MJO LPT, and its maximum area was 95% larger than the median non-MJO LPT system. The vast majority of LPT systems with rain volume \(>5 \times 10^9\) mm\(-\)km\(^2\) and area \(>8 \times 10^6\) km\(^2\) are MJO LPT systems. The largest MJO LPT systems (e.g., \(>10 \times 10^6\) km\(^2\)) accounted for two to three times as much rain volume compared with non-MJO LPT systems of comparable area. This is in large part due to the longer duration of MJO LPT systems (Figures 5a and 5b). The MJO is a copious producer of rain.

The MJO LPT systems occur across a wide spectrum of areas and volumetric rain, with considerable overlap from Boreal winter to summer and from El Nino to La Nina. There was little significant difference in terms of median area and volumetric rainfall, though five of the six systems with the greatest volumetric rain (\(>11 \times 10^7\) mm\(-\)km\(^2\)) occurred during El Nino (Figure 14b). The characteristics of MJO convection remain similar regardless ENSO phases, which is consistent with the results shown in Table 1. The median Boreal winter MJO was associated with 20% greater rain volume and 11% greater maximum area than in Boreal summer (Figure 14c). Nevertheless, the largest LPT systems observed were during Boreal summer, which is associated with MJO-monsoon interactions. The most pronounced MC barrier effect in April, October,
and November as shown in Figure 13 is associated with generally weaker MJO LPT systems in the spring and fall than in December–February (Figure 14d).

8. Conclusions

The LPT method for tracking MJO convection introduced by Kerns and Chen (2016) has been improved and expanded to the global tropics—midlatitudes (50°S–50°N) for the full annual cycle over 20 years (June 1998 - May 2018). This method provides a Lagrangian object-oriented perspective of the MJO as a weather phenomenon with diverse characteristics varying from event to event. The updated LPT algorithm can better identify MJO events that are interspersed with westward propagating large convective systems that are prone to short (<7 days) periods of westward retreat. A total of 215 MJO LPT systems was tracked during the 20-year period. One of the most important features of MJO LPT systems is that they represent MJO convection explicitly with both zonal and meridional variations, which cannot be captured using existing MJO indices such as the RMM index. The meridional positions of the MJO relative to the equator may affect large-scale circulation in response to heating associated with MJO convection and, therefore, downstream impact of the MJO. To facilitate future research of the MJO and applications, we provide online supporting information that contains plots of each of the MJO LPT systems presented in this study, an extensive table with summary information of each case, links to access to the database, and a version of the Python LPT code on GitHub. They will be released upon publication of this article.

The 20-year MJO LPT data analysis in this study provides new insights regarding the MJO convective initiation, seasonal to interannual variability, and the MC barrier effects on the MJO. A majority of MJO LPT systems (63% (136 cases) initiated over the tropical IO, while 26% (55 cases) formed over the MC and tropical western Pacific (Table 1, Figure 13) and 11% (24 cases) over the western Hemisphere (Figure 4b). The locations of western Hemisphere MJO LPT systems are consistent with the OLR composites for phase 8 of the RMM index. For more than 60% of the 215 cases, the MJO convection eventually propagated poleward of 15° latitude into the subtropics as a propagating area of large-scale precipitation. Whether the convection propagated into the southern Hemisphere, northern Hemisphere, or remains near the equator may affect downstream teleconnections associated with the MJO.

The MJO LPT systems identified over the 20-year period present a unique opportunity for directly quantifying the MJO contribution to global rainfall (e.g., Figures 2 and 3). The MJO accounts for 40–50% of the annual rainfall over the Indo-Pacific warm pool (Figure 7). MJO LPT rainfall is noticeably lower over the large islands of the MC and near the Equator between Borneo and Papua New Guinea. The largest MJO contribution to the annual mean is over the equatorial eastern IO, the southern South China Sea, and the Indonesian seas. This result raises an interesting question whether the MJO can be viewed as an “anomaly” from a climatological mean to study the MJO.

There is a distinct seasonal and interannual variability in the MJO LPT systems. During Boreal winter, the maximum track density of MJO LPT systems passes directly over the MC (Figures 9). In contrast, during Boreal summer, there is an axis of MJO LPT tracks and rain from the Bay of Bengal eastward into the western Pacific, which is likely related to the Asian monsoon and the BSISO. MJO LPT systems peak in January, and their minimum occurrence is in July–September (Figure 8). MJO LPT systems tend to be somewhat weaker in Boreal summer (Figure 14) and not propagate as far east (Figure 9). During the 20-year period, over twice as many MJO LPT systems occurred during La Nina conditions compared with El Nino (Figure 11, Table 1). During El Nino years, the greatest contribution of MJO in terms of rain is over the equatorial western Pacific (Figure 11).

MJO LPT systems cross the MC throughout the year. However, ~40% of MJO LPT systems initiating in the IO do not propagate east of 130°E and are considered to have been blocked by the MC. The MC barrier effect is most pronounced during the spring and autumn transitions (Figure 13) when the overall MJO convection strength is relatively weak in April, October, and November (Figure 14). However, there is no significant variability in the fraction of MJO LPT systems blocked by the MC during El Nino, La Nina, and neutral ENSO conditions (Table 1). During Boreal summer, the centroids of many of the MC-crossing cases pass to the north of the large islands of the MC (Figure 9). Most MC-crossing cases in Boreal summer did not have to contend with the largest islands of the MC. In contrast, the centroids of MC-crossing cases in Boreal winter tend to track across the central MC, while the heaviest rain occurs over the seas of the southern MC.
(Figures 9e and 9g). During the passage of the MJO across the MC, rain occurs throughout the MC, but the heaviest rain tends to occur in the southern MC where local thermodynamic conditions, including moisture buildup, may be more favorable (e.g., Kim et al., 2017). MJO LPT systems that cross the MC tend to reach their maximum areal extent as they exit the MC (Figure 12b). This may reflect that for Boreal winter crossing cases, the MJO convection spreads out further from the Equator during passage across the MC. Clearly, further study is needed to clarify how the MJO convection interacts with the MC.

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