Vertical Structures of Anvil Clouds of Tropical Mesoscale Convective Systems Observed by CloudSat

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ABSTRACT

A global study of the vertical structures of the clouds of tropical mesoscale convective systems (MCSs) has been carried out with data from the CloudSat Cloud Profiling Radar. Tropical MCSs are found to be dominated by cloud-top heights greater than 10 km. Secondary cloud layers sometimes occur in MCSs, but outside their primary raining cores. The secondary layers have tops at 6–8 and 1–3 km. High-topped clouds extend outward from raining cores of MCSs to form anvil clouds. Closest to the raining cores, the anvils tend to have broader distributions of reflectivity at all levels, with the modal values at higher reflectivity in their lower levels. Portions of anvil clouds far away from the raining core are thin and have narrow frequency distributions of reflectivity at all levels with overall weaker values. This difference likely reflects ice particle fallout and therefore cloud age. Reflectivity histograms of MCS anvil clouds vary little across the tropics, except that (i) in continental MCS anvils, broader distributions of reflectivity occur at the uppermost levels in the portions closest to active raining areas; (ii) the frequency of occurrence of stronger reflectivity in the upper part of anvils decreases faster with increasing distance in continental MCSs; and (iii) narrower-peaked ridges are prominent in reflectivity histograms of thick anvil clouds close to the raining areas of connected MCSs (superclusters). These global results are consistent with observations at ground sites and aircraft data. They present a comprehensive test dataset for models aiming to simulate process-based upper-level cloud structure around the tropics.

1. Introduction

The objective of this study is to understand the vertical structure and probable microphysical characteristics of anvil clouds associated with tropical mesoscale convective systems (MCSs), the largest convective cloud systems of the tropics (see Houze 2004). Since tropical MCSs are primary foci of latent heat release in the tropics (Mohr and Zipser 1996; Nesbitt et al. 2000; Yuan and Houze 2010, hereafter YH10; and others), this work will provide a foundation for future investigations of the role of MCSs in the water budget and diabatic heating structure of the tropics. The overall latent heating of MCSs usually maximizes in the upper troposphere because of the combination of heating from both the convective and stratiform components of MCSs (Houze 1982, 1989). Both geographical and seasonal differences in latent heat profiles are key parameters for general circulation models (GCMs) to reasonably replicate the mean large-scale circulation (Hartmann et al. 1984; Houze 1989; Mapes and Houze 1995; Lin et al. 2004; Schumacher et al. 2004).

MCSs inject a large quantity of ice particle mass into the upper troposphere to form extensive, long-lasting nonprecipitating anvil clouds (Houze 1993, 2004). The amount and vertical distribution of cloud ice water content and the thickness of tropical anvils significantly affect both the magnitude and structure of the radiative heating profile (Ackerman et al. 1988). Gray and Jacobson (1977) proposed that differential radiative heating associated with large, long-lasting organized mesoscale weather systems is a significant factor causing observed diurnal variations of heavy rainfall and large cloud systems over oceans and land. Webster and Stephens (1980) showed
that tropical anvil clouds with large areal coverage can result in significant net radiative warming in the upper troposphere. Houze (1982) illustrated that the longer lifetime of MCS anvil clouds makes their radiative impact nonnegligible. Machado and Rosson (1993) found that anvil clouds of deep cloud clusters reinforce their internal latent heating structure through their radiative effects and thus potentially affect the lifetime of MCSs. Recent studies show that in the tropics upper-level anvil clouds, intense precipitation, stronger top-of-atmosphere radiation anomalies, and “top-heavy” upward motions are spatially coherent at time scales ranging from a day to a month (Yuan and Hartmann 2008; Yuan et al. 2008). GCM studies further confirm that upper-level clouds associated with deep convection have powerful influences on both the convection and large-scale circulation and thus indicate the importance of realistic simulation of tropical anvil properties (Randall et al. 1989; Zender and Kiehl 1997).

Although the importance of anvil clouds associated with deep convection has been recognized in these larger contexts, the mechanisms controlling the generation and maintenance of the upper-level clouds are not well documented or understood. This deficiency of knowledge is one important source of uncertainty in cloud feedback in climate-change predictions and general circulation model simulations (Colman 2003; Stephens 2005; Clement and Soden 2005). Clement and Soden (2005) found that in their general circulation model the tropical-mean radiation budget was significantly affected by the tropical upper-level cloud amount, which was assumed to be the water left in the atmosphere by the convective parameterization scheme (Arakawa and Schubert 1974). Their results emphasize the need to better understand the microphysical mechanisms controlling how the deep convection produces upper-level clouds.

Cloud-resolving models (CRMs) have benefitted from field measurements of detailed cloud observations for more realistic simulation of MCS anvil clouds (Krueger et al. 1995), but the very limited number of field observations do not constitute a statistically satisfactory test bed for CRMs. Lopez et al. (2008) found that one of the most current CRMs failed to simulate the right amount of anvil clouds over tropical convective regions with the consequence that longwave and shortwave radiative patterns could not be accurately simulated compared to satellite observations. Thus, the time–space climatological variation of tropical anvil clouds and their relationship to deep convection is crucial to improve relevant GCM parameterizations.

The CloudSat Cloud Profiling Radar (CPR; Im et al. 2005) now provides globally sampled cloud vertical structure information. It has therefore become possible to determine globally sampled statistical properties of anvil clouds generated by MCSs. Considering that CloudSat CPR only scans a thin vertical cross section of the atmosphere, YH10 developed an automated approach to objectively identify MCSs by combining CloudSat CPR data with co-orbiting satellites of the A-Train constellation (L’Ecuyer and Jiang 2010; see also http://aqua.nasa.gov/doc/pubs/A-Train_Fact_sheet.pdf). Specifically, YH10 combined data products from the Advanced Microwave Scanning Radiometer–Earth Observing System (AMSR-E), the Moderate Resolution Image Spectroradiometer (MODIS; King et al. 1996) onboard NASA’s Aqua satellite, and the CloudSat CPR. Without combining several products it is not possible to identify MCSs from satellite data because their defining properties involve a combination of cloud-top and rainfall characteristics, which are not covered by any single instrument. In this study, we further analyze the set of MCSs identified by YH10 to analyze the internal vertical structures of MCS anvil clouds and how these structures vary over the whole tropics. Thus, we provide a statistically meaningful test bed suitable for process-based model tests and lay the groundwork for calculating and understanding the global radiative effects of MCSs.

Data and methodology used in this study are introduced in section 2. The MCS cloud vertical profile and anvil definition are shown in section 3. Statistical properties of MCS anvil cloud structures composited for different conditions are presented in section 4, with conclusions and a summary in section 5.

2. Data and methodology

a. Data

In this study, we use data from sensors aboard two A-Train satellites: Aqua and CloudSat, which were launched in May 2002 and April 2006, respectively, as part of the A-Train satellite constellation (Stephens et al. 2002). They are in a sun-synchronous near-polar orbit at approximately 705 km above the earth’s surface and fly over the equator at approximately 0130 and 1330 local time. We analyze data for the entire year of 2007 from Aqua’s MODIS and AMSR-E and CloudSat’s CPR. Since we wish to focus on the tropics, we restrict the dataset to observations obtained between 30°N and 30°S.

1) MODIS AND AMSR-E

The MODIS instrument has 36 spectral channels between 0.415 and 14.235 μm. In this study, we use the brightness temperature of channel 31 of 10.8 μm (Tb11). The Tb11 data are obtained from the MYD006_L2
product at the resolution of approximately $5 \text{ km} \times 5 \text{ km}$ pixels at nadir and increase up to approximately $12 \text{ km} \times 6 \text{ km}$ at the edge of the satellite swath (see http://modis.gsfc.nasa.gov/ and http://www.data.gov/geodata/g599488 for more detailed information).

AMSR-E is a forward-scanning passive microwave radiometer sensing polarized radiation at six frequencies between 6.9 and 89 GHz. (The AMSR-E instrument and retrieval algorithms are explained in detail online at http://sharaku.eorc.jaxa.jp/AMSR/index.html.) The AE_Rain product used in this study is obtained from the National Snow and Ice Data Center (NSIDC). It contains instantaneous estimates of rain rate and rain type, based on the Goddard Space Flight Center (GSFC) profiling algorithm, which is rooted in a Bayesian retrieval scheme over oceans and a regression of scattering signals to surface rainfall over land (Kummerow et al. 2001; Wilheit et al. 2003; Kummerow and Ferraro 2006). It is based primarily on modeling the absorption and emission effects on microwave signals for specified cloud temperatures, water vapor, and hydrometeor profiles, for which rainfall absorption and emission are predominant at lower frequencies while ice scattering dominates at higher frequencies (Kummerow and Ferraro 2006). The footprint resolution of the AE_Rain product is approximately $4 \text{ km} \times 6 \text{ km}$. Intervals between two adjacent satellite scan lines are approximately 8 km.

2) **CLOUDSAT**

*CloudSat* CPR points nominally in the nadir direction only and operates at the frequency of 94 GHz, for which backscatter from clouds can be measured. It has the horizontal resolution of 2.5 km along track by 1.4 km across track. Its effective vertical resolution at nadir is 240 m. The estimated operational sensitivity of *CloudSat* CPR ($\sim -32 \text{ to } -30 \text{ dBZ}$) is insufficient to see thin cirrus with small ice water content. However, since the main foci of our study are anvil clouds associated with MCSs as they relate to active precipitation, the inability for *CloudSat* to sense extremely thin clouds is not a major drawback. Nevertheless, representations of clouds in this study are subject to the detection limit of the *CloudSat* CPR. It is critical when comparing *CloudSat* observations with model output to account for the radar limitations. Future inclusion of thin clouds detected by the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) is necessary when calculating the radiative heating. The cloud mask, reflectivity field, and gaseous absorption from the Geometric Profile (2B-GEOPROF) product (version 011; release R04) are used in this study. Detailed information about the *CloudSat* hydrometeor detection algorithm is provided by Marchand et al. (2008). In this study the cloud mask values greater than or equal to 20 are considered cloudy pixels. It is worth mentioning that the representation of cloud layering by the *CloudSat* CPR should be read with caution since the cloud mask product does not distinguish between cloud and rain. Hence, cloud layers embedded in rain cannot be identified. The overall impact on cloud layering due to this instrumental limit is unknown.

b. Methodology

Our approach is to objectively identify MCSs through which the *CloudSat* track passes so that we are able to locate CPR measurements belonging to MCSs. Then anvil clouds are separated from the raining portions of MCSs and analyzed in a composite framework. The method of identifying MCSs is described in detail in YH10. Table 1 is adapted from YH10 to summarize the key features objectively identified from MODIS and AMSR-E data. The active MCSs defined in this way are responsible for 56% (YH10) of total tropical instantaneous rainfall and thus represent the primary latent heat source of different tropical zones. According to YH10, additional decisions (see Table 1) are made to divide each MCS into rain core, light rain, and no rain regimes.

3. Cloud-top histograms of MCSs

The fractional coverage of MCS anvil clouds and the frequency of occurrence of MCS high-topped clouds as functions of their thickness and the distance to their raining center were investigated in YH10. In this study, we focus on the internal vertical structure of MCS anvil clouds as shown by the profiles of reflectivity seen by the CPR. Compared to passive satellite radiometers, an advantage of the *CloudSat* CPR is that it resolves the vertical structure of clouds rather than just providing a column-integrated measurement. Aspects of cloud microphysical structure can be inferred by close analysis through the CPR’s detailed reflectivity measurements. However, inferences from the highly resolved CPR data are complicated somewhat by the presence of multiple cloud layers so that it is not trivial to prefilter the CPR data to isolate the anvil clouds.

Following YH10, we subdivide the dataset into eight tropical deep convective zones, representative of characteristic tropical convective regimes (Fig. 1). We first examine cloud-top histograms in each of these regions. Figure 2 shows that MCS cloud tops have one dominant mode above 10 km in all eight regions. Additionally, almost no difference exists between the distribution of the cloud top of the highest cloud layers and of all cloud layers above 10 km in all regions. This suggests that most situations in which multilayer clouds are present have one cloud layer with its top higher than 10 km
(high-topped clouds) and other (usually one) cloud layers with cloud tops below 10 km. In addition to the high-topped cloud mode, there are some modes found below 10 km. Two of them are found above the freezing level (6 and 8 km). One shallow mode is present near 3 km and an additional mode near 1 km is present over the ocean in the nonraining regime.

Multilayer clouds are found in both rain cores and light rain portions of MCSs, with relatively more frequency of occurrence in the light rain areas. The cloud top of the lowest cloud layer is mainly below 10 km, which indicates that when multilayer clouds occur in raining areas, precipitation is most likely from shallow and/or moderately deep convection (such as cumulus congestus or developing deep convective cells). Vertical distributions of the lowest cloud tops systematically shift toward shallower clouds from rain cores to lightly precipitating portions of MCSs. In rain cores of MCSs with multiple layers, moderately deep convection dominates, while both shallow convection and moderately deep convection dominate in the light rain areas. In nonraining areas of MCSs with multilayer clouds, shallower clouds are present to an even greater degree in the distributions, and the mode at 1 km is more dominant. However, this 1-km mode should be read with caution since it is too close to the surface and may be partially an artifact due to surface clutter (Marchand et al. 2008).

It is worth mentioning that the representation of cloud layering by the CloudSat CPR should be read with caution since the cloud mask product does not distinguish between cloud and rain. Hence, cloud layers embedded in rain cannot be identified. The overall impact on cloud layering due to this instrumental limit is unknown.

YH10 divided MCSs into separated MCSs (SMCSs) and connected MCSs (CMCSs), where the latter are MCSs that share a common rain area [they include “superclusters,” as described by Nakazawa (1988), Chen et al. (1996), Houze (2004), and others]. Figure 3 shows that SMCSs consist of mostly one- and two-layer clouds over all regions and in all regimes (>90%). One-layer clouds cover 78%–90% over raining regimes and 49%–71% over weakly raining and nonraining regimes. Occurrences of multilayer clouds are not much different between light rain and nonraining regions. Only SMCSs in the Africa (AF), South America (AM), and eastern Pacific (EP) regions barely show significant different fractional coverage

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Name</th>
<th>Definition</th>
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<tbody>
<tr>
<td>HCC</td>
<td>High cloud complex</td>
<td>Region of MODIS Tb11 contained within a single 260-K isotherm</td>
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<tr>
<td>HCS</td>
<td>High cloud system</td>
<td>Portion of HCC associated with a particular minimum value of Tb11</td>
</tr>
<tr>
<td>PF</td>
<td>Precipitation feature</td>
<td>Region of AMSR-E AE_Rain parameter surrounded by 1 mm h⁻¹ contour</td>
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<tr>
<td>RC</td>
<td>Raining core</td>
<td>Portion of any PF overlapping and/or located within an HCS</td>
</tr>
<tr>
<td>HRA</td>
<td>Heavy rain area</td>
<td>Portion of PF &gt; 6 mm h⁻¹</td>
</tr>
<tr>
<td>MCS</td>
<td>Mesoscale convective system</td>
<td>Any HCS whose largest RC satisfies the following criteria:</td>
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<tr>
<td></td>
<td></td>
<td>1) &gt;2000 km² in total area</td>
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<td></td>
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<td>2) Accounts for &gt; 70% of the total area with rain &gt; 1 mm h⁻¹ inside the HCS</td>
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<td>3) Minimum cloud-top temperature above the RC (indicated by Tb11RC1min) &lt; 220 K</td>
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<td></td>
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<td>4) &gt;10% of RC is occupied by HRAs</td>
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<tr>
<td>Separated MCS</td>
<td></td>
<td>The largest RC of the MCS is part of a PF that contains less than three dominant RCs of any MCS.</td>
</tr>
<tr>
<td>Connected MCS</td>
<td></td>
<td>The largest RC of the MCS is a part of a PF that contains dominant RCs of at least three MCSs.</td>
</tr>
<tr>
<td>Raining area</td>
<td>AE_Rain &gt; 1 mm h⁻¹</td>
<td></td>
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<tr>
<td>Light raining area</td>
<td>AE_Rain ≤ 1 mm h⁻¹ and CloudSat indicates rain presence*</td>
<td></td>
</tr>
<tr>
<td>Nonraining area</td>
<td>AE_Rain ≤ 1 mm h⁻¹ and CloudSat indicates no rain</td>
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*The maximum reflectivity of the profile between 1 and 2 km above the surface is greater than −10 dBZ, or the maximum reflectivity in the three adjacent bins including the earth’s surface is less than 25 dBZₑ, where Zₑ is the equivalent radar reflectivity.

FIG. 1. Eight tropical convective regions selected for analysis: Africa (AF), Indian Ocean (IO), Maritime Continent (MA), western Pacific (WP), South Pacific (SP), eastern Pacific (EP), South America (AM), and Atlantic (AT).
at the 95% confidence level for two-layer clouds based on a t test. To perform the t test, independent cloud data are picked out at first based on the autocorrelation of reflectivity data according to Bretherton et al. (1999). We then subdivide the data from each region into 50 subaverages. The t tests are then performed using the mean and standard deviation of these subaverages.

In contrast, multilayer clouds are significantly less frequent in raining regions (significant level > 95%). Differences between the eight geographical regions are small except for the MCSs in EP, which have the least area covered by single-layer clouds over both light rain and nonraining regimes (significant level > 95%). This finding is in agreement with Kubar and Hartmann (2008), who suggested that more latent heat is associated with shallower convection in light rain regions over the EP. Performing the same analysis on CMCs leads to similar results (not shown). One exception is that no significant regional differences are found.

4. Internal structures of MCS anvil clouds

a. Identification of MCS anvil and analysis of their vertical structure

In the remainder of this paper, we focus on MCS anvil clouds. To pick out the anvil clouds, we first note that Figs. 2 and 3 suggest 10 km as a reasonable natural cutoff height to separate clouds of deep systems from those of shallower systems. Accordingly, we select all such high-topped clouds; they account for greater than 86% of total cloudy bins in all active MCSs. In YH10 (see Fig. 3 of their paper), such high-topped clouds were shown to have two major modes: one with cloud base near the surface (deep precipitating) and the other with elevated cloud base mainly above the 0°C level (anvil cloud). Here we define anvil clouds as high-topped clouds with cloud base higher than 3 km regardless of whether or not a lower precipitating cloud exists. Although they do not contribute much rain, the occurrence of lower-topped clouds below anvil clouds is important to the vertical distribution of moisture and radiative heating. However, they are beyond the scope of this study and will be investigated in the future.

In this study (as noted in the introduction), we focus on and examine their internal structure as indicated by radar reflectivity and infer microphysical processes therefrom. Cloud microphysical properties are important for understanding conversion processes between different forms of hydrometeors and hence latent heating processes. The amount, distribution, and phase of cloud water, along with its size distributions and shapes, are also crucial for radiative heating calculations. To date the most direct measurement of detailed cloud microphysics properties is via aircraft in situ measurements. However, the limited number of available aircraft measurements does not provide enough samples to construct a statistically satisfactory cloud database. Although the spaceborne CPR measurements provide only an indirect indication of microphysical processes, the statistics of the massive numbers of CloudSat CPR reflectivity vertical profiles, sampled over the entire tropics, provide very useful insights into cloud processes and how they vary regionally and seasonally. Analyzed appropriately, these data can be compared to the output of cloud-resolving models to determine the accuracy of the models. In this study, we examine joint probability distribution functions (PDFs) as functions of height and reflectivity, that is, contoured frequency by altitude diagrams (CFADs; Yuter and Houze 1995). We use CFADs in this study to gain further insight into the vertical distribution of hydrometeors and possible microphysical processes within anvil clouds. CFADs can also be compared to statistically analyzed model output. Because the hydrometeors of anvil clouds are our focus, we only use cloudy pixels with reflectivity greater than −27.5 dBZ following Marchand et al. (2009). In each CFAD, we plot the entire distribution normalized by dividing the observed frequency by the maximum frequency of any height–reflectivity bin in order to compare CFADs between regions. Therefore, in each CFAD, the contour values range from 0.1 to 0.9 with a step interval of 0.1.

Internal structures of anvil clouds are important not only because they provide insight into microphysical properties and processes within anvil clouds, but also because they perhaps reflect microphysical processes occurring in the genesis of the anvil clouds. Large numbers of ice particles generated by dynamical processes in the updrafts of the raining cores of MCSs are detrained laterally into the nonraining anvil clouds and modified later by microphysical processes occurring within anvil clouds. So ideally it would be important to determine anvil structure changes with time. However, the exact life stage of anvil clouds is very hard to obtain directly using satellite snapshots. Hence, the distance between anvil clouds to the raining core may serve as an indirect/approximate measure for the age of anvil clouds. Considering the fact that thinner anvil clouds usually occur more frequently farther away from their raining centers, CETRONE and HOUZE (2009) break MCS anvil clouds into different thickness categories when the accompanying precipitation field is not available. In a similar way, we divide anvil clouds into thick (thickness > 6 km), medium thick (2 < thickness < 6 km), and thin (thickness < 2 km) clouds. Because our combined MODIS, AMSR-E, and CloudSat technique is able to locate the position of
FIG. 2. Normalized PDFs of cloud-top height for active MCSs, showing data from (a) raining clouds, (b) weakly raining clouds, and (c) nonraining clouds. Black and blue lines, respectively, represent PDFs of the cloud-top height of all cloud layers and the highest layers. The red line represents PDFs of the cloud-top height of the lowest layer of multilayer clouds. Each row represents one region. The normalization is the total number of CPR profiles within each category so that individual curves integrate to their fractional coverage within each category. Since almost all CPR profiles within MCSs contain cloudy pixels, blue curves integrate to nearly 1.
FIG. 2. (Continued)
clouds relative to MCS rain cores, we further stratify our composite analyses according to the distance from the raining region of MCSs.

As pointed out in section 2, different algorithms produce the AE_Rain product over land and ocean. The different effective footprint sizes associated with two algorithms and the beam-filling problem in the retrieving might generate uncertainties about the distance to active rain areas. However, previous work suggests that the 85-GHz channel rather than the low-frequency channels controls rain retrievals over oceans from basically the same algorithm as in AE_Rain if there is appreciable ice scattering (Jiang and Zipser 2006). However, to what extent this can reduce the overall difference in the effective resolution of resolvable raining elements in the rain rate retrievals over ocean and land is not clear. As explained in YH10, we have taken steps to minimize this uncertainty, but it nevertheless remains. Since physical reasoning seems to account for the differences in land and ocean statistics we show below, we suspect that this uncertainty does not obscure our results.

b. Representations of cloud microphysical properties through radar reflectivity

The CPR reflectivity of cloudy volumes is determined by the backscattering of cloud particles, which largely depends on the particle size distribution (PSD). According to Heymsfield et al. (2002), the PSD in tropical anvil clouds can usually be approximated by gamma-type functions:

\[ N(D) = N_0 D^\mu e^{-\lambda D}, \]

where \( N_0, D, \mu, \) and \( \lambda \) are the intercept parameter, ice particle maximum diameter, dispersion, and slope, respectively. In practice \( N_0 \) and \( \mu \) are usually correlated so that mainly two parameters, \( N_0 \) and \( \lambda \), control the PSD. Given a single variable such as radar reflectivity, it is not possible to explicitly know both parameters. Although much progress has been made, to accurately retrieve cloud microphysical properties from current spaceborne cloud radar measurements remains a big challenge to meteorologists (Heymsfield et al. 2008). On the other hand, the statistics of radar reflectivity have proven to be very useful in diagnosing and improving the microphysics of the most current cloud-resolving models (e.g., Eitzen and Xu 2005; Lang et al. 2007; Blossey et al. 2007; Zhou et al. 2007; Li et al. 2008; Matsui et al. 2009; Lang et al. 2011). Hence, in this study, we focus on analyzing the reflectivity field only.

To better link radar reflectivity with cloud microphysics it is helpful to seek physical insight into the variability of reflectivity associated with cloud microphysics through accurate in situ aircraft measurements. Figure 4 is based on stratiform and anvil cloud data within deep convective systems collected during several Lagrangian-type spiral descents conducted by aircraft in field campaigns (Heymsfield et al. 2002, 2008). These slow aircraft descents were Lagrangian in the sense that the flight path approximated the fall trajectory of the primary ice particles in the sampled cloud. Clouds sampled included stratiform precipitating regions and anvils of convective cloud systems in Florida, Brazil, and the Marshall Islands. These size distributions have been corrected objectively to account for shattering on the inlets of the probes that made the measurements (Field et al. 2006). The reflectivities were simulated based on measured PSDs according to Matrosov et al. (2005).

Figures 4a and 4b show that \( Z_e \) strongly increases with decreasing \( \lambda \) (broadening PSD) with higher temperatures. Figures 4c and 4d, on the other hand, indicate very little relationship between \( N_0 \) and \( Z_e \) except that larger \( N_0 \) values are likely associated with lower temperatures. Note that \( \lambda \) tends to be inversely proportional to the mean particle diameter [if the particle size distribution is
(a), (b) Scattering plot of simulated radar reflectivity against $\lambda$ of PSD for (a) 35 and (b) 94 GHz. (c), (d) As in (a), (b), respectively, but against the $N_0$ of PSD. Black dots are for all data; purple dots are for data with temperature colder than $-30^\circ$C; green dots are for data with temperatures between $-10^\circ$ and $0^\circ$C.

Fig. 4.
FIG. 5. CFADs of thick anvil clouds from separated active MCSs for each of the regions identified (by two-letter codes) in Fig. 1, for the
areas (a) within 25 km, (b) between 25 and 70 km, and (c) beyond 70 km from the closest raining pixel of the largest rain core. Black solid
curves show the medians of the CFADs. To help show how the medians change with distance from the rain area, the dashed curves in (b)
and (c) repeat the position of the solid curve in (a). Shaded regions cover areas between the 10th and 90th percentiles at a given height.
Numbers shown in the top-right corner of each panel are the sample size.
FIG. 5. (Continued)
exponential—i.e., if $\mu = 0$—then $\lambda$ is in fact exactly the inverse of the median volume diameter; see Houze et al. (1979)]. Higher values of reflectivity may be due to either higher concentrations of particles or the existence of large particles in the PSD. Figures 4a and 4b clearly indicate statistically that larger reflectivities in anvil clouds are due to the presence of larger particles since $\lambda$ is inversely proportional to mean particle size and there is no consistent relationship of reflectivity and $N_0$ (in fact larger $N_0$ values tend to correspond with weaker reflectivity). Imagery from the cloud particle imager (CPI) probe further suggests that the broadening of PSDs and the corresponding decrease in $N_0$ with distance below cloud top are due primarily to the aggregation of large particles and the depletion of smaller particles (Heymsfield et al. 2002).

For wavelengths in the range of the CPR and other cloud radars, non-Rayleigh scattering and nonspherical scattering effects come into play at larger particle sizes. This fact is illustrated by comparing results for two radar frequencies. The results in Figs. 4a and 4b are almost the same when the $Z_e$ is smaller than 0 dB, whereas they differ substantially when $Z_e$ is larger. For example, the $Z_e$ almost does not exceed 20 dB and is curved significantly when the temperature is warmer than $-10^\circ\text{C}$ for 95 GHz, whereas $Z_e$ simulated for 35 GHz can reach as large as 30 dB.

Although the aircraft data in Fig. 4 are based on a limited set of field measurements, they provide a solid empirical physical foundation to link cloud microphysics with radar reflectivity, and we use these data as guidance to interpret the CFAD results shown below. Moreover, an individual reflectivity measurement provides the mean back scattering of all the hydrometeors in a finite sampling volume (≈2 km $\times$ 240 m $\times$ 1.4 km). This grid scale is sufficiently small to indicate bulk characteristics of the mean particles size distribution on the convective and mesoscale within MCS anvil clouds.

c. Thick anvils of SMCSs

When the anvils are divided into thick, medium, and thin categories, the primary variability of vertical structure is seen in the thick anvils. We therefore discuss them first.

1) INCREASE OF REFLECTIVITY TOWARD THE CLOUD BASE IN THICK ANVILS

In Fig. 5, CFADs of SMCS thick anvil clouds show that the high-frequency mode tilts toward lower reflectivity with increasing height. The highest frequency concentrates at higher reflectivity and in the lower portions of the clouds. According to Fig. 4, this result indicates that larger particles tend to occur in the lower portions of anvil clouds. The lines of median values cross modal values, indicating that the skewness of reflectivity distribution changes with height, with the broader side shifting from stronger reflectivity near the cloud top to weaker reflectivity near the cloud base. This behavior suggests that aggregation processes play an important role in anvil clouds, broadening the size distributions and thereby decreasing the slope. In stratiform clouds the vertical air motions are generally not strong enough to advect ice particles upward; instead they drift downward. The lack of strong vertical air motion also eliminates the possibility of significant ice particle growth by diffusion due to competition between ice particles and riming in the stratiform clouds. It is suggested from the CFADs (interpreted in relation to Fig. 4) that the ice particles are growing by aggregation and, depending on the upward motions, through vapor diffusion, while falling slowly toward cloud base. These hypothesized processes are moreover consistent with aircraft in situ cloud measurements (Sassen et al. 1989; Heymsfield and Donner 1990; McFarquhar and Heymsfield 1996, etc.). The curved CFAD patterns beyond the reflectivity of 0 dBZ are likely due to the combination of both the non-Rayleigh effect and nonspherical scattering because the back scattering no longer increases significantly with the particle size (Fig. 4).

2) NARROWING OF THICK ANVIL CFADs AND WEAKENING OF OVERALL REFLECTIVITY WITH INCREASING DISTANCE TO ACTIVE RAIN AREAS

In addition to the general increase of modal values with decreasing altitude, different distributions are found within the thick anvils at increasing distance from the raining centers of MCSs. Closest to their raining centers, the thick anvils have the broadest distribution of reflectivity at any level. The highest frequencies occur around the altitude of 10 km and between 0 and approximately 10 dBZ. Moving away from the raining center, CFADs of thick anvil clouds tend to have narrower distributions at most levels (8–14 km) and the overall reflectivity is systematically weaker, especially in the upper portions of the anvil clouds. The lines of median points of CFADs of anvils close to active rain areas almost overlap with lines of the 90% tail of CFADs of anvils far away from active rain areas.

The broader distribution of reflectivity seen in thick anvil clouds close to the active rain area of an MCS is likely due to a greater variety of processes being involved in producing ice particles in anvil clouds close to raining areas. Large particles are detrained directly from different levels of updrafts with different strengths within the raining areas. These large particles include graupel produced by riming vigorous convective and
aggregated ice particles resulting from the microphysical processes occurring in stratiform rain regions (Houze 1997). Sedimentation, vapor deposition, and aggregation processes also undoubtedly occur in the non-precipitating anvil clouds, under even weaker upward motions. The narrowing of the reflectivity distribution and the weakening of overall cloud reflectivity fields with increasing distance from the raining center are qualitatively consistent with the increase of age of the thick anvil clouds with increasing distance from the active raining areas, as with time the larger particles would have settled out, leaving behind the slower-falling smaller particles. This sedimentation, or “size sorting” process (McFarquhar and Heymsfield 1996), eliminates the largest particles with time so that older anvil clouds should have both lower water content and a preponderance of smaller particles. Our results statistically but indirectly (through reflectivity sampling) are consistent with aircraft in situ upper-level cloud measurements (Sassen et al. 1989; Heymsfield and Donner 1990; McFarquhar and Heymsfield 1996, etc.).

3) LAND/OCEAN VARIATIONS IN CFADS OF THICK ANVILS

CFADs for portions of anvil clouds far away from active raining areas of MCSs tend to be similar in all regions and seasons (not shown), which is consistent with a study combining ground and satellite measurements (Mace et al. 2006). The ice generation is evidently dominated by stratiform cold cloud microphysics, in which vapor diffusion and aggregation processes are controlled by the thermodynamic stratification of the anvil cloud rather than the dynamical conditions prevailing in raining cores. This result suggests a way of generalizing parameterizations of anvil cloud microphysics in cloud/climate models for anvil clouds loosely connected to active precipitation.

On the contrary, although CFADs of thick anvils are generally similar, there are deviations from the norm for CFADs of MCS thick anvil clouds over land compared to those over ocean: (i) compared to oceanic MCSs, those in the two continental regions (AF and AM) appear to have broader reflectivity distributions, especially in the upper portions of anvil clouds within 25 km of raining areas; and (ii) the CFADs change faster when moving away from raining areas in the continental cases than those in oceanic cases, which suggests that particles are larger with higher fall speeds in continental MCSs anvil clouds.

We further illustrate how CFADs of thick anvil clouds change with distance by using the contour plot in Fig. 6. Since the two continental regions have similar behaviors, they are grouped together to maximize the sample size. For the same reason the six oceanic regions are combined.

Both the median point and the 90th percentile point of the reflectivity distribution in thick anvil clouds are located at higher reflectivity when close to active raining areas of continental MCSs, but they decrease faster within the first 70 km so that oceanic MCS anvils show slightly stronger reflectivity between approximately 25 and 70 km. Beyond 70 km, there is little difference between continental and oceanic MCSs. The changes of CFADs are more prevalent in the upper portion of anvil clouds (>9 km). That difference is reasonable since the upper portions of the clouds keep losing large particles while in the lower portion of clouds large particles both fall in from above and fall out from the cloud base and both non-Rayleigh scattering and nonspherical scattering effects reduce the sensitivity of reflectivity to the particle size.

Figure 6 also shows that contours of the median point of CFADs change relatively slowly with increasing distance compared to those of the point of 90th percent tail for both continental and oceanic MCSs, especially above 9 km. Here we interpret the rate of change by comparing the slope of contours rather than the contour density. One explanation for this difference is that the rate of sedimentation is affected more strongly by the larger particles present in the continental MCSs.

There are several reasons for the land–sea difference in MCS anvil clouds. Consistent CFAD results regarding the difference between land and ocean MCS thick anvil clouds are found using ground-based upward-pointing cloud radar data obtained at three Atmospheric Radiation Measurement (ARM) ground sites (Cetrone and Houze 2006), which suggests that the beam attenuation is not
FIG. 7. As in Fig. 5, but for medium thick anvil clouds.
FIG. 7. (Continued)
The distance of the anvil cloud in the median range from the active raining area is no longer a good indicator of its age.

4) Potential Impacts of Cloud Locations on CFAD Results of Thick Anvils

Because CFADs of thick anvils result from anvil clouds with various thicknesses and vertical locations and originate from MCS precipitating cores with various top heights, the representation of cloud properties by CFADs might be potentially affected by these factors. To test the robustness of our results we have broken our anvil composites to finer thickness bins. We have also aligned the cloud top at the same level (i.e., the ordinate of CFADs is the distance to the cloud top instead of the actual height). Similar results are obtained for all analyses. For simplicity and the space consideration we choose to use the greater thickness bin and represent them in the ordinate of the natural altitude. Furthermore, as indicated by YH10 (i.e., their Figs. 3, 7, 12, and 13), the vertical distributions of the top of MCS raining cores are similar except that in EP and the Atlantic (AT) MCSs systematically have lower tops. This ensures that information shown in CFADs seems most likely related to variations of internal microphysics properties of anvil clouds originating from precipitation cores whose top altitudes have a similar shape of vertical distributions. However, further analyses involving the use of more MODIS measurements (such as the minimum Tb or optical thickness) under the compositing framework in the future are highly desired.

d. Medium thick and thin anvil clouds of SMCS

Figure 7 shows that medium thick anvil clouds are mostly located above 10 km. CFAD-based results and interpretations for medium thick anvil clouds are similar to those for thick anvil clouds, except all differences are smaller. Noticeable narrowing of CFADs and decreases in overall reflectivity values are found when moving away from raining areas. Similar but weaker land–sea differences are still present. The reflectivity of medium thick anvils is mostly below 0 dBZ.

The variations in CFADs of thin anvil clouds are almost negligible. Hence CFADs for all thin anvil clouds are shown in Fig. 8. Thin anvils have very low reflectivity values (usually less than −20 dBZ) and tend to center around 12.5–13 km for all regions.

e. Structures of anvil clouds of CMCS

CFADs of anvils of CMCS and variations with distance are generally similar to that of SMCS anvils under same conditions for all regions, except for anvil clouds...
within 25 km of their raining areas. Figure 9 compares CFADs for the anvils of SMCSs and CMCSs. Figure 10 compares CFADs normalized differently; in this case, they are normalized such that the histogram at each altitude is divided by the total number of observations at that altitude. For space consideration, only CFADs of thick anvil clouds are shown. Since two continental areas show similar results for all analysis, they are combined to represent the land case (AF and AM). For the same reason, two oceanic groups are created [EP and AT; and the Indian Ocean (IO), Maritime Continent (MA), western Pacific (WP), and South Pacific (SP)]. The most apparent difference is that CFADs of the anvil clouds in CMCSs tend to show a sharply peaked, narrower histogram at most levels, whereas the SMCSs show a mode of high reflectivity concentrated in the lower portion of the cloud. Figure 10 more clearly shows the differences between reflectivity histograms since the differences are more pronounced in the modal values than in the median points or the 10th and 90th percentile points between 8 and 14 km. The modal values of reflectivity histograms of anvils of CMCSs are smaller than that of SMCSs in upper levels. Such narrower-peaked, high-frequency distribution tilting toward weaker reflectivity with increasing height in the CFAD is characteristic of a stratiform cloud in which the ice particle growth is being dominated by vapor diffusion and aggregation, systematically increasing the particle sizes as the particles fall slowly down through the anvil cloud (Yuter and Houze 1995). Less presence of stronger reflectivity in the upper part of CMCS anvil clouds is consistent with the large horizontal size of the stratiform anvil regions of these connected systems. Thus, we infer that most of the cloud is of a stratiform nature, dominated by ice particles drifting down and growing and less affected by the detrainment of large ice particles into it from active convective cells. This interpretation is an indication that the thick anvil clouds close to active raining areas in CMCSs are more closely related to neighboring stratiform rain areas than nearby convective cells. The CMCSs are the largest cloud systems in equatorial regions, and are sometimes characterized as superclusters or “super convective systems” (Nakazawa 1988; Mapes and Houze 1993; Chen et al. 1996), and they are noted for their gigantic stratiform rain areas. It is likely that such large systems are favored by more “sustainable” conditions (Yuter and Houze 1998) and are able to develop large stratiform rain fraction (Schumacher and Houze 2003). More particles detrained...
into anvil clouds in such systems are associated with stratiform rain microphysics.

5. Conclusions and summary

CloudSat CPR data show that active MCSs have one dominant mode of clouds in all tropical climatological regimes—high-topped clouds with cloud tops above 10 km. Most overlapping of cloud layers consists of one cloud layer from this mode and other cloud layers with cloud tops below 10 km. Two intermediate modes are found with tops above the freezing level (~6 and ~8 km). Another mode has tops near 3 km, and an additional mode just above 1 km is present over ocean in the non-raining regime (though the latter could be affected by data artifacts). One- or two-layer clouds account for 90% of cloud coverage in all three regimes investigated (rain, light rain, and no rain). In precipitating regions of active MCSs, multicloud layers occur primarily in light rain regimes and not within the primary raining cores of the MCSs. When multilayer precipitation is observed, the high-topped cloud overlies shallow and moderately deep convection. Differences among eight geographical regions in the tropics, including both continental and oceanic regions, are small except that MCSs in the EP region have the fewest areas covered by single-layer clouds for light rain and nonraining portions of MCSs.

CFADs of thick anvil clouds generally show that thick anvil clouds closest to the actively raining area of an MCS tend to have a broad distribution of reflectivity at all levels. The modal reflectivity value is concentrated in the lower portions of the anvil clouds. With increasing distance from the active raining cores of MCSs, CFADs of thick anvil clouds show the reflectivity values generally weakening and the reflectivity modes becoming increasingly narrow, especially in the upper part of the

![Fig. 9. CFADs of thick anvil clouds from (top) separated active MCSs and (bottom) connected active MCSs for data from the area within 25 km to the closest raining pixel of the largest rain core (RC1). Black solid curves are profiles of the median point of CFADs. Shaded regions cover areas between the 10th and 90th percentiles. Numbers shown in the top-right corner of each panel are the sample size.](image-url)
Overall the modal values of reflectivity increase with decreasing altitude.

These CFAD results are consistent with ground-based cloud radar data (Cetrone and Houze 2006). The CloudSat CPR data of our study thus now show that these properties are consistent worldwide and as such provide a valuable target for model simulations of MCSs around the globe. The observed variation of CFAD structure of thick anvil clouds with respect to distance from the active rain area of the MCS is consistent with the age of the anvil cloud in relation to its distance from the active raining areas of its parent MCS. Aircraft observations of anvil clouds have also been interpreted in terms of cloud age (McFarquhar and Heymsfield 1996). Younger and thicker anvil clouds are closer to active raining regions and are expected to have numerous particles detrained from precipitating cores. These particles are produced by more vigorous convection in the precipitating region, and among these are larger graupel particles produced by riming in the strong updrafts of deep convective cells, especially in the case of more intense continental convection. The presence of the larger particles in the anvils gives a broader distribution of sizes and hence stronger reflectivity at the upper levels. The larger particles fall out more quickly, while the smaller detrained ice particles continue to grow by vapor deposition and aggregation in anvil clouds while they fall to lower levels more slowly. Hence, the CFADs become narrower with distance from the raining core of the MCS, especially at upper levels.

CFADs of anvil clouds farthest away from active rain areas of MCSs are similar for all regions and anvil thicknesses. However, CFADs for thick anvil clouds show notable differences between continental and oceanic MCS anvils:

- Broader CFADs and generally higher reflectivity are found in thick anvils over continental MCSs when close to active rain areas.

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FIG. 10. As in Fig. 9, but for normalized CFADs of thick anvil clouds. For normalized CFADs each level is normalized by dividing the total sample size of each level so that each level shows a PDF that integrates to 1.
• The frequency of occurrence of stronger reflectivity in the upper portion of thick anvil clouds decreases faster with increasing distance from the raining region in continental MCSs.

These differences are likely due to a combination of factors differing between land and ocean: over land we might expect greater lower tropospheric buoyancy, lower midtropospheric entrainment rates, excessive ice freezing, and less “sustainability” of stratiform rain regions. The CFADs of CloudSat CPR data seem consistent with all of these differences. However, the explanation of differences between land and ocean MCSs remain somewhat uncertain until all these factors can be sorted out. AMSR-E algorithms differences between land and ocean remain a factor. The fact that the land–sea differences in CFADs shown in this study are consistent with previous studies of MCSs and general physical expectations indicates to us that our results are not seriously impacted by this uncertainty.

“Superclusters,” which fall into our category of connected MCSs (CMCs), display some special characteristics. CFADs of thick anvil clouds closest to the actively raining area of CMCs tend to have more sharply peaked and narrower histograms at most levels compared to those of SMCSs, suggesting that the anvils of this category in CMCs are more intimately connected with stratiform than convective rain areas.

Although unable to provide detailed microphysics properties as aircraft measurements can, the large spatial and temporal coverage and the massive and growing size of the dataset obtained by CloudSat and the other A-Train satellites provide a powerful, statistically satisfactory test bed for global models that must either parameterize or explicitly predict MCSs in the context of the general circulation and climate. The commonality of internal structures of anvil clouds located far away from active raining centers points out the possibility of developing generalized parameterization of anvil cloud microphysics based on accurate, comprehensive, but spatially and temporally limited field measurements (such as ARM ground sites) for anvil clouds loosely connected to active precipitation. However, our results indicate that the structures of anvil clouds close to active precipitation will be somewhat more difficult to represent since these reflect physical processes taking place in the precipitating region and are crucial for understanding the generation of anvil clouds more closely linked to precipitation processes. This variation of anvil cloud internal structures with distance (time) from active rain areas, further variations of these differences related to land–sea contrast, and the unclear uncertainties associated with AMSR-E data demonstrate the need for both further investigation of satellite observations and cloud model simulations leading to not only the better understanding of MCS physical processes but also improvements of remote sensing products.

The statistics of vertical structures of anvil clouds shown in this study, along with the bulk horizontal and vertical dimensions of anvil clouds presented by YH10, lay the groundwork for understanding the role of MCSs in the global water budget and for determining the radiative impact of MCSs on the tropical circulation. Results shown in this study also present a goal for models aiming to simulate upper-level cloud structure around the globe.

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