Evolution of the Population of Precipitating Convective Systems over the Equatorial Indian Ocean in Active Phases of the Madden-Julian Oscillation

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Submitted to Journal of the Atmospheric Sciences

November 2012

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Abstract

Three-dimensional radar reflectivity fields from a dual-wavelength Doppler polarimetric radar deployed in the equatorial Indian Ocean during an international field campaign to study the Madden-Julian Oscillation (MJO) are used to identify deep convective (DCC) and wide convective (WCC) echo cores, and broad stratiform (BSR) echo regions. Large-scale dynamic and thermodynamic environments during the life cycle of the various forms of extreme echo structures are analyzed using ECMWF ERA-interim reanalysis data and three-hourly atmospheric soundings taken at a site near S-PolKa. The frequency of occurrence of the three different echo structures with respect to the time of maximum rain accumulation for each of eleven rain episodes that occurred during active MJO phases shows that DCC events were most frequent before the maximum rainfall, WCC events were most frequent during the rainfall maximum, and BSR regions were most frequent in the later part of the rainfall episode. Composites of the synoptic conditions during the rainfall episodes indicate how the surrounding atmosphere changes as the dominant membership of the cloud population changes from DCC to WCC to BSR echoes. These results support the stretched building-block notion of tropical convection and confirm satellite-based interpretations of DCC, WCC, and BSR statistics in terms of mesoscale convective lifecycle stages.
1. Introduction

The Madden-Julian Oscillation (MJO, Madden and Julian 1971, 1972) accounts for a major component of the intraseasonal variability of the tropical general circulation, and it is closely connected with the variation of the convective cloud population over the equatorial Indian Ocean (Zhang 2005). This study uses a series of observational datasets collected during the Dynamics of the Madden-Julian Oscillation (DYNAMO) field project and its partner program, the Atmospheric Radiation Measurement (ARM) Program’s MJO Investigation Experiment (AMIE). These campaigns collected data over the Indian Ocean and West Pacific, where the MJO originates and manifests most robustly. The goal was to obtain information that will allow scientists to obtain details of the convective cloud field and to relate these details to the large-scale circulation of the MJO. The four-month period of data collection in DYNAMO/AMIE was long enough to provide detailed observation of cycles of the convective population during occurrences of the MJO over the Indian Ocean. However, the area of detailed data collection was small and ultimately the results must be related to the large-scale circulation of the tropics.

To connect the measurements of DYNAMO/AMIE to the MJO, it will be necessary to upscale the information obtained at the field observation sites to the planetary scale of the MJO. One important pathway for this upscaling is to relate the observations at the field sites to satellite data. Ordinary infrared or passive microwave imagery alone is limited in what it can provide in terms of insight into convective clouds in the MJO because it does not provide three-dimensional structural information. Satellites with active radars on board can, however, be used to provide climatological information of the
structure of deep convective systems. The Tropical Rainfall Measuring Mission (TRMM) satellite (Simpson and Adler 1988; Kummerow et al. 1998, 2000) has a 2 cm wavelength precipitation radar on board, and the CloudSat (Stephens et al. 2002) satellite features a millimeter wavelength cloud radar. One of the limitations of using these tools is that it is difficult to determine the probable lifecycles of the convective entities producing satellite based statistics because TRMM and CloudSat sample any given location by snapshots widely separated in time. One goal of the present study is the use of the excellent time continuity of the field-program measurements to improve interpretations of the statistics obtained with such satellite snapshot data.

Yuan and Houze (2010) and Yuan et al. (2011) have used CloudSat combined with infrared and passive microwave data to determine the climatology of mesoscale convective systems over the whole tropics. However, they were able only to identify mesoscale convective systems in the mature stage of development. Their technique cannot identify developing or dissipating systems. Houze et al. (2007), Romatschke and Houze (2010), Romatschke et al. (2010), and Rasmussen and Houze (2011) have used the TRMM radar to characterize the climatology of deep convection over continental regions of South Asia and South America. Their methodology identifies three types of echo objects: deep convective cores, wide convective cores, and broad stratiform regions. These papers assume that these three types of echo entities signify deep convective cloud systems in early, middle, and late stages of development. While this assumption seems reasonable in light of the literature on convective cloud systems, it has never been verified by surface-based radar data.
In this study we use ground-based radar data obtained with the National Center for Atmospheric Research (NCAR) S-PolKa radar deployed in the central Indian Ocean near the equator on Addu Atoll in the Maldives to determine the occurrence of DCC, WCC, and BSR echoes relative to the development in time of MJO rainfall episodes. Our results will show that the frequency distributions showing the occurrence of DCC, WCC, and BSR echoes peak at a sequence of times, respectively, and that the large-scale environment reflects these shifts in the membership of the cloud population during any given rainfall episode. The results presented in this work thus confirm that that satellite-based statistics on the frequencies of occurrence of the three types of echo objects examined herein indicate where deep convection forms, matures, moves and dissipates, as has been speculated in previous studies of TRMM radar data and thus underpin the use of such echo interpretation in a companion study of the climatology of TRMM radar data obtained in the MJO (Barnes and Houze 2012).

This study also provides physical insight into the connection between the convective cloud population and the larger-scale dynamics of the MJO. Specifically, we will present evidence consistent with the "stretched building block" notion of convective interaction with the large-scale environment, as proposed by Mapes et al. (2006). They hypothesized that "there is a natural selection in the atmosphere for wave packets whose phase structure produces a local, Eulerian sequence of cloud zone-supporting anomalies that aligns with the convective cloud system life cycle." The precipitation of the MJO during DYNAMO/AMIE occurred in episodes of 2-4 days, longer than the lifetime of even the largest convective cloud elements but much shorter than the time scale of an MJO active
phase. We will show that the large-scale conditions varying over the DYNAMO/AMIE
area on the 2-4 day time scale correspond to a stretching of the convective lifecycle, and
that evolution of the statistical preference for DCC, WCC, and BSR radar echoes is
synchronized with this synoptic-scale variation as would be expected if the larger-scale
wave phases were selectively aligning with convective lifecycle stages.

2. Datasets

The S-PolKa radar was deployed on the island of Hithadoo (0.6°S, 73.1°E) located on
the Addu Atoll in the Maldives from 1 October 2011 through 15 January 2012. The S-
PolKa scanning strategy included surveillance (SUR) scans for mapping the entire area of
radar coverage (360° of azimuth) out to a range of 150 km. Data were recorded in
azimuth bins of 1°. The SUR scans were conducted at elevation angles ranging from 0.5
to 11.0 degrees (Figure 1a). Figure 1a shows that the maximum elevation angle for the
SUR is limited in altitude such that it can determine the heights of echoes greater than a
given height only beyond a certain range. For example, to resolve reflectivity fields up to
8 km height, one can only consider ranges between 41 km and the maximum radar range
(150 km). The dot-dash lines in Figure 1a indicate three such ranges corresponding to
echo heights of 8, 10, and 12 km.

The SUR scans were followed by a set of elevation angle scans at a sequence of fixed
azimuths (Such elevation scans are known as RHI scans because in the early days of
radar they were displayed on a screen known as a "range height indicator"). Data were
recorded in elevation angle bins of 0.5°. The RHI scans were designed to record data with
fine vertical resolution over the two azimuthal sectors shown in Figure 1b. The first, encompassed most of the northeast quadrant covering azimuths from 4 to 82° and was designed to record data over a wide oceanic sector that was nearly free of surface clutter. The second, a narrower sector over a oceanic southeast quadrant that covered azimuths from 114 to 140° was chosen to match the location of the vertically pointing KAZR radar placed at the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) site on Gan island (0.7°S, 73.2°E), which was about 9 km from the S-PolKa site. RHI scans were conducted by moving the antenna continuously in the vertical direction so that data could be recorded at angle increments from -0.5° up to a 45° elevation (Figure 1c). As for the SUR scans, only certain ranges of data coverage were considered (the initial range is indicated by the dot-dash line in Figure 1c) because these ranges resolve reflectivity fields up to a given echo height. The entire sequence of SUR and RHI scans was repeated at 15-min intervals.

Figure 1b shows that the horizontal area of RHI scans covers only about 20,000 km². This limited area coverage prevents the identification of broad stratiform regions, which by definition in the present study are ≥ 40,000 km² in area, with the RHI scans alone. To be able to analyze the behavior of BSRs within the RHI sectors we first identify BSRs using the SUR scans (which cover about 60,000 km²) and then we match the location of a BSR in a SUR scan to the corresponding radials in the RHI scan obtained nearest in time to the SUR scan.

The radar reflectivity data used in this study was the final, quality controlled S-PolKa data set from the S-band radar. The data were fully calibrated for noise correction and
with atmospheric attenuation applied. Details of the S-PolKa parameters and quality control procedures are on the website http://www.eol.ucar.edu/projects/dynamo/spol/.

The polar coordinate data for the SUR and RHI scans were interpolated from the original polar-coordinate format to a three-dimensional Cartesian grid using the NCAR Sorted Position Radar INTerpolator (SPRINT; Mohr and Vaughn 1979). The grid element size of the Cartesian data is 0.5 km x 0.5 km in the horizontal and 0.5 km in the vertical. The existence of DCC, WCC, and BSR echo volumes was determined by analysis of the Cartesian interpolated reflectivity fields. A rain classification technique based on the methodology of Churchill and Houze (1984), as modified by Steiner et al. (1995) and most recently by Yuter and Houze (1997) was used. The classification algorithm was applied to the interpolated reflectivity field at the 2.5 km level in order to objectively separate the radar echoes into convective and stratiform components. Parameters\(^2\) of the Yuter and Houze (1997) version of the algorithm were tuned specifically for the S-Polka reflectivity field observed during DYNAMO by testing the algorithm results against RHI data to minimize false indications of convective and stratiform echoes. This tuning procedure is described in Steiner et al. (1995).

The radar-derived precipitation amounts used in this study are computed using a “hybrid” polarimetrically tuned version of the reflectivity-rainrate relation of \(R=(aZ)^{1/b}\),

\(^2\) The best classification results were found running the algorithm at the 2.5 km level, and using \(a=10\), \(b=64\), and \(Z_t=40\) as values of the parameters in eq. B1 of Yuter and Houze (1997). The thresholds were set to 11 km as background radius and 5 km as the convective radius.
where $a=0.027366$ and $b=1.44$ (M. Katsumata, personal communication 2011). Details of
the algorithm and the parameters used for the calculation of rain amounts are provided at
http://www.eol.ucar.edu/projects/dynamo/spol/parameters/rain_rate/rain_rates.html. The
parameters of the reflectivity-rainrate relation are still being refined. However, for this
the absolute amounts of rainfall are not critical. More important are the time variation of
the rainfall and the subdivision of rain into convective and stratiform components.
Neither the time variation nor the convective/stratiform separation are sensitive enough to
the exact rain rate to have any effect on our present results.

Meteorological conditions in the vicinity of the radar location were obtained from two
sources. A sounding was launched every 3 h at the Gan site. Time series of wind,
temperature and specific humidity were interpolated in space from these soundings at 100
m vertical resolution and were also interpolated in time to fill in missing data points.
European Centre for Medium-Range Weather Forecast (ECMWF) interim Re-analysis
(ERA-interim) data (Berrisford et al. 2009) was used to document the synoptic conditions
over the region surrounding S-PolKa. Specifically, we used three-dimensional six-hourly
data for zonal, meridional and vertical wind components, divergence field, potential
temperature, and specific humidity on a $1.5^\circ \times 1.5^\circ$ grid. Time series anomalies of each
atmospheric field were computed by subtracting the time mean at each pressure level
from the time series data for the ARM sounding and ERA-interim data, respectively.
3. Definitions of deep convective cores, wide convective cores and broad stratiform regions

Following the methodology of Houze et al. (2007), Romatschke and Houze (2010), and Romatschke et al. (2010), who examined data from the TRMM radar, we identify convective and stratiform echoes that develop extreme characteristics of intensity, height, or horizontal extent. Specifically, we identify and extract from the radar echo patterns of DCC, WCC, and BSR echoes as they were defined in those previous studies. First, we identify the regions identified as convective and stratiform echoes by the tuned Yuter and Houze (1997) algorithm. Next, within the convective echo region, we locate intense echo cores by extracting all contiguous three-dimensional echo volumes containing equivalent radar reflectivity values exceeding 30 dBZ. We then determine the following subsets of these echo objects:

- **Deep convective cores (DCCs)** are intense echo cores whose maximum heights are $\geq 8$ km above mean sea level. This category includes young and vigorous convective cells with strong updrafts.

- **Wide convective cores (WCCs)** are intense echo cores whose horizontal areas exceed 800 km$^2$. This category captures regions where intense convective cells have aggregated into mesoscale areas of active vigorous cells. They are often part of large mesoscale convective systems (MCS, Houze 2004) in an intensifying stage of development where individual convective cells merge together.
Deep and wide convective cores (DWCCs) are intense echo cores that fall into both of the previous two categories, i.e., are both deep and wide.

Finally, within stratiform echo regions, we identify one subcategory:

- Broad stratiform regions (BSRs) as those contiguous stratiform radar echoes without any reflectivity threshold that extends over a horizontal area ≥ 40,000 km². This category represents parts of mature stage of MCS comprised mainly of large stratiform rainy areas (Houze 2004).

The threshold of 30 dBZ used here to define intense echo cores is lower than that originally used in Houze et al. (2007) and Romatschke et al. (2010) of 40 dBZ. The higher value was useful for continental regions, however, echoes reaching this intensity are rarer over oceans. Barnes and Houze (2012) have found that the 30 dBZ threshold is more useful over the tropical oceanic environments considered here. The height and area thresholds used here for WCCs and BSRs were chosen after sensitivity analysis of different height-area combinations as will be explained later.

4. Occurrence of deep convective echo types during MJO precipitation episodes

a. Overall frequency of events

Throughout the October 2011 to January 2012 period of the DYNAMO/AMIE campaign, three main periods of enhanced precipitation occurred over the S-PolKa area in association with active phases of the MJO over the Indian Ocean. Figure 2 shows the hourly time series of accumulated rain over the region covered by the S-PolKa radar for
these three periods: 15-27 October, 16-28 November, and 15-27 December. During these enhanced periods, the rainfall was highly variable on the synoptic time scale. The precipitation came in 11 episodes of significant rain accumulation, each with a mixture of convective and stratiform rainfall. These episodes tended to have a two-day duration and to be separated by 2-4 days during active MJO phases; October events tended to be at two-day intervals, while in November and December they were at 4-6 day intervals.

Powell and Houze (2012) provide a comprehensive discussion of the clouds and precipitation observed through the entire DYNAMO/AMIE observational period. Table 1 shows the total occurrence of convective radar echo entities for the deep and wide categories defined in section 2b and sampled during the three enhanced precipitation periods of the MJO. The statistics are presented using both SUR and RHI scanning strategies and were evaluated for different combinations of vertical heights and horizontal areas of the convective echo cores defined in section 3. Similarly, Table 2 shows the total occurrence of broad stratiform radar echo events for different combinations of horizontal areas. The evaluation of different combinations of height-area thresholds gives us confidence that our results on the different forms of deep convective are not especially sensitive to the choices of thresholds. The threshold choices that we have made lead to a total of 611 (1484) DCC echo entities that reach 8 km or greater in height, 628 (169) WCC echoes covering areas greater than 800 km², 169 (235) events falling in to both DCC and WCC categories, and 122 BSRs with areas $\geq 40,000$ km² when evaluated using SUR (RHI) scans.
b. Composites of echo occurrence relative to time of maximum rainfall

Figure 3 shows frequency of occurrence of each type of echo structure found at each hour from 24 h before (negative values) to 24 h after (positive values) the maximum in rain accumulation for each of the eleven rain episodes seen in Figure 2. In addition, Figure 3 shows the composite of rain accumulation for the 11 rainfall episodes combined. The zero time for each episode is the time of its maximum value in the running mean rainfall accumulation curve in Figure 2. Table 3 lists these dates and times. We calculated the composites in Figure 3 from both SUR and RHI scanning strategies. The results from the two datasets are remarkably similar in the distribution of the frequency of radar echo structures. They show that as time progresses from -24 h of the maxima in rain accumulation, the number of DCC events increases and reaches a broad maximum in frequency around -10 h for SUR scans and -5 h for the RHI scans. Around the same time, the frequency of events that are categorized as both deep and wide increases reaching a maximum around the same time as the maximum in rain accumulation. There is a second peak in the frequency of occurrence of DCCs in RHI scans not observed in the SUR scans because the areas covered by both scanning strategies are different. As the population of DCCs decreases towards the maximum in rainfall accumulation, the population of WCC events increases lagging that of the DWCCs by ~2 h. At 0 h, the broad stratiform regions begin to appear and reach a maximum around +8 h.

The progression of radar echo structures presented in Figure 3 can be related to the life stages of the individual convective cloud systems that produced the precipitation. The appearance first of DCCs, while the rainfall first begins to accumulate indicates that the
precipitating cloud population is dominated by deep convective systems in early stages of
development when convective cells tend to be separated from each other but intense,
produced by strong deep penetrating local updrafts. As time progresses, relative to the
maximum rainfall, such individual towers aggregate to form interconnected regions of
intense convection that produces the highest accumulation of rain. The maximum
occurrence of WCC echoes following the maximum of DCCs and lagging the maximum
in DWCCs indicates that as the rain episode progresses the population of precipitating
clouds becomes dominated by intense cells aggregating into larger units, likely to form
MCSs. It is well known that as MCSs mature and dissipate the convection composing
them produces mesoscale areas of stratiform rain, which last for hours and may or may
not be attached to the remaining active convection. The maximum of BSR echoes in the
declining period of the rain episode indicates that the population was dominated by
mature and dissipating MCSs as the areal rainfall decreased. The second author's
anecdotal experience in closely monitoring the S-PolKa radar echoes throughout the four-
month period of the radar deployment is consistent with this interpretation of the radar
echo statistics; i.e., that the rainfall episodes were dominated in their early stages by deep
cells, later by mesoscale units with the characteristics of mature MCSs, and ended with
large regions stratiform rain dominating the echo pattern.
5. Environmental conditions associated with the evolution of radar echo structures during MJO precipitation episodes

To investigate the large-scale environmental conditions during the eleven rain episodes, we composited data from the Gan soundings and from ERA-interim reanalysis variables. The sounding variables provide measurements of the atmospheric conditions in the immediate vicinity of the radar site. We use ERA-interim variables over a region around the radar site (1.5°S-1.5°N, 72.0°E-75.0°E) to indicate conditions over a broader region surrounding the radar.

a. Environmental time composites for rainfall episodes

Figure 4 shows time-height composite plots of potential temperature and specific humidity relative to the maximum in rain accumulation at 0 h. In addition, a composite of convective available potential energy (CAPE) anomalies for the time evolution of the soundings is included in plot. At around –15 h before the maximum in rain accumulation, a shallow layer of positive potential temperature anomalies appears in both time sections (Figures 4a, 4b). In addition, the potential temperature anomaly is decreasing with height at around -10 to -6 h in Figure 4a and around -15 to -11 h in Figure 4b. At the same time that the surface reaches a maximum in potential temperature anomalies, the lower-level specific humidity increases and reaches an anomalous maximum at around -9 to -6 h before the rain maxima when calculated using the Gan sounding and around -12 to -9 h for ERA-interim data. These data all point to destabilization occurring before the maximum in rain accumulation and accordingly, the CAPE increases during this time. After the maximum in low-level specific humidity, the potential temperature changes to
negative anomaly values while the specific humidity anomaly increases with height. When the time reaches the 0 h corresponding to the maximum in rain, the atmosphere cools and becomes moist at middle levels and dry at lower levels. The CAPE decreases, and the environment persists until the surface and the atmospheric middle levels reach a minimum of specific humidity around +15 h.

Figure 5 shows time-height composite plots of divergence and vertical velocity calculated using ERA-interim reanalysis data. At –20 h, negative anomalies of surface divergence appear and decrease to a minimum (i.e., peak low-level convergence) at around –10 h. During this same time period, pressure velocity decreases, indicating enhanced upward motion with a maximum at the 750 hPa level between –10 and 0 h. After this time, vertical velocity anomalies increase, and the center of convergence seen at the surface before the maxima in rain shifts upward reaching the 500 hPa level with a maximum value at +12 h. At the same time, the lower levels of the atmosphere become anomalously divergent with maximum values around +10 to +15 h after the maxima in rain accumulation.

Figure 6 shows time-height plots for zonal and meridional wind anomalies compositied for -24 to +24 h from the maximum in rain accumulation. Figure 6a, calculated using the Gan soundings, shows an anomalous low-level easterly wind at around -20 h before the maximum in rain accumulation occurs. Around -12 h, the wind anomaly reverses to westerly. The anomalous westerly wind is maximum at 850 hPa, just before the maximum in rain accumulation. At the same time, anomalous northerly wind increases with height reaching a maximum at around 700 hPa. After the maximum in rain
accumulation, the anomalous westerly wind decreases and reverses again toward an anomalous easterly component at around +20 h. The anomalies of zonal and meridional wind calculated using ERA-interim data (Figure 6b) behave remarkably similarly, except that the maximum in westerly wind anomaly is reached several hours after the maximum in rain accumulation. The upper-level zonal wind anomalies (i.e., around 200 hPa) in both Figure 6a and b show a similar progression from easterly to westerly anomalies, but the magnitude attains higher values at a later time than their surface counterpart. An increase in low-level westerly wind anomalies as the most intense rainfall propagates has been observed in association with the passage MJO disturbances across the region (Lin and Johnson 1996; Chen et al. 1996; Zhang and McPhaden 2000; Benedict and Randall 2007).

These statistical composite behaviors during the time period of the rainfall episode are analogous to the way that individual deep convective cloud systems behave on the shorter time scale of an individual cloud system. An individual MCS forms when deep cells occurring separately in early stages aggregate to form mesoscale units of deep convection in the MCS's midlife stages, and produce a stratiform rain area in its mature to later stages (Houze 2004). The leading side of the MCS taps into the most unstable air. The result is low-level convergence and growing convective cells, which then evolve into precipitating stratiform cloud mass that destabilizes the lower levels. An individual MCS typically develops an ascending front-to-rear flow rising from a convergent zone on its leading side. In the trailing stratiform region, midlevel convergence feeds a descending rear-to-front flow and divergence occurs at levels below the ascending front-to-rear flow.
We see a similar sequence qualitatively in the series of Gan sounding data in Figures 4, 5, and 6, but on a much longer time scale than an individual MCS. In addition, the peak statistical frequencies of occurrence of DCC, WCC, and BSR radar echoes follow a temporal sequence in line with these sounding data. I.e., over the 2-day period of a precipitation episode, the convective statistics (not the individual convective cloud systems) indicate that the synoptic-scale conditions in the earlier part of the 2-day episode favor MCSs in their earlier stages of development, and that as the 2-day period continues the large-scale conditions are increasingly those favorable for the persistence and/or amplification of the later stratiform stages of development of individual MCSs.

This behavior of the echo statistics viewed against the background of the synoptic-scale evolution suggests that the synoptic-scale wave pattern constituting the environment of the convection during a precipitation episode embedded in the MJO systematically favors convection in early, middle, and late stages of development, respectively, in the phases of the wave that progress over a location during the 2-day period of the episode.

These composite time series are thus consistent with the stretched building-block notion of Mapes et al. (2006), according to which the changing makeup of the ensemble of precipitating clouds over a time period greater than the timescale of individual cloud systems, such as the MJO rainfall episode considered here, coincides with a temporal sequence of thermodynamic variables analogous to but on a longer timescale than the lifecycle sequence of an individual MCS. It seems unlikely that without a wave originating from some larger-scale dynamics that such an orderly 2-day sequence of events could occur. However, as noted by Mapes et al. (2006), the convective population
may well feedback positively to the wave structure and make this type of convectively
coupled wave eminently more observable. Since the convective population is weighted
toward a particular stage of convective development in a given larger-scale wave phase
environment, it stands to reason that the convective population would imprint itself on the
larger-scale wave in a positively reinforcing sense.

\[ b. \textit{Spatial distribution of environmental properties at different times during rainfall }
\textit{episodes} \]

To investigate how the synoptic conditions vary in space during the time periods of
the precipitation episodes studied here, we have employed the ERA-interim reanalysis
data (Section 2). Figure 7 shows longitude-height composites of the reanalysis zonal-
vertical wind, divergence and specific humidity anomalies averaged over the 1.5°S to
1.5°N latitude band at three representative times during the composite rainfall episode.
The vertical wind is exaggerated 1000 times to allow a comparison with the horizontal
wind.

Twenty-four hours before the maximum in rain accumulation (Figure 7a), low-level
easterly wind and low specific humidity were present in the vicinity of the radar. At the
same time, west of the radar location (around 65°E), there is a region of low-level
convergence and positive anomalies of specific humidity. As time progresses from –24 to
–6 h, the region west of the radar that is favoring moistening and low-level convergence
moves eastward towards the radar region. By –6 h, the atmosphere around the radar
location is moist, with strong vertical motion and low-level convergence (Figure 7b). At
this time, the upward motion associated with divergence penetrates to the highest level
(up to 400 hPa) around the same time as the frequency of DCC events is greatest (Figure 3). These behaviors are analogous to the early stage of MCS development, but on a larger scale, and these time periods correspond to when DCCs and WCCs are more prevalent. From –6 until +12 h, the lower atmosphere cools and dries, and the low-level convergence decreases at the radar site (not shown). The region of high moisture, low-level convergence, and upward motion continues moving eastward, while in the region near the radar downward motion and divergence set in (Figure 7c). Between +6 and +12 h the lower atmosphere has the lowest potential temperature and specific humidity anomalies. These later-period characteristics are analogous to MCSs in later stages of development with large stratiform rain areas. This time period is when BSRs are most frequent (Figure 3). It is remarkable that both the sounding time series and the reanalysis data show a large-scale behavior analogous to MCS evolution, but on an expanded time scale.

6. Conclusions

This study has identified and examined the most extreme convective entities detected by the NCAR S-PolKa radar during the DYNAMO/AMIE field campaign. We have analyzed the S-PolKa three-dimensional reflectivity field to identify three basic types of echo objects, which have been used in previous studies to analyze TRMM satellite radar observations of deep convection over other regions of the earth (Houze et al. 2007; Romatschke and Houze 2010, Rasmussen and Houze 2011). The satellite data are in the form of snapshots, which make the results difficult to interpret with certainty. This study
is the first to apply this approach to temporally continuous ground-based radar data, and
the results verify interpretations made in studies using TRMM data. In addition, the
results provide insight into the nature of the convective cloud populations producing MJO
rainfall episodes over the Indian Ocean.

From October 2011 through early January 2012, three main active phases of the MJO
occurred, and within these active phases, the rain in the vicinity of the S-PolKa radar was
concentrated in eleven episodes separated by 2-6 days—much shorter periods than the
time scale of an MJO active stage. This 2-6 day modulation likely is due to westward-
propagating synoptic-scale equatorial waves. We performed a running mean to highlight
the eleven episodes and identify their times of peak rainfall accumulation over the area
observed with S-PolKa. We have shown that each of the eleven rain episodes was
characterized by an ensemble of deep convection that went through a sequence of
statistical states such that each statistical state was dominated by convective systems in
successively later stages of development:

- The number of deep convective cores tended to occur before the maximum in
  rainfall accumulation.
- The number of wide convective cores was maximum around the same time as the
  maximum in rain accumulation.
- The frequency of broad stratiform regions maximized significantly several hours
  after the maximum of rain accumulation.
At any given time the cloud population produced echo elements of all three types, but the frequencies of each echo type maximized in the above order. Since mesoscale convective systems (Houze 2004) begin with an outbreak of convective cells, then grow upscale to mesoscale proportions as the cells aggregate into horizontally contiguous mesoscale units, this sequence of statistical states relative to the time of maximum rainfall accumulation implies that prior to the rain maximum the intense convective elements are dominated by deep cores but that the period of maximum rainfall is produced by more mature mesoscale convective systems. As the rain accumulation drops off in the later part of the rainfall episode, the cloud population is dominated by MCSs in later stages of development with large stratiform regions.

To gain insight into this systematic variation of the convective population statistics over the 2-day episodes, we composited both the Gan sounding and ECMWF ERA-interim reanalysis variables to investigate the connection of the changing cloud population to the large-scale environment during the eleven MJO rainfall episodes. The results show unstable conditions in the early part of the rainfall episode, when DCC echoes were most frequent. By the time of the maximum rainfall, the cloud population was dominated by WCC echoes, which are a signature of the presence of a maximum number of mature MCSs. The large-scale vertical motion was a maximum at this time, with a pronounced convergence signature at low levels. During the period of declining rain accumulation over the radar area, stabilization occurred, and the large-scale mean motion was downward in the mid-to-low troposphere, with strong divergence at low levels. These stages are analogous to the lifecycle stages of an individual MCS, but they
manifest on a longer time scale and over a bigger area than an individual system. Thus, the large-scale environment and convective population exhibit characteristics consistent with the stretched building-block hypothesis of Mapes et al. (2006). Coincident with the membership of the cloud population changing from an ensemble containing a predominance of young deep but relatively separate convective cells to a population dominated by mature MCSs to a population with older MCSs with large stratiform regions, the large-scale conditions take on the aspect of a "stretched" analog to the typical MCS lifecycle. Hours before the maximum in rain accumulation, when the ensemble is dominated by DCCs, the surface westerly wind and convergence increase, the atmosphere warms and becomes moister, and the CAPE reaches a peak, i.e., the environment is favorable for deep convection to occur. When WCCs become most frequent near the time of the peak of the rainfall episode upward motion maximizes. Then as BSRs have their greatest frequency, stabilization occurs, evaporative cooling increases, and low-level convergence and upward motion decrease and reverse to downward motion and low-level divergence. This simultaneous behavior of the convective population and synoptic-scale environment is entirely consistent with Mapes et al.'s hypothesis of a "natural selection" in the atmosphere for waves whose phases produce a local Eulerian sequence of structures aligning with convective lifecycle behavior.

Studies using TRMM satellite radar data to examine the climatology of deep convection have compiled statistics of DCCs, WCCs, and BSRs and have speculated that when statistical maxima of these echo types occur in a sequence of geographical
locations, the locations of the maxima indicate regions where mesoscale convective systems tend to form, mature, and dissipate, respectively. However, since the TRMM orbits obtain only snapshots of the radar echo pattern at widely separated times, it has not been possible to verify these speculations. The time continuity of the ground-based S-PolKa radar used in the present study has been able to determine that the statistical maxima of DCC, WCC, and BSR frequencies do indeed occur in a temporal sequence consistent with mesoscale convective system lifecycle stages. In a concurrent study, Barnes and Houze (2012) are using 14 years TRMM radar snapshots to identify DCCs, WCCs, and BSRs over broad expanses of the Indian and West Pacific Oceans during different phases of the MJO. Our study provides ground-validation for that climatological investigation by making it possible to interpret the concentrations of each of the echo types seen by the TRMM radar as representative of lifecycle stages of the deep convection producing precipitation in the MJO. Such satellite datasets are a primary pathway for upscaling results from the DYNAMO/AMIE field experiment to the scale of the MJO and in turn for providing observational information for modeling studies aimed at understanding the coupling of convection to the large-scale circulation of the MJO.

The S-PolKa radar data collected in DYNAMO/AMIE have the potential to add information that will further underpin satellite interpretations of the MJO radar echo climatology. A further strength of the S-PolKa radar is that it can use its S-band dual-polarimetric capability to identify the dominant hydrometeor types producing the radar echoes. The scanning strategy of the S-PolKa radar (Section 2, Figure 1c) was designed to optimize the information on hydrometeor types by applying techniques such as that of
Vivekanandan et al. (1999) to deduce the most probable vertical profiles of hydrometeor types in each of the echo seen by the radar. In a future article, we will apply such methods to the echo types identified in this study. That future article will enhance the basic echo type results of the present study with information on the microphysical processes most responsible for producing the precipitation in the early, middle, and late stages of MJO rainfall episodes. The results of the present and future studies of data collected by the S-PolKa radar in DYNAMO/AMIE will thus provide information on the nature of MJO convection that will help guide numerical simulations of global and regional models used to simulate and forecast MJO behavior.

**Acknowledgements:** This research was supported by National Science Foundation Grant AGS-1144105, National Aeronautics and Space Administration Grant NNX10AH70G, and Department of Energy Grants DE-SC0001164/ER-64752 and DE-SC0008452. We are grateful to the NCAR science team for providing the quality-control radar data used in this study. Stacy Brodzik helped with software and data management. Scott Powell provided the interpolated DOE/ARM sounding data. Kristen Rasmussen, Hannah Barnes and Scott Powell contributed helpful comments. Beth Tully provided graphics and editing support. ECMWF ERA-interim data used in this study was obtained from the ECMWF data server.
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Table 1. Number of echo structures observed in each extreme convective category for different height-area combinations during both S-PolKa reflectivity data scanning strategies. Numbers in parentheses are percentage of the total number of convective events in each combination and scanning strategy. Bold numbers corresponds to the selected combination of height-area used for the analysis.

<table>
<thead>
<tr>
<th></th>
<th>SUR scans</th>
<th></th>
<th>RHI scans</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DCC</td>
<td>WCC</td>
<td>DCC-WCC</td>
<td>DCC</td>
</tr>
<tr>
<td>6 km – 800 km²</td>
<td>5210</td>
<td>175 (3%)</td>
<td>654 (11%)</td>
<td>7354 (95%)</td>
</tr>
<tr>
<td></td>
<td>(86%)</td>
<td></td>
<td>(11%)</td>
<td>(0%)</td>
</tr>
<tr>
<td>8 km – 800 km²</td>
<td>611 (43%)</td>
<td>628 (45%)</td>
<td>169 (12%)</td>
<td>1484 (79%)</td>
</tr>
<tr>
<td></td>
<td>(43%)</td>
<td></td>
<td>(12%)</td>
<td>(9%)</td>
</tr>
<tr>
<td>10 km – 800 km²</td>
<td>73 (9%)</td>
<td>734 (87%)</td>
<td>33 (4%)</td>
<td>763 (64%)</td>
</tr>
<tr>
<td></td>
<td>(9%)</td>
<td></td>
<td>(4%)</td>
<td>(23%)</td>
</tr>
<tr>
<td>10 km – 1000 km²</td>
<td>82 (12%)</td>
<td>562 (84%)</td>
<td>24 (4%)</td>
<td>797 (72%)</td>
</tr>
<tr>
<td></td>
<td>(12%)</td>
<td></td>
<td>(4%)</td>
<td>(17%)</td>
</tr>
</tbody>
</table>
Table 2. Same as Table 1, but for broad stratiform regions and using SUR scans only.

<table>
<thead>
<tr>
<th>Area</th>
<th>BSR</th>
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<tbody>
<tr>
<td>35000 km²</td>
<td>165</td>
</tr>
<tr>
<td><strong>40000 km²</strong></td>
<td><strong>122</strong></td>
</tr>
<tr>
<td>50000 km²</td>
<td>93</td>
</tr>
</tbody>
</table>
Table 3. Date and time of the selected maxima in rain accumulation for the 11 rainiest events during the October 2011 to January 2012 period of the DYNAMO campaign.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (UTC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-16-2011</td>
<td>08:00</td>
</tr>
<tr>
<td>10-18-2011</td>
<td>18:00</td>
</tr>
<tr>
<td>10-20-2011</td>
<td>20:00</td>
</tr>
<tr>
<td>10-22-2011</td>
<td>01:00</td>
</tr>
<tr>
<td>10-24-2011</td>
<td>03:00</td>
</tr>
<tr>
<td>10-26-2011</td>
<td>02:00</td>
</tr>
<tr>
<td>11-18-2011</td>
<td>03:00</td>
</tr>
<tr>
<td>11-23-2011</td>
<td>07:00</td>
</tr>
<tr>
<td>11-27-2012</td>
<td>02:00</td>
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<tr>
<td>12-20-2011</td>
<td>21:00</td>
</tr>
<tr>
<td>12-23-2011</td>
<td>20:00</td>
</tr>
</tbody>
</table>
Figure Captions

Figure 1. (a) Beam elevation angles used for the surveillance scans of the S-PolKa radar during DYNAMO/AMIE. The number at the end of each line gives the angle in degrees. (b) Azimuth angles used during the elevation angle scans (RHI) scans. (c) RHI scan recording angles for the S-PolKa radar. Dot-dashed lines in (a) and (c) denote the initial distances for the range of radar data used to determine vertical heights (see text).

Figure 2. Hourly time series of total (red), convective (green) and stratiform (blue) accumulated rain over the region of radar coverage. Black dashed line shows the running mean series of 24 h total accumulated rain, which was used to locate the maxima in rain accumulation for the purpose of compositing the data.

Figure 3. Composites of the frequency of occurrence of each of the different types of radar echo structures defined in Section 2 during 24 h before (−) and 24 h after (+) of the composite maximum in rain accumulation (dash-dot curve) calculated with a) SUR and b) RHI scanning strategy data. The axis for the colored curves is at the right of each plot. The rainfall accumulation composite is computed by centering each of the eleven rain episodes in Figure 2 on the time of the maximum of its running-mean curve in Figure 2.

Figure 4. Composite time-height sections of potential temperature (shading in K, relative to the color palette) and specific humidity (black contours in g kg$^{-1}$, solid contours indicating positive values) anomalies from -24 h to +24 h around the maxima in rain accumulation. The profiles are calculated using (a) three-hourly DOE ARM
rawinsonde observations and (b) ERA-interim reanalysis data. The red curve in (a) and (b) is the composite time series of CAPE anomalies with values indicated by the right-hand axis in each plot.

**Figure 5.** Same as in Figure 4b, but for divergence (shading in $s^{-1}$, relative to the color palette) and vertical velocity (contours in $10^{-3}$ hPa $s^{-1}$, solid lines indicating positive values) anomalies calculated using ERA-interim reanalysis data.

**Figure 6.** Same as in Figure 4, but for composite time-height sections of zonal (shading in m s$^{-1}$, relative to the color palette) and meridional (contours in m s$^{-1}$, solid line indicating positive values) wind anomalies.

**Figure 7.** Latitudinal-averaged composites of ERA-interim divergence (shading in $s^{-1}$, relative to the color palette), specific humidity (contours in g kg$^{-1}$, solid blue lines indicating positive values) and zonal-vertical wind (vectors) anomalies for (a) $-24$ h (b) $-6$ h and (c) $+12$ h from the maxima in rain accumulation. The vertical line at 73.1°E indicates the location of the S-PolKa radar.
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