Global Variability of Mesoscale Convective System Anvil Structure from A-Train Satellite Data

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ABSTRACT

Mesoscale convective systems (MCSs) in the tropics produce extensive anvil clouds, which significantly affect the transfer of radiation. This study develops an objective method to identify MCSs and their anvils by combining data from three A-train satellite instruments: Moderate Resolution Imaging Spectroradiometer (MODIS) for cloud-top size and coldness, Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) for rain area size and intensity, and CloudSat for horizontal and vertical dimensions of anvils. The authors distinguish three types of MCSs: small and large separated MCSs and connected MCSs. The latter are MCSs sharing a contiguous rain area. Mapping of the objectively identified MCSs shows patterns of MCSs that are consistent with previous studies of tropical convection, with separated MCSs dominant over Africa and the Amazon regions and connected MCSs favored over the warm pool of the Indian and west Pacific Oceans.

By separating the anvil from the raining regions of MCSs, this study leads to quantitative global maps of anvil coverage. These maps are consistent with the MCS analysis, and they lay the foundation for estimating the global radiative effects of anvil clouds.

CloudSat radar data show that the modal thickness of MCS anvils is 4–5 km. Anvils are mostly confined to within 1.5–2 times the equivalent radii of the primary rain areas of the MCSs. Over the warm pool, they may extend out to 5 times the rain area radii. The warm ocean MCSs tend to have thicker nonraining and lightly raining anvils near the edges of their actively raining regions, indicating that anvils are generated in and spread out from the primary raining regions of the MCSs. Thicker anvils are nearly absent over continental regions.

1. Introduction

In the tropics, upper-level clouds containing ice and mixtures of ice and liquid water strongly affect the transfer of shortwave and longwave radiation and modulate the radiative heating structure through the atmosphere (Webster and Stephens 1980). Conducting experiments with a general circulation model, Clement and Soden (2005) concluded that the tropical mean radiation budget is significantly affected by the amount of upper-level ice clouds in the tropics. Such clouds are associated with both deep convection and large-scale upward motions (Luo and Rossow 2004). Satellite observations have shown further that a large portion of the ice clouds connected with deep convection in the tropics are upper-level anvil clouds associated with intense precipitating deep convection (Kubar et al. 2007; Yuan and Hartmann 2008; Yuan et al. 2008). These anvil clouds are produced largely by mesoscale convective systems (MCSs; Houze 2004). Because MCSs produce a large proportion of tropical rainfall, they are primary latent heating agents in low latitudes. Moreover, since the rainfall of MCSs is partially in the form of stratiform precipitation (Houze 1982, 1989, 1997, 2004), they bias the latent heating toward the upper troposphere, in the form of “top heavy” latent heating profiles, which must be accounted for to properly simulate the large-scale mean circulation of the tropics (Hartmann et al. 1984; Lin et al. 2004; Schumacher et al. 2004). The top-heaviness of heating profiles associated with MCSs is further strengthened by radiative heating within the nonprecipitating anvils, which are widespread, long-lasting, and concentrated in the upper troposphere (Houze 1982).

The latent heating effects of MCSs are becoming fairly well established quantitatively (Tao et al. 2001; Schumacher et al. 2004; Tao et al. 2006, 2007). However, the radiative heating effects of the anvils of MCSs are not
well established, because up to now it has been difficult to establish quantitatively the amount of anvil cloud associated with a given amount of MCS precipitation. The objective of our study is to address this problem by taking advantage of the coordinated observations of the A-train satellites (Stephens et al. 2002). By using three different but synchronized A-train satellite instruments to glean information on (i) cloud-top horizontal structure and coldness, (ii) horizontal precipitation patterns, and (iii) cloud vertical structure, we are able to objectively identify and characterize MCSs, map them globally, and separate their anvil and raining components. To analyze cloud-top horizontal structure and coldness, we use the brightness temperature pattern of the 11-µm channel from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua satellite. To locate and quantify the raining portions of the MODIS-identified cloud tops to separate the raining and nonraining anvil portions of MCSs, we employ measurements of the rain field by the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E), also on Aqua. To determine the vertical structure of the raining and nonraining anvil portions of MCSs identified by MODIS and AMSR-E, we use the CloudSat Cloud Profiling Radar (CPR; see Stephens et al. 2002).

The power of the methodology developed in this study is that it can be applied objectively and automatically and therefore take advantage of the massive satellite datasets now being compiled. Identification of mesoscale cloud system tops from satellite brightness temperature patterns has been done previously by tracking the colder cloud images (Williams and Houze 1987; Mapes and Houze 1993; Chen et al. 1996). But these methods do not separate raining from nonraining areas. Cetrone and Houze (2009) accomplished an important step by separating the anvil portions of MCSs and analyzing their vertical structure with satellite data by first tracking the MCSs manually in geosynchronous infrared imagery and then using the CloudSat CPR to identify and analyze the nonraining anvil portions. Although successful, that approach is severely limited because it requires identifying MCSs by tracking them in time, and it involves several steps of manual labor. Thus, the study was restricted to a few limited spatial domains and periods. To avoid these problems, we have developed a method that does not require any manual intervention or tracking. Thus, it can be applied to instantaneous fields of data and to virtually unlimited sample sizes to obtain a robust and global climatology of tropical MCSs. The philosophical difference between our previous studies and this paper is that here we use spatial continuity constraints of size and intensity rather than time continuity (i.e., tracking) to identify MCSs.

By establishing a way to quantitatively derive a climatology of the anvil clouds of tropical MCSs, this study further lays the groundwork for calculating the global radiative effects of MCSs. The paper is laid out as follows: Section 2 describes the datasets; section 3 outlines the methodology for combining MODIS, AMSR-E, and CloudSat data to objectively identify MCSs and separate their precipitating and nonraining anvil components; section 4 exhibits the results of applying the methodology to 1 yr of A-train data; section 5 presents an analysis of the anvil structures identified by the methodology; and section 6 states our conclusions.

2. Data

Aqua and CloudSat were launched in May 2002 and April 2006, respectively, as part of the A-train satellite constellation (Stephens et al. 2002). They are both in a sun-synchronous near-polar orbit at ~705 km above the earth’s surface and fly over the equator at approximately 0130 and 1330 LT. 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.

a. MODIS

The MODIS is a whiskbroom scanning radiometer with 36 channels between 0.415 and 14.235 µm. In this study, we use the brightness temperature of channel 31 of 10.8 µm (TB₃₁). This channel is in the atmospheric window in which gases and aerosols in the atmosphere only weakly absorb outgoing infrared radiation. Hence, TB₃₁ is a good index of cloud-top height when clouds are deep (optically thick with high cloud tops). When clouds are optically thin, emissions from warmer surfaces (including lower clouds) below high clouds can penetrate upward so that warmer brightness temperatures are observed when thinner upper-level clouds are present. Within tropical MCSs that have thick and thin anvils extending from deep precipitating areas while keeping cloud-top heights almost unchanged (or varying little), the increase of TB₃₁ away from deep raining areas usually is due to the decrease of cloud thickness and the dilution of cloud water content. The TB₃₁ data are obtained from the MYD006_L2 product at the resolution of ~(5 × 5) km pixels at nadir and increase up to ~(12 × 6) km at the edge of the satellite swath (available online at http://www.data.gov/geodata/g599488).

b. AMSR-E

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 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 2007). 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 (see Kummerow and Ferraro 2007 for details). The AE_Rain product used in this study is provided at a footprint resolution of ~\((4 \times 6)\) km. Intervals between two adjacent satellite scan lines are ~8 km.

c. CloudSat

CloudSat CPR operates at the frequency of 94 GHz (wavelength \(\approx 3\) mm), 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 \([-32 \text{ to } -30] \text{ dBZ}\) is insufficient to see thin cirrus with small ice water content. However, since the main focus of our study is 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. The cloud mask, reflectivity field, and gaseous absorption from the 2B-GEOPROF product (version 011; release R04) are used in this study.

3. Methodology

a. Steps in the analysis

To document the cloud reflectivity profiles observed by CloudSat CPR in the anvil clouds of the MCSs, we first objectively identify the MCSs lying in the path of the CloudSat by a joint analysis of the MODIS TB11 infrared temperature pattern and the AMSR-E AE_Rain precipitation pattern along the track of the A-train satellites. Not only can MCSs be identified in this way but also the TB11 and AE_Rain data can be used to identify the raining and anvil portions of the MCSs. Thus, we determine exactly which CPR profiles are in the anvils of MCSs.

The key characteristics describing an active MCS are that it

- Has a large area of rainfall.
- Has a rain area containing subregions of more intense convective rain and less intense stratiform rain.

Figure 1 shows the flow of decision making and analysis in which we quantify the above criteria to identify the MCS anvil clouds that lie in the path of CloudSat. The left-hand side of the figure indicates how we first use MODIS and AMSR-E to determine the existence and internal structure of MCSs. The steps in the procedure indicated by the flowchart are based on definitions of a hierarchy of features that are identifiable in the MODIS TB11 and AMSR-E AE_Rain data products. These features are summarized in Table 1 and explained below.

The analysis procedure indicated in Fig. 1 starts by examining the MODIS TB11 for coldness of cloud top. A high cloud complex (HCC; see Table 1) is defined as the region contained within a closed isotherm of TB11 = 260 K. The choice of this temperature threshold is explained in section 3c. Figure 2a illustrates the identification of an HCC via an idealized example of TB11 contours in which three HCCs are each bounded by a closed black 260-K contour.

One HCC may contain more than one cold center of high cloud top. Therefore, the TB11 data are further investigated to locate each minimum of cloud-top temperature within the HCC. A cold center is defined as the region within the warmest closed TB11 contour surrounding the TB11 minimum. Figure 2b illustrates the identification of two cold centers within a single HCC. The top-right portion of Fig. 2c shows how one HCC may consist of two HCSs. Each HCS determined in this way is shown in Fig. 2c by a different color. The top-right portion of Fig. 2c shows how one HCC may consist of two HCSs.
structure, which is determined from the independently observed AMSR-E AE Rain field. The middle column of Fig. 1 indicates the steps in the analysis of the AE Rain field. A precipitation feature (PF; see Table 1) is any contiguous rain area contained within the 1 mm h⁻¹ contour of AE Rain. A heavy rain area (HRA; Table 1) is defined as any region within a closed contour of 6 mm h⁻¹. The HRA is a rough proxy for the convective portion of the PF. The rationale for choosing the thresholds of 1 and 6 mm h⁻¹ is provided in section 3d. Several PFs are indicated in the idealized example in Fig. 2d. Note that rain and upper-level cloud-top fields may not line up exactly. As in the bottom example PF in Fig. 2d, one PF may extend out of an HCS and possibly overlap more than one HCS. The portion of the PF that overlaps or is embedded within the HCS is called a raining core (RC; Table 1). The RC of the yellow HCS in Fig. 2d would be only the portion of the PF that is inside the boundary of the yellow HCS. An HCS is defined to be an MCS if it contains an RC satisfying certain criteria of size, rain intensity, and coldness of overlying cloud top. These criteria are listed in Table 1 and will be explained further in section 3g.

The portion of an MCS outside of the raining core is the anvil cloud that we analyze with CloudSat observations. For example, if the RC of the yellow HCS in Fig. 2d satisfies the size and intensity criteria for an MCS, the yellow region outside the PF would be the nonraining anvil of this MCS. This procedure locates the anvil clouds of MCSs that we analyze using the CloudSat GEOPROF-2B data product (right-hand column of Fig. 1).

### b. Matching between different satellite products

The analysis steps illustrated in Fig. 1 require overlaying the TB₁₁ and AE Rain data. To facilitate the overlaying, the AMSR-E data are regridded into the MODIS footprint using the nearest-neighbor method. Moreover, similar to Liu et al. (2008), we shift the AMSR-E footprint in the backward along-track direction for 7–17 km from the edge to the center of the satellite granule to have the proper geometrical match of detected atmospheric columns between the two sensors. We have found that this adjustment systematically increases the matching between heavier raining pixels and colder TB₁₁ pixels. About 5% more raining pixels (rain rate > 1 mm h⁻¹) are enclosed by the TB₁₁ = 235-K isotherm after the adjustment (not shown). MODIS and AMSR-E data are then regridded to the CloudSat footprint using the nearest-neighbor method, and the matched TB₁₁ and AE Rain data are assigned to CloudSat profiles that fall within the MODIS footprint. No spatial or temporal averaging of CloudSat profiles is performed, which preserves the high CloudSat horizontal and vertical resolution.

### c. Temperature threshold for identifying HCCs

The first step in the analysis of the TB₁₁ data (left-hand side of Fig. 1) is to identify the HCCs, which are defined by the TB₁₁ of 260-K threshold. Here we give the rationale for choosing this threshold. We expect that the value of TB₁₁ should increase away from the convective center as the upper-level nonprecipitating cloud originating from convection becomes thinner and less dense. Since we are interested in the anvil portions of MCSs, we would like to choose the warmest possible TB₁₁ threshold, to enclose the entire anvil out to its thinnest edges. However, there are some difficulties in doing this.

First, there is no simply defined cutoff TB₁₁ value that separates upper-level clouds from lower clouds and clear sky. In a spatially contiguous cloud system, the TB₁₁ can vary from less than 200 K to more than 290 K
from the thickest anvils out to the very thin cirrus at its edges. Over tropical oceans, the cirrus often connects different MCSs centered spatially far away from each other. Since the lifetime of the cirrus generated by the MCS can be much longer than the precipitating period of an MCS, it is difficult to know where cirrus appearing in a satellite snapshot has formed. Hence, it is almost impossible to find the real edge of an MCS solely using polar-orbiting satellite data. We must artificially make a cutoff at some threshold to define the boundary of an MCS. The frequency of occurrence of different types of anvils will therefore depend to some extent on the way we draw the line to define the MCS.

Second, anvil clouds from separate MCSs can merge with each other (Williams and Houze 1987). Methods based on a single temperature threshold for identifying and tracking tropical cloud systems have focused primarily on the coldest (most likely precipitating) part of the MCS and do not take into account the fact that the region within a single threshold may contain multiple cold centers and/or multiple RCs, as illustrated schematically in Fig. 1. A single extremely cold threshold (e.g., \( \sim 208 \) K) can work well in some regions (Williams and Houze 1987; Mapes and Houze 1993; Chen et al. 1996). However, our purpose is to gain a more comprehensive understanding (i.e., over all of the tropics) of the upper-level clouds of MCSs, which exhibit a variety of cloud-top temperature conditions. The scheme illustrated in Fig. 1, which defines an HCC by a relatively warm temperature threshold, allows us to include MCSs with various cold cloud-top temperature structures and allows us to include the majority of the anvil cloud surrounding the colder cloud-topped interior regions of MCSs.

To select an appropriate threshold to identify an HCC, we have plotted a joint probability distribution...
function (PDF) of MODIS and CloudSat CPR data (Fig. 3a). The bulk geometry of the clouds seen by the CPR is sometimes very complicated, especially when multiple cloud layers are present. To reduce the complexity, we group clouds based on the CloudSat 2B-GEOPROF cloud mask into layers located in three altitude ranges. In a given CPR cloud profile, any connected cloudy pixels are treated as one cloud layer. If clear pixels between two adjacent layers number <4 (i.e., ~1 km vertical space of clear sky), then these two layers are considered as one layer. If the highest pixel of a cloud layer is not below 10 km, then the cloud layer is defined as a “high-topped cloud layer.” If the highest pixel is between 5 and 10 km, then the cloud layer is defined as “middle-topped cloud layer.” For each layer with the top below 5 km, it is defined as a “low-topped cloud layer.” The thickness of each type of cloud layer is then obtained by counting the total number of cloudy pixels of all cloud layers belonging to the same category. Note that a high-topped cloud element could have the top above 10 km and the base extending to the surface to form a deep cloud. The PDF in Fig. 3a shows the high-topped cloud thickness and the associated MODIS TB_{11} sampled over the tropical ocean (30°S–30°N) for the 1-yr dataset used in this study. Two distinct modes are present, which can be better explored from Fig. 3b, showing the same dataset as Fig. 3a, except that the ordinate has been replaced by the base height of the lowest high-topped cloud layer. The two distinct modes shown in Figs. 3a,b are associated with two distinct types of clouds: very deep (probably precipitating) clouds and elevated anvils (with a base above 0°C level, which is ~5 km). The rarity of high-topped clouds with a base between the top of the boundary layer and the 0°C level (~5 km) is likely because detrainment from high-topped clouds occurs mostly above the melting level, and the ice particles in the detrained layer have small fall speeds, sublimate slowly, and are displaced laterally great distances by wind shear, thus producing thick and laterally extensive anvil cloud layers. However, when the updraft activity of a deep cloud with a low base ceases, the lower portion of the cloud quickly vanishes as the raindrops left behind scavenge out any remaining cloud drops and with their large terminal velocities quickly fall to the surface, leaving a cloud-free zone below the melting layer.

Figure 3c is a cumulative PDF showing that over the tropical ocean TB_{11} = 260 K encloses more than 95% of each high-topped cloud category with thickness >6 km. The abundance of thin upper-level clouds (<6 km of column thickness) is associated with warmer brightness temperatures up to 290 K that cannot be easily distinguished from low clouds. In this study, only a small fraction of these thin clouds is included in the high cloud system defined by TB_{11} = 260 K. Results for land areas are similar to those of oceanic areas and are not shown for space consideration. Consistent with this analysis, we use a 260-K threshold to identify an HCC. Once an HCC is identified by a closed contour of TB_{11} = 260 K, we subject the HCC to further analysis to locate the HCSs and MCSs located within it, as indicated in Fig. 2 and as discussed in section 3a. Note that the use of 260 K might artificially identify clear skies as clouds over snow-covered high mountain areas. However, in the tropics such areas are rare and the locations of them are fixed (like the Himalaya). Hence, such regions are not specifically treated in our algorithm since we can easily exclude them in our analysis.

d. Selection of rain-rate thresholds for identifying PFs and HRAs

The aim of the analysis of the MODIS and AMSR-E data indicated in Fig. 1 is to identify the MCSs lying in the path of CloudSat and then to separate each MCS into its raining and nonraining (anvil) portions. In this and the next two subsections, we discuss how we analyze the raining portions of HCCs to determine if the HCSs within the HCC are MCSs and to further break each MCS down into its raining and anvil subcomponents.

The middle section of Fig. 1 indicates the steps in analyzing the AMSR-E AE_Rain field to determine whether HCSs seen in the TB_{11} pattern have rain areas (RCs) sufficiently large, intense, and cold enough to qualify an HCS as an MCS. The first step is to identify PFs. However, the selection of a rain-rate threshold for PFs is complicated by the fact that the AE_Rain algorithms differ over land and ocean.

In our study, eight regions noted for their convective activity are selected for study (Fig. 4). Some of these are over land, and some are over oceans. Figure 5 shows the cumulative probability distributions (pixel count) of the rain area and rainfall as functions of rain rates. Two oceanic areas are selected since, of all oceanic regions, the west Pacific (WP) has the most rain at higher rates, while the east Pacific (EP) has the most rain at the lower rates. Figures 5a,c show that over the oceanic areas, a large portion (~55–70%) of the area covered by precipitation has light rain (rain rate <1 mm h^{-1}); however, the light rain produces only a small fraction (~9–18%) of the total rainfall. In contrast, over land areas, light rain is seldom observed because of the detection limit of the rainfall retrievals over the land (see Kummerow et al. 2001; Wilheit et al. 2003). To account for the difference between ocean and land retrievals, we remove all light rain pixels. Figures 5b,d show the result: the curves converge in the cumulative probability distributions in terms of both the rain area and rainfall over the rain
rate ranging from 1 to \( \sim 6 \) mm h\(^{-1}\). Consistent with this result, we choose 1 mm h\(^{-1}\) as the threshold for defining the area of a PF. This procedure retains \( \sim (30\%\text{-}45\%)\) of the total raining area and \(82\%\text{-}91\%)\) of total rain amount over oceans. Hereafter, “raining area” and “total rainfall” are all counted with respect to pixels with AMSR-E rain rate \( \geq 1 \) mm h\(^{-1}\).

We define any region within a PF that is enclosed by a closed contour or AE_Rain values \( \geq 6 \) mm h\(^{-1}\) to be an HRA (section 3a; Table 1). The purpose is to identify the portions of PFs that are most likely to be composed of active convective precipitation. Methods for subdividing the precipitation in an MCS into convective and stratiform (lighter) components show that when high-resolution radar data are available, a simple threshold is not a completely accurate way to separate the convective and stratiform rain (Steiner et al. 1995). Numerous studies have considered precise ways to separate convective and stratiform precipitation from radar and passive microwave remote sensing data (Churchill and Houze 1984; Steiner et al. 1995; Olson et al. 1996; Kummerow et al. 2001). In this study, we do not have the means to apply one of these methods. Schumacher and Houze (2003) found that the mean convective rain rates over tropical oceans and landmasses were 5.8 and 10.2 mm h\(^{-1}\), respectively. From these numbers, it appears that our use of a 6 mm h\(^{-1}\) threshold to define HRA is almost sure to capture convectively active portions of PFs over most of the tropics. Slight uncertainty arising from this threshold should not affect our results significantly since we only use HRAs as indicators of the likely presence of active convection; we do not calculate rain amounts based on the threshold used to locate them.

e. Determination of rain area size from AMSR-E data

An MCS is usually considered to be a cumulonimbus system that has become large enough to support a contiguous rain area of mesoscale dimension (Houze 1993; Mohr and Zipser 1996; Nesbitt et al. 2000; Houze 2004).

The frequencies are normalized by dividing the raw numbers in each bin by the largest number occurring in any given bin, so that contour values range from 0 to 1. (b) Joint PDF showing the frequency of occurrence of high-topped clouds as a function of CPR-determined lowest height of cloud base and cloud thickness. (c) Cumulative PDF of cloud thickness and TB\(_{11}\). Cumulative distribution is computed for each thickness bin and normalized by dividing by the total samples in that bin. Bin sizes are 1 km for cloud base height and 1 km for thickness.
Accordingly, for an HCS identified by the procedures described in section 3a to qualify as an MCS, we require its raining area to be of a minimum size for its parent HCS to be defined as an MCS. As indicated in Figs. 1 and 2, we find this area systematically by first identifying PFs in the AMSR-E data and then determining their overlap with HCSs to locate the RCs within an HCS. When identifying any system consisting of spatially contiguous pixels from a satellite image, a sampling problem occurs when a system is close to the edge of a satellite swath, where it is likely to be truncated by the swath so that the size of that system computed from the satellite image is smaller than its real size. As a result, the size distribution of PFs or HCSs identified in this way will be artificially

FIG. 5. (a) Cumulative frequency of raining areas as a function of rain-rate threshold. (b) As in (a), but rain rates \(< 1\) mm h\(^{-1}\) are excluded. (c) Cumulative frequency of instantaneous rain amount as a function of rain-rate threshold. (d) As in (c), but rain rates \(< 1\) mm h\(^{-1}\) are excluded. Abscissas are in logarithmic scales. Ordinates are in percent.
distorted to some extent. This has been called the “narrow swath effect” (Mohr and Zipser 1996; Nesbitt et al. 2000; among others). This effect will be greater for larger systems since they have a greater chance of being truncated by the swath. To determine this effect quantitatively, we have divided the AMSR-E swath into fourths, as shown schematically in Fig. 6a. Figures 6b,c show the cumulative frequency of PF size. The PFs are grouped according to the portion of the satellite swath in which their central points are located. Data included are for the tropical belt of 30°S–30°N. The distribution sampled from region 4 should be least affected by the narrow swath effect, while that sampled from region 1 should be most affected. Size distributions for deep PFs ($T_{B11} < 208$ K found in the system) and shallow PFs (no $T_{B11} < 273$ K found in the system) are displayed separately. The abscissas are scaled at the accumulated frequency derived from a standard normal distribution. The ordinates are labeled with size of PFs on logarithmic scales. Plotted this way, the observed distribution should be a straight line if it is lognormally distributed (i.e., if the logarithm of the variable is normally distributed). For deep PFs, the size distributions sampled from portions 2–4 are similar for almost all sizes, while the distribution sampled from portion 1 (the edge portion) departs from the other distributions at a relatively large size of $\sim (200)^2$ km$^2$. For shallow PFs (Fig. 6c), such a departure is not noticeable since shallow systems seldom reach that large size. Figure 6b indicates that only counting PFs located in the center three-quarters of the satellite swath can reduce the truncation effect while still keeping a large portion of useful data. We therefore eliminate all PFs and HCSs centered in the outer one-quarter of the swath from our dataset.

As indicated by Fig. 6, the areal size distributions of the rain areas of both deep and shallow PFs in the central three-quarters of the swath can be approximated by lognormal distributions. The tendency toward a lognormal size distribution for precipitating systems has been noted previously in tropical convection studies based on radar echoes (Lopez 1976; Houze and Cheng 1977; Lopez 1977, 1978). These nearly lognormal distributions indicate peak probability density values at very small sizes and long tails that slope off smoothly with increasing size. These similarities to previous studies lend confidence to our methodology, although the physical explanation for the lognormality of tropical convective distributions remains unclear and is beyond the scope of the current study.

f. Rain area size and cloud-top temperature used to define an MCS

As the final step in determining whether an HCS is an MCS (Fig. 1, left-hand box), the RCs located in the HCS must be evaluated to determine if the net rain area of the HCS satisfies all the size and cloud-top coldness criteria of an MCS (Table 1). These criteria assure that the rain area of an MCS not only exceeds a certain size but also is associated with deep convection. To develop these criteria more specifically, we first define $A_{RC1}$ as the total area covered by the largest rain core (RC1) in an HCS. We represent the minimum cloud temperature of the cloud top overlying the RC1 area of an HCS with the variable $T_{b11RC1\text{min}}$, which is calculated as the mean value of the coldest decile of MODIS $T_{B11}$ data located over $A_{RC1}$. These two variables form the basis for a set of joint probability distributions from which we can determine objective criteria for the size and cloud-top temperatures of RC1s that we can use to determine the existence of an MCS. The joint probability distributions are shown in Fig. 7. The area scale is expressed as the horizontal dimension given by $\sqrt{A_{RC1}}$. The frequency per unit interval of $T_{b11RC1\text{min}}$ and $\sqrt{A_{RC1}}$ are weighted by the mean total rain flux of HCSs in each interval of $T_{b11RC1\text{min}}$ and $\sqrt{A_{RC1}}$, so that the color field in Fig. 7 indicates the fraction of total tropical rain that is produced by all HCSs in each bin of the distribution. Each panel in Fig. 7 represents one of the geographical regions indicated in Fig. 4. The abscissa of each panel is on a logarithmic scale. The vertical lines in Fig. 7 show that the majority of tropical rainfall (60%–78%) is produced by HCSs with RC1 larger than 2000 km$^2$ ($\sim 45^2$ km$^2$). The horizontal lines show that most of the rainfall is from rain areas with $T_{b11RC1\text{min}} < 220$ K. We therefore choose 2000 km$^2$ as the RC1 size criterion and 220 K as the RC1’s cloud-top minimum temperature criterion to determine that an HCS qualifies as an MCS. These criteria assure that the MCSs examined in this study account for the bulk of the latent heat released in the tropics.

From Fig. 6 and other studies of tropical convection, we know that the size distribution of rain areas in the tropics tends toward lognormal with no natural peak in the size distribution, a fact that makes the selection of a cutoff size of a rain area to define an MCS somewhat arbitrary. The above criteria of 2000 km$^2$ and 220 K bring an aspect of physical significance to the definition of an MCS by choosing area and cloud-top height criteria that guarantee that the MCSs are the systems accounting for major latent heat release in the tropics.

In addition, the size criterion is generally consistent with other studies in which more detailed radar and other data are used to assess the detailed behavior of individual convective systems. Such studies have suggested that an MCS can be thought of as a cloud system that occurs in connection with an ensemble of cumulonimbus clouds and produces a contiguous precipitation area $\sim 100$ km or more in horizontal scale in at least one direction.
However, the application of a cut-off size is further complicated by the fact that the exact size of a contiguous precipitation area is instrument and method dependent. Different sensors or retrieving algorithms can both affect the detection limit for light rain and hence change the physical meaning of the terms “rain” and “no rain” in different datasets. The apparent size of a rain area is significantly affected by the sensitivity of the instruments and/or methods to lighter precipitation. Since we have filtered the AMSR-E AE_Rain dataset to exclude rain rates < 1 mm h⁻¹ (Fig. 5), the rain areas in our dataset are expected to be somewhat smaller than those seen in more sensitive datasets. For our dataset we have computed the diagonal distance of each PF according to the along-track and cross-track coordinates. It is found that our size cutoff of 2000 km² is roughly equivalent to applying the one-dimensional 100-km criterion on the diagonal distance. This cutoff is also similar to the MCS size criterion used by Mohr and Zipser (1996) and Nesbitt et al. (2000) to define tropical MCSs, although the definition of a raining area in their study is not exactly the same as in ours.

g. Identification of MCSs

The final step in the analysis procedure indicated in the left-hand dashed box in Fig. 1 is the determination of whether each HCS qualifies as an MCS. The four criteria applied to each HCS for this purpose are listed in Table 1. These criteria are applied to the RC1 in the HCS.

The first two criteria in Table 1 are that the RC1 in the HCS must exceed 2000 km² and must account for at least 70% of the total raining area of the HCS. Usually an MCS is defined in terms of a contiguous rain area (Houze 2004), and the second of these criteria assures that the raining area is mostly contiguous. The contiguity criterion eliminates from consideration MCSs that may be just forming, with just a few disconnected rain areas, or MCSs that may be dissipating with fragments of previously more active rain areas. Thus, our study is limited to active MCSs, which account for 56% of total tropical precipitation in our dataset.

Fig. 6. (a) Schematic of subregions of a satellite granule. Each numbered area accounts for one-quarter of the area of the granule. (b) Size distributions of AE_Rain areas located within deep precipitating systems (the coldest TB₁₁ of the PF < 208 K). (c) As in (b), but for shallow precipitating systems (the coldest TB₁₁ of the PF > 273 K). The abscissas are scaled by the accumulated frequency of a standard normal distribution. The ordinates are in logarithmic scales. Plotted this way, the observed distribution would be a straight line if it were lognormally distributed.
The coldness criterion assures that the main rain area of the MCS is associated with deep convection. The <220-K minimum temperature criterion is based on the results of the previous section and along with the rain-area size criterion assures that the MCSs in this study are the major latent heating agents in the tropics. The fourth criterion assures that the MCS contains some active convection (as discussed in section 3d).

Our active MCSs include a small number of tropical cyclone systems, which likely only have very minor effects on our statistical analysis of MCSs shown later. The AMSR-E Tropical Cyclone Database (version 1.0) was obtained from the Earth Observation Research Center, Japan Aerospace Exploration Agency (available online at http://SHARAKU.eorc.jaxa.jp/TYP_DB/index_e.shtml). In 2007, 376 (out of 10,533) AMSR-E granules captured named tropical storms. For each named storm, the time and location are obtained when the AMSR-E captures its precipitating region. If we make the extreme assumption that any precipitating pixels within a 500-km radius to the center of a named storm belong to that system, then only ~1.5% of our active MCSs are from these systems.

FIG. 7. Joint PDFs of the total instantaneous rainfall as a function of the mean TB11 of the coldest 10% of the largest rain core (RC1) of each HCS and the dimension of the RC1 (square root of its area). The abscissas have logarithmic scales. The bin sizes are 4 K and 0.05 for the TB11 and for the log10 of the square root of the area of RC1. Each panel represents one of the regions indicated in Fig. 4. For the value of each bin, the numerator is the summation of rainfall from all HCSs that fall in that bin. The denominator is the total tropical rainfall. All rainfalls are computed based on areas with rain rates >1 mm h⁻¹. The values in each panel are normalized by dividing the maximum value of each panel so that they all range from 0 to 1. The numbers in each panel show the percentage of rainfall contributed from the large box (enclosed by the vertical and horizontal lines) into which the numbers fall.
h. Subcategories of MCSs

Sometimes one contiguous rain area lies under the high cloud tops of two different active MCSs (Fig. 8). Part of this contiguous rain area constitutes an RC of the first MCS, while another part of the contiguous rain area forms an RC of the second MCS. In this case we refer to the MCSs as **connected MCSs** to distinguish them from the more common **separated MCSs**. The definitions of these two types of MCSs are included in Table 1. Connected MCSs tend to occur over warm oceans where MCSs are crowded together, and newer MCSs are frequently triggered in the vicinity of older MCSs. In these situations, rain areas from older systems often merge with those of new systems in myriad patterns (Williams and Houze 1987; Mapes and Houze 1993). Because of this tendency, we have subdivided the active MCSs into separated MCSs and connected MCSs. Table 2 shows that 56% of the total tropical rain is produced by active MCSs, 16% falls in connected MCSs (mostly over warm oceans) and 40% falls from separated MCSs. On average, the connected MCSs have narrower anvil regions than separated MCSs. The ratio of total rain area to total cloud area (as determined from TB11 according to the procedure described in section 3a) is 37% for connected MCSs and 28% for separated MCSs.

While the active MCSs identified in this study account for 56% of tropical precipitation, and thus the majority of tropical latent heating, our analysis shows that they account for only 29% of the total high cloud-top coverage (defined by the 260-K TB11 threshold). Studies of the effects of deep clouds on the radiative heating profile of the tropics will need to include both the active MCSs and all other types of high-topped clouds. We have therefore compiled a database of the non-MCS cloud systems as well as MCSs in preparation for a future paper in which we will investigate radiative effects of high-topped clouds in the tropics.

4. Mapping of tropical MCSs and their anvils

a. Distribution of tropical MCSs

Since our methodology of identifying MCSs via joint analysis of MODIS cloud-top temperature and AMSR-E rain-rate fields is a new technique, we perform a qualitative test to determine if the identified MCSs are generally consistent with current knowledge of the climatology of tropical convection. To check this consistency, we map the locations of MCSs identified by our methodology over the entire tropics. Figure 9 shows the MCS locations by season, MCS size, and MCS type.

In December–February (DJF), small separated MCSs are by far more frequent over land—specifically tropical Africa (AF) and South America (AM; Fig. 9a). The overall size of an MCS is largely controlled by the size of its stratiform precipitation region. It is well known that stratiform precipitation areas of tropical convective systems produce more rain over ocean than land (Schumacher and Houze 2003). It is therefore not surprising that the small separated MCSs occur primarily over land. Figure 9b shows that large separated MCSs also occur frequently over Africa and South America, but that they also occur with great frequency over the Maritime Continent (MA) region (Indonesia–Malaysia–northern Australia). The oceanic conditions in the Maritime Continent region would be expected to favor the occurrence of

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**Table 2. Number and precipitation contributions of HCSs passing criteria listed in Table 1.**

<table>
<thead>
<tr>
<th>Conditions satisfied</th>
<th>Number of HCS (relative percentage)</th>
<th>Percentage of total tropical rainfall (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criteria 1</td>
<td>111,913 (100%)</td>
<td>74%</td>
</tr>
<tr>
<td>Criteria 1 and 2</td>
<td>95,082 (85%)</td>
<td>64%</td>
</tr>
<tr>
<td>Criteria 1, 2 and 3</td>
<td>74,399 (66%)</td>
<td>59%</td>
</tr>
<tr>
<td>Criteria 1, 2, 3 and 4</td>
<td>Separated MCSs 52,274 (47%)</td>
<td>40%</td>
</tr>
<tr>
<td>Criteria 1, 2, 3 and 4</td>
<td>Connected MCSs 15,063 (13%)</td>
<td>16%</td>
</tr>
</tbody>
</table>

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Figure 9c shows that connected MCSs are frequent only over the warm Indian Ocean (IO) and west Pacific open ocean regions. The connected MCSs are the largest cloud systems in equatorial regions, and are sometimes characterized as “super clusters” or “super convective systems” (Nakazawa 1988; Mapes and Houze 1993; Chen et al. 1996). The connected MCSs do not develop over the Maritime Continent region. This result...
is consistent with the diurnal cycle that occurs over the patchwork of islands and waterways of the Maritime Continent region. The land–ocean contrast of the small landmasses and intervening oceans drives a powerful diurnal cycle that leads to large MCS development over the seas in the morning but shuts down further development in the afternoon (Houze et al. 1981). Consequently, MCSs over the Maritime Continent region cannot develop to the gigantic proportions of super clusters or connected MCSs. This can only happen over the warm open ocean regions.

In June–August (JJA), small separated MCSs continue to occur over tropical Africa and South America, but they shift northward and with somewhat less frequency than in the northern winter (Fig. 9d). In addition, small separated MCSs are seen with significant frequency over eastern Asia in association with the summer monsoon. Figure 9e shows that large separated MCSs occur with high frequency in association with both the Asian, African, and American monsoons. These monsoonal associations are consistent with studies of aircraft and satellite data, which show the occurrence of convective systems with large stratiform precipitation areas in the region of the Bay of Bengal, Bangladesh, and Burma during the summer monsoon (Houze and Churchill 1987; Houze et al. 2007; Romatschke et al. 2010). Figure 9e also shows that large separated MCSs are absent over the Maritime Continent at this time of year, which is consistent with the fact that the DJF pattern over this region seen in Fig. 9b is driven by the low-level convergence of the northern wintertime Asian monsoonal outflow across the South China Sea with the northern Australian summer monsoonal circulation. These monsoonal circulations are absent during the JJA season shown in Fig. 9e. Figure 9f shows that the connected MCSs are again evident over the open warm Indian and west Pacific Oceans but with less frequency than in DJF. Another region of frequently connected MCS occurrence in JJA is in the east central Pacific intertropical convergence zone. This region is also a warm open ocean region of the type that favors connected MCSs, and at this time of year, the convection is forced strongly by maximum seasonal convergence of the south-easterly and northeasterly trade winds over the narrow warm near-equatorial ocean region just north of the cold equatorial ocean current in this region (Mitchell and Wallace 1992). This region does not support connected MCSs in the northern winter when the convergence lies to the south of the warm ocean region.

b. Climatology of MCS anvil clouds

As discussed above an active MCS identified in our study consists of both raining areas and anvil clouds, the latter having AMSR-E rain <1 mm h⁻¹. Since we can separate the anvil portions of MCSs in this way, we have mapped the frequency of occurrence of anvil cloud across the tropics (Fig. 10). These maps show that overall the annual mean coverage of anvil cloud associated with small separated MCSs is quite small, with maxima (~0.6%) over Africa and South America, where small separated MCSs are most frequent. They are also found frequently over large islands within the Maritime Continent area of the Indian and west Pacific Oceans. In contrast, anvil clouds from large separated MCSs occur in broader regions over oceans and are favored over open water rather than over islands, except around the island of New Guinea. Anvil clouds from large separated MCSs occur with maximum frequencies ~10 times those of small separated MCSs, and they cover several times more area overall. The maximum frequency of occurrence of anvils of large separated MCSs is around the South China Sea (>5%). Anvil clouds from connected MCSs are by far more common over open ocean areas, with most of them found over the Indian Ocean, Bay of Bengal, South China Sea, and west Pacific warm pool. As expected, the distribution of MCS anvil clouds is qualitatively consistent with MCS mapping seen in Fig. 9, since they are generated from and spatially tightly connected with those MCSs being in their active stage. However, it is unprecedented to have quantitative mapping of the frequency of occurrence of anvil clouds. This quantitative mapping is a direct benefit of the objective MCS and anvil identification methodology developed in this study and lays a foundation for calculations of the radiative effects of these anvil clouds.

Figure 11 shows the climatology of annual mean anvil clouds from all active MCSs and all other (non-MCS) high cloud systems. As noted in section 3h, although active MCSs dominate the latent heat release in the tropics, they only account for approximately one-quarter of tropical anvil clouds associated with HCSs. To fully evaluate the role of radiative heating of upper-level clouds in the tropics, both the MCS and non-MCS anvil clouds will need to be assessed. The results in Figs. 10, 11 will together facilitate such quantitative assessments. Figure 11 shows that overall the anvil clouds from active MCSs concentrate in tropical deep convective regions and that the fractional coverage of them is relatively small, <10% in most areas. Anvil clouds from other HCSs have a much broader coverage, especially over oceans, where they reach ~30% coverage in the eastern Indian Ocean to the west of Sumatra and have >10% coverage over all major convective regions. They also expand farther toward the north from the east Pacific and Atlantic (AT) intertropical convective zones. Some anvil clouds from subtropical HCSs can be found poleward
of $\pm 20^\circ$N, with maxima located at the Himalayas and the South Pacific (SP). The latter maximum is likely related to midlatitude storm dynamics, while the former maximum should be read with cautions since it is likely resulting from the misidentification of clouds due to the cold surface (see section 3c).

5. Anvil cloud structures

The discussion of Fig. 9 in section 4 suggests that our methodology locates and categorizes MCSs in a way that is consistent with previous literature. Moreover, we know that the MCSs selected account for about 56% of tropical rainfall. The MODIS–AMSR-E analysis, however, only allows us to geolocate MCSs and their anvil portions. To understand the effect of anvils on radiative transfer in the tropics, more detailed information on the three-dimensional structure of the anvils is needed. Such information cannot be provided by the MODIS–AMSR-E analysis. This section describes how we obtain this additional data, by analyzing the CloudSat CPR observations along tracks intersecting the MCSs geolocated by MODIS and AMSR-E. The CPR data provide statistics of the morphology and internal structure of MCS anvils, and these statistics lead to a composite knowledge of tropical MCS anvil structure.

a. Locating and classifying CloudSat profiles in relation to MCSs

In the joint analysis of MODIS TB$_{11}$ and AMSR-E AE_Rain fields described in the preceding sections, we used a cutoff of 1 mm h$^{-1}$ to separate the RCs of MCSs from their anvil regions. This rather high threshold was employed to make the AMSR-E data subsets equivalent in their ability to indicate precipitation features over land and ocean (section 3d). The CloudSat CPR data, too, contain information on the existence of lighter rain,
and they have no bias between land and ocean. It is possible, therefore, to use the CPR data to subdivide the MODIS–AMSR-E anvil regions into lightly raining and nonraining portions according to CPR. The CloudSat 2C-PRECIP-COLUMN product provides rain retrievals, including both the presence and intensity of surface precipitation using the near-surface radar reflectivity and an estimate of path-integrated attenuation (Haynes et al. 2009); however, it is limited to oceanic and inland open water only. Following Stephens and Wood (2007), we use a simpler way to determine the existence of precipitation over either land or ocean (without an estimate of rain rate) by noting when either

- the maximum reflectivity of the profile between 1 and 2 km above the surface is $>-10 \, \text{dBZ}_e$, where $Z_e$ is the equivalent radar reflectivity, or
- the maximum reflectivity in the three adjacent bins including the earth’s surface is $<25 \, \text{dBZ}_e$.

The use of 1 $\sim$ 2-km layer instead of the lowest 1 km above the surface used in Stephens and Wood (2007) is to eliminate the contamination due to the surface clutter (Marchand et al. 2008). Considering that CloudSat is downward pointing, we add the latter condition in addition to Stephens and Wood (2007) to take into account the strong attenuation due to the heavy rain. We have analyzed all CloudSat CPR profiles observed over the tropical ocean during 2007 and found that the presence of precipitation determined by our simple method is consistent with that from the CloudSat 2C-PRECIP-COLUMN to $\sim95\%$ ($\sim95\%$ of the presence of precipitation predicted by one method can be captured by the other in both directions).

We have compared all instances of rain occurrence for all active MCSs seen along the CloudSat track by our method with our analysis of the AE_Rain field. Over both ocean and land $\sim(94\%–97\%$) of the locations with significant rainfall detected by the AMSR-E (AE_Rain $>1 \, \text{mm h}^{-1}$) are also identified as raining by CloudSat. Data points where both CloudSat detects the existence of rain and AE_Rain indicates rain rates $>1 \, \text{mm h}^{-1}$ contribute $\sim97\%$ of precipitation (based on AE_Rain $>1 \, \text{mm h}^{-1}$) over oceans and $\sim94\%$ over land. There are 25\% of the CloudSat profiles over oceans and 24\% over land that do not have significant precipitation in AMSR-E but are nevertheless identified as precipitating by the CloudSat CPR. Thus, while the AMSR-E threshold of $1 \, \text{mm h}^{-1}$ captures the heavier rain rates that are responsible for the majority of latent heat release in the tropics, the CloudSat CPR profiles capture those anvils from which lighter rain is falling but not contributing significantly to latent heating. These weakly precipitating anvils are useful to distinguish from nonraining anvils because they are likely denser and thicker clouds and thus stronger absorbers of radiation. To make this distinction, we group CloudSat profiles into the following three categories:

Fig. 11. As in Fig. 10, but showing area covered by anvil clouds associated with (a) all active MCSs and (b) all other HCSs.
FIG. 12. High-topped cloud occurrence as functions of normalized distance $L_N$ from the center point of the largest raining core out to the CloudSat footprint for separated active MCSs. Columns (a)–(c) respectively show data from raining clouds (category 1 in text), weakly raining clouds (category 2 in text), and nonraining anvils (category 3 in text); N and F are the sample size and the percentage of area covered by high-topped clouds sampled in each category. Percentage in parentheses is the same as F but for clouds with thickness $>6$ km. Contours show frequency of occurrence in bins of 1 km for thickness and 0.4 for normalized distance. To facilitate comparison of figure panels, the contoured frequencies in each row have been normalized by dividing by the total sample (i.e., N) found in the left panel of each row. To account for the sampling area difference associated with different bins of $L_N$, contoured frequencies in each bin of $L_N$ are further normalized by dividing by the virtual area associated with that bin (i.e., the area of the circular belt at a given $L_N$ with width of 0.4 in $L_N$ space).
Type 1: Raining cloud profiles: $\text{AE}_\text{Rain} > 1 \text{ mm h}^{-1}$.

Type 2: Light raining cloud profiles: $\text{AE}_\text{Rain} \leq 1 \text{ mm h}^{-1}$ and CloudSat indicates rain presence.

Type 3: Nonraining anvil cloud profiles: $\text{AE}_\text{Rain} \leq 1 \text{ mm h}^{-1}$ and CloudSat indicates no rain.

In the remainder of this study, we will examine the type 1–3 profiles associated with the high-topped cloud layers (defined in section 3c) seen by CPR.

b. Separated active MCSs

1) REPRESENTATION OF CPR PROFILES IN JOINT PROBABILITY DISTRIBUTIONS

In this section, we analyze the bulk vertical structures of separated active MCSs by examining statistics of the three types of profiles defined in the last section. In particular, we have compiled statistics for all profiles.
that extend through high-topped cloud layers that are parts of MCSs. We display these statistics in Fig. 12 in the form of joint PDFs compiled for each of the geographical regions in Fig. 4. The coordinates of the PDFs are cloud thickness on the ordinate and normalized horizontal distance on the abscissa. This horizontal coordinate is determined for each CloudSat profile obtained in an active MCS by first computing the distance \( L \) from the center point of the RC1 out to the CloudSat footprint. This distance is then normalized because MCSs exhibit a wide range of sizes. The normalized distance is defined by \( L_N = L/R_E \), where \( R_E \) is the equivalent radius of the RC1 in the MCS; that is, \( R_E \) is the radius of a circle with the same area as the RC1. The numbers printed in each panel of Fig. 12 indicate the sample size. The quantity \( N \) is the total number of type 1, 2, or 3 CPR profiles sampled in high-topped cloud layers in a given geographical region, \( F \) is the percentage of the \( N \) samples taken in active MCSs, and the number in parenthesis is the same as \( F \) but for high-topped clouds thicker than 6 km. Overall, more than 98% of MCS cloud profiles contain high-topped clouds.

To obtain Fig. 12, the number of profiles in thickness bins of 1 km and normalized distance bins of 0.4 are determined and contoured. Figure 12a is for all of the type 1 profiles obtained in high-topped cloud layers within separated active MCSs in a particular geographical region. Figures 12b,c are similar except for type 2 and 3 profiles, respectively. To facilitate consistent quantitative comparisons between different regions that have different sample sizes, we have normalized the contour values in Fig. 12 by dividing the number of profiles in each bin of each panel by the total number of samples \( N \) shown in each panel of Fig. 12a. Contour values are further scaled by dividing by the virtual area of sampling associated with each bin in \( L_N \) space; that is, \( \sigma[(L_N + \Delta L_N)^2 - L_N^2] \). Thus, the contour values in each panel are proportional to the probability that the high-topped cloud profiles in active MCSs in a particular geographic region are observed for a given layer thickness and normalized distance from the center of the largest RC of the MCS.

Since the normalized distance \( L_N \) depends on the size of RCs determined from the AMSR-E, systematic biases could arise from using the AE_Rain product. To test the robustness of our results, we rescaled \( L_N \) to adjust for the existence of the lightly raining areas not included in the AMSR-E raining cores by dividing \( L_N \) by \( \sqrt{1 + N_2/N_1} \), where \( N_1 \) and \( N_2 \) are the numbers of profiles in categories 1 and 2. We also recomputed the PDFs relative to the real distance from the center \( L \) and the distance from CloudSat footprints to the edge of their rain core. Qualitatively, these variations on the calculations all showed similar results, thus giving us confidence in the conclusions discussed.

2) RAINING REGIONS

The panels located in Fig. 12a show that CloudSat profiles obtained in high-topped cloud layers in regions of MCSs with significant precipitation (i.e., type 1 profiles in MCSs) are dominated by layer thicknesses \( >10 \) km. The frequency decreases rapidly thereafter with increasing \( L_N \). Clouds in this category are rarely observed for \( L_N > 1 \); that is, they are mostly within the raining core, since if all raining cores were to have the shape of circular discs and they were all in single-core systems, then the probability of seeing raining profiles would be 0 for \( L_N > 1 \).

3) LIGHTLY RAINING REGIONS

The Fig. 12b panels show the PDFs for type 2 profiles in MCSs. These profiles are located outside the dominant raining core of the MCS but nevertheless include some light rain. These PDFs exhibit a thick mode (thicknesses 14–15 km) and a thin mode (layers <6 km thick). The thick mode is the most prominent. It shows that the deep clouds in this category are only slightly less thick than those of the more heavily raining profiles shown in the Fig. 12a panels. In contrast to the more heavily raining profiles, the lightly raining profiles are located mostly near \( L_N = 1 \) and extend to \( L_N \sim 2 \), more over oceans and less over continents, which indicates that the lightly raining anvils are located at the edges of, rather than within, the dominant raining cores of MCSs. This result suggests that the lightly raining anvils constitute the outer portions of the deep precipitating areas; they may still rain lightly but with intensities too weak to exceed the AMSR-E 1 mm h\(^{-1}\) threshold. The anvils associated with the thinner mode seen in the Fig. 12b panels have thicknesses of \( \sim (1–8) \) km and peak values occur at \( L_N = 1.0 \sim 1.4 \), indicating that these thinner clouds tend to be at or just beyond the outer sides of the raining cores of MCSs. The thin mode in the Fig. 12b panels indicates the likely presence of thinner high-topped clouds separated from a lower raining cloud layer—that is, thinner high-topped anvils overlapping a low-topped or middle-topped lightly raining cloud layer. Such multilayered precipitation is an important feature of tropical cloud systems as recently found by Stephens and Wood (2007). These lower clouds may be shallow convective cells too small in scale for AMSR-E to detect significant rainfall from them. They may possibly be small convective cells forced by cold
pool dynamics occurring below the upper-level cloud layer.

4) ANVIL REGIONS OF ACTIVE SEPARATED MCSs

The Fig. 12c panels for nonraining anvils (type 3) are a primary focus of this study. By separating these PDFs from those for the raining and lightly raining portions of MCSs, we can extract quantitative information about the bulk properties of nonraining anvils. Prior to CloudSat, little quantitative information on the anvils of MCSs has been available. The PDFs in Fig. 12c are visually strikingly different from the two precipitating anvil types. The dominant mode is for much thinner cloud layers. The modal thickness in Fig. 12c is 4–5 km, as compared to the raining PDFs in Figs. 12a,b. These Fig. 12c panels emphasize the clouds with elevated bases comprising the mode seen in the top-left-hand portion of Fig. 3b, whereas the panels of Figs. 12a,b emphasize the low-based thick cloud mode seen in the bottom-right portion of Fig. 3b.

The Fig. 12c panels show that the dominant modal thickness of 4–5 km highlighting the occurrence of elevated nonraining anvil cloud occurs most frequently at distances $L_N = 1.5 - 2.0$ from the center of the dominant raining core of the MCS. The Fig. 12c panels further show that these elevated nonraining anvils of separated active MCSs rarely extend beyond $L_N = 4$ and never beyond $L_N = 5$. They extend farthest (out to $L_N = 4.8$) in the MA, where the large separated MCSs occur most frequently (Fig. 9b).

The Fig. 12c panels show several important differences in MCS anvil structure between land and ocean and between different parts of the ocean. The land MCSs are dominated by the thinner anvil mode; the Fig. 12c panels for West Africa and the Amazon (AM) show by far the most pronounced thin anvil modes of all the regions analyzed. The thin anvil modes for these continental regions are surrounded by tightly packed contours, indicating relatively little tendency to have very deep anvils (almost always <10 km and mostly <5 km thick), and the anvils tend to be laterally confined (mostly $L_N < 3$). The tendency toward more confined and shallower anvils in intense convection in West Africa was noted by Schumacher and Houze (2006) and Cetrone and Houze (2009).

The Fig. 12c panels show that the occurrence of thick nonraining anvils (>10 km) is generally infrequent. Nonetheless, over the six oceanic regions, thick nonraining anvils occur often enough to produce a weak secondary mode in the PDFs at $L_N = 1.0 - 1.5$—that is, near the edges of the dominant raining cores of the MCSs. This weak mode in nonraining thick anvils is at a similar location to the mode seen in the weakly raining anvils in the Fig. 12b panels. The edges of the primary rain area of an oceanic MCS are evidently characterized by a thick cloud layer, which may or may not be raining lightly. This interpretation would be consistent with the profiles in the panels of Figs. 12b,c showing that the thick anvils in the nonraining profiles are somewhat less thick (by ~1 km) than those in the lightly raining anvils. Indeed, there is an overall trend toward the thick anvils to be at slightly lower altitudes progressing from raining to lightly raining to nonraining profiles in Figs. 12a–c, respectively. Although the nonraining anvil clouds thicker than 10 km are mostly limited to regions within $L_N = 1.0 - 1.5$ in all land and ocean regions, the outlying contours in the PDFs for all six oceanic regions show that the anvils thicker than 10 km do occasionally extend beyond $L_N = 2.5 - 3.0$. In the MA, the outlier contours show nonraining anvils thicker than 10 km occurring sometimes out to $L_N = 3.2$.

Last, we note a difference between MCS nonraining anvils in the oceanic regions of the intertropical convergence zone (EP and AT) compared to anvils seen over the broad warm pool of the WP, MA, IO, and SP regions. The anvils in the EP and AT regions have PDFs similar to the other oceanic regions, except that the contours show that the anvils are overall systematically thinner (by ~1 km) and do not extend as far laterally. In the ET and AT regions, 10-km-thick clouds are almost never found beyond $L_N = 2.4$.

The sample size numbers printed in the panels of Fig. 12 carry information regarding the net area covered by the type 1–3 cloud categories. The percentage $P$ in the Fig. 12a panel is equivalent to the fractional area of the MCS high-topped clouds that are covered by the significantly raining clouds. The numbers in parentheses in the panels of Figs. 12b,c are equivalent to the fractional area of the MCS high-topped clouds that are covered by the lightly raining and nonraining clouds that are at least 6 km thick. Using the numbers in parentheses, we find that the combined fractional coverage of thicker (>6 km deep) high-topped clouds from types 2 and 3 is about 40% over the warm oceans (IO, MA, WP, and SP), while they cover approximately 30%~35% over continents and the intertropical convergence zone (AF, AM, EP, and AT). From these percentages, we infer that MCSs over the warm oceans are more efficient in producing deep lightly precipitating clouds and thicker nonraining anvil clouds for a given area of raining cores.

To summarize the characteristics of nonraining anvils revealed by the panels of Fig. 12c: their PDFs are dominated by anvils <$\sim$10 km thick, with a modal thickness of about 4–5 km. Continental MCSs are almost completely dominated by these less thick nonraining anvils. These elevated less thick anvils are most frequent at distances...
$L_N = 1.5 - 2.0$ from the center of the dominant raining core of the MCS but may extend out to as far as $L_N = 5$ in MCSs over warm oceans. Over the warm pool ocean regions, thicker nonraining anvils (>10 km thickness) occur near the edges of the actively raining regions of the MCSs, as do lightly raining thick anvils, indicating that the thick anvils are generated in and spread out from the primary raining regions of the MCSs. These thicker anvils are extremely rare over land, and they are not very common over the intertropical convergence zones of the eastern Pacific and Atlantic.

c. Connected active MCSs

Figure 13 is similar to Fig. 12, except that it shows the structures of connected rather than separated active MCSs. The values of $F$ in the Fig. 13a panels showing the fractional area covered by significant rain are greater for
the connected MCSs (36%–45% in Fig. 13 compared to 27%–37% in Fig. 12). In addition, the values of $F$ in the Fig. 13c panels show that the fractional area covered by anvil clouds is less for the connected MCSs (31%–40% in Fig. 13 compared to 39%–50% in Fig. 12). These differences are reasonable according to the definition and concept of a connected MCS (Fig. 8). A connected active MCS actually consists of a cluster of active MCSs whose raining areas are merged with each other. Under this condition, there is not much space left for anvil clouds to fill.

Comparison of the PDF contours in Figs. 12, 13 reveals further differences between the connected and active MCSs. Most obvious is that the contours contract to the left in all the panels of Fig. 13c compared to the panels of Fig. 12c. That is, the nonraining anvils of connected MCSs do not extend laterally as far as they do in separated MCSs. The most extreme difference is for

![Fig. 13. (Continued)](image-url)
the warm pool systems (IO, MA, WP, and SP), where the less thick nonraining anvils (<6 km deep) of the connected MCSs do not extend beyond $L_N = 3.5 – 4.0$, whereas they extend out to $L_N = 5$ in the separated MCSs.

6. Conclusions

We have for the first time quantitatively mapped the occurrence of MCS anvil clouds over the whole tropics. Up to now, this goal has been unreachable because of the difficulty of separating the precipitating cores of the MCSs from their anvil cloud components. The A-train satellite formation, however, has provided sufficient information to solve this problem. By using a particular combination of AMSR-E rain data, MODIS brightness temperature, and CloudSat radar profiling information, we have identified MCSs in a physically meaningful fashion, separated out their anvil components, and determined their anvil morphology and how that morphology varies over the entire tropics.

The essence of the methodology, described in section 3 of this paper, is to jointly analyze the MODIS TB11 and AMSR-E AE_Rain fields to identify MCSs (Fig. 1). The selection of thresholds for each of these fields is crucial. To eliminate biases between land and ocean rain estimation techniques, we use an AE_Rain threshold of 1 mm h$^{-1}$. To minimize ambiguities regarding whether upper-level cloud originated from MCSs, we choose the TB11 threshold of 260 K to identify upper-level cloud systems that could potentially be associated with an MCS. To assure that a cloud system was an MCS, we required that its main precipitation region be at least 2000 km$^2$ and that the cloud-top temperature above it reached a minimum of <220 K. These two conditions assure that the cloud systems identified as active MCSs account for the majority (~56% in our dataset) of tropical rainfall. Since MCSs have no natural cutoff size, it is necessary to invoke another criterion: we use the physically significant requirement that MCSs be the systems responsible for a large portion of tropical rainfall. This requirement seems reasonable, since MCSs are important in determining the vertical profile of latent heating in the tropics (Houze 1982, 1989). This profile in turn largely determines the structure of the large-scale mean tropical circulation (Hartmann et al. 1984; Lin et al. 2004; Schumacher et al. 2004).

Mapping the MCSs identified by our methodology reveals global patterns of MCSs that are qualitatively consistent with current knowledge of tropical convection and adds quantitative measures of the climatological variability of MCS structure. Small separated MCSs are numerous mainly over the continental tropical regions of Africa and South America. Large separated MCSs occur frequently in these same continental regions. In addition, large separated MCSs occur with great frequency over the Maritime Continent, where relatively few small ones occur; evidently, the oceanic conditions in the Maritime Continent region favor growth of the MCSs to larger sizes. Connected MCSs ("super clusters") occur primarily over the warm pool regions of the Indian and west Pacific Oceans, where oceanic and atmospheric environmental conditions are often ideal for deep convection (e.g., during active phases of the MJO) and the diurnal cycle is weaker so that systems can reach their full potential of size [perhaps through the bidiumer cycle suggested by Chen and Houze (1997)]. Connected MCSs are likely prevented from occurring over the Maritime Continent because of the stronger diurnal cycle associated with the islands and peninsulas interspersed with the warm water in that region (Houze et al. 1981).

Since our methodology not only separates MCSs from other high-topped cloud systems but also separates the raining portions of MCSs from the nonraining portions, we have been able to map quantitatively the frequency of occurrence of MCS anvils (as well as anvils of non-MCSs) over the whole tropics. The availability of this climatology of MCS anvils will facilitate future calculations of the tropics-wide effects of MCSs on the vertical distribution of radiative heating. Mapping of the anvil coverage over the tropics will be the foundation for determining the horizontal distribution of radiative heating in the tropics. The horizontal variability of the latent heating profile across the tropics is now fairly well known via measurements of the convective and stratiform rain ratios detected by the TRMM satellite (Tao et al. 2001; Schumacher et al. 2004; Tao et al. 2006, 2007). In comparison, the horizontal variation of radiative heating profiles in the tropics has been relatively poorly known up to now even though it is known that the MCS anvils may contribute significantly to the vertical distribution of heating (Houze et al. 1980; Webster and Stephens 1980). The maps of anvil occurrence presented here provide a first step toward alleviation of this problem.

By analyzing CloudSat CPR profiles through the MCSs identified by our methodology, we have not only examined the horizontal distribution of MCS anvil clouds but also determined bulk aspects of their vertical structure. The nonraining anvils of MCSs throughout the tropics are mostly <~10 km thick, with a modal thickness of about 4–5 km. Over Africa and the Amazon, the MCSs are almost completely dominated by these less thick anvils. The less thick anvils are mostly located within distances of 1.5–2 times the equivalent radii of the primary rain areas of the MCSs. Over warm oceans the less
thick anvils may extend farther, especially over the warm pool of the Indian and west Pacific Oceans, where the less thick anvils may extend out to 5 times the equivalent radii of primary rain areas of the MCSs. The warm ocean MCSs are also characterized by thicker nonraining and lightly raining anvils near the edges of the actively raining regions of the MCSs, indicating that thick anvils are generated in and spread out from the primary raining regions of the MCSs. Such thicker anvils are nearly absent over continental regions.

The morphology and climatological variability of MCS anvils structures determined in this study lay the groundwork for determining the radiative effect of MCSs on the tropical circulation. To compute this heating accurately in the various types of anvil clouds associated with MCSs, further details of the three-dimensional structure must be sought. In this study, we have investigated only the bulk horizontal and vertical dimensions of anvils. The CloudSat CPR data contain further information on the vertical distribution of radar reflectivity within the anvils. This reflectivity is related to the ice water content of the anvils, and it varies depending on the part of the tropics in which MCSs are located, as has been seen in both cloud- and ground-based cloud radar data in selected regions (Cetrone and Houze 2009). Using CloudSat data in relation to the full tropical climatology of MCSs derived here, we will be able to determine more comprehensively how the internal structures of MCS anvils vary across the tropics. Then it will be possible to use radiative transfer calculations (e.g., McFarlane et al. 2007) to calculate heating profiles empirically across the tropics. These extensions of the present work are underway.

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