Variation of Lightning and Convective Rain Fraction in Mesoscale Convective Systems of the MJO

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ABSTRACT

Characteristics of mesoscale convective systems (MCSs) in regions affected by the Madden–Julian oscillation (MJO) are investigated using a database of MCSs observed by the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E). Lightning occurrence detected by the World-Wide Lightning Location Network (WWLLN) is composited in a framework centered on the MCSs. During MJO active periods, MCSs are more numerous and larger, as the convective features persist and attain greater horizontal scales. Anomalies of the lifted index, derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim) fields, indicate that MCS environments are more stable during MJO active periods.

Over the Indian Ocean, Maritime Continent, and western Pacific, lightning density in an MCS maximizes during the time that the total number of systems begins to increase as the MJO is beginning to be more active, implying both more vigorous convection and less extensive stratiform rain areas at this transitional time of the MJO. The peak in MJO precipitation coincides with peak occurrence of interconnected MCSs with larger stratiform rain fraction, shown by the Tropical Rainfall Measuring Mission satellite, while composites of lightning frequency show that during MJO active periods the zone of lightning is contracted around the centers of MCSs, and flashes are less frequent.

1. Introduction

The Madden–Julian oscillation (MJO; Madden and Julian 1971, 1972; Zhang 2005) modulates tropical atmospheric variability at intraseasonal (30–80 day) time scales, and its primary effects are observed over the region extending from the central Indian Ocean eastward to the western Pacific Ocean. In a typical MJO episode, a region of enhanced deep convection and mesoscale cloudiness and precipitation is preceded by low-level moisture convergence in association with convectively coupled Kelvin and Rossby waves (Gill 1980; Hartmann et al. 1984; Houze et al. 2000). The active convective disturbance within the MJO usually develops over the Indian Ocean, propagates eastward across the Maritime Continent, and dissipates in the western or central Pacific Ocean. The nature of the cloud population and underlying ocean conditions during the MJO have received attention during two intensive field campaigns: the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE; 1992/93) and Dynamics of the MJO/Atmospheric Radiation Measurement (ARM) MJO Investigation Experiment (DYNAMO/AMIE; 2011/12). Besides the active convective region, the MJO has a suppressed phase populated by shallow clouds and isolated convection. Deeper convective clouds predominate in the cloud population as the active period begins, and as the active period progresses some of the deep convection takes the form of mesoscale convective systems (MCSs; Mapes and Houze 1993; Chen and Houze 1997; DeMott and Rutledge 1998; Houze et al. 2000; Tromeur and Rossow 2010; Riley et al. 2011; Del Genio et al. 2012; Barnes and Houze 2013; Powell and Houze 2013; Yuan and Houze 2013; Guy and Jorgensen 2014). The MCSs are characterized by extensive stratiform precipitation areas adjoining active convective regions (Houze 2004). The largest MCSs have sometimes been referred to loosely as “superclusters” or

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“superconvector systems” (Nakazawa 1988; Mapes and Houze 1993; Chen et al. 1996). Anvil clouds emanating from MCSs and other deep convection remain prevalent as the MJO decays or propagates eastward (Del Genio et al. 2012).

Many studies have reported an increase in the number of MCSs during the MJO active period. Zuluaga and Houze (2013) showed further how the number of MCSs is modulated by synoptic-scale waves during active periods. Rowe and Houze (2014) have examined the microphysical structures of the MCSs during active MJO periods. Guy and Jorgensen (2014) analyzed DYNAMO aircraft data and found broad echo-top-height distributions in MCSs during the MJO active period. However, few if any studies have examined the variability of the convective nature of individual MCSs during the MJO. In this paper, we use lightning data and satellite radar data to analyze the variability of individual MCS convective characteristics as a function of MJO phase.

It is recognized that during an active MJO period convection is favored by large-scale low-level converging winds and deep moisture (Zhang 2005) and diurnal variability is suppressed (Sui and Lau 1992). The increased tendency for deep convective clouds to organize into MCSs is one result of this more favorable convective environment. Moderately strong midlevel environmental shear further aids the occurrence of MCSs during these times (Barnes and Houze 2013). Using A-Train satellite data, Yuan and Houze (2010) analyzed two categories of MCSs: connected MCSs (CMCSs), in which three or more MCSs are connected by a common rain area, and separated MCSs (SMCSs), in which a rain area is associated with just one or two MCSs (see section 2a for further details). Although the snapshots provided by the A-Train satellite cannot follow MCSs in time, the CMCSs most likely represent the merging of multiple MCSs (Williams and Houze 1987; Mapes and Houze 1993) and include the superclusters described by Nakazawa (1988). Yuan and Houze (2013) observed increased fractional areal coverage of both SMCSs and CMCSs during the active period of the MJO, with CMCS coverage varying more strongly than that of SMCSs. Variability in precipitation contribution from CMCSs matched overall MJO precipitation variability in each geographic region they considered, while that of SMCSs did not. These previous studies all indicate the likelihood that MCS characteristics vary as a function of MJO phase and that CMCSs play an especially important role, showing the most pronounced variation with respect to stage of the MJO.

Research to identify how MCS characteristics vary across an MJO has up to now not taken full advantage of the availability of lightning observations that indicate the locations of the most convectively active portions of cloud systems. Kodama et al. (2006) and Morita et al. (2006) reported an out-of-phase relationship between lightning and precipitation during the MJO. Virts et al. (2013b) observed enhanced diurnal lightning variability downwind of mountain ranges over the Maritime Continent region throughout the MJO cycle. These studies analyzed either the general occurrence of lightning following the MJO’s evolution (Morita et al. 2006) or maps of lightning frequency of occurrence (Kodama et al. 2006; Virts et al. 2013b). MJO-related lightning variability in specific members of the cloud population has not yet been investigated. In this paper, we analyze lightning associated with individual MCSs that were identified objectively in data from NASA’s A-Train satellite constellation by Yuan and Houze (2010). For this study, we have organized the members of their MCS database according to phases of the MJO to examine the climatological-mean characteristics of MCS lightning productivity as well as the occurrence of lightning in MCSs as a function of MJO phase. In addition, we obtain further insight into the variability of MCS structure and behavior in the context of the MJO by analyzing lightning occurrence and the convective and stratiform precipitation features identified by Liu et al. (2008) from data of the Tropical Rainfall Measuring Mission (TRMM) satellite.

2. Data

a. MCSs identified in A-Train observations

In this study, we analyze MCSs seen in A-Train satellite observations obtained during 2007–10. Yuan and Houze (2010) describe a technique for identifying MCSs using observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) instruments on the Aqua satellite. Contiguous observations of MODIS 10.8-µm brightness temperatures (TB10) less than 260 K are used to identify “high cloud systems” (HCSs). The AMSR-E AE_Rain product (Kummerow et al. 2001; Wilheit et al. 2003; Kummerow and Ferraro 2007) is used to identify where rain is falling from an HCS at a rate of more than 1 mm h⁻¹. Yuan and Houze (2010) call the innermost portion of the HCS, where rain is falling, the “raining core” of the HCS. In order for an HCS to be categorized as an MCS, it must contain at
least one raining core and satisfy the following characteristics:

- Largest raining core is larger than 2000 km$^2$ in total area.
- Largest raining core accounts for over 70% of the total area with rain rate greater than 1 mm h$^{-1}$ inside the HCS.
- Minimum cloud-top temperature above the raining core is less than 220 K.
- Heavy rain, defined as greater than 6 mm h$^{-1}$, is observed in more than 10% of the raining core area.

MCSs identified by these criteria account for 57% of rainfall (and hence latent heating) in the latitude belt of 30°N–30°S. As described above, the MCSs are then divided into SMCS and CMCS categories based on how many MCSs are associated with a common rain area. The Yuan and Houze (2010) designation of three or more linked MCSs as “connected” is a stringent criterion to be more certain that the cloud systems in question came about through merging, as described by Williams and Houze (1987) and Mapes and Houze (1993). Previous work has shown that the separated and connected MCSs exhibit different patterns climatologically relative to land and ocean (Yuan and Houze 2010).

b. WWLLN lightning

The ground-based World Wide Lightning Location Network (WWLLN) detects very low-frequency (VLF) lightning sferics and locates lightning to within about 5 km and less than 10 $\mu$s (Abarca et al. 2010). WWLLN preferentially detects cloud-to-ground lightning, and its global detection efficiency is estimated to be approximately 10% of all lightning strokes during the period included in this study (Rodger et al. 2009; Abarca et al. 2010; Rudlosky and Shea 2013). Based on comparison with the TRMM Lightning Imaging Sensor (LIS; see section 2d), WWLLN has a lower detection efficiency over land than it does over the ocean (Rudlosky and Shea 2013; Virts et al. 2013a). When comparing regional lightning statistics, we will present results based on both lightning datasets.

Lightning in the vicinity of MCSs is analyzed as follows: each MCS is assigned a coordinate system with the center of its largest raining core at 0°, 0° relative latitude and longitude, and a 0.25° latitude $\times$ 0.25° longitude grid is created in the system-relative coordinates. Lightning strokes recorded by WWLLN within a 1-h window centered on the time of the MODIS overpass are assigned to the relative latitude–longitude grid boxes, based on their orientation relative to the MCS. The result of this analysis is a map of lightning frequency relative to the center of each MCS, expressed as the number of strokes observed per square kilometer per hour. The lightning frequency maps do not distinguish whether the lightning was produced by the MCS or by neighboring convection. From these maps, we calculate lightning density, defined as the lightning frequency per unit area of the MCS. Only lightning strokes in a grid box containing a portion of the MCS high cloud are included in the calculation, so most lightning produced by other deep convection is excluded.

c. ERA-Interim lifted index

It is important to relate lightning and MCS occurrence to the convective instability of the environment. Because cloud electrification and lightning occur when graupel and/or hail particles are within clouds (Williams 1988; Zipser and Lutz 1994; Baker et al. 1995; Houze 2014; and others), the relevant instability conditions are specifically those that are most conducive to the occurrence of large concentrations of supercooled water that can be accreted onto ice particles to produce graupel and/or hail. In many studies, the convective available potential energy (CAPE) of the environment is used as an indicator of instability. However, CAPE is the vertically integrated buoyancy, and CAPE may therefore be large even if the buoyancy at any given altitude is small. In such cases, clouds cannot attain large concentrations of supercooled water. For the purpose of the present study, we therefore use the lifted index (LI), which is a measure of the likely buoyancy of parcels in the lower troposphere. That is, it is an indicator of the possibility of parcels obtaining large vertical velocities and hence high condensation rates (and liquid water contents) in the low to midlevels of the troposphere, where water vapor mixing ratios are the greatest. LI is defined as the difference between the observed 500-hPa temperature and the temperature of an air parcel lifted moist adiabatically from the surface to the 500-hPa level. Negative values of LI indicate that the lifted parcel is warmer than its environment and, thus, positively buoyant. We calculate LI using European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim; Dee et al. 2011) fields, which are available four times daily at 1.5° horizontal resolution. At each grid point, the climatological monthly-mean LI is subtracted from the calculated LI for each of the four synoptic observation times in order to remove the seasonal and diurnal cycles of LI.

d. TRMM precipitation and lightning

Using TRMM observations, Liu et al. (2008) compiled a database of radar precipitation features (RPFs) defined as contiguous areas of TRMM radar echo (i.e., areas of precipitation). From that database, we analyze
15 years (1998–2012) of RPFs greater than 2000 km² in area—the threshold size for the Yuan and Houze (2010) MCS database. To limit the analysis to features capable of producing lightning, we include only RPFs for which the maximum height of the 30 dBZ contour is at least 6 km. TRMM echoes are designated as convective or stratiform, based on the vertical profile and horizontal variability of the reflectivity (Awaka et al. 1997; Schumacher and Houze 2003). The Liu et al. (2008) database includes the convective and stratiform rain volumes for each RPF, from which we calculate the convective rain fraction as the convective rain volume divided by the total rain volume.

The database also includes the number of lightning flashes observed in each RPF by the Lightning Imaging Sensor (LIS; Christian et al. 1999)—a TRMM-borne staring optical imager with an estimated detection efficiency of about 80%–90% (Boccippio et al. 2002). An RPF lightning density analogous to the MCS lightning density can be calculated by dividing the flash count by the RPF size and the viewtime (the length of time the RPF was observed by LIS).

The TRMM satellite was in a 35° inclination orbit, permitting it to observe the full diurnal cycle of convection, while the A-Train satellites operate in a sun-synchronous orbit, with equatorial crossings at 0130 LT. Analysis of data from TRMM and the International Satellite Cloud Climatology Project (ISCCP) indicate that the MJO does not significantly affect the diurnal phase of the areal coverage of deep convective cloud (Tian et al. 2006), although other studies have noted that the diurnal peak in rainfall and lightning over the Maritime Continent and near-coastal waters occurs 1–3 h earlier during the MJO suppressed and developing stages (Rauniyar and Walsh 2011; Oh et al. 2012; Virts et al. 2013b). We will demonstrate that MCS characteristics observed by the TRMM and A-Train sensors reveal a consistent pattern of variability during the MJO.

e. MJO index

The evolution and strength of the MJO can be represented using the real-time multivariate MJO (RMM) index (Wheeler and Hendon 2004). In this study, we analyze MCSs on days when the magnitude of the RMM index was greater than one standard deviation, and we exclude the remaining days (about 15% of the total data period), when the MJO was weak. We identify active and suppressed periods of the MJO for a given region by calculating the mean precipitation rates from the 3-hourly gridded TRMM 3B42 dataset (Huffman et al. 2007) during each MJO phase.

3. MCS characteristics by region

The climatological distribution of MCSs over the warm-pool region is shown in Fig. 1, and Table 1 summarizes the number and characteristics of systems over
four regions of interest. As noted by Yuan and Houze (2010), SMCSs are frequently observed over the Maritime Continent region. CMCSs are not frequent over the Maritime Continent but nevertheless account for about 30% of all MCSs in the Indian Ocean ITCZ extending westward from Sumatra south of the equator, the western Pacific Ocean ITCZ centered around 5°–7°N, and the SPCZ extending southeast of New Guinea. CMCSs reflect the merging of multiple convective systems, which is common over the regions considered here (Williams and Houze 1987; Mapes and Houze 1993; Chen et al. 1996), and their formation is favored by the greater sustainability of convection over these open broad oceanic convergence zones (Yuter and Houze 1998; Schumacher and Houze 2003; Yuan et al. 2011). Because of their longevity and horizontal extents, CMCSs are expected to have extensive stratiform regions, which is consistent with the larger stratiform area and rain fractions seen over these regions (Schumacher and Houze 2003). Accordingly, RPFs over the Maritime Continent have larger convective rain fractions than those over the oceanic regions (Table 1).

As noted in section 2, lightning is produced by convective clouds with strong updrafts, in which collisions between ice crystals and graupel produce electrical charge separation via the noninductive process (Williams 1988; Zipser and Lutz 1994; Baker et al. 1995). Oceanic convective clouds tend to have weak updrafts compared to those over land (LeMone and Zipser 1980; Zipser and LeMone 1980; Jorgensen and LeMone 1989; Zipser 1994), and analysis of TRMM data has shown that lightning-producing convective clouds are significantly more likely to be found over land than over the ocean (Toracinta et al. 2002; Cecil et al. 2005; Zipser et al. 2006). MCS and RPF lightning densities (defined in section 2) exhibit pronounced land–ocean differences: lightning densities in MCSs over the Maritime Continent are up to an order of magnitude larger than in those over the open-ocean regions (Table 1). A ground-based lightning network near Papua New Guinea during TOGA COARE reported similar proportions between land and ocean lightning frequency (Orville et al. 1997). Contrasts up to two orders of magnitude are observed between flash rates in MCSs over the open ocean and MCSs over larger tropical landmasses such as Africa and South America (Nesbitt et al. 2000).

Cloud-to-ground lightning, which is usually in the form of negative flashes, is mostly produced in the deep convective portion of an MCS (Rutledge and MacGorman 1988; Holle et al. 1994). Some lightning occurs in the stratiform portion, and those flashes are disproportionately positive (Goodman and MacGorman 1986; Rutledge and MacGorman 1988; Rutledge et al. 1990; Carey et al. 2005). Thus, while lightning density as we have defined it primarily reflects the strength of the convection, it also depends on the proportion of the convective rain area to the total MCS area. In the regions considered in this study, those with larger MCS lightning densities also have larger RPF convective rain fractions and vice versa (Table 1). However, convective rain fraction varies less than 10% from region to region, while as we have seen, lightning density varies by up to a factor of 10.

With these general climatological characteristics of MCSs in mind, we now focus on the variability of the convective characteristics of individual MCSs during the MJO.

### 4. MCS variations during the MJO

#### a. Example of the composite analysis technique: The Maritime Continent

To illustrate how our compositing method determines the lightning characteristics of MCSs, we present analysis for SMCSs observed over the Maritime Continent region. Composites of lightning in SMCSs over the Maritime Continent when the MJO is active (RMM phases 3–4–5) and suppressed (RMM phases 7–8–1) are shown in Fig. 2. In both composites, lightning is most frequently observed near the center of the SMCS (0°, 0° in relative latitude and longitude). The lightning frequency in SMCSs varies with the MJO: there is a roughly 50% increase in the peak lightning frequency.

**Table 1.** Number of MCSs and RPFs (with area larger than 2000 km² and maximum height of 30-dBZ contour above 6 km) over the regions outlined in Fig. 1. Also shown is the percentage of MCSs that are part of a CMCS, mean MCS and RPF lightning density (×10⁻³ strokes per square kilometer per hour), and mean convective rain fraction in the RPFs.

<table>
<thead>
<tr>
<th>Region</th>
<th>Number of MCSs</th>
<th>Percentage CMCSs</th>
<th>MCS lightning density</th>
<th>Number of RPFs</th>
<th>RPF convective rain fraction</th>
<th>RPF lightning density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indian Ocean</td>
<td>20,760</td>
<td>29.5</td>
<td>0.20</td>
<td>39,742</td>
<td>0.59</td>
<td>1.75</td>
</tr>
<tr>
<td>Maritime Continent</td>
<td>33,548</td>
<td>17.6</td>
<td>2.02</td>
<td>76,769</td>
<td>0.62</td>
<td>19.71</td>
</tr>
<tr>
<td>Western Pacific</td>
<td>20,218</td>
<td>30.0</td>
<td>0.17</td>
<td>46,210</td>
<td>0.57</td>
<td>0.81</td>
</tr>
<tr>
<td>SPCZ</td>
<td>18,555</td>
<td>29.3</td>
<td>0.54</td>
<td>30,323</td>
<td>0.60</td>
<td>2.03</td>
</tr>
</tbody>
</table>
during the suppressed period compared with the active period. An out-of-phase relationship between local or regionally averaged lightning and precipitation in relation to the MJO was previously noted by Kodama et al. (2006) and Morita et al. (2006).

As noted in section 2, we expect greater lower-tropospheric instability to be conducive to stronger convective updrafts, liquid water content, graupel, and, hence, lightning. To assess the stability of the MCS environments, each SMCS was assigned the LI value derived from ERA-Interim fields for the grid point nearest to its center. Mean LI anomalies for each MJO phase are shown in Fig. 3. SMCSs are observed in significantly more stable environments during the MJO active period (positive LI anomalies and large numbers of SMCSs during MJO phases 3 and 4) and more unstable environments during the suppressed period. The timing of the stability extrema is similar to that of lightning—both the highest lightning frequencies and lowest LI anomalies are observed during phase 8 and vice versa during phases 4 and 5.

During all MJO phases, lightning frequency decreases with distance from the center of the SMCS (Fig. 2). However, the lightning maximum is noticeably broader during suppressed periods, when the mean SMCS size is smaller and decreasing (Fig. 3). Examination of Fig. 2 reveals that the area of enhanced lightning extends somewhat beyond the indicated size of the MCS (and certainly beyond the convective core), particularly during the suppressed period. Composites produced using a shorter, 20-min observation window are quite similar to Fig. 2 (not shown), so the broad lightning maxima cannot be explained by MCS propagation during the observation window. The broader lightning maximum during the MJO suppressed period may reflect an increase in the number and lightning productivity of neighboring deep convection.

b. Lightning behavior as the MJO progresses

Precipitation reaches maxima over the eastern Indian Ocean, Maritime Continent, western Pacific, and SPCZ during MJO phases 3, 4, 5, and 7, respectively (Fig. 4), in accordance with the eastward propagation of the MJO. In each region, the precipitation maximum is followed approximately 3–4 phases later by a precipitation minimum, indicative of the suppressed period of the MJO. Figure 5 shows the number of each type of MCS observed over each region as a function of MJO phase. Comparison with Fig. 4 reveals that for each region considered, CMCSs are most numerous during the MJO phase corresponding to peak precipitation. The greater connectedness of MCSs during the MJO active period is related to the increase in midlevel moisture (Yuan and Houze 2013) and other factors promoting and/or caused by the development of deeper and wider convective
systems. The number of CMCSs is more strongly modulated by the MJO (by over a factor of 2 in each region) than the number of SMCSs—a result also noted by Yuan and Houze (2013). The overall increase in number of SMCSs during active MJO phases is consistent with the greater probability of MCSs occurring in the vicinities of each other and thus increasing the likelihood of mergers to produce CMCSs. Mapes and Houze (1993) likewise found that the occurrence of large deep convective cloud clusters was more strongly affected by the MJO than that of smaller clusters.

SMCSs exhibit somewhat different timing than the CMCSs, and this timing reflects the character of the MJO in each region. Over the Indian Ocean, there is a broad maximum in SMCS occurrence from phase 8 to phase 3, while CMCS occurrence peaks during phase 3. This behavior indicates that the genesis of an MJO episode is marked by the frequent occurrence of MCSs, with an increased occurrence of larger and more connected MCSs as the MJO episode strengthens. Over the Maritime Continent, SMCSs peak in occurrence one phase before the CMCSs, illustrating the increasing aggregation of cloud features during the active period. The MJO begins to weaken as it enters the western Pacific, and the number of SMCSs peaks at nearly the same time as the CMCSs. Over the SPCZ, the occurrence of CMCSs maximizes before SMCSs, indicating that the conditions are becoming less favorable for maintaining MCSs of large size as the MJO moves eastward into regions less favorable for convection. Williams and Houze (1987) noted that MCSs undergo both mergers and splits, and the less favorable conditions for maintaining large MCSs could lead to splitting up of CMCSs. This behavior is worthy of further investigation but is beyond the scope of the present study. This result is similar to the findings of Barnes and Houze (2013), who examined the occurrence of deep convective cores, wide convective cores, and broad stratiform regions, as seen in TRMM radar data, over the Indian and western Pacific Oceans. They found that over the Indian Ocean both wide convective cores and broad stratiform regions (which were associated with MCSs) peaked somewhat after the deep convective cores. However, Barnes and Houze (2013) did not attempt to analyze the TRMM data over the Maritime Continent because their echo-object identification criteria were not applicable over land or mixed land-and-ocean regions. Here we find a progression of convective feature types over the Maritime Continent that is consistent with their analysis of the Indian Ocean west of the Maritime Continent. Barnes and Houze (2013) also found that over the SPCZ region east of the Maritime Continent the deep and wide convective cores peaked in occurrence one phase after the broad stratiform regions, which is again consistent with the notion that MCSs decrease in size and degree of organization as the MJO decays.

Figure 5 further demonstrates that both SMCSs and CMCSs are observed in each geographical region during all MJO phases, which is in agreement with the conclusion of Riley et al. (2011), Del Genio et al. (2012), and Barnes and Houze (2013) that the MJO modulates the relative frequency of occurrence of the various members of the cloud population.

Figure 5 also shows lightning density as a function of MJO phase. Over the Indian Ocean, the largest lightning densities in both SMCSs and CMCSs are observed during phase 7, one phase after the minimum in precipitation (Fig. 4) and just as the number of MCSs begins to increase. Lightning densities are low during phases 2–5, during which time the MCS occurrence maximizes and then rapidly decreases as the area of MJO enhanced convection shifts eastward. Similarly, peak lightning densities over the Maritime Continent and western Pacific are observed within one phase of the precipitation minimum. MCSs over the SPCZ exhibit somewhat different behavior. There, the highest lightning densities are observed 2–3 phases after the peak MJO precipitation. In each geographic region, the absolute magnitude of the variations in lightning density with respect to the MJO is comparable in separated and connected MCSs. However, while the maximum and minimum SMCS lightning densities are significantly different from each other at the 99% confidence level for each region except the SPCZ, CMCS lightning density varies significantly with MJO phase only in the Maritime Continent region.

Lightning density in RPFs similar in size to MCSs exhibits MJO-related variability similar in timing to Fig. 5.
(not shown): peak lightning is observed at or just after the
time of minimum domain-mean rainfall (and vice versa) for
each region except the SPCZ, where it occurs a few phases
after the peak rainfall. Thus, the behavior of the lightning
density relative to MCSs in the MJO is robust and in-
dependent of the analysis approach used to identify MCSs.

\(c. \text{ Consistency of lightning with convective rain}
\)
\(\text{fraction and the stretched-building-block hypothesis}\)

Convective rain fraction, determined from the
TRMM radar, varies with phase of the MJO (Fig. 6), and
we would expect that lightning occurrence should bear
a consistent relationship to the convective rain fraction.
Over the Indian Ocean, Maritime Continent, and
western Pacific, convective rain fractions are lowest
during the MJO active period, either concurrent with or
one phase after the peak precipitation (cf. Fig. 4). As
previously noted by Yuter and Houze (1998), the
greater amount of precipitation during the active period
is primarily due to increased stratiform precipitation.
The converse—that deep, intense convective clouds
contribute proportionally more precipitation during the
MJO suppressed period (when areal rainfall is minimal)—
was demonstrated in analysis of radar data from TOGA.
Our results are in agreement: Fig. 6 shows that convective rain fractions increase during the suppressed period, peaking at one phase after the time of minimum precipitation. Convective rain fraction in TRMM RPFs and lightning density in MCSs (Figs. 5 and 6) thus exhibit similar timing with respect to the MJO. Over the SPCZ, convective rain fraction is also smallest during the MJO active period, but there the minimum is observed during phase 6, one phase before the peak precipitation. It is worth noting that convective rain fraction varies more strongly as a function of system size than by region or MJO phase. Smaller precipitation systems tend to have proportionally less extensive stratiform rain areas: RPFs corresponding in size to the smallest and largest 50% of MCSs have mean convective rain fractions of approximately 0.6–0.7 and 0.35–0.45, respectively.

The results in Figs. 5 and 6 show that the evolution of the characteristics of individual MCSs over the Indian Ocean and Maritime Continent during the MJO consists of a progression from few organized convective systems, to deep convective systems with frequent lightning that are more akin to young MCSs, to extensive stratiform precipitation areas akin to those associated with older MCSs. The statistical progression of variables of lightning and convective rain fraction relative to MJO phase is an
upscale analog of the life cycle of an individual convective cloud or MCS but takes place on a time scale of weeks—much longer than the lifetime of the individual clouds. Recently, Zuluaga and Houze (2013) examined the evolution of the cloud population relative to the precipitation episodes during MJO events in DYNAMO. They too observed a statistical sequence of cloud properties aligning with the life cycle of an MCS, but with a time scale of about 2–4 days. The stretched-building-block model (Mapes et al. 2006) proposes that convective clouds and MCSs “in different stages of a large-scale wave have different durations of shallow convective, deep convective, and stratiform anvil stages in their life cycles,” such that the evolution of the statistics of the cloud population associated with the wave align with the evolution of individual convective clouds. Our analysis focuses on a single stage of the convective life cycle (MCSs at or near the mature stage) and is based on snapshots when the satellites pass overhead. Nevertheless, the variability that we observe in the number and characteristics of individual MCSs during the MJO is consistent with the stretched-building-block model.

5. Conclusions

MCSs occur frequently over the region extending from the central Indian Ocean to the western Pacific Ocean, but the strength of the convection that they contain and the degree of organization vary with respect to phase of the MJO and from one region to another. The previous study of Barnes and Houze (2013) using TRMM data to characterize convection in the MJO considered the Indian Ocean and western Pacific regions but not the Maritime Continent located between the two regions. In this study, we use a wider variety of datasets—A-Train, WWLLN, and TRMM—and we fill the regional gap by examining convective behavior over all three zones.

The lightning data analyzed here indicated that MCSs over or near the islands of the Maritime Continent tend to contain more vigorous convection than their counterparts over the central Indian Ocean and western Pacific. MCSs over the Maritime Continent have large lightning densities, while MCSs in the oceanic convergence zones are more connected and have proportionately larger stratiform rain fractions. Regional (land versus ocean) differences in lightning frequency are much larger than variations associated with the MCS size or category or with MJO phase, while convective rain fraction varies most strongly by system size. This result implies that the landmasses of the Maritime Continent are a major factor in making the convective elements more intense.

The MJO modulates the number, size, structure, and intensity of MCSs over a region stretching from the central Indian Ocean to the western Pacific Ocean. Our results are entirely consistent with previous studies (Kodama et al. 2006; Morita et al. 2006; Virts et al. 2013b) that reported more frequent lightning during the MJO suppressed period. However, in this study we have extended the analysis to lightning in specific members of the convective cloud population—namely, the large MCSs. Based on the results in this paper, the evolution of the typical characteristics of MCSs during a typical MJO episode over the Indian Ocean and Maritime Continent can be described as follows:

- After a period of relatively low regional-mean precipitation, individual deep convective clouds begin to increasingly aggregate into small, separated MCSs. At this time, lower-tropospheric instability promotes strong convective updrafts, resulting in frequent lightning flashes, while the drier conditions in the middle and upper troposphere (not shown) limit the extent of the areas of stratiform precipitation.

- Over the next several weeks, MCSs become more numerous, and lightning becomes less frequent as the near-storm environments become less unstable. Stratiform raining areas become more extensive, both in absolute size and in proportion to the total MCS size. As they appear in greater frequency, MCSs are more likely to merge, and large connected MCSs peak in occurrence at the same time as the regional-mean precipitation.

- As the area of MJO-related enhanced convection shifts eastward, MCSs decrease in number and size. The merging of MCSs occurs less frequently at this stage, and convective precipitation accounts for an increasing proportion of total MCS precipitation. Environmental conditions are more unstable in the less convectively active phases of the MJO, leading to increased lightning frequencies in the MCSs that manage to occur at these more suppressed times. Probably additional lightning occurs during these times in more isolated convective cells and convective systems that do not satisfy the criteria of MCS designation.

Examination of Fig. 5 reveals that MJO-related variability in lightning density is more statistically significant in the smaller, separated MCSs, which also produce more frequent lightning than the larger CMCSs. The number of CMCSs varies more strongly by MJO phase, more than doubling in occurrence during the active period.

The above evolution of the statistics of MCS characteristics during the MJO forms an upscale analog to the
canonical MCS life cycle—a result that would seem to be consistent with the stretched-building-block hypothesis of Mapes et al. (2006). The sequence as described above applies over the Indian Ocean and the Maritime Continent, reflecting the strengthening and mature stages of the MJO, and, to a lesser extent, to the western Pacific ITZC, where the MJO begins to weaken. Over the SPCZ, a variation of this behavior is noted, as lightning density and convective rain fraction maximize just after the peak in precipitation, as the MJO decays. Conditions are apparently not as favorable for maintenance of larger convective systems in this part of the domain affected by the MJO convection. We also note that comparison of Fig. 5 with the results of Barnes and Houze (2013) indicates that areal coverage of deep convective cores often is not synchronized with lightning density during the MJO. The convective rain fraction appears to have a more direct relation to the occurrence of lightning. Direct analysis of lightning associated with deep and/or wide convective cores, using the TRMM LIS, could provide useful clarification of this point and is a topic of further study that we recommend.

When comparing results based on the Yuan and Houze (2010) and RPF databases, a consistent picture emerges of the distribution of MCSs and the statistical variability of their characteristics from region to region and during the MJO, indicating that our results are not dependent upon which specific methodology is used to identify MCSs. The categorization of MCSs observed by Yuan and Houze (2010) as separated or connected permits analysis of the impact of the MJO on the population of the largest convective features likely to have been formed by the merging of smaller systems. The increased incidence of clustering of MCSs during the active period, and the increase in extensive stratiform raining areas indicated by TRMM, contain important implications for the vertical distribution of latent heating associated with the MJO, which in turn feeds back onto the large-scale dynamics.

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