GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L03804, doi:10.1029/2007GL032811, 2008

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Vertical structure of tropical oceanic convective clouds and its relation to precipitation

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Received 27 November 2007; accepted 2 January 2008; published 5 February 2008.

[1] 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 have high tops that are nearly two km deeper than moderately raining or non-raining high clouds. 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. Clouds with tops below 9.5 km contribute 38% to *total rainfall* in the West Pacific and 47% in the East Pacific, but they contribute 60% and 74% to *total rain area*, respectively. **Citation:** Kubar, T. L., and D. L. Hartmann (2008), Vertical structure of tropical oceanic convective clouds and its relation to precipitation, *Geophys. Res. Lett.*, *35*, L03804, doi:10.1029/2007GL032811.

1. Introduction

[2] Tropical convection plays an important role in the energy and moisture balances of Earth. Previous research has shown important differences between the structure of convection in the West Pacific (WP) and East Pacific (EP) ITCZ regions. The net radiative effect of clouds in the ITCZ is more nearly neutral in the WP and more negative in the EP [*Hartmann et al.*, 2001]. The inference of precipitation from microwave and infrared techniques is very different in the WP and EP, and these differences appear to be related to differences in cloud structure [*Berg et al.*, 2002]. *Schumacher and Houze* [2003] indicate a possible feedback between a higher stratiform rain fraction and stronger SST gradients in the EP. Using four independent datasets, *Zhang et al.* [2004] have observed a shallow circulation in the EP, and *Back and Bretherton* [2006] have shown significant differences in the mean vertical velocity profiles in the WP and EP, with vertical motion concentrated higher in the atmosphere in the WP than in the EP. The availability of simultaneous measurements of cloud structure from CloudSat and precipitation from AMSR on the A-Train (see *Stephens et al.* [2002] for more) provide a new opportunity to understand the differences in convection in the WP and EP.

[3] The extent to which cloud top heights vary is likely related to the SST, SST gradients, mesoscale and large-scale dynamics, and the intensity of convective systems. Considerable variations in SST structure are apparent across the ITCZ from 5°–15°N, where the WP, from 120°–160°, is an area of very high SSTs (median of 29.0°C from mid June 2006 through mid June 2007), and relatively low SST gradients, as compared to the 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 (available at http://www.cdc.noaa.gov), with version two data used [*Reynolds et al.*, 2002]. 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 its relation to precipitation.

[4] It is known that differences in high cloud fraction per unit rain rate exist in the WP and EP. *Kubar et al.* [2007] used MODIS and AMSR data to 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 ($\tau < 4$) 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.

2. Data

[5] We use data from CloudSat, which is the first satellite-borne 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 [*Stephens et al.*, 2002]. 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 2.5 km along track by 1.4 km across track, along with its effective vertical resolution of 240m, give CloudSat a small spatial footprint and good

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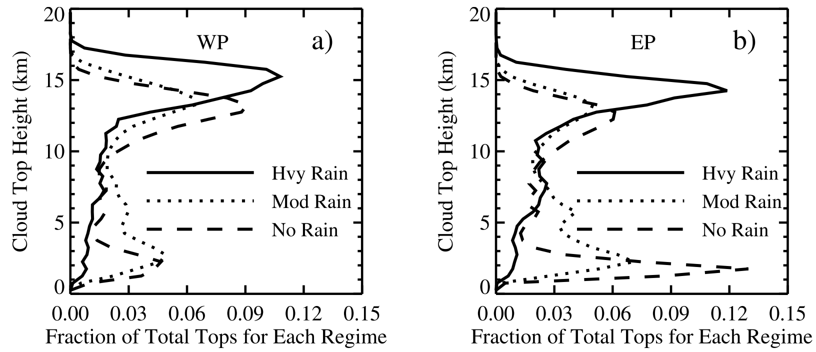

Figure 1. (a) WP and (b) EP cloud top PDFs for different rain categories (categories defined in text).

vertical resolution, but only for a nadir curtain (Cloudsat Standard Data Products Handbook is available at: http://www.cloudsat.cira.colostate.edu/dataHome.php).

[6] CloudSat has an estimated operational sensitivity of -32dBZ, which prevents CloudSat from seeing some thin cirrus. Since the main focus of our study is cloud structure as it relates to precipitation, the inability for CloudSat to sense all thin clouds is not viewed as a major drawback.

[7] 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 [*Wentz and Meissner*, 2000]. Microwave sensitivity becomes saturated when instantaneous rain rates exceed 25 mm/hr, though during this one-year period of analysis (mid June 2006 through mid June 2007), observed rain rates do not exceed 15.3 mm/hr in our regions of interest.

3. Methodology

[8] 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 four cloud layers. For all the *cloudy* profiles in this one-year analysis, 88% in the WP and 89% in the EP have either one or two cloud layers.

[9] The collocation methodology is straightforward, and simply matches the AMSR rain rate with all the CloudSat profiles that fall within its 25 km 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. Cloud Tops of Precipitating and Non-Precipitating Clouds

[10] We first examine the vertical structure of clouds as a function of rain rate regime from AMSR. We examine PDFs of all cloud tops for non-precipitating clouds, for raining clouds in which the rain rate is below the 90th rain rate percentile in each region, and for clouds in which the rain rate is equal to or greater than the 90th percentile (3.8 mm/hr and 3.7 mm/hr in the WP and EP, respectively). The percentiles of rain rate are for all raining profiles, with a rain rate threshold of 0.1 mm/hr. Though by definition clouds with rain rates that exceed the 90th percentile only comprise 10% of the rain *area*, they account for 47% and 50% of total rain *amount* in the WP and EP, respectively.

[11] Figure 1 shows the PDFs of cloud tops for these various rain rate categories, labeled as 'no rain', 'mod rain', and 'hvy rain'. The high mode of heavily precipitating clouds in both the WP and EP are nearly two km higher than moderate and no precipitation cases. The peak of heavily precipitating high clouds in the WP is between 15 and 16 km, with only 0.8% of heavily precipitating clouds ascending to above the mean tropical tropopause of 17 km. Relatively few heavily precipitating clouds have cloud tops lower than 9.5 km (19% in the WP and 27% in the EP), and the overall cloud top height distribution has a relative minimum near 9.5 km. Moderately precipitating high clouds generally have similar high cloud distributions as non-precipitating high clouds, though high clouds are more common in the WP for both categories.

[12] Low and middle cloud (tops lower than 9.5 km) distributions are considerably different for moderately raining versus non-raining clouds, particularly in the EP. Non-raining clouds are mostly boundary-layer clouds (around two km), whereas moderately raining low and middle 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]. The greater abundance of low and middle moderately raining or non-raining clouds in the EP seems consistent with the 'bottom-heavy' vertical velocity profile there.

5. Contribution to Total Rain From Different Clouds

[13] We next 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, in which the lowest top is greater than 9.5 km, 2) low and middle clouds only (tops lower than 9.5 km), and 3) high clouds over low and middle clouds. Figure 2a shows that as rain rate increases, the fraction of clouds that are *high clouds only* 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 low and middle clouds than high clouds in both regions, though more so in the EP (Figure 2b). The fraction of only low and

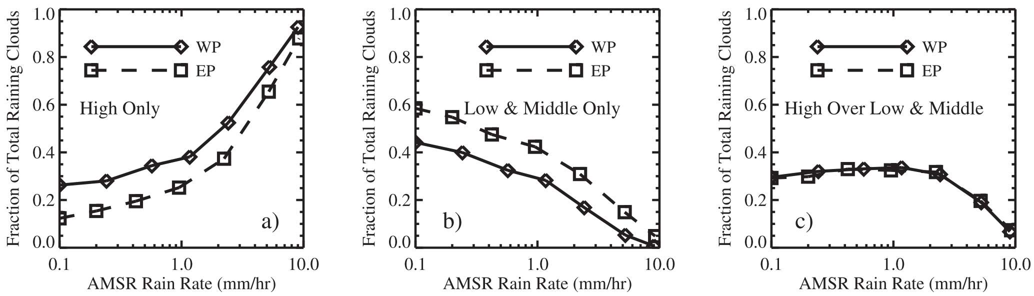

Figure 2. Fraction of clouds that are (a) high clouds only, (b) low and middle clouds only, and (c) high clouds over low and middle clouds. High clouds have tops >9.5 km.

middle clouds decreases precipitously with increasing rain rate in both regions. High clouds over low and middle clouds primarily represent situations in which high thin clouds overlie lower precipitating clouds, and their relationship with rain rate is very similar in both regions (Figure 2c).

[14] Next, we examine the mean rain rate as a function of cloud top, which we present in Figure 3a, 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, which may be a result of stronger low-level convergence there. When deep convection fires up, if stronger upward motion is present, we might expect it to be balanced by stronger rain rates.

[15] 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 lowest cloud top height, r(z), by the probability of a given *raining* cloud top height, p(z). These are shown Figures 3a and 3b, respectively. The contribution to total rain amount, which we call the *precipitation density* (mm/hr/km), is shown in Figure 3c, and the total area under each curve is the mean rain rate for the given region. The WP and EP have large peaks in *precipitation density* at just above 15 km and near 14 km, respectively. The moderate contribution from clouds between about three and nine km represents the contribution to total rain from low and middle clouds. Low and middle clouds contribute less to total rain amount in the WP, at 38%, versus 47% in the EP. In terms of *total rain area*, low and middle clouds contribute 60% in the WP and 74% in the EP. Thus, though precipitating low and middle clouds are more widespread, high clouds contribute more substantially to *total rain amount*, especially on a per unit area basis (see *Lau and Wu* [2003] for warm rain contribution to rain area versus rain amount).

6. High Thick and Middle Thick Cloud Systems

[16] We now examine *cloud systems*, which we define as a contiguous group of profiles along the flight track that is identified as cloudy. High thick convective cloud systems must contain at least one profile with a cloud thickness of at least 10 km. Many deep convective systems are extensive, with a mean size of about 340 km in the WP and 370 km in the EP. While deep convective cloud systems cover 27% of the WP and 24% of the EP from mid June 2006-mid June 2007, these differences are not statistically significant at the 95% confidence level, as revealed by a t-test analysis. We compute the t-test by subdividing the data from each region into 50 subaverages and using the standard deviation of these subaverages to compute confidence limits.

[17] Figure 4a shows the PDFs of all cloud tops within high thick 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. 67% of all deep convective system clouds are high clouds in the WP, and 56% in the EP. Within deep convective cloud systems, low clouds with tops around two km are more prevalent in the EP.

[18] Next, we examine some statistics of middle thick convective cloud systems, whose cloud thickness must

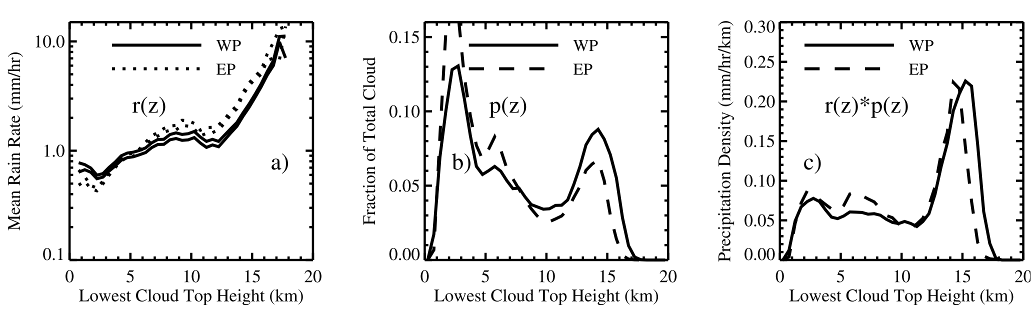

Figure 3. (a) Mean rain rates versus cloud top heights r(z), assuming the lowest cloud is raining. The two curves for WP and EP indicate the 99% confidence intervals. (b) PDFs of cloud tops p(z) of lowest raining clouds in each profile. (c) *Precipitation density*, r(z)●p(z) (mm/hr/km).

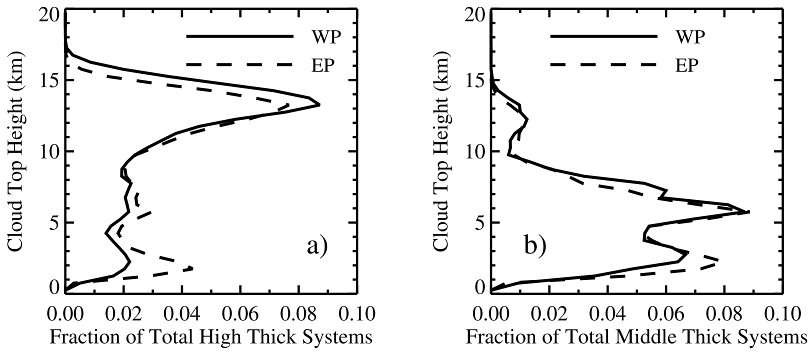

Figure 4. PDFs of cloud tops of (a) all high thick convective systems and (b) middle thick convective systems in the WP and EP.

exceed five km but whose cloud top must be below 9.5 km for at least one profile. While overlying high clouds are permitted, no high clouds with thicknesses greater than five km are allowed. Middle thick convective systems likely encompass precipitating congestus clouds or perhaps convection that is still developing, possibly into deep convection at a later time.

[19] Figure 4b shows the PDFs of all cloud tops of middle thick convective cloud systems, and indicates a clear peak in cloud tops around six km. 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 middle thick systems is 2.0%, versus 3.0% in the EP, and the t-test analysis reveals that these differences are statistically significant. The greater amount of middle thick systems in the EP is consistent with the stronger surface convergence in the EP. Also, the mean size of middle thick systems is considerably smaller in the WP at 40 km, versus 90 km in the EP.

7. Summary and Implications

[20] This study has demonstrated that heavily precipitating clouds in the WP and EP are rather similar qualitatively, with more precipitation coming from clouds with lower tops in the EP. The real difference lies in *moderately raining or non-raining clouds*, where the WP has a much smaller abundance of low and middle 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.

[21] We have demonstrated that low and middle clouds contribute 38% and 47% to *total rain amount* in the WP and EP, respectively. Mean rain rates (where it is raining) are slightly higher in the WP (1.37 mm/hr versus 1.29 mm/hr in the EP), probably because there are more high clouds there, which have substantially greater mean rain rates than low and middle clouds. Since rain rate increases substantially as cloud top increases, especially for clouds higher than 12 km, 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.

[22] We have also seen that the vertical structure of high thick 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 high thick convective cloud system fractional horizontal coverage in the WP and EP is 0.27 and 0.24, respectively, but this difference is not statistically significant. WP and EP high cloud differences instead stem from high thin clouds, which cover a significantly larger fraction of the WP at 0.33 versus 0.24 in the EP, irrespective of whether they are part of a contiguous cloud system.

[23] **Acknowledgments.** This work was supported by NASA grant NNG05GA19G.

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