Characteristics of Precipitation, Cloud, and Latent Heating Associated with the Madden–Julian Oscillation

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ABSTRACT

This study investigates the evolution of cloud and rainfall structures associated with Madden–Julian oscillation (MJO) using Tropical Rainfall Measuring Mission (TRMM) data. Two complementary indices are used to define MJO phases. Joint probability distribution functions (PDFs) of cloud-top temperature and radar echo-top height are constructed for each of the eight MJO phases. The genesis stage of MJO convection over the western Pacific (phases 1 and 2) features a bottom-heavy PDF, characterized by abundant warm rain, low clouds, suppressed deep convection, and higher sea surface temperature (SST). As MJO convection develops (phases 3 and 4), a transition from the bottom-heavy to top-heavy PDF occurs. The latter is associated with the development of mixed-phase rain and middle-to-high clouds, coupled with rapid SST cooling. At the MJO convection peak (phase 5), a top-heavy PDF contributed by deep convection with mixed-phase and ice-phase rain and high echo-top heights (>5 km) dominates. The decaying stage (phases 6 and 7) is characterized by suppressed SST, reduced total rain, increased contribution from stratiform rain, and increased nonraining high clouds. Phase 7, in particular, signals the beginning of a return to higher SST and increased warm rain. Phase 8 completes the MJO cycle, returning to a bottom-heavy PDF and SST conditions similar to phase 1. The structural changes in rain and clouds at different phases of MJO are consistent with corresponding changes in derived latent heating profiles, suggesting the importance of a diverse mix of warm, mixed-phase, and ice-phase rain associated with low-level, congestus, and high clouds in constituting the life cycle and the time scales of MJO.

1. Introduction

The Madden–Julian oscillation (MJO; Madden and Julian 1972) is a dominant feature in the tropical ocean–atmosphere, linking weather and climate variability. Theories and observational characteristics of MJO and its influence on tropical cyclones, midlatitude weather, monsoon variability, air–sea interaction, relationships with atmospheric angular momentum and El Niño, and predictability have been reported in a large number of previous studies. [See Lau and Waliser (2005) for a review of observations and theories related to MJO.] Because of the highly multiscale organization associated with MJO (Nakazawa 1988; Lau et al. 1989; Hendon and Liebmann 1994; Wheeler and Kiladis 1999; Masunaga et al. 2006), realistic simulation of MJO is now considered one of the most fundamental tests of climate model physics and a major challenge to climate modeling. Early theoretical studies (Lau and Peng 1987; Kemball-Cook and Weare 2001) found large sensitivity of the MJO propagation to the vertical heating distribution, demonstrating that a lower heating profile can produce a slower phase speed closer to the observed MJO. Wu (2003) has argued that low-level heating is essential in the build-up phase of the MJO and is critical in determining the time scale of MJO. Lin et al. (2004) have shown that heating profile associated with MJO is top heavy, indicating the importance of stratiform rain. Other mechanisms such as evaporation–wind feedback, frictional Ekman pumping, discharge–recharge, radiative heating feedback, moisture-convergence and air–sea interaction, as well as...
combinations of these mechanisms, may also play important roles (Hayashi and Golder 1993; Wang and Li 1994; Emanuel et al. 1994; Hu and Randall 1994; Waliser et al. 1999; Marshall et al. 2008).

Contemporary observational studies have shown the abundance of low- and midlevel cloud (cumulus congestus) in the tropical atmosphere (Johnson et al. 1999). Recent satellite studies have shown that warm-rain processes are much more prevalent in the tropics than previously considered (Short and Nakamura 2000; Lau and Wu 2003; Masunaga and Kummerow 2006; Jakob and Schumacher 2008). Shallow convection and cumulus congestus are found to be actively involved in vertical transport of heat and moisture prior to the onset of deep convection (Benedict and Randall 2007). Atmospheric model experiments have shown that, in addition to stratiform and deep convective processes, heating and moistening by shallow boundary layer and congestus are necessary to realistically produce the wide range of tropical temporal and spatial variability, including MJO (Khouider and Majda 2007). Modeling studies have shown that warm-rain processes may play an important role in regulating the time scales of MJO convective cycles through dynamical feedback induced by cloud radiation and latent heating (Lee et al. 2001; Lin and Mapes 2004; Lau et al. 2005). Using a community climate model, Zhang and Mu (2005) suggest that shallow convection helps to precondition the atmosphere for MJO by moistening the lower troposphere. Yet, so far there is no strong observational evidence directly implicating the importance of low-level heating and moistening in the formation of MJO. This is partially due to the lack of vertical resolution in global observations of rainfall, cloudiness, and water vapor. Furthermore, cumulus parameterization in general circulation models (GCMs) and diagnostic calculations of atmospheric heating from large-scale circulation and thermodynamic fields (Yanai et al. 1973) tend to emphasize aspects of the tropical circulation driven by organized deep convection. Shallow convection and boundary layer processes are generally not well represented, even in state-of-the-art GCMs (Waliser et al. 2003; Slingo et al. 1996; Sperber et al. 2005; Lin et al. 2006). Hence, shallow circulation features and low-level heating processes may be unrealistically weak or entirely absent in reanalysis and differ substantially among observations and GCM results (Zhang and Nolan 2008). The undiagnosed shallow-heating–circulation may also introduce bias in the vertical distribution of diabatic heating in GCMs, which typically have spontaneous and overly strong convective processes. This could be a reason why GCMs are unable to simulate the time scales of MJO. Most recently, Li et al. (2009) in their sensitivity study of MJO also show the importance of sufficient diabatic heating in the lower troposphere (presumably from shallow convection) in MJO simulations. However, because there are no direct observations of latent heating, determining realistic heating profiles for MJO from observations remains elusive. Because vertical heating profiles are closely linked to the characteristics of cloud and rain processes, identifying their roles in the MJO life cycles and their relationships with the large-scale environment is key to better understanding MJO mechanisms and improving representation of MJO heating processes in GCMs.

In this paper, we examine the structures of MJO based on the Tropical Rainfall Measuring Mission (TRMM) observations. Section 2 describes the TRMM data products and the two MJO indices used in this study. Section 3 shows the results of the composite analyses based on the two indices. Section 4 presents the concluding remarks.

2. Data and analysis procedure

We use the TRMM, version 6, data products for the period from 1 January 1998 to 31 July 2001 (1308 days) for this study. The TRMM spacecraft orbit was boosted from 350 to 402 km in August 2001 to save fuel. As a result, the TRMM products may have an abrupt change in characteristics as a result of the orbit boost. To avoid the artificial change, the data used here are only for the preboost period. These include precipitation radar (PR) echo-top height (ETH, product 2A23); visible and infrared scanner (VIRS) channel-4 brightness temperature (Tb, derived from product 1B01); TRMM Microwave Instrument (TMI) surface rain rate (RR, product 2A12); TMI-derived sea surface temperature (SST), cloud liquid water (CLW), and precipitable water (PW) from Remote Sensing Systems (available at http://www.remss.com); and convective rain (CR) and stratiform rain (SR) amount and ratio derived from product 3G68. Details on the TRMM sensors and data algorithms can be found in Kummerow et al. (1998). The TRMM, version 5, convective–stratiform separation algorithm is described and examined in Schumacher and Houze (2003), and the main changes in version-6 rain type classification are reported in Awaka et al. (2004). All TRMM data are processed to obtain their averaged values over a 0.5° latitude × 0.5° longitude × 1 day box.

Two methods of determining MJO phases are employed. For the MJO local phases, we use 20–70-day bandpass-filtered 200-hPa velocity potential derived from National Centers for Environmental Prediction (NCEP) Reanalysis 2 wind (hereafter referred to as the VP index) to construct daily and pentad composites of
various rain and cloud properties over the tropical western Pacific. For the MJO global phases, we use the Wheeler–Hendon MJO index, based on the combined empirical orthogonal functions (EOFs) of outgoing longwave radiation and zonal wind fields [Wheeler and Hendon (2004), hereafter referred to as the WH index] to construct similar composites. The WH index is available online (at http://www.bom.gov.au/bmrc/clfor/cfstaff/matw/maproom/RMM/).

The VP index provides specific timing information with reference to the organized upper-level divergence over the tropical western Pacific, whereas the WH index emphasizes the coherent variations of the entire MJO space–time evolution over the entire tropics. The two approaches are complementary, with the VP index pentad composites producing results very similar to those using the WH index. For economy, in this paper we show results of the daily composites for the VP index, and the vertical structure and latent heating composites based on the WH index only. The correspondence between the two indices is also discussed.

3. Results

a. Daily VP index composites

The close relationship of the filtered velocity potential with the eastward-propagating precipitation cluster associated with MJO for the year 1999 can be seen in Fig. 1a. Here, we can identify about seven MJO cycles, manifested in eastward-propagating rainfall clusters within regions of upper-level divergence. To obtain the VP index, the filtered velocity potential is averaged over the equatorial western Pacific region (10°S–10°N, 120°–150°E) (see rectangle in Fig. 4). Each peak (local maximum) of the MJO index with a value greater than one standard deviation is defined as Day 0 of a major MJO event. Because the reference index is based on a large-scale dynamic variable, only large-scale organized systems associated with MJO signals are captured. Following this procedure, we obtain 21 distinct active MJO events among the total data period (1308 days), highlighted in Fig. 1b, which shows the time series of the equatorial western Pacific average rain rate. On the basis of the index, we compute the daily composites of rain, clouds, and associated environmental characteristics to describe their evolution through the MJO cycle. For the composites, days are labeled relative to Day 0, positive for days after, and negative for days before. The daily composite runs for approximately a cycle of the MJO, from Day −15 to Day +15. All the rainfall and cloud statistics of a given day are defined from the unfiltered full-resolution data.

To describe the phase characteristics of RR, PW, CLW, Tb, and SST (Fig. 2) and their relationships, we define the scaled change as the deviation from the mean over the life cycle divided by the full amplitude of the oscillation, so that all variables will fit into the same scale within the −100% to 100% range. The expressions for conversion to the actual magnitudes of each variable are provided in the caption of Fig. 2. Figure 2a portrays a composite life cycle of MJO. Here, the maximum rain occurs (indicated in the bar chart) around Day −1 to Day +1, with the rain rate at about 50% higher than that of the mean. During the development stage, PW, CLW, and RR show a rapid increase beginning at around Day −10 and then they briefly level off, followed by a secondary increase around Day −4 to Day −2. Similarly, during the decaying stage, PW, CLW, and precipitation show a slower rate of decline up to Day +5, followed by a more rapid decline from Day +5 to Day +10. Overall, the rainfall distribution is somewhat asymmetric with respect to the maximum rain (Fig. 2a), having a slight skew toward heavier rain and more rapid build up than the decaying phase. The skewness is more pronounced in the frequency of occurrence (FOC) of CR events, which shows a bimodal distribution with the primary peak near Day −7 to Day −5 and a secondary maximum at Day −1.

The temporal variation of deep convection (large negative value in Tb) shows a two-step development in the build-up phase similar to PW, CLW, and RR, with a more smooth transition in the decaying phase (Fig. 2b). The SST remains relatively warm, up to the peak of the convective rain events (CR_FOC in Fig. 2a), and the rapid development of stratiform rain, as noted in the reduction of the ratio of convective rain FOC to stratiform rain FOC (CR/SR) (Fig. 2b), precedes the rapid drop in SST by several days. The SST drops rapidly from Day −6 through Day +1 as deep convection sets in. During its peak (Day −2 to Day +2) and early decaying phase (Day +3 to Day +8), the MJO is associated mostly with below-average SST. Whereas, the CR/SR ratio shows a maximum during the early development phase (Day −15 through Day −10) and steadily declines to a minimum at Day +5 and thereafter, indicating a steady conversion to more abundance of stratiform rain toward the decaying phase. Note from Fig. 2 that the magnitudes of the variations discussed earlier are substantially larger than the standard errors of the mean, indicating the results are statistically significant.

The eastward propagation of MJO rainfall from the Indian Ocean (65°–95°E) to the western Pacific (120°–150°E) is evident in the equatorial-averaged (10°S–10°N) time–longitude section of composite RR anomalies (Fig. 3a). At Day −15 to Day −10, an east–west dipole structure
FIG. 1. (a) Time–longitude section of equatorial (10°S–10°N) averaged rain rate (mm day$^{-1}$, color shaded) superimposed with the 20–70-day filtered 200-hPa velocity potential (contours) with domain of western Pacific between the two purple lines. (b) Time series of equatorial western Pacific (10°S–10°N, 120°–150°E) averaged rain rate with days of significant MJO signals highlighted.
FIG. 2. Composite daily evolution of (a) RR (in shaded bar), PW, CLW, and CR FOC and (b) RR (in shaded bar), Tb, SST, and CR/SR during the active half-cycle of MJO over equatorial western Pacific. The daily evolution has been smoothed by a 3-day running average. The actual magnitude of each variable can be obtained as follows: RR = $(3x + 6.92)$ mm day$^{-1}$; PW = $(2x + 54.3)$ mm; CLW = $(0.05x + 0.14)$ mm; CR_FOC = $(4x + 24.1)$%; Tb = $(7x + 270)$ K; SST = $(0.2x + 29.67)$ C; and CR/SR = $(0.3x + 1.72)$. The mean standard error of each variable is represented by the length of the horizontal line to the right side of each variable name.
with suppressed (enhanced) rainfall over the western Pacific (Indian Ocean) is found. Near Day −5 to Day 0, there is an abrupt shift of the precipitation maximum from the Indian Ocean to the western Pacific. At Day 0 to Day +5, the east–west dipole reverses sign, associated with the mature phase of the MJO over the western Pacific.

The total PW (Fig. 3b) shows a similar time–longitude structure to that of RR and a build up of abundant moisture a few days ahead of the rain maximum, presumably due to the effect of large-scale moisture convergence at the leading edge of the propagating MJO complex (Zhang 2005). During the early developing phase of the MJO (Day −15 to Day −10), there is a relative reduction of total PW over the western Pacific, reflecting the drying up of the atmosphere because of large-scale subsidence forced by enhanced convection over the Indian Ocean.

The SST anomalies (Fig. 3c) propagate eastward, with increased SST ahead and suppressed SST trailing behind RR and PW. Overall, the SST shows a substantial warmer state over much of the western Pacific during the early development stage (Day −15 to −5), which quickly switches to a cooler state during the mature and decaying phases (Day 0 to Day +10). The increased SST over the western Pacific during early development may be related to the relatively clear-sky conditions, which allow warming of the upper ocean, by increased solar radiation at the surface. The suppressed SST is likely due to the increased high-level nonraining clouds, which blocks off solar radiation from reaching the ocean surface. The maximum difference between the two states can reach about 0.5°C. The warmer SST during the MJO early development stage promotes warm rain and low-level moisture recycling as the system builds up convective available potential energy (CAPE). The warm-rain efficiency (WRE; Fig. 3d), defined as the ratio of rain rate to cloud liquid water for warm rain cloud types (see definition in the caption of Fig. 3), is enhanced during the warmer SST state, right up to the maximum MJO heavy rain development (Day 0) over the western Pacific.

The increase in warm-rain efficiency releases convective available potential energy and enhances moisture recycling in the lower troposphere, leading to increased warm-rain PW (WRPW) defined as the PW associated exclusively with warm-rain type (Fig. 3e). During the cooler SST state, which corresponds to the MJO decay stage, the warm-rain efficiency is reduced and WRPW decreases. These features appear to be characteristic of local effects imposed on the MJO organization by the Maritime Continent as the MJO convection propagates from the Indian Ocean to the western Pacific.

b. WH index composites

The WH index decomposes the MJO cycle into eight phases (see Fig. 7 of Wheeler and Hendon 2004). Phases 1–8 describe the coherent large-scale eastward propagation of MJO convection from the western India Ocean to the central Pacific. For the present analyses, the composites are constructed for strong MJO events (WH index amplitude >1) only. Figure 4a illustrates the correspondence between each day (Day −15 to Day +15) in the cycle of the aforementioned 21 active MJO events in the western Pacific defined by the VP index and each MJO phase defined by the WH index. The number in each grid box represents the number of occurrences (out of 21 events) when a particular lag day is associated with a particular strong (amplitude >1) MJO phase. The high correlation between these two indices is obvious, with gradual transition from MJO phases 1–3 in the early days (Day −15 to Day −10) to phases 4 and 5 for the center days (Day −2 to Day +2) and to phases 6–8 during the late days (Day +10 to Day +15) of the MJO cycle.
Figures 4b and 4c show the spatial distribution of composite rainfall anomaly from pentad data centered at Day 0 (based on VP index) and composite rainfall anomaly from phase 5 (based on WH index), respectively. The similarity of the two composites is evident. Both show the large spatial scale of the organization of MJO convection spanning a longitude sector a quarter of the circumference around the globe and covering 20°–30°.
of latitude, centered about the equator. Positive rainfall anomalies appear in the form of rain clusters over the western Pacific and Indonesia waters, coupled to negative anomalies over the Indian Ocean and the Maritime Continent of Sumatra and Borneo, in the form of an east–west dipole. These are well-known MJO signals, associated with an eastward-propagating large-scale east–west overturning circulation (Madden and Julian 1972; Lau and Chan 1985). The propagation signals along the equator are strong in all seasons, except in the boreal summer, where the MJO is strongly influenced by northward-propagating monsoon intraseasonal oscillations.

On the basis of both indices, more than 50% (11 of 21 cases) of western Pacific MJO peaks (phase 5) are found in the boreal spring and fall, 6 cases in the winter, and only 4 in the summer. The large contributions from the spring, fall, and winter are reflected in the somewhat symmetric distribution of MJO rain cells about the equator in Figs. 4b and 4c. Hence, the present analyses are focused on the symmetric component, as defined by the MJO eastward propagation along the equator. More detailed analyses, with a longer time series to allow more samples, are needed in future work to separate the antisymmetric component of the MJO associated with monsoon intraseasonal oscillations.

The approximate residence time, defined as the number of days per MJO event, in each of the eight phases in the WH index, is found to be in the range from 4.4 to 6.7 days (see Table 1, first row), with phases 1–4 (23.5 days), phases 5 and 6 (13.0 days), and phases 7 and 8 (10.0 days) denoting the developing, mature, and decaying phases of MJO convection over the western Pacific with a 40–50-day life cycle. Note that the lifetime of the MJO varies with season and can also depend on the state of El Niño–Southern Oscillation (Pohl and Matthews 2007). Because of the irregularity in its propagation, and the aperiodic nature of MJO, each phase is not necessarily followed sequentially by phase number, and the residence time for each phase can vary substantially from event to event. Despite these irregularities, the key features and the approximate residence times of WH index phases are in good agreement with the characteristics of MJO phases based on the pentad composite using the VP index. The earlier-mentioned analyses suggest that the present results are not sensitive to the choice of MJO indices. From here on, we present only results based on the WH index composites.

To examine the characteristics of clouds and rainfall associated with the eight MJO phases defined by the WH index, we have constructed a 2D cloud–rain probability distribution function (PDF) using Tb and ETH from all data points within the region (10°S–10°N, 120°–150°E) for the mean of all active phases as well as for each phase (Fig. 5). Because of the full-resolution data being used, each composite PDF is drawn from a sample size of approximately $3 \times 10^4$ paired data points. The PDF represents the joint frequency of occurrence of Tb and ETH within binned values, normalized by the total occurrence of all joint events within the region. For the purpose of the following discussion, Tb represents the cloud-top temperature and ETH, the nominal storm height—that is, the maximum height of detectable signal at 17 dBZ by the TRMM PR. Hence, ETH is not necessarily the maximum physical height reached by hydrometeors associated with the rain system.

The mean PDF of rain and cloud averaged over the western Pacific of all active (amplitude $>$1) phases of MJO is shown in Fig. 5a. A bimodal distribution with abundance of warm-low and cold-middle cloud and rain types is evident. By far the highest population is from the warm-low type, with Tb warmer than 273 K and the ETH below the altitude of the melting (or freezing) zone, which is climatologically located at approximately a height of 5 km in the tropics. The cold-middle type, identified as congestus cloud system, has high population centered rather narrowly near the melting level, with a wide range of cloud tops colder than 273 K. To facilitate the following discussions, we divide the PDF phase space into four main regimes: 1) warm-rain low-level cloud (WL) regime (Tb $>$ 273 K, ETH $<$ 4 km),

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Table 1. Contribution of the rain amount and rain event from the precipitating WL, MM, CM, and CH clouds at the eight phases of MJO. Percentages are computed with respect to total of the four rain types. Also listed is the average residence time of each phase.
representing liquid-phase rain processes occurring below the melting level; 2) the mixed-phase rain, middle-level cloud (MM) regime ($245 \, \text{K} < T_b < 273 \, \text{K}, 4 \, \text{km} < \text{ETH} < 6 \, \text{km}$), consisting of both liquid- and ice-phase rain but only with moderate storm heights and cloud tops; 3) cold cloud-top and medium storm height (CM) regime defined by ($T_b < 245 \, \text{K}, 4 \, \text{km} < \text{ETH} < 6 \, \text{km}$), associated with supercooled liquid phase, with mixed ice-phase precipitation; and 4) the cold rain, high-cloud (CH) regime ($T_b < 245 \, \text{K}$ and ETH $> 6 \, \text{km}$), representing deep convection with cold cloud tops. The CH type appears as the extreme form of CM type with notably higher ETH, most likely dominated by ice-phase precipitation because of the low $T_b$.

These four main regimes—WL, MM, CM, and CH—are consistent with the four tropical precipitation systems—shallow, cumulus congestus, deep stratiform, and deep convective—classified in the observed study of Masunaga et al. (2005). In addition to these four regimes, the mean PDF of the MJO active cycle also shows a nonnegligible
warm rain, middle-level cloud (WM) regime, which counts for about 9% of the total population. From Fig. 5, we note that the WL type dominates the warm-rain regime, and the evolution of the WM type follows closely to that of the WL type in nearly all phases of the MJO, hence a separate discussion on WM regime is omitted.

To focus on the changes in rain characteristics over the western Pacific during different phases of the MJO life cycle, we show the anomalous PDF (Figs. 5b–5i), defined as the deviation of the PDF at a particular phase from that of the mean (Fig. 5a). During the early build-up stage—that is, phases 1 and 2—there are abundant occurrences of the WL type (color shaded), coupled with a large deficit in the MM and CM types (black and white contours). The WL type is well distinguished from the MM and CM types, with maximum population at ETH of 2.5–4.5 km and Tb range of 290–300 K, well below the melting level near 273 K. Between phase 2 and phases 3 and 4, the PDF switches from a bottom-heavy to a top-heavy distribution, with a large increase in MM and CM types representing an increase in mixed-phase precipitation with medium ETH. This corresponds to the second stage of build up (see discussion for Fig. 2), when deep convection is developing.

At phase 5, which coincides with the maximum large-scale organization, the CM and CH types increase considerably, with most of the enhanced activities (color shaded) taking place at below temperature 273 K and altitude above 5 km, indicating the presence of mixed-phase and ice-phase precipitation. A broadening of the ETH implies that shallow, middle, and deep convection are present at the same time. However, some shallow or middle clouds may not be counted in the presence of high stratiform clouds as a result of cloud layering effects. At phase 6, deep convection reduces somewhat, with the convective system dominated by CM and MM types, with a wide range of cloud-top temperature. This phase corresponds to the presence of both precipitating and nonprecipitating high-level anvil clouds associated with mature and decaying convections (see discussion for Fig. 7). Phase 7 signals the decaying stage, where substantial amount of rain still comes from deep convective systems with ETH above 6–7 km while at the same time, low-level rain reappears. By phase 8, the PDF has a structure similar to phase 1, indicating the completion of an MJO cycle, with the WL-type rain reestablishes itself, at the expense of the CH and MH types.

Figure 6 summarizes the FOC of the four rain types as a function of the MJO phases. The WL type tends to have the highest FOC during the build up and phases 1 and 2, with the least FOC for the CM and CH types. The WL type remains abundant up to phase 3 and decreases

![Figure 6](image-url)
significantly at phases 5 and 6. The MM and the CH types grow steadily toward the mature phase, from phases 2 through 5. During the most active phase, phases 4–6, the MM and CM types occur most frequently, indicating abundance of mixed-phase rain and congestus clouds. From Table 1, at the peak convection over the western Pacific, phase 5, MM and CM types account for a total of 64% (30% and 34%, respectively) of the rain events among the four rain types and slightly more than 50% of the total rain amount (17% and 35%, respectively) together, whereas the CH type contributes only 20% of the rain events but 44% of the total rain amount. Note that during the entire active cycle, phases 1–8, the total rain comprises different rain cloud types with varying proportions, and no single type of rainfall dominates (>50%) the rain amount.

The previously noted asymmetry with respect to the developing and decaying phases is also evident in Table 1, indicated by more WL rain, and less MM and CM rain before (phase 4) compared to after (phase 6) the peak (phase 5). This asymmetry is related to the increasing stratiform rain contribution in the mature and decaying phases (see also Fig. 2). The asymmetry is also evident in the overall increase in FOC of nonprecipitating clouds with varying proportions, and no single type of rainfall dominates (>50%) the rain amount.

Analyses of the MJO rain and cloud PDF structures over the Indian Ocean show similar characteristics to those over the western Pacific, including the switch from the bottom-heavy structure in the build-up stage to the top-heavy structure as convection develops. Note that the convection development in the Indian Ocean precedes that in the western Pacific by about three phases. As a result, the Indian Ocean PDF at phase 2 is similar to the western Pacific PDF at phase 5 and shows a reverse relationship with the phase 2 western Pacific PDF. Nevertheless, there are some notable differences in both the mean and anomalous PDF structures between the two oceans, which may be related to the different basic states of the ocean–atmosphere system in the two ocean basins. The detailed analysis of these differences is the subject of a separate ongoing study.

c. Vertical heating profile

In this subsection, we estimate the vertical distribution of latent heating associated with the different phases of
the MJO using the TRMM daily latent heating product. This product differs significantly from the standard monthly latent heating product available from the TRMM data Web site, in that daily PR information has been incorporated into the input streams. Because this is an experimental product and no direct validation is possible, the results in this section are mostly exploratory and not definitive. Observed daily rain rate from TMI, stratiform-to-convective rain ratio, ETH, and other environmental conditions are matched to compose latent heating profiles based on the Goddard Cloud Ensemble model simulations over a variety of convective systems, including stratiform and convective systems, squall and nonsquall disturbances, and shallow and deep convections over land and over oceans (Tao et al. 1993). The daily profiles are constructed at all grid points in the MJO reference domain, and composites are constructed according to the MJO phases.

Figure 8 shows the mean heating profile as well as the anomalous heating during the eight phases of the MJO cycle. The contributions from heating with ETH less than and greater than 5 km are shown separately to demonstrate the relative contributions from shallow (liquid-phase and mixed-phase rain) and deep (ice-phase and mixed-phase rain) convection. Note that the magnitude of the mean heating (Fig. 8a) by shallow convection is about 30%–35% of that due to deep convection. The anomalous heating profile (Figs. 8b–8i) at each MJO phase is defined by the deviation from the mean profile. At phase 1, the anomalous heating of the lower troposphere is contributed by shallow convection (ETH < 5 km) as well as by low-level moist processes associated with deep convection (ETH > 5 km). At phase 2, both shallow convection and deep convection contribute about equally to the low-level heating. A switch from a bottom-heavy (warm and shallow convective rain) to a top-heavy (mixed convective and stratiform rain) heating profile occurs from phases 2 through 4, consistent with the PDF distribution shown previously (Fig. 5). Note that the anomalous low-level heating from shallow convection at phase 3 is most likely contributed by the abundant mixed-phase rain at this stage (see Fig. 5d). During phases 4 and 5, the heating profiles show a dipole structure with maximum heating at about 7–8 km and cooling below 2–3 km, typical of that associated with stratiform rain systems (Houze 1989; Tao et al. 2006; Jakob and Schumacher 2008). The decaying phase shows almost a mirror image in the heating profile relative to the build-up phase. At phase 6, mid- and upper-tropospheric heating reduces and low-level heating reverses sign, reflecting the reduction in warm-rain processes in the decaying phase. The reduction in liquid-phase rain processes continues in phases 6 and 7, with the deep heating profiles changing sign in the latter. Phase 8 completes the MJO cycle, with a large reduction in deep heating and a beginning of low-level heating processes. Even though the contribution to total heating by shallow convection is relatively small compared to deep convection, the shallow convection and associated warm rain may be important in the regulation of moisture, clouds, and SST, especially during the build-up phase of the MJO.

4. Conclusions

Using TRMM observations, we have documented the evolution of rainfall and cloud structures associated with MJO using both the VP and the WH indexes. The former emphasize the local development and the latter, the global development of MJO convective system. Results show that there are abundant warm rain and low clouds during the MJO early build-up phases—phases 1 and 2—over the western Pacific. During the next two phases—phases 3 and 4—approximately 10–15 days prior to the MJO peak phase, the tropical atmosphere switches from an anomalous low-level warm-cloud state to one with mid- to upper-level mixed-phase convection. The switch appears to be related to a similar transition in the coupled ocean–atmosphere system in the western Pacific, from a state of warmer SST and suppressed deep convection to a cooler SST state with reduced warm rain and enhanced deep convection. We find that increased low- to midlevel clouds and associated rainfall over a warmer equatorial western Pacific, which leads the deep convection (maximum rain rate) by three to four MJO phases (approximately 15–20) days, may play an important role in warming and moistening the lower troposphere in the developing phase of the MJO. The decaying phases of MJO—phases 7 and 8—are characterized by an increase in stratiform-to-convective rain ratio, lower SST, and more frequent occurrence of cold cloud tops associated with mature or decaying convective systems. The aforementioned characteristic features, including the switch in rain and cloud structures during the transition phases, are consistent with derived TRMM latent heating profiles, indicating increasingly more abundance of stratiform rain with upper-level heating and low-level cooling through the development to mature and decaying phases of the MJO.

Our results suggest that the heating–cooling processes during different phases of the MJO life cycle are constituted by a different mixture of warm, mixed-phase, and ice-phase rain associated with low-level, congestus, and high clouds. The multiscale interactions of these processes are important in determining the dynamics of the MJO. First and foremost, a better representation of physical processes in the life cycle of tropical convection
in moistening–drying and heating–cooling of the atmosphere in GCM is critical in determining the heating profiles and in simulating the time scales, the eastward propagation, and the supercloud structure development of the MJO. In particular, warm-rain processes and associated low-level heating and moisture recycling play important roles in the build-up phase of MJO. At present, GCM simulations of MJO all seem to be lacking in warm-rain and associated low-level moisture recycling processes. This aspect of model physics improvement deserves the highest attention for realistic simulation of the MJO.

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Fig. 8. MJO latent heating profiles based on the Convective Stratiform Heating (CSH) Algorithm (Tao et al. 1993) and daily averaged ETH: (a) mean state of the eight MJO phases and (b)–(i) difference between the heating profile of each phase, P1–P8, and the mean state. The three curves in each panel are red for ETH < 5 km, blue for ETH > 5 km, and green for total.
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