The Characteristics of Tropical Precipitation Profiles As Inferred From Satellite Radar Measurements

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Abstract

In this study, we analyzed the vertical precipitation profiles in the tropics derived from radar onboard the Tropical Rainfall Measuring Mission satellite. For a given rain type, principal component analysis was done to all the profiles that have similar rainfall rate at 2 km altitude. It is found that the first principal component can explain more than 80% of the variations in the profiles, and the reconstructed first principal components closely resemble the ensemble mean. It is therefore concluded that the mean profiles are representative of the typical pattern of the vertical precipitation structure. The mean profiles for deep convections and stratiform rains are then derived and analyzed for the entire year of 1998 in the tropical belt of 15°S to 15°N. The results show that on a logarithm scale the slopes of the profiles are approximately constants if the profiles are divided vertically into 3 or 4 layers. The difference in slopes among layers may reflect the difference of dominant microphysical processes by which the precipitating hydrometeors either grow or evaporate. The difference between rain profiles between over ocean and over land, and the variation of rain profiles with latitudes are also investigated in this study. As one of the applications of the typical profiles to satellite remote sensing, we calculated the brightness temperature — rainfall rate relations using profiles derived in this study and those provided by previous investigators. It is demonstrated that the brightness temperatures resulted from vertical profiles of previous investigators generally agree, to some extent, with those resulting from the profiles of this study. However, some significant discrepancies exist over some rainfall rate ranges and for high microwave frequencies. It is expected that using the profiles of this study will lead to the improvement of satellite rain retrievals because they are derived from a much larger set of observational data, and are more representative of precipitations in the tropics.

1. Introduction

Knowledge of the characteristics of the vertical precipitation profiles is important to at least the following two areas: cloud dynamics and thermodynamics including latent heating, and remote sensing algorithm development. First, the vertical precipitation profiles reflect the dynamical and microphysical processes in the clouds (e.g., Houze 1981; Szoke et al. 1986; Hobbs 1989; Liu and Takeda 1989; Zipser and Lutz 1994). By studying

the maximum radar reflectivity profiles of convective cells in mesoscale convective systems, Zipser and Lutz (1994) pointed out that the profiles' shape between land and oceanic cells show significantly difference in accordance to the different strength of updrafts. With the exception of the bright band near melting layer, the increase (decrease) of radar reflectivity toward the surface in stratiform clouds indicates the growth (evaporation) of precipitating particles through microphysical processes (Fujiyoshi et al. 1980; Hobbs 1989; Liu and Takeda 1989). Microphysical processes that involve water phase change will heat or cool the atmosphere through latent heat exchange. One of the major goals of the Tropical Rainfall Measuring Mission (TRMM) is to assess the latent heating profile through measuring hydrometeors' profiles (Simp-

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son et al. 1988; Tao et al. 1993).

Physical retrieval of surface rainfall rate from satellite microwave measurements requires knowledge of the vertical distributions of hydrometeors. Rainfall algorithm developers have been working on this problem for decades. A simple solution is to assume a "typical" hydrometeors' profile based on knowledge from limited observations (e.g., Wilhelm et al. 1977; Liu and Curry 1992; Petty 1994; Aonashi et al. 1996). For the typical profiles, it is usually assumed that a layer of raindrops with a constant or a variable rainfall rate exists below freezing level while hydrometeors above freezing level could be all ice, or a mixture of liquid and ice particles (Liu and Curry 1992; Aonashi et al. 1996). Above freezing level, the rate at which precipitation decreases with height is usually rather arbitrarily assigned. Another approach is to establish a database of hydrometeor profiles from cloud model simulations and/or limited observations. Rainfall retrieval is then done by minimizing the difference between the simulated and the observed brightness temperatures using the predetermined profile database. This approach has been used by a number of investigators (e.g., Kummerow and Giglio 1994; Smith et al. 1994; Evans et al. 1995). Retrieval accuracy in this type of algorithm heavily depends upon the database used. To improve the accuracy of the rainfall retrieval algorithms, for example, the rainfall algorithm for Advanced Microwave Scanning Radiometer (AMSR) on future Advanced Earth Observing Satellite II (ADEOS-II), more representative and more realistic vertical precipitation profiles are unarguably required.

Studies on precipitation profiles have been mainly based on surface radar observations in field experiments (Houze and Cheng 1977; Szoke et al. 1986; Jorgensen et al. 1985; Zipser and Lutz 1994; Steiner et al. 1995). The data samples, therefore, are limited by the location and duration of the individual experiment. Additionally, cases with heavy rainfall are intentionally selected because of the interests of these studies (e.g., convective cells in mesoscale convective systems). TRMM satellite was launched in late 1997, with its main goal of measuring tropical precipitation and latent heating distributions. Among a number of instruments, a precipitation radar (PR) is onboard. Data of vertical distributions of precipitation intensities that are derived from radar returns has been continuously gathered covering the entire tropical belt between

35°S and 35°N, which provides us a unique opportunity to examine the characteristics of the vertical profiles of precipitation over the entire tropics for all different seasons (Kummerow et al., 2000). This research is initially motivated by this opportunity.

The objectives of this study are two fold. First, we investigate the general patterns of vertical precipitation profiles, and find a representative pattern for each cloud type. Possible physical interpretations are also attempted. The second objective is to quantitatively parameterize the vertical profiles according to their type and rainfall rate. This parameterization has direct applications to satellite rainfall algorithm development.

2. Data

Precipitation profiles derived from TRMM PR are the main data source of this study. The PR is an electronically scanning radar operating at 13.8 GHz (Iguchi and Meneghini 1994). It scans $\pm 17^\circ$ from nadir with 49 positions resulting in a 220 km swath width and a horizontal resolution of 4.3 km at nadir. A standard TRMM product, 2A-25, is used in this study, which contains the rainfall rate from Earth surface (mean sea level) to 20 km altitude in every 250 m resolution. The rainfall rates are calculated from radar reflectivities with corrections for attenuation based on Iguchi and Meneghini (1994). Besides rainfall intensity, the TRMM product also contains information on rain types including stratiform, convective and others. The classification for convective and stratiform rains used in the TRMM V-method (Awaka et al. 1998) is adapted in this study. A rain profile is classified as stratiform rain if a bright band exists near the freezing level. When the bright band does not exist and any one value of radar reflectivities in the beam exceeds 39 dBZ (Awaka et al. 1998, Iguchi and Meneghini 1994), the profile is classified as convective rain. Profiles do not meet the definitions of either stratiform or convective rain are labeled as "others", with the following two exceptions: (1) the profile is classified as convective if radar reflectivity exceeds 30 dBZ in 12 or more vertical bins above freezing level; (2) the profile is classified as convective if radar reflectivity exceeds 30 dBZ and is adjacent to a "convective center" that has a radar reflectivity greater than 40 dBZ. Besides the TRMM standard rain type definition of convective, stratiform and others, we specifically defined "warm rain" as those convective rains that have echo top below freezing level. Warm rain is in-

cluded in the convective rains in the TRMM product. In this study, we will reorganize the convective rains into warm convection and deep convection, so that the latter does not include warm rains.

The PR data that are used in this study are from January 1 to December 31 of 1998. In each radar scan, we only pick up the nadir precipitation profile because of the following two reasons: (1) a nadir view provides a true vertical profile instead of a slant vertical profile; and, (2) surface contamination at the lowest layers is the minimum for nadir profiles compared to the profiles with nonzero zenith viewing angles. This filtering results in about 2% (one in 49) of the available radar profiles being analyzed. In addition, profiles over land with an elevation larger than 500 m above sea level were excluded from the analysis, to keep retrieved rainfall rate at the low atmosphere uncontaminated. Even with these filtering, we still have enough number of samples to obtain statistically meaningful characteristics because of the long duration (one year) of the data. The total number in our sample dataset is 41,868,935, and of them 2,928,346, or about 7% are precipitating. We define a precipitating profile as nonzero rainfall rate observed at 2 km altitude. The reason we use 2 km altitude instead of surface (0 km) is that radar returns near the surface are always contaminated. Additionally, in all profile diagrams shown below we only plot values above 1.5 km for ocean cases, and above 2 km for land cases.

Table 1 shows the characteristics of the precipitating samples used in the analysis. Of the precipitating profiles, about half (44.8%) are classified as "others" in which rainfall rates are too light to meet the threshold for convective rain. Although these rains cover a large area, their contributions to total rainfall are small (only ~12%) because they are all light rains. A more detailed analysis shows that 96.2% of the pixels determined as "others" have

rainfall rate at 2 km of less than 0.5 mm/h, 2.4% from 0.5 to 1.0 mm/h, 1.0% from 1.0 to 5.0 mm/h and only 0.4% greater than 5.0 mm/h. If we do not count these profiles, the area fractions for stratiform, deep convection and warm convection are 79.9%, 11.5%, and 8.6%, respectively. Warm convection contributes about 2% of total precipitation, while the contributions by stratiform rain and deep convection are equally important, i.e., about 45% by stratiform and 42% by deep convection, a result being consistent with Bell and Suhasini (1994) and Liu et al. (1995). Many rainfalls (13.5% out of 44.8% in area fraction, 3.7% out of 11.8% in rain total) with warm tops are classified to "others" because of their light rainfall rates. If we add all rains with warm tops from both warm convections and others, the total area fraction and rain amount for warm rains become 18.2% and 5.4%, respectively, which are comparable with earlier studies (Petty 1999; Liu et al. 1995). However, it should be kept in mind that the warm rains here are defined by echo top, not cloud top.

3. Results

In this section, we first examine the characteristics of the precipitation profiles according to their types. Principal component analysis using empirical orthogonal functions (EOFs) is applied to find the representative patterns of the profiles. A parameterization is done to mathematically describe the typical profiles. The variability of the profiles according to regions, seasons and surface type (land or ocean) are also discussed.

3.1 Horizontal distribution of rain events

The number ratio of a particular rain type to total observations (i.e., area fraction) is calculated for each $1^\circ \times 1^\circ$ box during the entire year of 1998 and its horizontal distribution is shown in Fig. 1. The ratio for the rain type "others" is not shown because its ratio map is featureless, and the ratio is almost uniformly distributed in the tropical belt with a value of ~3–4%. The zonally averaged values of the number ratio are shown in Fig. 2. On zonally average, stratiform and others have a similar ratio of ~3–4% while the ratios for deep and warm convections do not exceed 1%. Stratiform rains are the dominant precipitation type in terms of area coverage, and have three maxima in the zonal frequency distribution: one near the equator and two in the mid latitudes. Deep convections occur most frequently in the intertropical conver-

Table 1. Statistics of sample radar precipitation profiles

Rain Type	Number of Profiles	Area Fraction	Rain Total Fraction	Average Rainfall Rate
Stratiform	1,291,595	44.1% (79.9%) ^a	44.9%	1.3 mm/h
Deep Convection	186,420	6.4% (11.5%) ^a	41.6%	8.6 mm/h
Warm Convection	138,435	4.7% (8.6%) ^a	1.7%	0.5 mm/h
Others (warm/cold) ^b	1,311,896 (394,867 / 917,029) ^b	44.8% (13.5%/31.3%) ^b	11.8% (3.7%/8.1%) ^b	0.35 mm/h (0.37/0.34) ^b

^a Percentages in the parenthesis indicate the fractions without counting "Others" as precipitating profiles

^b Values in the parenthesis are for those with echo top below/above freezing level

Fig. 1. Horizontal distribution of the number ratio (area fraction) of (a) stratiform, (b) deep convection, and (c) warm convection profiles to total observations. Different halftone scales are used for each rain type for better showing of the horizontal structures.

Fig. 2. Latitudinal distribution of the number ratio of a specific rain type to total observations.

gence zone (ITCZ). Unlike stratiform rainfalls, the occurrence frequency of deep convections does not have peaks in the mid latitudes. Warm convections have higher frequencies in the subtropical oceanic regions in both hemispheres, particularly in north Pacific, southeast Pacific, south Indian, and southwest Atlantic Oceans. The abundance of warm shallow precipitation near Hawaii was reported by early investigators (e.g., Takahashi and Lee 1978), which is clearly shown in Fig. 1c.

Since the rainfall rates are very light (average 0.35 mm/h at 2 km altitude), the rain type of others is not included in the data analysis in the following sections. It is also worth mentioning that some 8.4% of the nonprecipitating profiles (no rain at 2 km) have measurable radar returns above 2 km. The frequency of radar echo for these profiles typically peaks near 5 km (freezing level) and decreases both up and downward (not shown). It is plausible that these profiles are caused by precipitating ice particles aloft which are evaporated before reaching 2 km altitude.

3.2 Principal component analysis

Let us first examine some examples of the PR observed vertical precipitation profiles in the western Pacific (10°S – 10°N , 140 – 180°E). Figure 3 shows the spaghetti diagram of the profiles for: (a) deep convections that have average rainfall rate of about 10 mm/h (8 to 12 mm/h) at 2 km altitude, and (b) stratiform rains that have average rainfall rate of about 5 mm/h (4 to 6 mm/h) at 2 km altitude. A total of 257 deep convection and 418 stratiform profiles are plotted in the figure, covering data for the year 1998. Individual profiles appear to be quite different from each other even though their rainfall rates near 2 km are almost the same. The biggest difference seems to be near the freezing level where radar reflectivity is enhanced (bright band) by the melting of ice particles. The derived rainfall rate at this level is not correct because of the enhancement.

In the search for regularities of these profiles, a principal component (PC) analysis is performed using EOFs (Kutzbach 1967). The central question we are trying to answer through the PC analysis is whether there is a statistically dominant pattern in the profiles given a rain type and a rainfall rate at 2 km. The amplitude profiles for the three leading PCs are shown in Figs. 4a and 4c for deep convection and stratiform profiles, respectively. In the figure, the contribution of each PC to the to-

tal variance is indicated in parenthesis in the up-right corner of each diagram. The three leading PCs count for more than 96% of the total variance in the profiles. The most noticeable feature is the predominance of the first PC that can explain 88% of the total variance for deep convection and 91% for stratiform profiles. The reconstructed profiles

Fig. 3. Spaghetti diagrams for vertical precipitation profiles for (a) deep convection, and (b) stratiform rains for rainfall rate of 10 mm/h at 2 km in the region of western Pacific Ocean.

Fig. 4. The amplitudes of the three leading principal components (a and c) and their reconstructed profiles (b and d). The mean profiles are also shown in (b) and (d). P1, P2 and P3 are for the first, second and third principal components. The percentage in the parenthesis (a and c) indicates the percent of variance that each component can explain.

based on the first three PCs, as well as the mean profiles (simple average of the profiles in Fig. 3), are shown in Figs. 4b and 4d. It is shown that the reconstructed first PCs closely resemble the mean profiles, especially for stratiform rains.

For stratiform rains, the second and third PCs are related to the variation in strength and altitude of the bright band. The change in the strength of the bright band may be due to the variation in ice particle size and/or shapes. The second PC in deep convections shows a dipole structure between surface and 5 km. It is interpreted that it reflects the convective cells at early or dissipation stages. In these stages, a majority of the raindrops either is still up aloft (early stage) or falls near the ground (dissipation stage). A study using this development stage information to further characterize tropical convections is underway. The third PC for deep convection shows a wave-like pattern. We could not come up with a satisfactory physical explanation for the pattern, if there is any.

In summary, the second and third PCs for stratiform profiles are related to the strength and position of the bright band. The bright band is a phenomenon connected to phase change rather than mass flux (rainfall rate) change of hydrometeors. For deep convective profiles, the second PC may be an indication of the developing stages of individual cells. The first PC, which reflects the mean profile, is the predominant component that can explain more than 88% of the total variance in both deep convection and stratiform rains. This is true to rainfalls not only in the western Pacific, but also for the entire tropics as shown in Table 2, which gives the contributions of the three leading PCs for the tropical belt of 15°S to 15°N. We differentiate profiles over ocean and land because they show clear differences in shapes as shown later in the next section, probably due to stronger vertical velocity in convections over land as discussed by Zipser and Lutz (1994). The land areas defined in this study include maritime-continent regions. The predominance of the first PC becomes more evident as the rainfall rate increases. We interpret this tendency as the indication that the first PC has better representation for well-developed rain systems.

The predominance of the first PC implies that the reconstructed first PC, or the mean profile, is statistically meaningful enough to represent the characteristic pattern of vertical precipitation profiles. In other words, given a rain type (convective/stratiform) and a rainfall rate at 2 km, the

Table 2. Contribution to total variance (in %) by the first three leading PCs for the tropical belt of 15°S to 15°N

R ₂ ^a	Deep Convection								Stratiform							
	Ocean				Land				Ocean				Land			
	N ^b	PC1	PC2	PC3	N ^b	PC1	PC2	PC3	N ^b	PC1	PC2	PC3	N ^b	PC1	PC2	PC3
1	2115	72.1	15.0	4.7	350	79.3	12.2	3.3	3751	79.5	9.9	2.4	567	80.4	7.7	3.5
5	6064	82.5	10.8	2.7	1160	75.6	13.1	5.0	5650	90.7	3.5	1.6	1117	90.9	2.7	1.8
10	5359	87.4	8.0	1.7	1222	84.8	8.4	2.6	2106	92.2	2.8	1.5	348	92.7	1.9	1.7
15	2419	89.5	6.2	1.4	628	86.2	8.4	1.9	229	91.9	3.2	1.5	51	93.9	2.1	1.2
20	1241	91.0	5.2	1.3	348	83.8	9.3	2.5								
25	641	90.8	5.5	1.3	235	86.3	8.7	2.1								
30	390	90.0	5.1	2.1	174	92.4	4.1	1.1								

^a Rainfall rate (mm/h) at 2 km altitude^b Number of profiles

rainfall rate profile tends to follow the mean profile with statistically significant likelihood. This finding is interesting in the following two ways: First, it implies that there is a common physical process working in the tropical cloud systems that determines the general pattern of the rain vertical profiles; second, it provides a constraint, at least in a statistical sense, to formulating models of vertical hydrometeor structures that can be used in satellite rain retrieval algorithms.

3.3 Characteristics of the vertical precipitation profiles

As discussed in the previous section, the mean profiles, which are similar to the first PC in the EOF analysis, explain most of the variation in vertical precipitation profiles. Therefore, it is reasonable to use the mean profile to represent the characteristics of vertical precipitation distribution. We describe these characteristics in this section according to rainfall type and rainfall rate at 2 km. We confine our focus on the tropical belt between 15°S and 15°N since the freezing level height is almost constant at 5 km without substantial change during the year. The profiles in higher latitudes of subtropics are compared with the tropical profiles in the next section. Additionally, the profiles of warm convections are discussed in section 3.5.

Figure 5 shows the mean profiles over ocean whose rainfall rates at 2 km altitude are 1, 5, 10, 15, 20, 25 and 30 mm/h, respectively. The numbers of the original profiles for averaging have been listed in Table 2. Because there is no sufficient number of samples, stratiform profiles for rainfall rates larger than 15 mm/h are not processed. For stratiform rains, the bright band near 4.5 km sep-

Fig. 5. Mean vertical profiles for rains over ocean for rainfall rates of 1, 5, 10, 15, 20, 25 and 30 mm/h at 2 km.

arates two totally different variation regimes. Below the bright band, rainfall rates are almost constant with only a slight decrease toward the surface, implying that raindrops experience no further growth or may undergo slight evaporation. Above the bright band, a sharp downward growth of rainfall rates occurs within a layer 1 km deep, followed by a slower growth above. This feature has been observed and explained by previous investigators (e.g., Houze 1993, Chapter 6). It is explained that

while falling from above, ice particles grow mainly by vapor deposition at high level, which is the slowest microphysical growth mode. While they are near freezing level, the ice particles may grow by deposition, riming, and more importantly, aggregation. The last process increases the particle size dramatically, which in turn sharply increases radar reflectivity. The bright band itself is a result of melting process, that does not reflect the change in mass flux.

The mean profiles for deep convections display different characteristics from those of stratiform profiles. The maximum of rainfall rate appears at a much lower level (2–3 km) than the height of the stratiform bright band. A tendency of decreasing rainfall rate toward the surface can be seen below the maximum rainfall rate level, especially for heavier precipitations, which indicates the possibility of raindrop evaporation. Above the maximum rainfall rate level, we can generally divide the vertical distribution into three regimes: (1) a slow drop off from the maximum level to freezing level (~5 km), (2) a rapid drop off in the layer of 1 to 2 km in depth above freezing level, and (3) another very slow drop off above. While the pattern above freezing level is quite similar to those in stratiform profiles, the additional growth (toward surface) of rainfall below freezing level is unique to the convective profiles, which may be an indication of growth by coalescence.

Some precautions are necessary when interpreting the downward drop below the level of rainfall rate maximum. While it is quite possible that the drop off is due to evaporation, another possibility, i.e., attenuation of radar echo, may also be a factor although attenuation corrections have been applied in the derived rainfall rate products.

Similar to Fig. 5, the mean profiles of rainfall over land are shown in Fig. 6. The profiles for stratiform rainfalls are very similar to those over ocean (Fig. 5). However, the deep convective profiles have significant difference from those over oceans. The height of the maximum rainfall rate is at 3–4 km, higher than that in the over ocean profiles. As a result, the layer where it may correspond to growth by coalescence becomes very shallow. For the same surface rainfall rate, the growth layer above freezing level is deeper than that in the ocean cases. In other words, the bulk of the growth occurs at a higher altitude. Below the maximum rainfall rate level, the drop off of rainfall rate toward surface becomes more evident than those over ocean cases.

Fig. 6. Mean vertical profiles for rains over land for rainfall rates of 1, 5, 10, 15, 20, 25 and 30 mm/h at 2 km.

This may be an indication of more severe evaporation over land areas, although we cannot exclude the possibility of attenuation as discussed earlier. Zipser and Lutz (1994) compared radar reflectivity profiles observed over land to those observed over ocean using the maximum radar reflectivity (the maximum reflectivity at each level in an 8 km × 8 km box) of convective cells. They also found that land profiles are generally deeper than ocean profiles. Their explanation is that the vertical velocity of convective cells over land is generally greater than that in oceanic convective cells.

In studying the profiles of the maximum radar reflectivity of convective cells in GATE (Global Atmospheric Research Program Atlantic Tropical Experiment), Szoke et al. (1986) found that the slope of $\text{dBZ}[\text{dBZ}=10\log Z]$, where Z is radar reflectivity and $\log$ is 10-based logarithm] is about -1.25 dBZ/km for the layer between cloud base and freezing level, and about -5 dBZ/km above freezing level; both values are nearly constant with little dependence on individual cloud systems. Aonashi et al. (1996) used this relationship for their rainfall rate retrieval algorithm. Since the Z and R (rainfall rate) is related by $Z=aR^b$, where a and b

are constants, dBZ is proportional to $\log R$. To examine how the GATE maximum radar reflectivity profiles compares to our mean profiles of the entire tropics, we plotted the mean rainfall profiles on a logarithm scale (Fig. 7). The data used to plot this figure are the same as those used for Figs. 5 and 6. From Fig. 7, it appears that the slopes are fairly constant within each layer if the layer's divisions are those shown in the figure by dotted lines.

For deep convections, the bottom layer is from surface to the level of the maximum rainfall rate, that is about 2.5 km deep for ocean cases and 3.5 km deep for land cases. The second layer locates above the bottom layer but below freezing level. This layer is about 2.25 km deep for ocean cases and 1.25 km deep for land cases. The third layer is about 2 km deep above freezing level for both ocean and land cases, followed by a top layer above it. For stratiform rains, the rainfall rate in the bottom layer (from surface to bright band) does not show a clear tendency. The second layer locates above the bright band, having ~ 1.5 km for ocean cases and 1.0 km for land cases. It is not clear

Fig. 7. The profiles in a logarithm scale. The horizontal dotted lines show the divisions of vertical regimes. The slope in each regime appears to be nearly constant. The thick lines, that are determined visually, indicates the typical variation in vertical of the profiles. Numerical values of slopes in Table 3 are derived from these thick lines.

whether the difference in the depth between ocean and land has any physical explanation. Then a top layer with slower growth is located above the second layer. In order to have a quantitative representation, we draw a line (thick line in the figure) in each layer by visual determination to indicate its characteristic slope. It is seen that these lines fit the best to the profiles of 15–20 mm/h for deep convections, and 5–10 mm/h for stratiform rains. The numerical values of these slopes are listed in Table 3 in both $\Delta \log R / \Delta z$ and $\Delta \text{dBZ} / \Delta z$ (in parenthesis), where z is height. The Z – R relation used to make the conversion is $Z = 200R^{1.6}$ (Aonashi et al. 1996). For deep convections over ocean, the slopes in $\Delta \text{dBZ} / \Delta z$ compares well with those for GATE given by Szoke et al. (1986) if we view everything above 0°C level as a whole layer.

It is interesting to see that there is no visible difference between over ocean and over land stratiform rains except for a slightly shallower layer just above the bright band for rains over land. It is also noticed that the slopes for the upper-most layer are almost identical for all rain regardless of rain and surface type. The most significant difference between deep convections over ocean and over land appears to be that land rains have a deeper rain layer. This difference needs to be taken into account when formulating rain profile models for satellite rain retrievals.

3.4 Seasonal and latitudinal variabilities

The seasonal variation of the mean vertical precipitation profiles (for convective rainfall rate of 10 mm/h and stratiform rainfall rate of 5 mm/h at 2 km) is shown in Figs. 8 and 9 for deep convections and stratiform rains, respectively. The plots are differentiated by whether they are over ocean or land, and by whether they are near the equator (15°S – 15°N) or at high latitudes (north of 30°N). It is seen that within the tropical belt of 15°S to 15°N ,

Table 3. Characteristic slopes of mean profiles*

Deep Convection			Stratiform		
Layer*	Ocean	Land	Layer*	Ocean	Land
above surface	0.02	0.03	surface to bright band	0	0
2.5 km/3.5 km	(0.32)	(0.48)	4.5 km/4.5 km		
below 0°C level	-0.08	-0.11			
2.25 km/1.25 km	(-1.3)	(-1.8)			
above 0°C level	-0.43	-0.33	above bright band level	-0.63	-0.63
2 km/2 km	(-6.8)	(-5.3)	1.5 km/1.0 km	(-10.1)	(-10.1)
upper most	-0.24	-0.21	upper most	-0.23	-0.23
	(-3.8)	(-3.4)		(-3.7)	(-3.7)

* The slopes are represented by $\Delta \log R / \Delta z$, R is rainfall rate in mm/h, z is height in km, and log is 10-based logarithm. The values in parenthesis are $\Delta \text{dBZ} / \Delta z$, where dBZ is radar reflectivity in decibel.

* The two values are layer depth for ocean/land.

Fig. 8. Seasonal and latitudinal variations of the mean profiles for deep convections. DJF: December, January, February. MAM: March, April, May. JJA: June, July, August. SON: September, October, November.

Fig. 9. Same as Fig. 8 but for stratiform rains.

the variation with seasons is minimal regardless of rain and surface types. However, it displays a clear seasonal variation at latitudes higher than 30°N . Due to the decrease in air temperatures in cold seasons at latitudes of 30°N to 35°N , the bright band height in winter lowers by more than 2 km from its summer high. So does the bulk of the rain layer. During winter, the altitude of bright band in stratiform rains and the altitude of the maximum rainfall rate in convections become lower than 1.5 km and 2 km for ocean and land cases, respectively, which are lower than the lowest level we deem to have uncontaminated data.

3.5 Warm convections

Most of the warm convections are observed only in the subtropical oceans (Fig. 1). The mean profiles for rainfall rates of 1, 2, 3, 4, and 5 mm/h near 2 km are shown in Fig. 10. EOF analysis shows that the first PC can explain more than 90% of the variance and the reconstructed profile from the first PC resembles the mean profile. It is shown that there is a rainfall rate maximum below 2 km, and the altitude of this maximum rises as rainfall rate increases. Above the maximum rainfall rate level, the slopes are nearly proportional to the rainfall rate at 2 km, resulting in $\Delta \log R / \Delta z \approx -0.6$ or $\Delta \text{dBZ} / \Delta z \approx -10$. Below the maximum rainfall

Fig. 10. Mean profiles for warm convections. Rainfall rates at 2 km are 1, 2, 3, 4, and 5 mm/h.

rate level, it appears that evaporation causes the rainfall to decrease toward the surface. However, it is hard to quantify the rate of decrease because the peaks are too close to the lowest level having uncontaminated data.

4. Implications to satellite microwave remote sensing

Vertical precipitation profiles are needed in developing rain retrieval algorithms using satellite microwave measurements since the top of the atmosphere brightness temperatures vary depending upon the details of the vertical precipitation structure even though the rainfall rates at the surface are the same. There are basically two ways to utilize the vertical profiles in rain retrievals. One is to use a typical profile given the rain type and surface rainfall rate. Then a forward radiative transfer simulation can relate the observed brightness temperature to surface rainfall rate (Wilheit et al. 1977; 1991; Liu and Curry 1992; Aonashi et al. 1996). Another is to establish a large database that contains all the possible profiles. Once the observation of a spectrum of brightness temperatures is obtained, a large number of radiative transfer simulations are then conducted using the prior designed database to find the best match between the observed and simulated brightness temperatures (Kummerow and Giglio 1994; Smith et al. 1994; Evans et al. 1995). In this section, we demonstrate how the first retrieval method, i.e., the typical profile method, is affected by the difference in vertical profiles.

Wilheit et al. (1977; 1991) assumed that the rainfall rate is constant below freezing level and there are no raindrops above freezing level. Their models are designed for frequencies lower than 22 GHz for which the ice scattering is believed unimportant. Liu and Curry (1992) used profiles that have a constant rainfall rate below freezing level but a mixture of ice and liquid above the freezing level. The top of the precipitation layer in their model increases with surface rainfall rate, and the rainfall/snowfall rate above freezing level decreases linearly to the top of the precipitation layer. Aonashi et al. (1996) used profiles that are based on the maximum radar reflectivity observations during GATE (Szoke et al. 1986). The slopes in their model are -1.25 dBZ/km below freezing level and -5.0 dBZ/km above freezing level. In the following discussions, we compare the relationships between brightness temperature and surface rainfall

rate using the aforementioned profiles and the profiles with slopes listed in Table 3. The frequencies that are considered here are 18.7 and 89 GHz; both are from AMSR on the future ADEOS II satellite.

Fig. 11. Horizontally polarized brightness temperatures versus rainfall rates for ocean cases. Frequencies of 18.7 and 89 GHz in the AMSR channels are used. OC: deep convection over ocean, OS: stratiform over ocean, WL: Wilheit et al. 1977, LI: Liu and Curry 1992, AO: Aonashi et al. 1996.

Fig. 12 Same as Fig. 11 but for land cases.

The relations between rainfall rate and brightness temperature are shown in Fig. 11 for rains over ocean and in Fig. 12 for rains over land. The radiative transfer model of Liu (1998) is used to calculate the brightness temperatures. Only horizontally polarized brightness temperatures are shown in the figures. The curves of OC, OS, LC and LS are for the profiles of deep convection over ocean, stratiform over ocean, deep convection over land and stratiform over land, respectively. A mixture of ice and liquid are assumed in the layer just above freezing level for deep convection, or bright band for stratiform rains, and all hydrometeors in the top-most layer are assumed to be ice. The curves of WL, LI and AO are for the profiles given by Wilheit et al. (1977), Liu and Curry (1992) and Aonashi et al. (1996), respectively. For the sake of focusing on differences caused by precipitation profiles, we did not include cloud water in the calculations. We simulated stratiform rains only up to 15 mm/h, because higher rainfall rates for stratiform are not frequently observed. Marshall and Palmer (1948) size distribution is used for rain drops, and Sekhon and Srivastava (1970) size distribution is used for ice particles (snow). The bulk density of ice particles is assumed to be 0.1 g cm^{-3} . A standard tropical atmospheric profile (U.S. Standard Atmosphere, 1976) is used in the radiative transfer simulation. The sea surface temperature is assumed to be 300 K, and the land surface emissivity is assumed to be 0.9.

It is interesting that the curves for deep convection and stratiform rains differ little from each other for ocean cases (Fig. 11), although the patterns of their profiles are quite different (Figs. 5). It is plausible that the arc shape of the deep convection profiles has an equivalent effect on upwelling microwave radiation to the shape of the constant rain below 0°C level of stratiform. This also explains why for 18.7 GHz over ocean the Wilheit et al. profiles result in similar brightness temperatures to those of the profiles given in this study. For 18.7 GHz, the Aonashi et al. and Liu and Curry profiles cause underestimation of brightness temperatures at lower and higher rainfall rates, respectively. For 89 GHz, there is no rainfall rate signature when the Wilheit et al. profiles are used (Note: the Wilheit et al. profiles were not designed for using high microwave frequencies), while brightness temperatures based on both the Aonashi et al. and the Liu and Curry profiles follow the same general direction as those of this study. But, both profiles

result in underestimation of brightness temperatures to some extent. It is noticed that the brightness temperatures based on the Aonashi et al. profile have a better match with those based on the profiles derived in this study when the rainfall rates are sufficiently large (e.g., $R > 20 \text{ mm/h}$). This is reasonable because the Aonashi et al. profiles are derived from only heavy rainfalls over oceanic areas (i.e., GATE). It is also worth mentioning that 89 GHz brightness temperatures show no visible difference between convective and stratiform rains when using profiles derived from this study. From Fig. 5, it is seen that precipitation rates above freezing level are similar between convective and stratiform rains. Because we did not make differences in microphysical properties (such as particle density, size distribution, etc.) between convective and stratiform rains in the radiative transfer model, the brightness temperatures for the two rain types result in very similar values. However, it is not clear in nature whether the microphysical properties are the same for the two rain types. If they are not, brightness temperatures may be different even though their rain profiles are similar. This question needs to be investigated in future studies.

Over land (Fig. 12), there is not much rain signature in the 18.7 GHz channel because of the high emissivity of land surface. For 89 GHz, the Aonashi et al. and the Liu and Curry profiles generate brightness temperatures following the same general direction as those of this study with some differences. Because the brightness temperatures at 89 GHz are the most sensitive to the solid precipitating particles, the discrepancy reflects the differences of precipitation profiles above freezing level among these precipitation profile models.

The simulation results indicate that rainfall rate retrievals can be different to a certain extent depending on the "typical" rain profiles used in the algorithm. The profiles used by previous investigators are satisfactory to some extent while improvements are still needed. The mean profiles provided in this study are therefore useful for the algorithm improvement at least in the tropics. As indicated in section 3.5, since the profiles in higher latitudes depend on the height of the freezing level, special considerations on the freezing level dependence are required for algorithms dealing with rainfalls in high latitudes.

5. Conclusions

In this study, we analyzed the vertical profiles

observed by TRMM precipitation radar. The central question we intended to answer is: Is there a typical vertical precipitation profile given a rain type and a surface rainfall rate? If yes, what is its typical pattern and how does it impact on satellite rain retrievals? While the difference of the profiles between tropics and higher latitudes has been represented, the regions of our main focus are between 15°S and 15°N where the freezing level is constant during the year.

Following the classification in the standard TRMM product, we analyzed the profiles that are determined as deep convections, stratiform rains, and warm convections. The contribution to total rain is about 42% from deep convection, 45% from stratiform rain, and 2% from warm convection. For a given rain type, principal component analysis was conducted to all the profiles that have similar rainfall rate at 2 km altitude. It is found that the first principal component can explain more than 80% of the variations in the profiles, and the reconstructed first principal components closely resemble the ensemble mean. Therefore, it is concluded that the mean profile is representative of the typical pattern of the vertical precipitation structure. Besides convective, stratiform and warm rains, approximately 45% of the rainy pixels are classified as "others" which contributes a rain amount of about 12% of the total. The pixels appear to be distributed "randomly" all over the place and more than 96% of them have a rainfall rate of less than 0.5 mm/h.

The mean profiles for deep convections and stratiform rains are then derived from the data of 1998 in the tropical belt of 15°S to 15°N. It is shown that on a logarithm scale the slopes of the profiles are approximately constants if the profiles are divided vertically into 3 or 4 layers depending on the rain types. The different values in the slopes may reflect the microphysical processes by which precipitating hydrometeors either grow or evaporate. For the purpose of developing remote sensing algorithms, the numerical values of the slopes have been given in Table 3. To the authors' knowledge, this study is the first in surveying the vertical precipitation profiles in such an extended area (15°S to 15°N) and over such a long time period (one entire year). The difference between rain profiles between over ocean and over land, and the variation of rain profiles with latitudes are also shown in this study.

As one of the applications of the typical profiles to satellite remote sensing, we calculated the

brightness temperature — rainfall rate relations using profiles of this study and those proposed by previous investigators. It is demonstrated that the brightness temperatures resulted from vertical profiles of previous investigators generally agree, to some extent, with those resulting from the profiles of this study. However, some significant discrepancies exist over some rainfall rate ranges and for high microwave frequencies. It is expected that using the profiles of this study will lead to improvement of satellite rain retrievals because they are derived from a much larger set of observational data, therefore, are more representative of precipitations in the tropics.

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