The Vertical Structure of Tropical Oceanic Convective Clouds and its Relation to Precipitation

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Abstract

Cloudsat cloud radar data are used to investigate the vertical structure of cloud systems of the ITCZ across the West and East Pacific and its contribution to precipitation. Cloud radar data are collocated with precipitation rates from the Advanced Microwave Scanning Radiometer (AMSR) to examine differences in cloud top PDFs for different rain rate regimes. Heavily precipitating clouds mostly have high tops that are two to three km deeper than moderately raining or non-raining high clouds. Moderately raining clouds and non-raining clouds are much more bottom-heavy in the East Pacific. Rain rate increases with cloud height, especially for clouds higher than 12 km, with nearly a tenfold rain rate increase from 12 km to the tropical tropopause. Shallow clouds with tops below 9.5 km contribute 28% to total rainfall in the West Pacific and 40% in the East Pacific, but they contribute 51% and 67% to total rain area, respectively.

1. Introduction

The vertical distribution of cloud heights ranges from low, marine stratocumulus to mid-level congestus to deep convective cumulonimbus clouds. The extent to which these cloud top heights vary is likely related to the large-scale circulation, local and non-local SSTs, SST gradients, and the intensity of convective systems. Considerable variations in SST structure are apparent across the North Pacific ITCZ from 5°-15°N, where the West Pacific (WP), from 120°-160°, is an area of very high SSTs (median of 28.9°C from mid June 2006 through mid March 2007), and relatively low SSTs gradients, as compared to the East Pacific (EP) (210°-260°), where SST gradients are higher but the median SST is considerably lower (27.7°C). SSTs are from the NOAA Optimum Interpolation Climate Diagnostics Center, with version two data used. It has been shown by Back and Bretherton [2006] and Back [2007] that while both the WP and EP are areas of mean ascent, the WP has a much more ‘top-heavy’ vertical velocity profile compared to the more ‘bottom-heavy’ vertical velocity profile in the EP. Back [2007] also derives a predictive
model of the tropical distribution of rainfall in which vertical motion is divided into deep and shallow modes, which are controlled by absolute SST and SST gradients, respectively. We use CloudSat cloud radar and AMSR microwave rain rate data to provide a more detailed analysis of the structure of deep and shallow convective systems in the WP and EP and their relation to precipitation.

It is known that differences in high cloud fraction per unit rain rate exist in the WP and EP. Kubar et al. [2007] show that high anvil cloud, with cloud tops colder than 245K, and intermediate visible cloud optical depth between 4 and 32, increases with rain rate, but is more abundant in the WP versus the EP. The most striking difference in high clouds, however, is that thin high clouds (τ<4) in the WP are approximately twice as abundant compared to the EP for a given rain rate. Luo and Rossow [2004] estimated that 44% of tropical thin cirrus clouds are directly detrained from convection, while 56% form in-situ, which suggests that the large-scale environment in the WP, with a more top-heavy profile, could be responsible for the greater sustainability of high thin cloud there, rather than differences in the deep convective core structure. Because CloudSat can detect shallow clouds under high clouds, our study also compares both deep and shallow convective systems in the WP and EP.

2. Data

We use data from CloudSat, which is the first satellite-born cloud radar (sun-synchronous), with an operational frequency of 94 GHz, for which backscatter from clouds can be measured. It was launched in April 2006, and data have been available since June 2006. As it is part of the A-train satellite constellation, it closely follows the orbit of the satellites Aqua, PARASOL, and Aura. The A-train has two equatorial passage times of approximately 1:30 a.m. and 1:30 p.m. local time. Its horizontal resolution of 2.5km along track by 1.4km across track, along with its vertical resolution of 240m, give CloudSat a small spatial footprint and good vertical resolution,
but only for a nadir curtain (Cloudsat Standard Data Products Handbook is available at:


CloudSat has an estimated operational sensitivity of -32dBZ, which prevents CloudSat from seeing cirrus, thinner than $\tau \sim 1.5$ (Mace, 2007). When the optical depth increases from 0.5 to 0.75, for instance, CloudSat goes from seeing 40% to 60% of high thin clouds. Though CloudSat misses 18% of thin cirrus, it only misses 1% of total cloud ice mass (Mace, 2007).

We also collocate the cloud data with instantaneous rain rate data from AMSR, aboard the Aqua satellite. AMSR data are gridded with a horizontal resolution of 25km by 25km. Microwave sensitivity becomes saturated when instantaneous rain rates exceed 25 mm/hr, though during this period of analysis (mid-June 2006 through mid-March 2007), observed rain rates do not exceed 15 mm/hr in our regions of interest.

3. Methodology

The CloudSat cloud mask product, which utilizes the radar reflectivity to determine cloud layers, is used to discriminate between cloudy and clear profiles. The algorithm implemented for this study can sense up to two cloud layers. While more than two cloud layers can exist, early results from CloudSat indicate that in the tropics, 70% of clouds occur in one layer, 25% in two layers, and only 5% in three layers (Mace, 2007). In a cloud overlap statistical study by Wang and Dessler [2006] using ICESat/GLAS data, nearly 90% of tropical clouds occur in single or double layers. Our study shows that when clouds are heavily precipitating, they are very likely to consist of a single deep layer.

The collocation methodology is straightforward, and simply matches the AMSR rain rate with all the CloudSat profiles that fall within its 25km footprint. No spatial or temporal averaging is performed, and all CloudSat profiles are assigned the precipitation of the AMSR pixel in which
they fall. Not averaging the profiles preserves the high CloudSat horizontal and vertical resolution.

4. Deep and Shallow Convective Cloud Systems

To examine the vertical cloud structure in the WP and EP, we begin by examining cloud systems, which we define as a contiguous group of profiles along the flight track that is identified as cloudy. Deep convective cloud systems must contain at least one profile with a cloud thickness of at least 10 km. Our analysis indicates that many deep convective systems are extensive, with a mean size of about 350 km in both regions. They also contain a potpourri of cloud tops, from boundary layer to mid-level congestus to deep cumulonimbus clouds, some of which penetrate to near the tropical tropopause of ~17 km. While deep convective cloud systems cover 29% of the WP and 25% of the EP from June 2006-March 2007, these differences are not statistically significant at the 95% confidence level, as revealed by a t-test analysis. We perform this test (and other t-tests in subsequent analyses) by subdividing the data from each region into 40 subaverages and using the following formula for t:

\[
t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{s_p^2 \left( \frac{1}{n_1} + \frac{1}{n_2} \right)}}
\]

(1)

where \(\bar{x}_1\) and \(\bar{x}_2\) refer to the means of our 40 subsamples (i.e. cloud fraction), \(n_1=n_2=40\), and \(s_p^2\), the pooled sample variance, given by:

\[
s_p^2 = \frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{n_1 + n_2 - 2}
\]

(2)

In (2), \(s_1^2\) and \(s_2^2\) are the variances of the subaverages.

Figure 1a shows the PDFs of all cloud tops within deep convective systems in the WP and EP. The distribution of high clouds looks remarkably similar in the WP and EP, with only a
slightly greater abundance of high clouds in the WP. If we define high clouds as clouds with tops
greater than 9.5 km, where a minimum in the cloud top frequency occurs, then 78% of all deep
convective system clouds are high clouds in the WP, and 68% in the EP. Within deep convective
cloud systems, low clouds with tops around 2 km are more prevalent in the EP, as are mid-level
clouds (~6 km).

Next we examine some statistics of shallow convective cloud systems, whose *lowest cloud*
top must not exceed 9.5 km, and whose cloud thickness must exceed five km for at least one
profile. Shallow convective systems likely encompass precipitating congestus clouds or perhaps
convection that is still developing, possibly into deep convection at a later time.

Figure 1b shows the PDFs of all cloud tops of shallow convective cloud systems, and
indicates a clear peak in cloud tops around six km that are likely precipitating congestus clouds.
Another peak is apparent between two and three km. A very small portion of the shallow
convective systems consist of high thin clouds around 12-13 km that overlie lower clouds. The
percent of the WP covered by shallow convective systems is only 2.4%, versus 4.5% in the EP,
and the t-test analysis reveals that these differences are statistically significant. The greater
amount of shallow systems in the EP is consistent with the stronger surface convergence in the EP.
Also, the mean size of shallow convective systems is considerably smaller in the WP at 48 km,
versus 105 km in the EP.

5. Vertical Structure and Coverage of High Thick, Shallow Thick, and High Thin Clouds

Instead of looking at clouds from a systems perspective, we now examine only particular
cloud types, irrespective of whether they are part of a contiguous cloud system. In Figure 2a, we
show histograms of clouds in which the lowest cloud is high (top greater than 9.5 km) and is
geometrically thick (thickness greater than 10 km), and also when the clouds are shallow and thick
(thickness greater than five km and top below 9.5 km). These are not PDFs as in Figure 1, but
instead distributions of *cloud fraction*. The WP has a statistically greater high thick cloud fraction compared to the EP, at 0.09 and 0.06, respectively. The shallow thick cloud fraction in the EP is not statistically different from the WP, at 0.05 versus 0.04, respectively. These two categories, high thick and shallow thick clouds, are two possible categories of precipitating clouds. We see here that the EP appears to be more bottom heavy in terms of its precipitating cloud distribution, which we quantify in a later section.

We also quantify the vertical distribution of high thin clouds, in which clouds thinner than five km are considered. Significantly more high thin cloud is observed in the WP, with a fractional coverage in the WP of 0.28, versus only 0.20 in the EP. We believe that many of these thinner high clouds are well removed from deep convection, since deep convective cloud systems in the WP and EP have similar vertical distributions, and since deep convective systems cover roughly the same domain fraction in each region.

6. **Cloud Tops of Precipitating and Non-Precipitating Clouds**

We next examine the vertical structure of clouds as a function of rain rate regime from AMSR. We examine PDFs of cloud tops for non-precipitating clouds, for clouds in which the rain rate is between the 25th and 75th percentiles, and for heavily precipitating clouds (rain rate greater than the 90th percentile). The percentiles of rain rate are for all raining profiles, with a rain rate threshold of 0.1 mm/hr.

Figure 3 shows the PDFs of cloud tops for these various rain rate categories. The heavily precipitating clouds in both the WP and EP are two to three km deeper than moderate and no precipitation cases. The peak of heavily precipitating high clouds in the WP is between 15 and 16 km, with only 0.5% of heavily precipitating clouds ascending to near or above the mean tropical tropopause of 17 km. Relatively few heavily precipitating clouds have cloud tops lower than 9.5 km (10% in the WP and 21% in the EP). Moderately precipitating high clouds generally have
similar high cloud distributions as non-precipitating high clouds, though high clouds are more common in the WP.

Shallow cloud (tops lower than 9.5 km) distributions are considerably different for moderately raining versus non-raining clouds, particularly in the EP. Non-raining shallow clouds are mostly very low boundary-layer clouds (around two km), whereas moderately raining shallow clouds are deeper, with two discernible peaks, at around three and six km. The secondary peak around six km could very well be classified as congestus clouds, as noted in such studies as Johnson et al. [1999]. Shallow clouds are much less common in the WP. The more bottom-heavy nature of cloud tops of moderately raining or non-raining clouds in the EP seems consistent with the ‘bottom-heavy’ vertical velocity profile there.

7. Contribution to total rain from different clouds

Finally, we attempt to quantify the contribution of different cloud heights to both total rain amount and total rain area in the WP and EP. We begin by examining the prevalence of clouds as a function of rain rate. We examine three cloud types: 1) high clouds only, 2) shallow clouds only, and 3) high clouds over shallow clouds. Figure 4a shows that as rain rate increases, the fraction of clouds that are only high clouds increases dramatically. For a given rain rate, more clouds are high clouds in the WP than the EP. For very light rain rates, more clouds are shallow clouds than high clouds in both regions, though more so in the EP (Figure 4b). The fraction of only shallow clouds decreases precipitously with increasing rain rate in both regions. The final category, high clouds over shallow clouds, primarily represents situations in which high thin clouds overlie lower precipitating clouds. The behavior of high over shallow clouds is the same in the WP and EP (Figure 4c).

Next, we examine the mean rain rate as a function of cloud top, which we present in Figure 5a, assuming that the cloud with the lowest top in each profile is raining. A fairly robust increase
in rain rate is observed with increasing cloud top height, except for the interval between 9 and 12 km, for which rain rate is approximately constant. The increase in rain rate with cloud top height is rapid for clouds deeper than 12 km. Note the logarithmic y-axis, so that a nearly tenfold increase in rain rate occurs as cloud tops rise from 12 km to 17 km, from ~1 mm/hr to ~10 mm/hr.

It is also noteworthy that significantly lower rain rates in the WP are associated with a given high cloud top versus the EP.

Finally, we compute the contribution to total rain amount as a function of cloud top height. We calculate this by multiplying the rain rate as a function of cloud top height, r(z), by the probability of a given cloud top height, p(z). These are shown Figure 5a and Figure 5b, respectively. The contribution to total rain amount, which we call the precipitation density (mm/hr/km), is shown in Figure 5c, and the total area under each curve is the mean rain rate for the given region. The WP and EP show large peaks at around 15-16 km and 13-14 km, respectively. The moderate contribution from clouds between about three and nine km represents the significant contribution to total rain from shallow clouds. Shallow clouds contribute less to total rain amount in the WP, at 28%, versus 40% in the EP. In terms of total rain area, shallow clouds contribute 51% in the WP and 67% in the EP. Thus, though precipitating shallow clouds are more widespread, high clouds contribute more substantially to total rain amount, especially on a per unit area basis.

8. Summary and Implications

We have seen that the vertical structure of deep convective cloud systems, which are defined to be contiguous cloudy profiles with at least one cloud containing a geometric thickness of at least 10 km, are fairly similar in the WP and EP. The deep convective cloud system fractional horizontal coverage in the WP and EP is 0.29 and 0.25, respectively, but this difference is not statistically significant. However, geometrically thin high cloud (thickness less than five
km) covers a significantly larger fraction of the WP at 0.28 versus 0.20 in the EP. As shown in
Kubar et al. [2007], optically thin high clouds (τ_{cloud}<4) exert a positive TOA warming, with these
clouds contributing to 10 Wm^{-2} greater TOA radiative forcing in the WP versus the EP.

This study has also demonstrated that heavily precipitating clouds in the WP and EP are
rather similar qualitatively, with the EP clouds only slightly more bottom-heavy. The real
difference lies in moderately raining or non-raining clouds, where the WP has a much smaller
abundance of shallow clouds relative to high clouds compared to the EP. This also may suggest
that deep convective cores are structurally similar in both regions, albeit a bit deeper in the WP.
High thin clouds contribute the most to differences in cloud top PDFs between the WP and the EP.

Finally, we have demonstrated that shallow clouds contribute 28% and 40% to total rain
amount in the WP and EP, respectively. Mean rain rates (where it is raining) are slightly higher in
the WP (1.42 mm/hr versus 1.25 mm/hr in the EP), probably because there are more high clouds
there, which have substantially greater mean rain rates than low clouds. Since rain rate increases
substantially as cloud top increases, especially for clouds higher than 12km, the mean rain rate for
a particular region is related to the distribution of heights of raining clouds. We also show,
however, that high clouds at a given altitude have greater rain rates in the EP, which may be a
result of the stronger low-level convergence there.

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References


Figure 1. (a) PDFs of cloud tops of all deep convective systems and (b) shallow convective systems in the WP and EP.

Figure 2. a) Cloud top histograms for all high thick clouds (cloud tops > 9.5km, and thickness > 10km) and low thick clouds (cloud tops < 9.5km, and thickness > 5km). b) Cloud top histograms for high thin clouds (thickness < 5km).

Figure 3. WP (a) and EP (b) cloud top PDFs for different rain rates (categories defined in text).

Figure 4. a) Fraction of clouds that are high clouds only, b) shallow clouds only, and c) high clouds over shallow clouds. High clouds have tops > 9.5km.

Figure 5. a) Mean rain rates versus cloud top heights \( r(z) \), assuming the lowest cloud is raining. The two curves for WP and EP indicate the 99% confidence intervals. b) PDFs of cloud tops \( p(z) \) of lowest raining clouds in each profile. c) Precipitation density, \( r(z) \cdot p(z) \) (mm/hr/km), representing the contribution from each cloud top to total rain amount in the WP and EP.
Cloud Fraction

Cloud Top Height (km)

High Thick Clouds
Shallow Thick Clouds

WP
EP

a) b)
AMSRR Rain Rate (mm/hr)

Fraction of Total Cloud

a) High Only
b) Shallow Only
c) High Over Shallow