

RESEARCH ARTICLE

10.1002/2014JD022934

Special Section:

The 2011–12 Indian Ocean Field Campaign: Atmospheric–Oceanic Processes and MJO Initiation

Key Points:

- Convection builds from congestus to deep mode in week prior to MJO onset
- Variability of ~30 days in echo top heights not seen over Maritime Continent
- Congestus leads deep convection by 4–8 days

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Citation:

Powell, S. W., and R. A. Houze Jr. (2015), Evolution of precipitation and convective echo top heights observed by TRMM radar over the Indian Ocean during DYNAMO, *J. Geophys. Res. Atmos.*, 120, 3906–3919, doi:10.1002/2014JD022934.

Received 2 DEC 2014

Accepted 1 APR 2015

Accepted article online 7 APR 2015

Published online 12 MAY 2015

Evolution of precipitation and convective echo top heights observed by TRMM radar over the Indian Ocean during DYNAMO

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Abstract Radar data from the Tropical Rainfall Measuring Mission show the evolution of echo tops of convective elements over the Indian Ocean and Maritime Continent during the Dynamics of the Madden-Julian Oscillation (DYNAMO) field campaign of 2011–2012. Echo top heights exhibited a bimodal distribution wherein cumulonimbi of moderate height constituted a “congestus mode” while vertically extensive cumulonimbus made up a “deep mode.” An intraseasonal time scale dominated variability in these modes from October to January over much of the Indian Ocean. Over the Maritime Continent, there was no clear intraseasonal signal in convective echo top heights. Where the intraseasonal oscillation was detected, radar echoes evolved from being dominated by the congestus mode to being characterized by more deep mode convection on time scales of less than 1 week. The areal coverage of congestus echoes began to increase 2–8 days prior to the rise in area of deep echoes. These satellite-derived results confirm that the time scale for convective deepening seen at individual DYNAMO observational sites is consistent with that of convection on the large scale over the Indian Ocean. Intraseasonal variability of zonal wind, temperature, and humidity as depicted by reanalysis is also consistent with that derived from rawinsonde observations during DYNAMO. Thus, the gradual buildup of convection as depicted by recent versions of the “discharge-recharge” hypothesis does not accurately describe evolutions of convection prior to MJO events observed during DYNAMO, although cloud moistening processes may still be relevant on time scales of 1 week or less.

1. Introduction

A critical problem faced by global atmospheric models in simulating intraseasonal variability of deep tropical convection is the transition of a cloud population from a mode of shallow clouds to one of deep convection. Zhang [2005] and Wang [2005] have summarized several proposed mechanisms that attempt to explain how and/or when this transition, also known as “onset” or “initiation” of Madden-Julian Oscillation (MJO) convective events, occurs. One such mechanism is a positive feedback between environmental humidity and the depth of cumulus convection that continues until the large-scale environment is favorable (i.e., moist enough) for widespread deep convection to develop and be maintained. According to this idea, known as “discharge-recharge” [Bladé and Hartmann 1993], gradual instability buildup occurs over the region where MJO onset occurs. More recent papers postulate that shallow cumuli and cumulus congestus moisten the lower to middle troposphere so that subsequent clouds can grow to greater heights. This process of “recharging” or “preconditioning” the tropical atmosphere for widespread, deep convection has been described as taking roughly 10–20 days [Kemball-Cook and Weare, 2001; Benedict and Randall, 2007].

The importance of preconditioning by cumuli to the transition of convection from shallow to deep has been questioned recently. Hohenegger and Stevens [2013] demonstrated how the time scale required for cumuli to moisten the midtroposphere is greater than the observed time scale of evolution of shallow convective elements to deep ones. However, their study focuses on individual convective elements or systems in the East Atlantic on time scales of several hours, and so their results do not necessarily apply to the longer transition period involved in the onset of a convective population in the MJO. Kumar et al. [2014] conclude for cloud populations near Darwin, Australia, that large-scale upward motion and advection of moisture are more important for tropospheric humidification than cumulus moistening processes prior to deep cumulonimbus development.

The time scale of the shallow to deep convection transition period as well as that of buildup of tropospheric humidity as posed in more recent versions of the discharge-recharge hypothesis has also been questioned.

Powell and Houze [2013] (hereafter PH13) used scanning precipitation radar data obtained during the Dynamics of the Madden-Julian Oscillation (DYNAMO) [Yoneyama *et al.*, 2013] campaign to conclude that observed convection transitions from a shallower mode during convectively suppressed periods to a deeper mode during active MJO periods in 3–7 days. That time scale is consistent with DYNAMO sounding network data analyzed by Johnson and Ciesielski [2013] and Ruppert and Johnson [2015]. A similar length of time was observed during a 1993 Tropical Ocean–Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) MJO event for the cloud population to evolve from a suppressed stage with smaller clouds to a mature stage consisting of clouds with extensive anvils [Kikuchi and Takayabu, 2004]. Xu and Rutledge [2014], based on shipborne radar results of MJO cases during DYNAMO, argue that the time scale of convective buildup is 12–16 days, but they define MJO convective onset at a time well after the deep and wide mesoscale convection associated with an MJO is first observed. These studies are all limited in two respects. The sounding array budget studies rely on indirect inference of cloud behavior, and the ship and island radar studies are limited to localities.

In this article, we show that the behavior of convection and the dynamic and thermodynamic structures of the troposphere observed within ~ 150 km of an island site at Addu City, Maldives ($\sim 0.63^\circ\text{S}$, 73.1°E), by PH13 is consistent with the same on the large scale. This demonstration is important because it increases confidence in conclusions reached using spatially limited data sets. For comparison, we will also briefly investigate the evolution of convection over the Maritime Continent between 100°E and 120°E . In doing so, we will compare the time series of convective echo top height derived from satellite data to those constructed using ground-based radar data. The time scale of convective buildup found in PH13 and corroborated by others will be confirmed using a data set composited over an oceanic domain much larger than that covered by ground-based radar. We will also compare time series of tropospheric dynamic and thermodynamic fields in rawinsonde and reanalysis data sets and discuss the time scale of tropospheric moistening over the Indian Ocean prior to MJO convective onset.

2. Data

The primary data set used is from the precipitation radar (PR) aboard the Tropical Rainfall Measuring Mission (TRMM) satellite [Kummerow *et al.*, 1998]. The TRMM PR has a wavelength of about 2 cm and thus detects precipitation particles. The PR data sets used are the version 7 TRMM 2A25 and 2A23 products, which contain estimated near-surface rain rate, three-dimensional spatial distribution of reflectivity, and rain-type (convective, stratiform, and other) classification [Awaka *et al.*, 1997]. Data were processed as in Houze *et al.* [2007] and Romatschke *et al.* [2010], and the data were mapped onto a $0.05^\circ \times 0.05^\circ$ Cartesian grid with 0.25 km vertical spacing. The TRMM precipitation radar has a minimum detectable reflectivity factor of about 17 dBZ, so echo top heights are determined by the height of the 20 dBZ contour. Echo tops are located as in PH13 by searching downward from the top of each column of the archived TRMM radar data. Echo top heights are only determined for regions classified as convective. Rain rates are taken from two version 7 TRMM products: (1) product 2A25, which consists of TRMM orbital data only, and (2) product 3B42 [Huffman *et al.*, 2007; ftp://meso-a.gsfc.nasa.gov/pub/trmmdocs/3B42_3B43_doc.pdf], which is generated using data from TRMM and other satellite platforms and thus covers the region more broadly than the orbital product only. We will compare precipitation time series from both to test the representativeness of the limited orbital data to a more complete picture of the regional precipitation as offered by the 3B42 product. Data span the dates 1 October 2011 to 15 January 2012, almost the entire period during which ground-based radar data were collected during DYNAMO at Addu City. However, most of the figures in this article display only data taken up to 1 January because conditions were highly suppressed during the first half of January. Three convectively active MJO events were observed during the period considered [Gottschalck *et al.*, 2013; Johnson and Ciesielski, 2013; Powell and Houze, 2013; Yoneyama *et al.*, 2013; Xu and Rutledge, 2014].

Large-scale composite wind and thermodynamic fields shown in section 4 are derived from ERA-Interim reanalysis (ERA-I) [Dee *et al.*, 2011]. Output used is from 100, 150, 200, 250, 300, 400, 500, 600, 700, 850, 925, and 1000 hPa. A low-pass Fourier filter is run on temperature fields with a cutoff of 1 day to eliminate strong diurnal variability in the reanalysis. As in PH13, anomalies are calculated relative to the mean of the fields from 1 October 2011 to 9 February 2012.

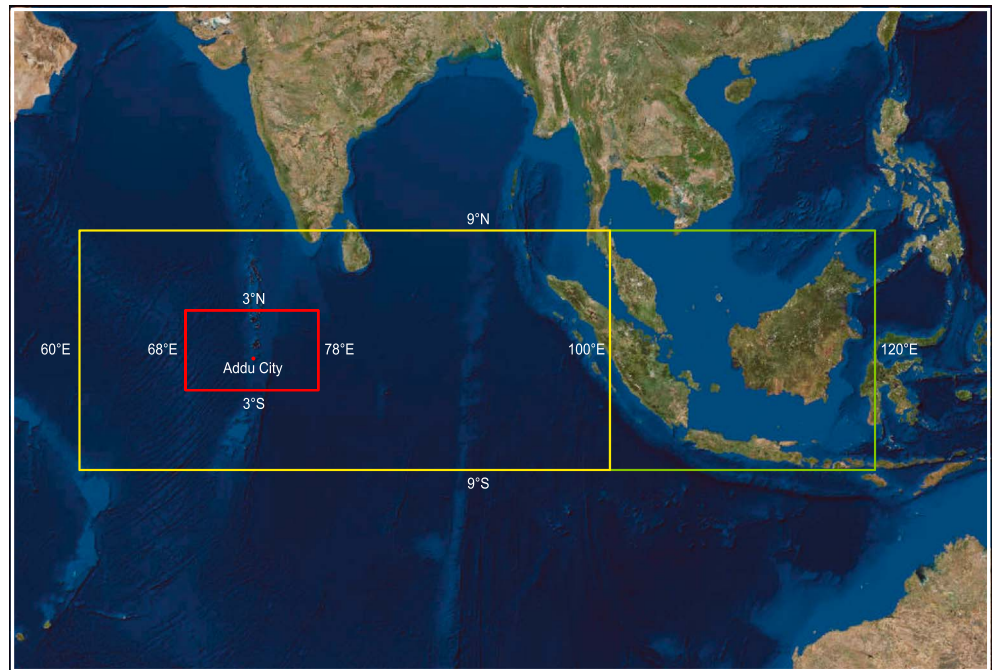


Figure 1. Map of the domains used in the text for compositing data. The yellow box encloses the “large-scale” domain as referenced in the text with sides at 9°N, 9°S, 60°E, and 100°E. The red box encloses a small domain near Addu City (labeled) with sides at 3°N, 3°S, 68°E, and 78°E as referenced in section 4. The green box has sides at 9°N, 9°S, 100°E, and 120°E and encloses the domain used for analysis over the Maritime Continent as described in section 3.4.

3. Echo Top Heights of Precipitating Clouds

3.1. Large-Scale Domain and Modes of Convective Echo Depth

The large-scale domain over the Indian Ocean is represented in our study by a box whose corners are located at 9°N, 60°E; 9°S, 60°E; 9°N, 100°E; and 9°S, 100°E (yellow box in Figure 1). The box covers nearly 9×10^6 km². The western edge of the box is positioned such that the onsets of all three MJO convective events are captured within the domain, and the eastern edge is a longitude at which the equatorial Indian Ocean

meets western Indonesia. The northern edge of the box is positioned so that the box is wide enough to contain convection near the equator and within the Intertropical Convergence Zone to its south. The box is symmetric across the equator and is narrow enough meridionally to avoid sampling much convection over the Indian subcontinent. The meridional extent of the domain extends to within the expected Rossby radius of deformation of an equatorially trapped Kelvin wave. It is also close to the latitudinal range from which data are used to compute indices of MJO activity [e.g., *Wheeler and Hendon, 2004*].

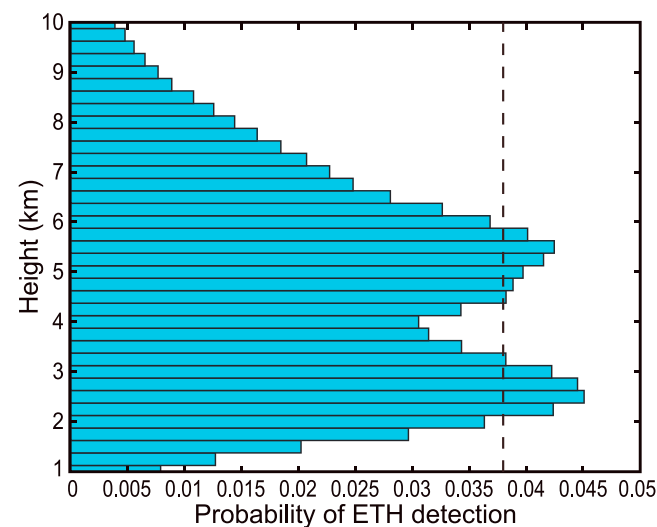


Figure 2. Probability distribution of 20 dBZ echo top height for all convective echoes between 9°S, 9°N, 60°E, and 100°E from 1 October 2011 to 15 January 2012.

Two distinct modes of convective echo top height occur in the large-scale domain. Figure 2 shows the two modes in the distribution of all echo top

heights from 1 October to 15 January. The dashed black line at probability 0.038 in Figure 2 has been added to aid in visualizing the heights of the two modes. One mode peaks at 2.5 km and is located broadly from 2.25 to 3.25 km, and the other peaks at 5.5 km and is located from about 4.5 to 6.25 km. Respectively, we will call these the “congestus mode” and “deep mode.” Because we are examining the top of the 20 dBZ contour rather than the cloud top, the congestus mode consists of precipitating clouds, which probably includes small cumulonimbi and precipitating cumulus congestus. These clouds correspond to the convective clouds in the middle category of the trimodal convective population inferred from soundings taken in the vicinity of MJO convection by *Johnson et al.* [1999] and seen in vertically pointing ground-based K band cloud radar data by *Hollars et al.* [2004] (see their Figures 2a and 2b). Because the TRMM radar only detects precipitating clouds, the small nonprecipitating cumuli of the trimodal distribution do not appear in Figure 2. The deep mode in Figure 2 corresponds to cumulonimbi reaching higher, into layers cold enough for extensive anvil cloud formation (i.e., the largest members of trimodal distribution). The bimodal distribution of precipitating cloud tops in Figure 2 has a signature in latent heating profiles derived by TRMM over much of the same region [*Barnes et al.*, 2015] and globally within the tropics [*Takayabu et al.*, 2010]. It is probably related to the bimodality seen in precipitating convective cloud depth throughout the tropics and subtropics as seen in C-band ship-based precipitation radar data in the Global Atmospheric Research Program Atlantic Tropical Experiment (GATE) (see Figure 20 of *Houze and Cheng* [1977]) as well as in TRMM data by *Short and Nakamura* [2000].

We will use the separation of the two modes of convection observed by TRMM to identify periods of MJO convective onset, which hereafter may be simply referred to as “convective onset” or “MJO onset.” It is important to understand that onset is not an event that occurs instantly or even within several hours. It is a process that takes place over multiple days. When convection observed by TRMM is predominantly in the deep mode (or sometimes bimodal with large numbers in each mode), we will consider the MJO to be active. When it is mostly in the congestus mode, the MJO will be considered suppressed. The transition from the congestus mode to the deep mode is part of MJO convective onset. As we will see below, this transition occurs over 2–8 days during DYNAMO. We acknowledge that this time scale may not be inclusive of the entire period of onset. Previous studies [*Kikuchi and Takayabu*, 2004; *Johnson and Ciesielski*, 2013] describe cases of convective depth increasing in two discrete increments—first from the shallow mode to the congestus mode, then from the congestus mode to the deep mode—and show that the time scale for convection to build from the shallowest mode to the deepest mode is approximately a week. Therefore, the transitions from predominantly congestus to deep convection that we observe below may be best described as the last stage of MJO onset.

3.2. Basin-Wide Convective Echo Top Heights and Precipitation

We are using orbital satellite data to evaluate large-scale convective echo top heights. Relative to our domain size, the swath width of TRMM is small, and generally, the TRMM platform will pass over the domain only twice a day. Thus, we are unavoidably evaluating the large-scale evolution of convection while observing only a fraction of the convection actually present within our domain. Table 1 shows the percentage of the domain sampled and the number of independent convective echo objects observed for 2 day intervals between 1 October and 31 December. Each 2 day interval is denoted by its end date. We define an independent convective echo object as any completely separate contiguous collection of pixels identified as convective in the available reflectivity and rain-type data. Figure 3 contains an example of the areal coverage of TRMM reflectivity data at 3 km altitude within a 2 day period between 15 and 16 October. During this and most 2 day intervals, between 35% and 55% of the domain is viewed by a TRMM overpass. Coverage only drops below 35% during the last few days of December. Any single overpass only views perhaps 10% or so of the entire domain. Thus, our method is possibly inappropriate for evaluating high-frequency variability in convection such as diurnal variability. Our focus, however, is on variability in convection on time scales of greater than 2 days. Therefore, what is important is not showing the evolution of convective echoes or convective systems over their lifetimes but rather having enough samples of independent convective entities within each 2 day interval to make conclusions about the evolution of their behavior, specifically their depth, on longer time scales. We will show below that the precipitation rain rates derived from orbital data for the time scales of interest are highly consistent with those derived using a more spatially complete 3B42 data set. We will presume that because the precipitation rates included by 2A25 data are consistent with those in 3B42 data, we can make conclusions about the large-scale behavior of convective depth using the orbital data.

Table 1. Percentage of Domain Observed by TRMM Overpasses and Number of Independent Convective Echo Objects Observed During 2 Day Intervals From 1 October to 31 December^a

Date	Percent of Domain Sampled	Number of Convective Echo Objects
2 Oct	42.8	1169
4 Oct	40.1	972
6 Oct	35.2	935
8 Oct	35.0	807
10 Oct	41.8	1212
12 Oct	46.1	1330
14 Oct	44.8	1274
16 Oct	46.2	1338
18 Oct	47.8	1692
20 Oct	53.5	1599
22 Oct	50.7	1910
24 Oct	51.4	1642
26 Oct	51.4	1824
28 Oct	47.0	1289
30 Oct	50.7	1416
1 Nov	48.6	1299
3 Nov	45.9	1128
5 Nov	42.4	924
7 Nov	46.9	1101
9 Nov	51.3	1580
11 Nov	43.5	1195
13 Nov	49.0	1582
15 Nov	53.6	1655
17 Nov	50.4	2000
19 Nov	55.0	1741
21 Nov	55.5	1670
23 Nov	54.5	1887
25 Nov	49.6	1572
27 Nov	50.1	1385
29 Nov	48.4	1383
1 Dec	43.5	1248
3 Dec	46.1	1079
5 Dec	47.8	1538
7 Dec	50.5	1426
9 Dec	47.6	1505
11 Dec	51.9	1524
13 Dec	49.8	1595
15 Dec	53.1	1590
17 Dec	51.0	1538
19 Dec	48.4	1410
21 Dec	49.2	1568
23 Dec	54.1	1765
25 Dec	51.7	1541
27 Dec	34.4	843
29 Dec	25.4	808
31 Dec	30.3	940

^aDates indicate the end of each 2 day interval.

Figure 4 contains a time series of a probability distribution function (PDF) of 20 dBZ echo top heights for convective echoes only derived from 2A25 orbital data within the large-scale domain discussed above. In order to appropriately represent wide convective entities, an echo top height is computed for each column of pixels classified as convective, and each PDF in the time series is computed from the echo top heights determined from all of the individual pixel columns. The time series, represented by the colored contours, is composed of several 2 day intervals, into which all available data are composited into a PDF normalized by the total number of pixel columns identified as convective during each time period. The red boxes along the time axis represent periods of convectively active conditions. They represent dates during which the derived latent heating profile from a sounding network *Johnson et al.* [2015] near and north of the equator between about 70°E and 80°E does not indicate suppressed conditions as shown by *Ruppert and Johnson* [2015]. The vertically oriented, black, dashed lines represent dates (16 October, 18 November, and 15 December) on which a mesoscale convective system was first observed by the ground-based S-PolKa precipitation detecting radar in association with three MJO events at Addu City. The modes of convection described above are separated by a partially transparent white stripe covering the heights between those to the right of the black line in Figure 2.

The blue (purple) lines near the bottom of Figure 4 represent time series of mean rain rates, including convective and stratiform precipitation, derived from 3B42 (2A25) and each also displayed as domain-wide means over 2 day intervals. The time series have excellent agreement in low-frequency (~30 day) variability. Some additional high-frequency variability is depicted in the 2A25 time series that is not shown in the 3B42 time series and vice versa. The Pearson's correlation coefficient ρ between the two is 0.91 with 95% confidence intervals $0.76 \leq \rho \leq 0.97$. The precipitation time series from the ground-based radar at Addu City (see Figure 2 of *Powell and Houze* [2013]) has much more pronounced high-frequency variability than the 3B42 time series but has similar low-frequency variability. Between the two, $\rho = 0.56$ and has a 95%

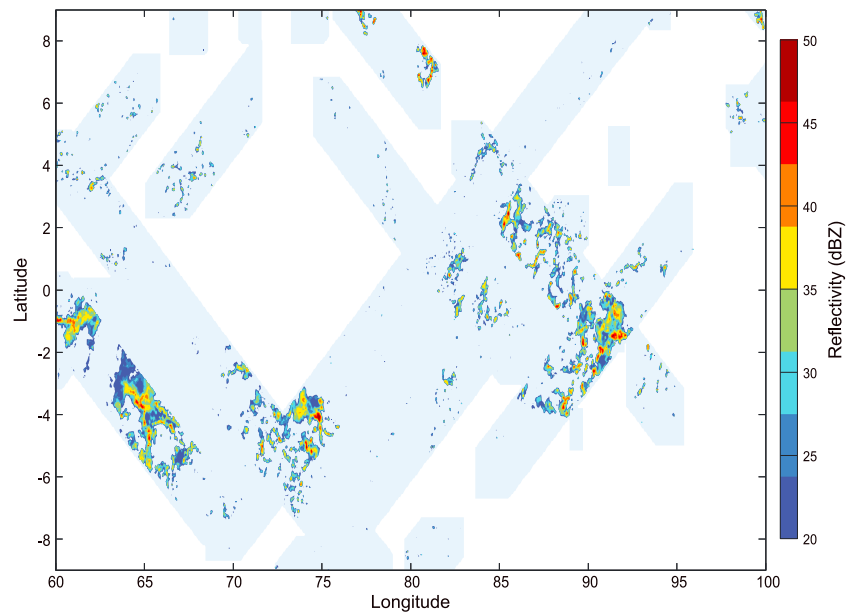


Figure 3. Radar reflectivity at 3 km altitude as observed by overpasses of the TRMM PR over the domain enclosed by the yellow box in Figure 1 from 15 to 16 October. The light blue areas indicate parts of swaths that were viewed by TRMM PR but did not contain radar echoes.

confidence interval of $0.25 \leq \rho \leq 0.77$. Because the 3B42 data set is derived from multiple satellite sources, it probably has the most accurate representation of large-scale mean precipitation rates. We have at least confirmed here that intraseasonal variability in the precipitation time series depicted by a ground-based radar with limited range and detected by a single satellite instrument covering a fraction of the domain of interest are representative of large-scale precipitation variability as viewed by a collection of satellites.

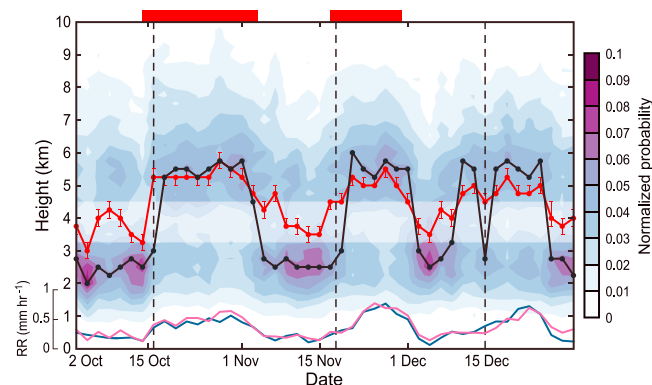


Figure 4. Time series of the normalized probability of 20 dBZ echo top height for a domain enclosed by 9°S – 9°N and 60°E – 100°E (yellow box in Figure 1) and smoothed to 2 day intervals during the interval of 1 October to 31 December. The black (red) line represents the mode (median) of the echo top height distribution. Each dot on the red and black lines represents the end of a 2 day interval. The red error bars bracket the 95% confidence intervals of the median. The dashed black lines represent the date on which a mesoscale convective system was first observed at Addu City as documented by Powell and Houze [2013]. The partially transparent white box covers heights that separate the two modes of convective echo top heights as described in the text. The blue (purple) lines at the bottom represent time series of 3B42 (2A25) domain-averaged rain rate also smoothed to 2 day intervals. The red boxes along the top time axis indicate convectively active periods.

Thus, we have confidence that their representations of the evolution of convection using a limited sample size are also consistent with the aggregate behavior of convection on the large scale, which cannot be completely and continuously observed using any current observational capabilities.

The red (black) solid lines in Figure 4 represent the median (mode) of the distribution at each 2 day interval. Each data point along the two lines is marked with a dot. The error bars on the median of the PDFs represent the 95% confidence interval of the median. A bootstrapping method, consistent with that described by Chu and Wang [1997], is used to determine the confidence intervals. From the pixel-based echo top heights used to derive the PDFs in Figure 4, a number of samples consistent with the number of individual convective echo objects during each 2 day interval (Table 1) are randomly selected with replacement,

and a median is computed each time. The process is repeated 5000 times, producing a distribution of medians. The error bars represent the inner 95% of this distribution. The PDFs of echo top height weigh convective echo objects by their spatial coverage; however, using the above method, the confidence on the median estimate is dictated more conservatively by the number of individual convective echo entities and not by total areal coverage of convective echoes.

Within the large domain, three periods of mostly deep mode convection and four periods of congestus mode convection were observed. During these periods, the echo top height population had a deep mode during 17 October to 3 November, 20 November to 1 December, and 10–25 (except near 15) December. Otherwise, the echo top height population was more characterized by congestus mode convection. Relative to other active periods, the distribution is more closely bimodal during the 10–25 December period. During that time period, the median echo top height seldom reached the congestus mode. Of the days with minimum median echo top height, only 3–4 October has a median in the congestus mode, and the 95% confidence interval then extends into the white shaded box that belongs to neither mode. However, the minima in median echo top height are 3.25–3.5 km, and they fall just outside of the congestus mode. Median echo top height reached the deep mode on 15–16 October, 16–17 November, and 10–11 December. Precipitation peaks associated with each MJO event were observed on 29–30 October, 26–27 November (24–25 November in the 2A25 time series), and 22–23 December. In terms of low-frequency variability, the broad peaks in surface precipitation occurred at the same times that the echo top height distribution was in the deep mode, which is consistent with a similar observation on shorter time scales by *Xu and Rutledge* [2014] that highest precipitation amounts occurred during periods of enhanced echo top height at the R/V *Revelle* near the equator and 80°E.

The modal echo top height transitioned from a congestus mode (3 km) to a deep mode (over 5 km) in just 2–4 days between 15 and 18 October near the beginning of an MJO event. The median echo top height increased from 3.25 km to 5.25 km, also in just 2–4 days (13–16 October). The modal and median echo top heights remained above 5 km for 14 and 16 days before decreasing. The modal echo top height quickly shifted back to the congestus mode while the median echo top height gradually decreased, reaching a minimum by 6–7 November. Near the onset of the November MJO event, the modal echo top height increases from 3 km to 6 km in 2–4 days (18–21 November). The median echo top height increases from a minimum of 3.5 km to 5.25 km in 6–8 days (14–21 November). Both the modal and median echo top heights remain within the deep mode until 30 November to 1 December. They reach minima, respectively, of 2.5 km and 3.5 km by 4–5 December. Near the onset of the December MJO event, the modal distribution increases from 3.25 km to 5.75 km in 2–4 days (8–11 December) and the median echo top height increases from 3.25 km to 4.75 km in 6–8 days (4–11 December). During each MJO case, the median echo top height does not reach its maximum until several days after the modal echo top height rapidly shifts from the congestus mode to the deep mode. The time scales reported above for median echo top height growth refer to the time scales of growth from a minimum to the deep mode near the earliest known time of MJO convective onset anywhere within the domain. We do not include in the time scales subsequent increases in median echo top height that occur once widespread deep convection and stratiform precipitation have become established. We also note that the rapid increase in modal and median echo top heights within the large-scale domain closely coincides with dates in October and November (dashed black lines in Figure 4) that the first mesoscale convective system was observed near Addu City. However, the domain-averaged echo top height increases prior to 15 December. This may have occurred because positive humidity and upward motion anomalies propagated into the Indian Ocean from the Maritime Continent after the November MJO event [*Johnson and Ciesielski*, 2013; *Powell and Houze*, 2015]. In fact, the real-time multivariate MJO index [*Wheeler and Hendon*, 2004] remained in Phase 4 or 5, indicative of widespread support for convection over the Maritime Continent, for nearly a month after active MJO conditions subsided over the central Indian Ocean during late November. Some of the middle and upper tropospheric moisture associated with convection near and over the Maritime Continent was undoubtedly advected westward over the Indian Ocean and helped sustain development of deep convection.

3.3. Histograms of Convective Echo Top Heights

Although the single mode of the echo top height distribution can shift rapidly, a more accurate way to describe what we have observed in each shift is a changeover from a singular congestus mode to a

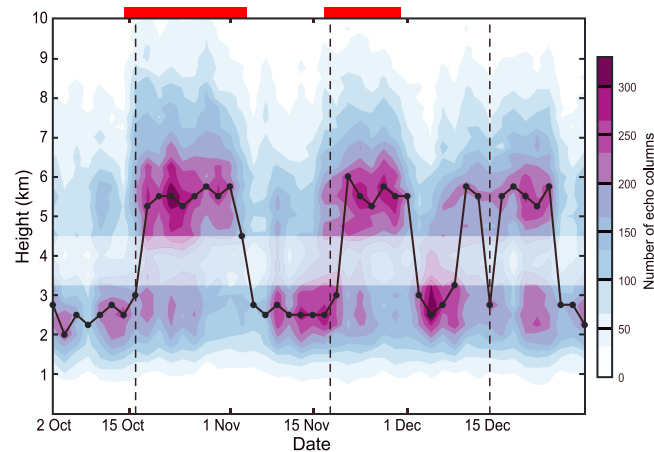


Figure 5. Time series, smoothed to 2 day intervals, of the histogram of detected 20 dBZ echo top heights between 9°S–9°N and 60°E–100°E for 1 October to 31 December. The black dashed lines, the solid black line and dots, and the white and red boxes are as in Figure 4.

phenomenon was to occur, then the buildup of the cloud population might still be described as gradual. Rather than a buildup specifically in echo top height, a buildup in the number or spatial coverage of convective elements could occur. Therefore, Figure 5 shows a nonnormalized histogram of echo top height using the same domain employed in Figure 4. As in Figure 4, the number of echo tops is expressed as the number of pixel columns falling within each bin. As such, the histogram essentially represents the observed areal coverage of echo top height within columns containing convective echo. Over 200 echo tops were observed in several height bins (recall vertical spacing in section 2) within the deep mode during convectively active periods. From 9 to 14 October and most of 9 to 23 November, the number of echo tops in each congestus mode (2.25–3.25 km) bin exceeded 150. After these dates, the number of congestus mode echo tops gradually decreased (with some small increases on short time scales) and deep convection dominated. The number of echo tops in the deep mode appears to have increased very quickly around 16 October and 15 November, while the increase in the amount of deep mode convection was more gradual in December and occurred prior to convective onset at Addu City.

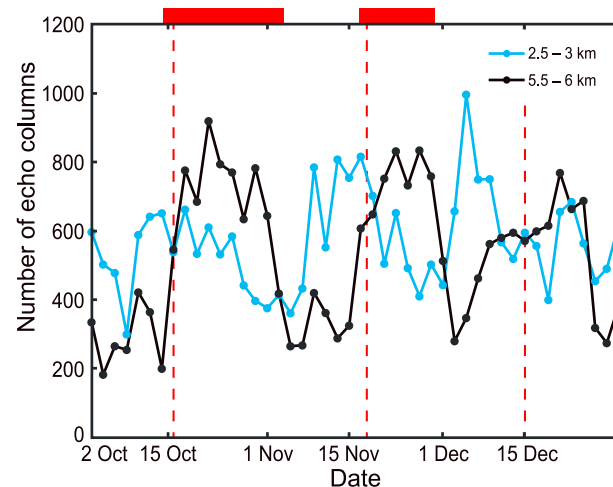


Figure 6. Line plot, in 2 day intervals, of the total echo tops detected at heights 2.5–3 km (blue) and 5.5–6 km (black) during the dates shown in Figure 5. The red dashed lines are the same as the black dashed lines in Figure 5, and the red boxes are as in Figure 4. The blue and black dots indicate the end of 2 day intervals.

distribution that is better described as bimodal and eventually dominated by the deep mode. The congestus mode often does not disappear but continues to exist as a secondary, weaker mode. The probability time series of 20 dBZ echo top height illustrates the time scale involved in the cloud population transitioning from having a predominantly congestus mode to a status in which deep mode convection predominates in the echo top height distribution. However, diagrams such as in Figure 4 only reveal the relative numbers of congestus to deep echo. Potentially, the relative amounts of each could remain about the same, while the absolute number of echoes in each mode increases slowly. If such a

To more closely investigate how quickly congestus mode, and then deep mode, convection becomes established, we employ Figure 6, which is a time series of the total number of echo top heights (counted by pixel column) detected within equally sized vertical bins (2.5–3 km and 5.5–6 km) in the congestus and deep modes during the same period. The red dashed lines are the same as the black lines in Figures 3 and 4. We note minima (<400) of echo top pixel counts in the deep mode during early October and just after each MJO event. These periods of extremely suppressed convection occurred during periods of deep layer tropospheric drying [Powell and Houze, 2013] and were possibly caused by horizontal advection behind areas of active convection [e.g., Kerns and Chen, 2014; Sobel et al., 2014; Adames and Wallace, 2014] and/or by

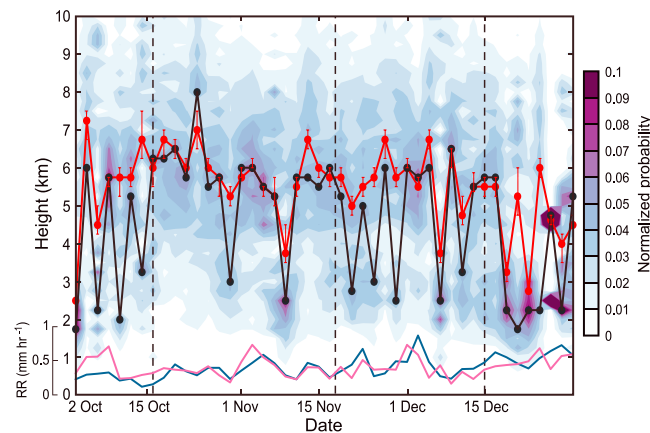


Figure 7. As in Figure 4 but for a domain enclosed by 9°N, 9°S, 100°E, and 120°E or the green box in Figure 1. The white and red boxes as seen in Figure 4 are omitted in this figure.

large-scale subsidence in a deep layer [Takayabu *et al.*, 2010]. During 7–12 October, the number of congestus echo tops increased from 300 to 641 before gradually decreasing after deep convection became established. The number of deep convective echo tops increased from 200 to 775 between 13 and 18 October and reached a maximum of 918 on 21–22 October. The congestus echo tops increased in number from 433 to 784 during 6–9 November before eventually decreasing in number about midway through the month. Deep echo tops increased rapidly in number from 288 to 607 between 14 and 17 November and continued to increase for 6 more days

to a total of 831 by 23 November. Congestus convective echo top numbers increased from 443 to 995 in 4–6 days between 30 November and 5 December, and areal coverage of deep convection followed with an increase in pixel column count from 280 to 562 in 6–8 days between 2 and 9 December.

Prior to each MJO event, congestus mode convection was prevalent and rapidly increasing in area for days prior to a rapid increase in areal coverage of deep mode convection. In October, November, and December, congestus convective areal coverage increased rapidly 6, 8, and 2 days, respectively, prior to the same for deep convective areal coverage. The rapid increases in congestus convective area began on 7–8 October, 6–7 November, and 30 November to 1 December. The same for deep convective area began on 13–14 October, 14–15 November, and 2–3 December. Roughly speaking, the areal coverage of congestus echo reaches its maximum at about the time the areal coverage of deep echo rapidly increases. The 2–8 day time scale reported above was also inferred by Ruppert and Johnson [2015] from heating profiles derived from a sounding network. The time period spanned between the minimum in congestus echo tops, and the maximum in deep echo tops was 12–22 days near the beginning of each MJO event (Figures 5 and 6). However, the maximum in the amount of deep convection occurred well after each MJO convective initiation within our large domain. Therefore, the total quantity of deep convective elements composited over the large scale maximizes after the widespread deep convection first appears somewhere in the domain. This behavior is consistent with the convection responding to a circulation or humidity anomaly moving eastward across the domain. Note that the distance between 60°E and 100°E at the equator is nearly 4500 km. Any anomalous circulation or humidity anomaly propagating eastward at a rate of 5 m s^{-1} , a typical rate for MJO propagation [Zhang, 2005], would require over 10 days to propagate through a domain of this size. We therefore would expect that the maximum coverage of deep convection would occur sometime after convective onset in the western portion of the domain.

3.4. Convection Over the Maritime Continent

Figure 7 is similar to Figure 4 but is composited within a box bound by 9°N, 9°S, 100°E, and 120°E or the green box in Figure 1. The 3B42 and 2A25 rainfall time series have a statistically significant correlation $\rho = 0.52$ ($0.22 \leq \rho \leq 0.73$), but they are not in as obvious agreement as were the 3B42 and 2A25 time series over the Indian Ocean. The PDFs of 20 dBZ echo top height suggest that the modes of convective echo top height are similar over this region as over the Indian Ocean; however, the convection during the period displayed is often dominated by the deep mode. Neither the time series of convective echo top height nor precipitation show clear intraseasonal variability. Nonetheless, Gottschalck *et al.* [2013] and Johnson and Ciesielski [2013] have argued that tropospheric wind signals associated with the MJO continue eastward across the Maritime Continent. Even the current authors have shown that positive anomalies of moisture and upward motion propagated from the Indian Ocean into the Maritime Continent during each MJO event observed during DYNAMO [Powell and Houze, 2015]. Figure 10 in Johnson and Ciesielski [2013]

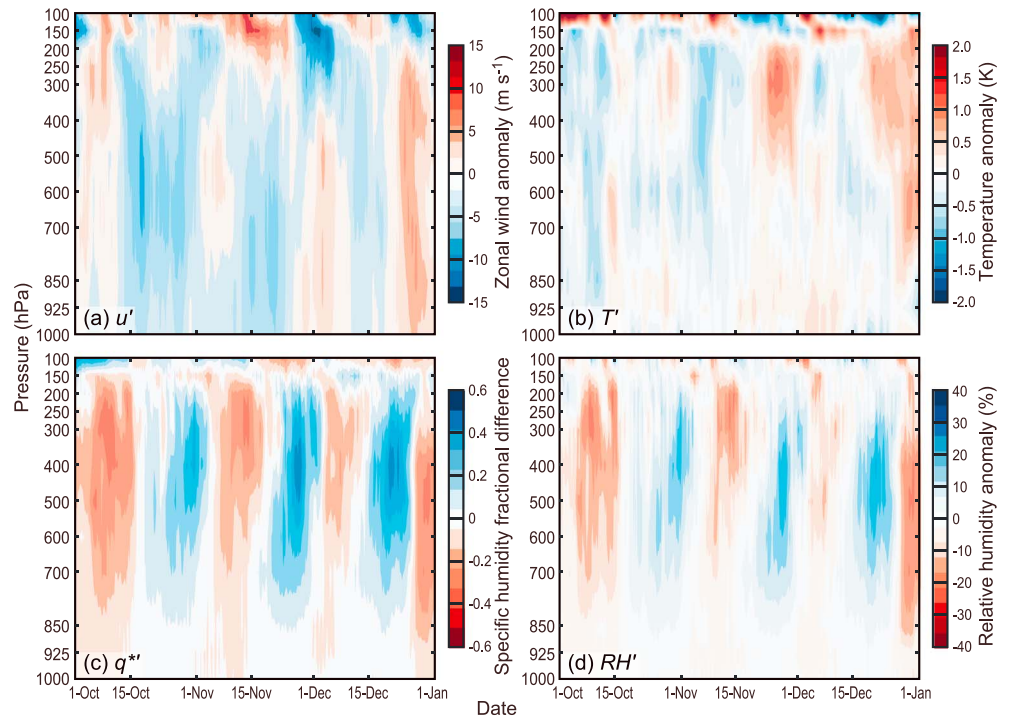


Figure 8. ERA-I-derived time series of anomalies of (a) zonal wind (u'), (b) temperature (T'), (c) fractional difference of specific humidity from its mean (q^*), and (d) relative humidity (RH') composited within a box bounded by 9°N , 9°S , 60°E , and 100°E (yellow box in Figure 1) from 1 October 2011 to 1 January 2012. As in Powell and Houze [2013], anomalies are calculated relative to means during the period of 1 October to 9 February.

shows that large precipitation amounts failed to propagate much past 110°E during the MJO event starting in October. They were present between 100°E and 120°E for only a short time during the second MJO event. Without further exploration, we speculate that factors other than the MJO (especially diurnal forcing over the islands and straits comprising the Maritime Continent) might be of first-order importance to precipitation and convective depth in this region.

4. Dynamic and Thermodynamic Fields From ERA-I

As seen in the prior section, our study is motivated not only to show the consistency of small-scale observations with large-scale convective behavior but also to determine the time scale of convective buildup as a test of the discharge-recharge hypothesis. A key component to the hypothesis is the time scale of moisture buildup. Other hypotheses for MJO convective onset [Matthews, 2008; Powell and Houze, 2015] invoke temperature or divergence fields to explain how widespread deep convection may develop. Therefore, showing that time series of wind, temperature, and humidity near single rawinsonde locations are consistent with those of the mean large-scale profiles of each is important. For this purpose, we appeal to the ERA-I reanalysis fields. Nasuno *et al.* [2015] concluded that despite having small cool and dry biases in the lower troposphere, that ERA-I was appropriate for moisture budget analysis over the Indian Ocean during DYNAMO.

Figure 8 illustrates profiles of anomalies of the zonal wind (u'), temperature (T'), specific humidity fractional difference (q^*), and relative humidity (RH'), which are computed as described in section 2. The fractional difference from the mean of specific humidity (q^*) is defined as

$$q^* = \frac{q - \bar{q}}{\bar{q}} \quad (1)$$

in which the overbars indicate a time mean at each pressure level for the period indicated in section 2. The profiles are composites of ERA-I columns of each within the large-scale domain used in section 3 and shown by the yellow box in Figure 1. Table 2 provides a list of correlation coefficients and 95% confidence intervals between the time series derived from rawinsonde data and from ERA-I using two domains. The smaller

Table 2. Pearson Correlation Coefficients ρ (in Center of Each Inequality Expression) and 95% Confidence Intervals Between Time Series of u' , T' , and q^{**} as Derived by Gan Rawinsonde Data and by ERA-I^a

	Small Domain (68°E–78°E and 3°N–3°S)	Large Domain (60°E–100°E and 9°N–9°S)
u'	$0.85 \leq 0.87 \leq 0.89$	$0.55 \leq 0.61 \leq 0.66$
T'	$0.68 \leq 0.71 \leq 0.73$	$0.52 \leq 0.56 \leq 0.59$
q^{**}	$0.80 \leq 0.81 \leq 0.82$	$0.61 \leq 0.64 \leq 0.66$

^aColumns are labeled by the domain used to composite ERA-I output. Each field is sampled every 6 h for the correlation calculation.

domain, depicted by the red box in Figure 1, is bound by 68°E, 78°E, 3°N, and 3°S. It is almost centered over Addu City and covers a little more than $7 \times 10^5 \text{ km}^2$, an area about 10 times as large as the area observed by the S-band ground-based radar located there during DYNAMO. Probably because ERA-I ingests the DYNAMO rawinsonde data, the ERA-I time series for u' , T' , and q^{**} correlate

strongly ($\rho > 0.8$) with the rawinsonde time series in the small domain. Compositing over a small domain allows us to maintain high-frequency variability in the fields that is not retained when we average over a large domain. For each of the large-scale anomalies displayed in Figures 8a–8c, moderate to strong correlations of around 0.6 exist between rawinsonde time series and ERA-I time series generated from output in a large domain. ERA-I effectively represents the intraseasonal variability in each field, especially the humidity and zonal wind anomaly fields. Moderate and significant correlation of $\rho = 0.59$ (95% confidence interval: $0.47 \leq 0.59 \leq 0.69$) also exists between q^{**} and mixing ratio fractional difference from the mean (not shown and calculated in the same way as q^{**}) derived from the Atmospheric Infrared Sounder (AIRS) over the same large domain. This confirms that ERA-I fields are consistent not only with single-location rawinsonde measurements but also with observations derived by satellite over an equally sized domain.

Relative humidity is largely influenced by specific humidity. RH' and q^{**} correlate at $\rho = 0.80$ (95% confidence interval: $0.77 \leq \rho \leq 0.82$). Temperature and relative humidity are only weakly correlated at $\rho = -0.24$ (95% confidence interval: $-0.29 \leq -0.24 \leq -0.19$). In fact, during the most convectively active periods, RH' above 500 hPa is positive at the same time that T' is positive. Widespread convective onset is thus more likely supported by tropospheric moistening than by cooling of the upper troposphere, a possibility posed by Matthews [2008].

The robust correlation between ERA-I output and rawinsonde observations within the small domain strongly implies that the 3–7 day time scale actually observed at Addu City is also present in ERA-I. The time scale of mean large-scale moistening, however, must be longer. One can easily approximate the time scale of moistening between 700 and 300 hPa in Figure 8c to be up to 2 or 3 weeks. Recall that the MJO dynamic signal propagates eastward, on average, at about 5 m s^{-1} , and would take about 10 days to cross the large domain employed above. If a disturbance enters the western edge of our large-scale domain, it might cause fairly rapid moistening there first. As the forcing for convection moves eastward, moistening will occur in an increasingly larger portion of the domain used in this study. Therefore, the time scale of moistening on the large scale is not necessarily indicative of the moistening time scale within subdomains of the large-scale region nor is it an accurate representation of the time scale for moisture buildup prior to MJO convective onset. Confusing the two time scales may have been one reason that some discharge-recharge theories hypothesized a 10–20 day period of moisture and convective buildup preceding MJO convective onset. On the large scale during DYNAMO, a 10–20 day buildup of moisture was valid; however, MJO convective onset began well before the large-scale moistening was complete.

5. Conclusions

We have investigated data from the Tropical Rainfall Measuring Mission (TRMM) precipitation radar (PR) and output from ERA-Interim (ERA-I) reanalysis to document large-scale variability of convective echo top height and tropospheric zonal wind, temperature, and humidity as observed within a domain representing much of the equatorial Indian Ocean through which three instances of the Madden-Julian Oscillation (MJO) propagated during DYNAMO. Data obtained within a small area near Addu City (0.63°S, 73.1°E) as documented by Powell and Houze [2013] (PH13) demonstrated consistent variability on time scales of more than 2 days. Specifically, the intraseasonal variability of ground-based radar and rawinsonde observations collected at Addu City during DYNAMO is consistent with the same on the large scale. Our conclusions are partially based on a limited data set of orbital TRMM satellite data; however, we have shown using

precipitation patterns based on extending the TRMM data with other satellite data that the samples captured represent mean convective behavior throughout the rest of the domain that was not sampled.

The 20 dBZ echo top heights of convection throughout the Indian Ocean occurred in modes near 2.5 km and 5.5 km (Figure 2). These two modes likely represent moderate cumulonimbi (also known as precipitating cumulus congestus) and vertically extensive, and often mesoscale-organized, convection. A third mode of shallow nonprecipitating cumuli, suggested by *Johnson et al.* [1999] and documented further by *Hollars et al.* [2004], is too weak to be detected by the 2 cm wavelength TRMM PR. We can take advantage of the natural separation of convection into these two distinct deeper modes to identify periods of MJO convective onset, which we have herein defined as the process of the convective distribution transitioning from the middle congestus mode to the deep mode. It follows that we can then determine the time scale over which this transition occurs, noting that there may also first exist a transition from a shallow mode to the congestus mode that we cannot observe using TRMM data.

Precipitating convection over the Indian Ocean near the equator underwent clear transitions from predominantly precipitating congestus to predominantly deeper convection and back to congestus during the period of the DYNAMO campaign in October 2011 to January 2012. Broad peaks of precipitation occurred alongside peaks in convective cloud depth. The evolution of echo top heights averaged throughout a large domain in the equatorial central and eastern Indian Ocean reveals how quickly the convective population develops a deep mode. Specifically, we note that prior to October–December MJO events, which were well documented by island-based radar at Addu City (PH13), modal 20 dBZ echo top heights increase from between 2.25 and 3.25 km to between 4.5 and 6 km in 2–8 days over a large portion of the central and eastern equatorial Indian Ocean. This result is consistent with the result of PH13 derived locally from an island radar of a buildup in the modal echo top height of convection 3–7 days prior to the first large-mesoscale convective system within their radar domain. Additionally, prior to each MJO event, the congestus mode of convection increased in areal coverage for 2–4 days, followed by a gradual decrease in the area of congestus mode convection and a 2–8 day increase in the coverage of deep mode convection. In October and November, the start of the increase in the coverage of deep mode convection within the large domain (indicating large-scale convective onset) closely coincides with convective onset detected by ground-based radar at Addu City as documented by PH13.

Convection and precipitation over the Maritime Continent between 100°E and 120°E and between 9°S and 9°N did not exhibit a clear signal of ~30 days that can be attributed to the MJO, despite indices of MJO activity [e.g., *Wheeler and Hendon*, 2004] suggesting the presence of an MJO-related circulation anomaly [*Gottschalk et al.*, 2013, Figure 11]. The MJO signal in the field of precipitating convection observed by TRMM radar was evidently overwhelmed in the region of the Maritime Continent by other variability, perhaps on shorter time scales, possibly including the strong diurnal variability owing to the land-ocean contrasts in the region.

The results over the Indian Ocean imply that the convective population over the whole ocean basin did not tend to gradually increase in depth from the congestus mode to the deep mode. Populations of congestus mode and deep mode convection with lesser amounts of convection having echo tops between the two modes were both present. At any time, of course, individual convective elements of intermediate height that were growing from the congestus to the deep mode may have been detected. The rapid increase in modal echo top height represents the time period over which the deep mode becomes the dominant one. The distribution was closer to bimodal during the transition from predominantly congestus to predominantly deep convection as the amount of congestus convection levels off or decreases. Deep convection becomes more common within the domain (Figures 5 and 6) as the center of the MJO disturbance moves eastward after initial convective onset to a location well within the large-scale domain used in this study.

Additionally, fields of zonal wind, temperature, and humidity anomalies are derived from reanalysis. Within a domain of size 10° longitude by 6° latitude near Addu City, the reanalysis time series of each field's anomaly is highly consistent with that observed by rawinsonde, which may not be particularly surprising because the reanalysis ingests nearby rawinsonde data. Therefore, the approximately 3–7 day time scale of moisture buildup in reanalysis in an area close to Addu City should be consistent with that directly observed. Within a large-scale domain of size 40° longitude by 18° latitude, low-frequency variability in reanalysis is correlated moderately to strongly with that observed via rawinsonde. It is also consistent with that derived from satellite data within the same domain.

Our results do not agree with the time scale of convective buildup traditionally discussed in the discharge-recharge theory and illustrated in schematic diagrams such as the one seen in *Benedict and Randall* [2007]. Additionally, at least for MJO cases observed during DYNAMO, a gradual buildup of convective cloud depth during the so-called “recharge” period is not an appropriate paradigm in which to view the transition of convection from shallow to deep in the days prior to and during MJO convective onset. Rather, a majority of precipitating cloud populations fall into one of two modes, and the number of clouds in each mode changes ~1 week prior to MJO convective initiation, with the moderately deep cloud increasing in areal coverage a few days prior to the deeper clouds doing so then generally decreasing in area as deep convection becomes established. Disagreement of our results with discharge-recharge is apparent because we have investigated the buildup of convection, both in terms of its cloud depth and quantity, prior to individual MJO events. Many studies that have supported discharge-recharge (section 1) consider a large domain and/or composite several MJO events together and conclude that humidity in the troposphere gradually increases over time scales of 2 weeks or more. (See PH13 for discussion of compositing the three DYNAMO events.) It has therefore often been hypothesized that cumulus growth leading to an active MJO period occurs over a similar time scale. We cannot rule out that gradual processes consistent with the discharge-recharge hypothesis occur prior to other MJO cases. Nor does this study address whether the physical processes associated with discharge-recharge might be working on time scales shorter than previously anticipated. However, for cases observed during the DYNAMO campaign, the current long-time scale discharge-recharge hypothesis does not describe the way that the population of precipitating convective clouds actually changed its statistical character. Whether cumulus moistening is critical for MJO onset on time scales of less than 1 week is left for another study and has already been addressed to some degree by others [e.g., *Ruppert and Johnson*, 2015] for DYNAMO cases.

Acknowledgments

The authors were supported by the National Science Foundation under grants AGS-1059611 and AGS-1355567 and the National Aeronautics and Space Administration under grants NNX10AH70G and NNX13AG71G. We acknowledge M. Zuluaga and H. Barnes for their comments on the original manuscript and three reviewers to their contributions toward improving the manuscript. D. Mehta drafted Figure 1. B. Tully refined the graphics. At the time of writing, TRMM data used in this study were accessible here: <http://mirador.gsfc.nasa.gov/cgi-bin/mirador/presentNavigation.pl?tree=project&project=TRMM&dataGroup=Orbital&CGISESSID=1e6fc9-c059167aa2a7ec89555c49dc36>. ERA-I data were downloadable at http://apps.ecmwf.int/datasets/data/interim_full-daily/?levtype=pl. S-Pol rain rate data time series were generated by the authors from data available at data.eol.ucar.edu/codiac/dss/id=347.017. AIRS data were accessible at <http://disc.sci.gsfc.nasa.gov/AIRS>.

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