Why does radar reflectivity tend to increase downward toward the ocean surface, but decrease downward toward the land surface?

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[1] Both ground and space borne radars have shown that radar reflectivity profiles below the freezing level have different slopes over land and ocean in general. This is critical in correctly estimating the surface precipitation rate in the usual situation in which the radar reflectivity cannot be measured as close to the surface as one would like. Using 14 years of Tropical Rainfall Measuring Mission precipitation radar observations, the variations of slopes of the radar reflectivity in the low troposphere are examined over the stratiform and convective precipitation regions. Radar reflectivity below the freezing level usually decreases toward the surface over land, but increases toward the surface over the ocean. Increasing reflectivity toward the surface is hypothesized to occur mainly when raindrops grow while falling through low clouds, which is favored by high humidity at low levels, and by updraft speeds lower than the fall speed of raindrops, both more likely over oceans. Other things being equal, proxy evidence is presented that the more intense the convection, the more likely reflectivity is to decrease toward the surface, and that this is at least as important as low-level relative humidity. Over monsoon regions with more moderate convection but higher humidity, such as southeast China and the Amazon, there are more profiles with reflectivity increasing toward the surface than over other continental regions such as Africa. Radar reflectivity tends to increase toward the surface in shallow warm rain systems in trade cumulus regions, but tends to decrease toward the surface when high reflectivity values are present at or above the freezing level.

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1. Introduction

[2] Accurate estimation of surface precipitation is critical in interpreting the global water cycle. Detailed observations of vertical structure of precipitation is important in understanding latent heat release, which plays an important role in the global circulation. Until the launch of the Tropical Rainfall Measuring Mission (TRMM) [Kummerow et al., 1998] satellite in late 1997, it was not possible to provide reliable surface rainfall estimates and vertical structure of precipitation with global coverage.

[3] The Ku band (13.4 GHz) TRMM precipitation radar (PR) scans precipitation systems with horizontal resolution of ~4 km and vertical resolution of 250 m from the top of precipitation system to near surface with the sensitivity of ~18 dBZ reflectivity [Kummerow et al., 1998]. Using the PR reflectivity closest to the surface, the rainfall estimates at near-surface levels can be derived [Iguchi et al., 2000, 2009]. This near-surface rainfall has been used as the “true” surface rainfall in many applications, such as calibrating the rainfall retrievals from microwave radiances [Gopalan et al., 2010] and generating the climatology of the global precipitation [Adler et al., 2003]. However, because of the contamination by ground clutter, the reliable PR reflectivity closest to the ground is ~0.5–1.0 km above the surface at nadir, but can be as high as 2–3 km off-nadir over complex terrain. This leads to an uncertainty in using the near-surface rainfall rate as the rainfall rate reaching the ground.

[4] Many studies show that the amount of rainwater reaching at the surface can be very different from that at a few kilometers above [i.e., Tripoli and Cotton, 1980; Rosenfeld and Mintz, 1988; Takemi, 1999; Fu et al., 2003]. For example, as shown in Figure 1, due to evaporation alone, the reduction of the amount of rainwater from 1 km height to the ground can be 100% for very light rain, and as high as 50% for heavy rain falling through a very dry environment. Most of the rainwater loss is due to the evaporation of the small raindrops. Because smaller raindrops have larger surface area/mass ratio and lower fall velocity, they evaporate more efficiently than large raindrops. Because radar reflectivity is mostly determined by the large raindrops, there is only a relatively small change of the radar reflectivity due to evaporation. Table 1 provides specific examples from Figure 1 illustrating that rainwater losses of 30–50% in the lowest km may be accompanied by reflectivity decreases of only about 1 dB.
Evaporation is just one of many ways that rainfall rate may vary from near surface to the ground. When there is a low cloud base and raindrops falling though clouds, the rainfall rate would increase due to the collection of cloud droplets [i.e., Liu and Fu, 2001]. When there is a strong wind shear near the surface, the vertically tilted structure of rainfall may also lead to large differences from the surface rainfall to that at a few kilometers above [i.e., Rutledge and Houze, 1987; Parker and Johnson, 2000]. Therefore, to correctly estimate the rainfall at the surface, it is important to understand the vertical gradient of both the rain rate and the radar reflectivity near the surface.

Subject to a similar problem, ground-based radar can only observe the reflectivity very close to the surface over flat terrain and close to the radar. Yet most operational radar networks have radars spaced quite far apart, such that the minimum effective height of the center of the radar beam may be 1–2 km or more above the surface. Therefore, there have been many studies trying to use the information of the vertical gradient of radar reflectivity to estimate the actual surface rainfall from ground-based radars [Fabry and Zawadzki, 1995; Vignal et al., 2000; Bellon et al., 2005]. But these studies are only over limited land regions. Using 3 years of TRMM PR data, Hirose and Nakamura [2002] investigated the vertical gradient of rainfall rate below 4 km during the Indian monsoon. Applying the same methodology to global data, they found that the vertical gradient of rainfall at low levels varies under different weather regimes over different regions [Hirose and Nakamura, 2004]. Also, using TRMM PR observations, Liu et al. [2008] showed that both the profile of maximum radar reflectivity and the profile of the areas with echo of 20 dBZ and greater tend to increase toward the surface in oceanic precipitation systems and decrease toward the surface in land precipitation systems. Attenuation of the Ku band PR reflectivity at low levels is one concern in these studies. However, great care has been taken to correct for attenuation, and there is no reason to believe that the near-surface reflectivity is biased systematically toward under- or overcorrection. [7] These same weather regime and regional dependences of vertical gradient of radar reflectivity are also found in observations by ground radars, when the data set is carefully selected to be quite free of attenuation or terrain complications. For example, numerous field programs in tropical ocean environments show reflectivity increasing downward below the 0°C level, and continuing to increase as the sea surface is approached. Szoke et al. [1986] and Szoke and Zipser [1986] used shipboard radars during the Global Atmospheric Research Program Atlantic Tropical Experiment (GATE) experiment, with maximum reflectivity at or below 500 m altitude. Cifelli et al. [2007], Johnson et al. [2005], and Yuter et al. [2005] all demonstrated a similar increase in reflectivity approaching the sea surface using ship- or island-based radars, not subject to attenuation and restricting the data set to close range to be able to have good vertical resolution at low levels. In contrast, Zipser and Lutz [1994] reported reflectivity profiles from a ground-based research radar in Darwin, Australia, that decreased toward the surface for continental storms while still increasing toward the surface for oceanic storms.

This study is to further explore the vertical gradient of the radar reflectivity at low altitudes by using 14 years of TRMM observations during 1998–2011. Section 2 introduces the data and methodologies used in this study. Section 3 presents the statistics of the slopes of the radar reflectivity in the low troposphere from the PR profiles at nadir, as well as that of the maximum radar reflectivity within the convective regions. The summary is given in section 4.

2. Data and Methods

To investigate the vertical gradients of the individual radar reflectivity profiles, ~25 million attenuation-corrected radar reflectivity observations were used. The reflectivity at low levels varies under different weather regimes over different regions [Hirose and Nakamura, 2004]. Also, using TRMM PR observations, Liu et al. [2008] showed that both the profile of maximum radar reflectivity and the profile of the areas with echo of 20 dBZ and greater tend to increase toward the surface in oceanic precipitation systems and decrease toward the surface in land precipitation systems. Attenuation of the Ku band PR reflectivity at low levels is one concern in these studies. However, great care has been taken to correct for attenuation, and there is no reason to believe that the near-surface reflectivity is biased systematically toward under- or overcorrection.
Using 14 years of PR radar reflectivity profile at nadir pixels, the slopes of reflectivity below 4 km are calculated. (a) Percentage of the nadir profiles with slope greater than 0 (reflectivity decrease toward the surface) in $2^\circ \times 2^\circ$ grids. Thin contours show the number of samples in each grid. Note that a higher proportion of the profiles decrease toward the surface over land than over ocean, especially over Africa and Australia. Regions with more positive/negative slopes are shown with warm/cold colors. Regions of interest in Figure 10 are shown with dashed boxes. (b) Fractions of nadir profiles with extreme positive/negative slopes greater than 1 dBZ/km increase. Only grids with more than 20 samples are shown.
smaller than 80 km

This excludes small isolated cumulus showers with size regions with at least 4 PR pixels are used to remove noise.

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18 dBZ (about the sensitivity of the PR) [e.g., Bolen and Chandrasekar, 2000; Liao and Meneghini, 2009]. Therefore, the attenuation is not considered to be an important issue here. Note that the slopes of reflectivity below 4 km may represent the general variation of the radar reflectivity below the freezing level in most cases, but not for subtropical precipitation during winter and sometimes in spring and fall when the freezing level is often lower than 4 km [Harris et al., 2000]. However, it would take a huge effort to find the freezing levels for millions of profiles. Therefore, the slopes below 4 km are used for both tropics and subtropics. But for this reason, the results over the subtropics are discussed with appropriate caution in the following sections.

3. Results and Discussion

3.1. Slopes of Radar Reflectivity Below 4 km in Nadir Profiles

[11] One concern is that attenuation might cause the decreasing of the reflectivity at low levels, especially when high reflectivity exists at high altitudes. However, there have been many studies showing that in the 2A25 product, the attenuation is well corrected by comparing to ground radars [e.g., Bolen and Chandrasekar, 2000; Liao and Meneghini, 2009]. Therefore, the attenuation is not considered to be an important issue here. Note that the slopes of reflectivity below 4 km may represent the general variation of the radar reflectivity below the freezing level in most cases, but not for subtropical precipitation during winter and sometimes in spring and fall when the freezing level is often lower than 4 km [Harris et al., 2000]. However, it would take a huge effort to find the freezing levels for millions of profiles. Therefore, the slopes below 4 km are used for both tropics and subtropics. But for this reason, the results over the subtropics are discussed with appropriate caution in the following sections.
Though most land regions between 36° S and 36° N have more than 40% of radars with reflectivity decrease toward the surface, some regions have less, for example, Southeast China, Bay of Bengal, and the Northeast coastal region of Brazil (Figure 2a). Xu and Zipser [2012] show that convection over these monsoon regions is relatively weaker than typical continental convection.

[11] Hirose and Nakamura [2004] showed that shallow rainfall profiles are more likely to have reflectivity increasing toward the surface. To understand this relationship further, the two-dimensional (2D) cumulative histogram of the radar profiles over tropical land and ocean are shown as a function of the slope of reflectivity below 4 km and the echo top height in Figure 3. There are more profiles with echo top below the freezing level over ocean than over land (Figures 3a and 3b). These profiles are predominantly increasing toward the surface with negative slopes over both land and ocean. Deep profiles with echo top above the freezing level have both positive and negative slopes below 4 km.

[12] Turning attention to stratiform precipitation regions, a similar analysis is completed for profiles with radar-detected bright bands. The general concept is that the stratiform region has strong evaporation with cooling in the low troposphere [Zipser, 1977; Houze, 1997], because stratiform precipitation frequently consists of light to moderate rainfall rates falling through unsaturated air below the freezing level. Therefore, decrease of radar reflectivity below freezing
In general, more convective profiles have predominately positive slopes. However, only about 50–70% of the bright-band profiles have positive slopes over most regions of the tropics and subtropics. This is consistent with Figure 3c. It is interesting that over Southeast Asia, less than 50% of the bright-band profiles have positive slopes (Figure 4a). This means that there are more profiles with increasing reflectivity toward the surface even in the stratiform rain area over this region. We speculate that these regional differences are mainly due to differing low-level relative humidity (RH) and differing fractional coverage of low clouds beneath the bright band, which are in agreement with high humidity from global reanalyses as discussed further in section 4.2.

The regional variations of the slopes of the deep and shallow profiles in convective regions are shown by the percent of nadir profiles with positive slopes in Figures 4b and 4c. In general, more convective profiles have reflectivity increasing toward the surface over ocean than over land, especially for the shallow profiles. Over land, deep convective profiles are somewhat more likely to increase toward the surface, except over deserts, the Brazilian plateau, India, Africa, and regions with high terrain. These regional differences are due to the different convective intensity and evaporation rate under various large-scale environments and will be discussed further in section 4.

### 3.2. Slopes of Maximum Radar Reflectivity Below 4 km in Convective Regions

In total, more than 21 million convective regions with at least four pixels are identified from 14 years of PR observations. The global distribution of the percent of the maximum reflectivity with positive slopes is close to the nadir profiles shown in section 3.1 (not shown). From a different perspective, Figure 5a shows the mean slopes of the maximum reflectivity profiles in the convective region with 40 dBZ echo. Over tropical land, mean positive slopes are found over Central Africa, the Brazilian Plateau, and northwest Australia. Steeply negative slopes are found over regions dominated by shallow rainfall over ocean. Comparing the mean slopes for deep and shallow convective regions in Figures 5b and 5c, deep convective regions tend to have...
reflectivity decreasing toward the surface, with higher values of the slope than the shallow convective regions. This implies that convective intensity could play an important role in the reflectivity structure at low levels and will be discussed further in section 4.1.

Figure 6. (a) Percentage with positive slope of maximum reflectivity below 4 km (reflectivity decreasing toward the surface) of the maximum reflectivity profiles in convective regions with maximum echo top height > 4.5 km in 2° × 2° grids in December–January–February (DJF). Thin contours show the number of convective regions with maximum height > 4.5 km in each grid in DJF. (b) Same as (a), but for convective regions in JJA. (c) Same as (a), but for convective regions with 40 dBZ echo top > 4.5 km. (d) Same as (a), but for convective regions with 40 dBZ echo top > 4.5 km in JJA. Only grids with more than 20 samples are shown.

Consistent with the seasonal variations of rain rate vertical profiles, as pointed out by Hirose and Nakamura [2004], under the different weather regimes, there are some large seasonal variations in the slopes of maximum reflectivity profiles as well. Removing the samples of shallow convective regions, the percents of the maximum radar reflectivity decreasing toward the surface (with positive slopes) in the convective regions with echo top above 4.5 km are shown in Figures 6a and 6b. In both summer and winter, the oceanic convective regions with ice have the maximum radar reflectivity mostly increase toward the surface, except near the west coast of continents in the Hadley cell transition zone with the dry environment. Over land in June–July–August (JJA), most convective regions with echo top > 4.5 km have maximum reflectivity decrease toward the surface, except those over Southeast Asia and the Amazon (Figure 6b). Over the subtropics during wintertime, there are lower percents of the positive slopes likely due to the low freezing level and the bright band being below 4 km, which means that higher values of the reflectivity are expected at lower levels. It is worth noting that when there is some high radar reflectivity (e.g., 40 dBZ) above the freezing level, the maximum radar reflectivity tends to decrease toward the surface over land and a large area of ocean, more over land than over ocean (Figures 6c and 6d).
This is additional empirical evidence that convective intensity plays an important role in the reflectivity structure at low levels.

4. Discussion

What are the fundamental reasons for the variations of the vertical gradient of radar reflectivity toward the surface? One obvious possibility that could account for some of the observed differences between land and ocean is that RH is often lower over land, and that evaporation is more likely to reduce reflectivity near the surface, especially for deep unsaturated layers. But another clear difference between land and ocean is that convective intensity is often greater over land, and we have already shown that the stronger the proxies for convective intensity, the more likely that reflectivity increases with height (positive slope). In this section, we evaluate the relative importance of these two factors, for the entire data set, and then for specific regions.

4.1. Convective Intensity

We shall now show additional evidence that the reflectivity slopes have a close relationship to commonly used proxies for updraft speed, which is what is often meant by convective intensity [e.g., Zipser et al., 2006]. Since updraft speed cannot be measured from satellites, we must use such proxies. Figure 7 shows the fraction of the positive slopes of the maximum radar reflectivity profiles below 4 km as the function of maximum echo top heights and maximum 30 dBZ echo top heights over tropical ocean (20°S–20°N). Numbers of samples in each 0.25 × 0.25 km bin are shown as contours. (b) Same as (a), except for the convective regions over tropical land. (c) Same as (a), except as the function of maximum echo top height and maximum 40 dBZ echo top height over tropical ocean (20°S–20°N). (d) Same as (c), except for the convective regions over tropical land.

![Figure 7](image_url)

Figure 7. (a) Fraction of the convective regions with positive slope of the maximum radar reflectivity profiles below 4 km as the function of maximum echo top heights and maximum 30 dBZ echo top heights over tropical ocean (20°S–20°N). Numbers of samples in each 0.25 × 0.25 km bin are shown as contours. (b) Same as (a), except for the convective regions over tropical land. (c) Same as (a), except as the function of maximum echo top height and maximum 40 dBZ echo top height over tropical ocean (20°S–20°N). (d) Same as (c), except for the convective regions over tropical land.
rate and likely varies the slope of the radar reflectivity profile. Raindrops do not fall through the clouds; they rise through the clouds and increase their size by collecting small cloud droplets, and thus have radar reflectivity increase toward the surface. The shallow rainfalls over ocean with low-level RH is lower, possible due to larger evaporation strength of the updraft plays an important role in the vertical gradient of the reflectivity in the low troposphere. When there is a weak updraft, the raindrops are more likely to fall distant from the updrafts, or within downdrafts, or as melted graupel, with the increased possibility of falling through unsaturated air.

In addition to these factors, we hypothesize that the strength of the updraft plays an important role in the vertical gradient of the reflectivity in the low troposphere. When there is a weak updraft, the raindrops are more likely to fall through the clouds and increase their size by collecting small cloud droplets, and thus have radar reflectivity increase toward the surface. The shallow rainfalls over ocean with dominant negative slopes are the good example of this scenario (Figures 3a, 3b, 4c, and 5b). However, when there is a strong updraft greater than the terminal velocity of raindrops, raindrops do not fall through the clouds; they rise. However, they rise more slowly than the cloud droplets, which are ascending at close to the speed of the updraft. Therefore, raindrops can continue to grow as they ascend, reaching larger size at and above the freezing level, helping to explain why the radar reflectivity decreases toward the surface. When they finally do fall to the surface, they are more likely to fall distant from the updrafts, or within downdrafts, or as melted graupel, with the increased possibility of falling through unsaturated air.

4.2. Low-Level RH

Low-level RH directly determines the evaporation rate and likely varies the slope of the radar reflectivity (Figure 1 and Table 1). It is important to understand its influence on the reflectivity structure at low levels. We temporally and spatially interpolate the relative humidity at 850 hPa from the European Center for Medium-range Weather Forecasts reanalysis (ERA-Interim [Dee et al., 2011]) to the center locations of each convective region. Then the fraction of the positive slopes of maximum reflectivity profiles of convective regions as the function of different relative humidity at 850 hPa and different reflectivity echo top heights are shown in Figure 9. Most of the maximum reflectivity profiles increase toward surface regardless of low-level RH when the echo tops are lower than 5 km (Figures 9a and 9b). When echo top reaches high altitudes (>7 km), positive slopes become more dominant when low-level RH is lower, possible due to larger evaporation rate.

The maximum height reached by the 30 dBZ echo is a better proxy for convective intensity than the maximum echo height, because substantial updraft speed is necessary for creating or lofting graupel to substantial heights. Figures 9c and 9d show that the percentage of positive slopes is very sensitive to the 30 dBZ echo top at all low-level RHs, and hardly sensitive to the RH itself at all. Comparing land and ocean (Figure 9a vs. Figures 9c and 9b vs. Figure 9d), the
main difference is found at very high RH at low levels for stronger and deeper convection. For such conditions, there is still a preference for negative slopes over oceans.

The impact of RH is evaluated further over different regions in Figure 10. Over the Amazon, Sahel, and China, maximum reflectivity is more likely to increase toward the surface when 30 dBZ echo top is below the freezing level (Figures 10a–10c). Note that even under low RH over the tropical Atlantic and east and west Pacific, the maximum reflectivity is still likely to increase toward the surface when the 30 dBZ echo top is low (Figures 10d–10f). When 30 dBZ reaches high altitudes, more maximum reflectivity profiles decrease toward the surface over Africa regardless of the low-level RH (Figure 10b). Comparing the Amazon and Sahel, the former resembles the global tropical ocean (Figure 9c) and the Sahel more closely resembles global tropical land (Figure 9d). It is interesting that the impact of low-level RH is more obvious over the east Pacific and Atlantic (Figures 10d and 10f) than the west Pacific (Figure 10e), with higher fraction of negative slopes under high 850 hPa RH when 30 dBZ echo top is high.

Note that ERA-Interim 850 hPa relative humidity must be regarded as a rough estimate of the large-scale environment for each convective feature and may not represent the specific environment of the storm. Nevertheless, the results suggest that low-level RH must be considered as a significant factor that is related to the slope of the maximum reflectivity profile below the 0°C level, but it may not be the dominant factor.

4.3. Diurnal Variation of the Reflectivity Slope Below Freezing

The properties of radar reflectivity in storms may vary at different stages of the life cycle [e.g., Yuter and Houze, 1995a, 1995b]. This leads to the question of the variation of the reflectivity slopes below freezing level in the storms at different stage of their life cycle. However, the stage of the life cycle of a storm cannot be inferred from the snapshots of TRMM. The diurnal variation of the properties of storms composited from individual snapshots may infer properties of convection during their life cycle, especially over land [e.g., Nesbitt and Zipser, 2003; Liu and Zipser, 2009].

Figure 9. (a) Fraction of the convective regions with positive slope of the maximum radar reflectivity profiles below 4 km as the function of maximum echo top heights and relative humidity at 850 hPa from ERA-Interim over tropical ocean (20°S–20°N). Numbers of samples in each 0.25 km × 5% bin are shown as contours. (b) Same as (a), except for the convective regions over tropical land. (c) Same as (a), except as the function of maximum 30 dBZ echo top heights and RH at 850 hPa from ERA-Interim over tropical ocean (20°S–20°N). (d) Same as (c), except for the convective regions over tropical land.
Therefore, the diurnal variations of the slopes of the reflectivity profiles at nadir below freezing level are examined in Figure 11. Consistent with earlier results (Figure 8), the negative slopes dominate in the nadir profiles below the freezing level when the 30 dBZ echo top is below the freezing level over both land and ocean. Consistent with previous literature, there is stronger diurnal variation in the number of profiles with 30 dBZ reaching at high altitudes over land than over ocean. It is interesting that nadir convective profiles with 30 dBZ reaching 5–10 km over land are more likely to have positive slopes in early afternoon (more growing convection) than those in evening and early morning (Figure 11b).
diurnal variation of fraction of positive slopes with same convective intensity is not seen in the stratiform profiles (Figure 11d). We may infer that the growing convection in the early afternoon tends to have strong updrafts, consistent with the previous figures showing that positive slopes are more likely with stronger convection, while we would not expect stratiform profiles to have strong convective drafts.

4.4. Short Summary of Discussion

[27] In general, the convection over land is stronger than that over ocean [LeMone and Zipser, 1980; Lucas et al., 1994; Zipser and Lutz, 1994], with stronger updrafts, although numerous exceptions occur. With this in mind, potential explanations for the observed differences in slope of radar reflectivity over land and ocean are listed:

- Reflectivity increases toward the surface.

  a. Shallow precipitating clouds, confined below a stable layer in the lowest 2–5 km. Assuming updrafts <4–6 m s⁻¹ (the fall speed of 1–2 mm diameter raindrops), any raindrops forming near cloud top will fall quickly, accreting and growing as they descend. Radar reflectivity should increase downward unless cloud base is quite high. This scenario seems to explain the observations in the trade wind regions, especially the transition between trade cumulus and stratocumulus regions over subtropical oceans, as well as the warm rain regions in cool seasons near the east coasts of Brazil, Madagascar, and Costa Rica. b. Cumulus or cumulonimbus convection with updrafts <4–6 m s⁻¹ below the freezing level. Over much of the tropical oceans, especially the east Pacific intertropical convergence zone (ITCZ) and the Atlantic ITCZ, as first documented during the GATE experiment, such weaker updrafts may be observed throughout the troposphere. By the same physical reasoning as in (1), raindrops should grow while falling through low-base clouds in a high RH environment.

  c. Orographic precipitation on a windward slope. Provided only that cloud base is low, and updraft velocities weak, similar reasoning leads to the hypothesis that raindrops continue to grow while falling. A good example of this in California was demonstrated by White et al. [2003].

- Reflectivity decreases toward the surface.

  a. Any precipitation falling from high-base clouds through highly unsaturated air, such as those over desert.
b. Any precipitation forming within updrafts \(>4-6 \text{ m s}^{-1}\), strong enough to loft raindrops to and above the freezing level. While this may be effective in clean air (with an active warm rain process operating at low levels within the cloud), it applies especially well for deep convection growing in air with high cloud condensation nuclei concentrations, in which warm rain is suppressed [Albrecht, 1989; Rosenfeld et al., 2008], such that most rain reaching the surface falls from melted graupel. That often means that the rain falls through a deep layer of unsaturated air farther away from the updrafts, and that a smaller fraction of rain falls through low clouds.

5. Summary

[26] Using 14 years of TRMM PR observations, the vertical gradients of the radar reflectivity below 4 km are investigated by using nadir radar reflectivity profiles as well as the maximum radar reflectivity profiles in convective regions in precipitation systems with size greater than 80 km\(^2\). Therefore, our results exclude small isolated rain showers, and all precipitation systems with maximum reflectivity smaller than the 18 dBZ sensitivity of the PR. Major findings include:

1. Consistent with earlier studies [Hirose and Nakamura, 2004], shallow precipitation systems have radar reflectivity increasing toward the surface. Regardless of the depth of the precipitation, radar reflectivity tends to increase toward the surface over ocean and decrease toward the surface over land.

2. Other things being equal, the proposed explanation for reflectivity increasing toward the surface is that raindrops grow while falling through clouds, more likely for weaker convection with updrafts smaller than raindrop fall speeds, and for high RH at low levels. Evidence is presented that either condition is more likely over ocean than over land, with convective intensity usually a more dominant factor than humidity. When updrafts are strong enough to loft raindrops to and above the freezing level, reflectivity usually decreases toward the surface.

3. When there are high radar reflectivity values above the freezing level, the radar reflectivity tends to decrease toward the surface. That is, the more intense the convection, the more likely that reflectivity decreases toward the surface.

4. Radar reflectivity mostly decreases toward the surface in the precipitation systems over the desert regions, most likely due to high cloud bases and low RH, but also, and at least as importantly, because convection over desert regions tends to be quite deep and intense when it occurs.

5. Monsoon regions have more cases with reflectivity increasing toward the surface than the regions with typical continental convection, presumably because convection is often of only moderate intensity [Xu and Zipser, 2012], and low level humidity is often higher.

6. About 40% of the radar reflectivity profiles with a detectable bright band have reflectivity increasing toward the surface, presumably because these are cases with higher RH and low clouds more likely below the 0°C level.

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