Improvements in Detection of Light Precipitation with the Global Precipitation Measurement Dual-Frequency Precipitation Radar (GPM DPR)

ATSUSHI HAMADA AND YUKARI N. TAKAYABU

Atmosphere and Ocean Research Institute, University of Tokyo, Kashiwa, Japan

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ABSTRACT

This paper demonstrates the impact of the enhancement in detectability by the dual-frequency precipitation radar (DPR) on board the Global Precipitation Measurement (GPM) core observatory. By setting two minimum detectable reflectivities—12 and 18 dBZ—artificially to 6 months of GPM DPR measurements, the precipitation occurrence and volume increase by ~21.1% and ~1.9%, respectively, between 40°S and 40°N.

GPM DPR is found to be able to detect light precipitation, which mainly consists of two distinct types. One type is shallow precipitation, which is most significant for convective precipitation over eastern parts of subtropical oceans, where deep convection is typically suppressed. The other type is probably associated with lower parts of anvil clouds associated with organized precipitation systems.

While these echoes have lower reflectivities than the official value of the minimum detectable reflectivity, they are found to mostly consist of true precipitation signals, suggesting that the official value may be too conservative for some sort of meteorological analyses. These results are expected to further the understanding of both global energy and water budgets and the diabatic heating distribution.

1. Introduction

A common understanding of precipitation in the tropics and subtropics has been developed based on more than 16 years of observations by the Tropical Rainfall Measuring Mission (TRMM) satellite, which was launched in November 1997. One of the instruments on board the TRMM is a precipitation radar (PR) that can probe three-dimensional structures of precipitation, which has advanced the understanding of precipitation systems. The TRMM PR has also played an extraordinary role in improving rainfall retrieval algorithms based on spaceborne passive infrared/microwave measurements.

Following the success of TRMM, the Global Precipitation Measurement (GPM) core observatory was launched successfully at the end of February 2014 and started its observations (Hou et al. 2014). On board the GPM core observatory is a dual-frequency precipitation radar (DPR) that operates in the Ku (13.6 GHz) and Ka (35.5 GHz) bands, making observations between ~65°S and ~65°N from a non-sun-synchronous orbit.

The primary objectives of the GPM DPR are to provide measurements of light precipitation and solid precipitation with a higher accuracy and a wider coverage in latitudinal span than those obtained by the TRMM PR. The obtained data are also expected to contribute to addressing unsolved problems, even in the regions of the tropics and subtropics that have been observed by the TRMM PR.

Improving the detection of light precipitation is considered to have a significant impact in producing more accurate information on which to base estimates of global energy and water budgets. Based on observations from spaceborne cloud radar and lidar, which can detect lighter precipitation than the TRMM PR, Trenberth et al. (2009) suggested increasing the precipitation amounts derived from the Global Precipitation Climatology Project (Adler et al. 2003) by an arbitrary 5%, to obtain consistency between global radiation budgets and evaporation. Lin and Hou (2012) investigated precipitation over the continental United States using the merged surface radar and rain gauge product from the National Centers for Environmental Prediction (NCEP) National Hourly Multisensor Precipitation Analysis Stage IV (Lin and Hou 2012).
They demonstrated that precipitation lighter than 0.5 mm h$^{-1}$, which corresponds to the minimum detectable precipitation rate of the TRMM PR, contributes 43.1% and 7.0% to the total precipitation frequency and amount, respectively. They also found that light precipitation of less than 0.2 mm h$^{-1}$, which corresponds to the minimum detectable precipitation rate of the GPM DPR (Hou et al. 2014), contributes 11.3% and 0.8% to the total precipitation frequency and amount, respectively, indicating that the GPM DPR functions over 99% of the precipitation spectrum.

GPM DPR is also designed, in combination with the GPM Microwave Imager (GMI; Draper et al. 2015), as a reference standard to calibrate and improve precipitation estimates from a constellation of spaceborne microwave and/or infrared sensors (Hou et al. 2014), as the TRMM PR and TRMM Microwave Imager (TMI) have done. The detectability enhancement of GPM DPR will provide a refined reference standard covering a broad spectrum, from light to heavy precipitation.

Light precipitation of the order of 0.1 mm h$^{-1}$ is mostly related to shallow precipitating clouds. Over eastern parts of the world’s oceans, where deep convection is typically suppressed, such shallow precipitation governs the total precipitation (Short and Nakamura 2000). Any of commonly used spaceborne radar and microwave/infrared radiometers is known to have deficits in detecting light precipitation (e.g., Behrangi et al. 2014a,b), so do gridded precipitation datasets based on their measurements (e.g., Burdanowitz et al. 2015). Some studies have investigated the processes of shallow precipitation in such regions using spaceborne cloud radar (e.g., Berg et al. 2010; Suzuki et al. 2011). The GPM DPR is expected to advance the understanding of such processes by producing measurements from its non-sun-synchronous orbit.

Another important purpose of the GPM DPR, in conjunction with the TRMM PR, is to produce three-dimensional distributions of latent heating (Simpson et al. 1996; Takayabu 2002; Shige et al. 2004, 2007; Tao et al. 2010). Even in the tropics, there is still no unified view with regard to the diabatic heating structure, because of the large discrepancies among current global reanalysis datasets and estimates from the TRMM observations (Ling and Zhang 2011, 2013; Yokoyama et al. 2014). The enhancement in detectability by the GPM DPR is expected to provide better quality quantitative information, especially for the latent heating related to shallow precipitation, which dominates over eastern parts of the oceans (Takayabu et al. 2010).

In this study, we investigate the impact of the enhancement in detectability provided by the GPM DPR over that of the TRMM PR. Six months of GPM DPR observations are used to calculate the statistics of precipitation that become detectable from use of the GPM DPR and to demonstrate the impact of the detectability improvement.

2. Data and methodology

The GPM DPR standard level 2 (L2) product, version 03B (Iguchi et al. 2015) is used in this study. The DPR L2 product actually comprises six datasets, which depend on the used measurements and retrieval algorithms. There are several major advances incorporated into the precipitation retrieval algorithm for GPM DPR (Seto et al. 2013; Iguchi et al. 2015; Seto and Iguchi 2015) compared to that for TRMM PR (Iguchi et al. 2000, 2009). In this study, we use three-dimensional radar reflectivity and precipitation data in the DPR L2A (2ADPR) normal swath (NS); corresponding to the Ku-band PR (KuPR) swath) dataset (referred to as 2ADPR_NS), in which both Ku- and Ka-band measurements are used to estimate physical quantities. The radar reflectivity of the 2ADPR_NS dataset in the center part of the KuPR swath is Ku-band radar reflectivity that has been attenuation corrected using a combination of Ku- and Ka-band observations that are available in this portion of the KuPR swath. We refer to these data as “reflectivity.” Note that measured reflectivity of the 2ADPR_NS product is that measured by KuPR. The nonzero reflectivity and precipitation rate are used only for pixels where “flagPrecip” is set, which is assigned for each angle bin and indicates the precipitation status. Both for the reflectivity and the precipitation rate, we use only the vertical bins above “binClutterFreeBottom,” below which the radar measurements are affected by surface/main lobe clutter.

We use only observations in the center part of the KuPR swath—that is, the nadir-looking ray (KuPR angle bin 25) plus four rays on either side of it—instead of all KuPR and Ka-band PR (KaPR) matched angle bins (13–37/1–25 in the KuPR/KaPR swaths, respectively). This is mainly to avoid the problem of sidelobe clutter contamination, which could influence the statistics of shallow precipitation significantly (JAXA 2014). As the objective of this study is to demonstrate the impact of the detectability enhancement of the GPM DPR compared with the TRMM PR, the focus is on latitudes between 40°S and 40°N, although this area is slightly larger than the TRMM PR domain (37.5°S–37.5°N).

1 To obtain these data from the GPM archive, one extracts the variables “zFactorCorrected” and “precipRate” for attenuation-corrected radar reflectivity and precipitation rates, respectively, that are stored in the NS group of the specific Hierarchical Data Format, version 5 (HDF5), level-2 data product known as “2ADPR.”
The data are available from 8 March 2014 [granule identification number (ID) 144], but in this study, 6 months of data—from 3 April to 3 October—are used (corresponding to granule IDs 540–3386), which are obtained after the orbit altitude of the satellite had stabilized at the altitude for nominal observations (which occurred around granule ID 533). Note that during this period, several software updates are applied to the KuPR to mitigate sidelobe clutter effects, which could have affected the observed reflectivity and precipitation rates. However, careful visual inspection of the data suggested that the influence of these special operations could be ignored for the purpose of this study (results not shown).

To examine the detectability enhancement, two different datasets are prepared and compared, in which reflectivity observations below specified threshold values are artificially masked out. Again, note that we use Ku-band reflectivities that are attenuation corrected using Ka- and Ku-band observations. One threshold is set to 18 dBZ, corresponding to the minimum detectable reflectivity of the GPM KuPR and GPM KaPR at matched scans (Hou et al. 2014). This also corresponds to the widely accepted minimum detectable reflectivity of the TRMM PR. The other threshold is set to 12 dBZ, corresponding to the minimum detectable reflectivity of the DPR in the Ka-band high-sensitivity scan mode (Hou et al. 2014; Toyoshima et al. 2015), although we do not fully use this high-sensitivity information in the analysis. These threshold reflectivities correspond to precipitation rates of around 0.7 and 0.2 mm h$^{-1}$, respectively. A more straightforward method might be a direct comparison of DPR and TRMM PR measurements for the same period. However, their sampling characteristics are very different, both spatially and temporally. Therefore, DPR datasets that had identical sampling characteristics and virtually different detectabilities are used to avoid the introduction of sampling errors and to allow the examination of only the effects of the detectability enhancement.

Although a pixel-by-pixel comparison between DPR and PR is not feasible, it is essential to check the consistency between them. We make a comparison of bulk statistics during the analysis period, such as spatial distributions of near-surface precipitation rates and convective–stratiform fractions of precipitation area/amount, between PR 2A25 and 2ADPR products. Figure 1 compares near-surface precipitation rates and stratiform precipitation area fractions between 2ADPR and PR 2A25 for the analysis period. There are good correspondences in the spatial patterns between the two for both statistics, ensuring the results in this study at least in a statistical manner, although there is some discrepancy in convective/stratiform precipitation types between 2ADPR and 2A25 as described in appendix A and in probability distribution of moderate–heavy precipitation. We further check these statistics for KuPR single-frequency (2AKu) product and confirm the consistency (not shown).
Some results from this study are shown separately for different precipitation types. The precipitation observed at each pixel is classified into one of three precipitation types, that is, stratiform, convective, or “other.” When both Ku- and Ka-band measurements are available, a new algorithm, which has been developed for the GPM DPR using dual-frequency measurement information (Le and Chandrasekar 2013; Iguchi et al. 2015), is applied to determine the precipitation types; otherwise, the classification method, which was developed originally by Awaka et al. (1997) for the TRMM PR, is applied. The precipitation type other indicates the existence of cloud that has no surface precipitation or that is possibly noise. Note that all shallow precipitation is classified as convective in the dataset of the current version (JAXA 2014), although it should be classified as convective in the TRMM PR products if it exhibits an isolated structure (Schumacher and Houze 2003). We make a comparison study using matchup observations between TRMM PR and GPM DPR to know how they correspond with each other (appendix A). In summary, the precipitation types stratiform and other correspond well with each other; therefore, the results for these two types in this study can basically be interpreted based on the knowledge of TRMM PR. However, the majority of convective precipitation in GPM DPR is determined as stratiform precipitation in TRMM PR; therefore, ones should bear this discrepancy in mind when examining the results in this study. It must be noted that this discrepancy does not necessarily mean better/worse quality of either the TRMM or GPM classification method.

3. Results

a. Frequency and volume increments by the detectability enhancement

Figure 2 shows reverse cumulative frequency distributions of the occurrence and volume versus near-surface precipitation rates for the different minimum detectability thresholds and different surface types. Note that we do not remove the latitudinal sampling bias associated with the orbital characteristics of the GPM core observatory, since latitudinal dependence of the observation frequency is very small within the analysis domain (appendix B). For all surface types, the minimum precipitation rate is around 0.3 mm h$^{-1}$ for the 18-dBZ threshold, whereas it is around 0.15 mm h$^{-1}$ for the 12-dBZ threshold. Note that these values do not mean the minimum detectable precipitation rates. The increments in occurrence and volume are largest over the oceans at 21.6% and 1.93%, respectively. The increments in occurrence over land and coasts are comparable at 19.0%, while the volume increment over land, 1.60%, is slightly larger than that over coasts, 1.29%. The increment of precipitation volume is an order of magnitude smaller than that of occurrence frequency because of its lightness of precipitation.

Table 1 summarizes the increments of occurrence frequency of near-surface precipitation resulting from the detectability enhancement. The overall increment of occurrence frequency is 21.1% between 40°S and 40°N. By surface type, the increments are 21.6%, 19.0%, and 18.9% over the oceans, land, and coasts, respectively (Figs. 2a–c). By precipitation type, the increments are
15%–16% and 17%–26% for stratiform and convective precipitation, respectively. It can be seen that the increments of the precipitation type other are particularly prominent, increasing by 13–16 times.

Table 2 summarizes the increments of volume of near-surface precipitation. The increments of volume are an order of magnitude smaller than for occurrence for all surface and precipitation types, except for the precipitation type other. The overall increment is 1.86% between 40°S and 40°N. By surface type, the increments are 1.93%, 1.60%, and 1.29% over the oceans, land, and coasts, respectively (Figs. 2d–f). By precipitation type, the increments are 1.3–1.7% and 0.9%–2.5% for the stratiform and convective types, respectively, and the most notable change can be seen for convective precipitation over the oceans. As with the increment of occurrence, the volume increments of the precipitation type other are greater, in this case by 5–6 times.

The impact of the detectability enhancement can be highlighted by consideration of the spatial distribution. Figure 3 shows the increments of occurrence and volume of near-surface precipitation owing to the detectability enhancement at each 5° × 5° grid cell. Within the TRMM PR observation domain (40°S–40°N), for both occurrence and volume, the most notable increase can be observed over the land region extending from the Sahara to the Arabian Peninsula. In these regions, the increments are more than 50% and 10% for occurrence and volume, respectively, probably related to light and rare precipitation in these very dry regions (Kelley 2014). Over land, higher increments in both occurrence and volume can also be seen over central Asia, the Tibetan Plateau, and western coasts of central South America. Over the oceans, notable increments of around 30% and 10% for occurrence and volume, respectively, are observed over eastern parts of the subtropical oceans. In most other regions, the occurrence increments are around 20%, while the volume increments are at most about 5%. The spatial pattern of pixel increments over the oceans (Fig. 3a) is quite consistent with a previous study using observations from TRMM PR and a Cloud Profiling Radar (CPR) on board CloudSat (Stephens et al. 2008), although the increments by the detectability enhancement of DPR over eastern parts of the oceans are still slightly smaller than those by the CloudSat CPR.

Although this study mainly focuses on the impacts of detectability enhancement within the TRMM PR observation domain, it is worth noting that the detectability enhancement has also clear impact outside the TRMM PR domain. Both the occurrence and volume show significant increments, especially over the Antarctic Ocean along 60°S, where light rainfall and snowfall are dominant (Behrangi et al. 2014a). The increments exhibit a zonally uniform increase with slight asymmetry, possibly related to storm-track activity (Hoskins and Hodges 2005). In the Northern Hemisphere, a significant increment can be observed over the Bering Sea. Relatively lower increments in the Northern Hemisphere are possibly due to the analysis period, when extratropical cyclones in the Northern Hemisphere are generally less active in summer.

b. Two kinds of increments in newly detected precipitation profiles

Figure 4 shows the 12-dBZ echo-top height distributions for those pixels that do not have precipitation echo anywhere in the vertical column for the 18-dBZ threshold but do have a precipitation echo (with or without near-surface precipitation) for the 12-dBZ threshold (solid lines), superimposed on 12-dBZ echo-top height distributions (dashed lines). Note that if there is more than one echo layer, the lower one is chosen; therefore, the frequency distributions might be biased toward lower echo-top heights, especially over the oceans. For all surface types, there are two modes in the incremental echo-top height distribution. One is a lower-tropospheric increment that exhibits a narrow distribution with its peak occurrence at around 1.5 km. The other is a midtropospheric increment that exhibits a relatively wide distribution with its peak occurrence at 6–7 km. The lower-tropospheric increment is dominant for all surface types, but it is most prominent over the oceans. About 80%, 60%, and 70% of the echoes produce nonzero near-surface precipitation over the oceans.

### Table 1. Increments of the occurrence of near-surface precipitation (%) by the minimum detectability enhancement from 18 to 12 dBZ for different surfaces and precipitation types.

<table>
<thead>
<tr>
<th>Surface type</th>
<th>Rain type</th>
<th>All</th>
<th>Stratiform</th>
<th>Convective</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>21.09</td>
<td>15.37</td>
<td>24.52</td>
<td>1252.04</td>
<td></td>
</tr>
<tr>
<td>Ocean</td>
<td>21.60</td>
<td>15.22</td>
<td>25.68</td>
<td>1195.86</td>
<td></td>
</tr>
<tr>
<td>Land</td>
<td>18.95</td>
<td>15.89</td>
<td>17.01</td>
<td>1506.51</td>
<td></td>
</tr>
<tr>
<td>Coast</td>
<td>18.92</td>
<td>15.40</td>
<td>20.38</td>
<td>1269.33</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2. As in Table 1, but for increments of precipitation volume (%).

<table>
<thead>
<tr>
<th>Surface type</th>
<th>Rain type</th>
<th>All</th>
<th>Stratiform</th>
<th>Convective</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>1.86</td>
<td>1.39</td>
<td>2.12</td>
<td>462.61</td>
<td></td>
</tr>
<tr>
<td>Ocean</td>
<td>1.93</td>
<td>1.32</td>
<td>2.46</td>
<td>465.16</td>
<td></td>
</tr>
<tr>
<td>Land</td>
<td>1.59</td>
<td>1.69</td>
<td>0.96</td>
<td>453.69</td>
<td></td>
</tr>
<tr>
<td>Coast</td>
<td>1.29</td>
<td>1.41</td>
<td>0.92</td>
<td>453.40</td>
<td></td>
</tr>
</tbody>
</table>
oceans, land, and coasts, respectively (not shown). The peak heights of the lower-tropospheric increments are slightly lower than the shallower peak of echo-top height distributions for the 18-dBZ threshold, demonstrating that the detectability enhancement enables capturing more shallow precipitation. The midtropospheric increment is more significant over land and coasts than over the oceans. The peak heights of the midtropospheric increments are \(1.5\) km higher than the deeper peak of echo-top height distributions for the 18-dBZ threshold. Most of the pixels for the midtropospheric increments are classified as the precipitation type other (Fig. 5) and have little contribution to near-surface precipitation. The results indicate that DPR can better observe light precipitation echoes aloft, such as anvil clouds, as further discussed below.

Figure 6 shows vertical distributions of the occurrence frequency of precipitation for the 12- and 18-dBZ thresholds for different precipitation types. For all precipitation types, an increase can be observed at every level from the near-surface level to around 15 km. This is probably due to the expansion of the top and lateral boundaries of the precipitation echo because of the detectability enhancement, although it could also possibly be due to noise contamination. A notable increase can be seen at 10–11 km, especially for the precipitation types stratiform and other, demonstrating that the detectability enhancement of the GPM DPR over the
TRMM PR enables capturing light precipitation at higher levels. Another notable increase is found at 1–3 km for the convective precipitation type, which is consistent with the higher increments in arid and convection-suppressed regions where shallow and light precipitation are dominant (Fig. 3).

We further checked whether the precipitation pixels with reflectivity between 12 and 18 dBZ are meaningful meteorological signals or contamination by noise or surface/main lobe clutters. Figure 7 shows the fraction of precipitation pixels with reflectivity between 12 and 18 dBZ that are contained in a precipitation area with maximum reflectivity above 18 dBZ. The fraction is calculated as the number of 12–18 dBZ pixels that are contained in horizontally contiguous precipitation pixels with the maximum reflectivity above 18 dBZ, or are located vertically next to precipitation pixels with reflectivity above 18 dBZ, divided by the total number of precipitation pixels with reflectivity between 12 and 18 dBZ at each altitude. For all precipitation types, more than 70% (50%) of 12–18 dBZ signals below 9 (11) km, except the lowest 1 km, are confirmed to be connected with significant precipitation systems in such a way. Therefore, most of 12–18 dBZ pixels are considered as meaningful meteorological signals. The actual fractions are expected to be higher than the values shown in Fig. 7, since some of the 12–18 dBZ signals are horizontally and vertically extended, but the maximum reflectivity in the area is below 18 dBZ as shown later (e.g., Fig. 11c). While this kind of validation cannot completely deny the possible contribution from surface/main lobe clutters to the increase of 12–18 dBZ pixels below ~2 km, the contribution is believed to be minimal because of the vertical coherency of the fraction higher up to 4 km. The fraction is highest for convective and stratiform pixels at altitudes higher and lower than 10 km, respectively. There is some variation depending on the surface types, where the fraction for convective pixels over land is highest above 10 km and is deepest among the three surface types (not shown). These results may suggest that the official value of minimum detectable reflectivity (18 dBZ for KuPR and KaPR matched scans) may be too conservative, and one may safely consider the 12–18 dBZ signals as meaningful meteorological echoes, at least between 2 and 10 km.

The notable amount of the shallow increments is mainly due to shallow, light precipitation systems over the convection-suppressed region, such as the eastern parts of the oceans, as shown in Fig. 3. Figure 8 shows an example of GPM DPR observations over the southeastern Pacific near Easter Island. In this scene, the number of precipitating pixels increases from 857 to 1390 for 18- and 12-dBZ thresholds, increasing by 62% by the detectability enhancement. There are a number of scattered weak echoes with the reflectivity between 12 and 18 dBZ (light blue pixels), along with organized echoes with moderate precipitation. Most of these weak echoes are not false precipitation due to noise contamination but
consist of real precipitation. Figure 8c shows the along-track cross section of reflectivity at the nadir angle bin. Weak precipitation echoes mostly exhibit an isolated structure, probably corresponding to precipitation associated with cumulus congestus, which is dominate in this region. Precipitation echoes below \( \sim 3 \) km exhibit a vertically aligned structure, while those above \( \sim 3 \) km are out of line to the right, probably due to strong vertical shear in horizontal wind (Fig. 8b). It is demonstrated that the detectability enhancement better captures the entire picture of such light precipitation.

The midtropospheric increments generally correspond to the precipitation type other, with an increment of about three times at 4–7 km (Fig. 6c). The peak height of the precipitation occurrence for the precipitation type other exhibits clear latitudinal dependence. In the deep tropics, the peak height is as high as 6–7 km (15°S–15°N). In the subtropics (15°–40°) and midlatitudes (40°–70°), the peak heights are higher in the summer hemisphere (around 6 and 3 km, respectively) than the winter hemisphere (around 4 and 2 km, respectively) (Fig. 9). Furthermore, the peak heights are higher over land than over the oceans (Fig. 10). It is interesting to note that only in the deep tropics is there a sharp peak at 4.5 km. Visual inspection shows that thin echo layers often exist around 5 km near organized precipitation systems, possibly indicating a relation to bright bands of very weak stratiform precipitation and/or so-called melting layer clouds (Mapes and Zuidema 1996; Yasunaga et al. 2008); however, further study is required to clarify its physical interpretation.

The results indicate that the midtropospheric increment is related to environmental conditions. In fact, the midtropospheric increment consists mainly of lower parts of anvil associated with organized precipitation systems, especially in the tropics. Figure 11 shows an example of GPM DPR observations near Costa Rica. A dramatic difference is evident in the detectability enhancement from 18 to 12 dBZ. For example, when the minimum detectability is set to 12 dBZ, the echo labeled as “P” exhibits an organized precipitation system accompanied by wide anvil clouds (Fig. 11a), whereas for the minimum detectability of 18 dBZ, it exhibits only a gathering of isolated convection and the organization is mostly obscured (Fig. 11b). All of the precipitation systems shown in Fig. 11 show similar three-dimensional expansion, where extended anvil clouds become more visible at 5–10-km altitude by the detectability enhancement (Figs. 11c,d). As anvil clouds are generally formed by ice-cloud outflows from cumulonimbus (Houze 1993, section 5.3.3), it is reasonable to assume that their existence in height is related to environmental conditions,
such as the 0°C level and convective instability. A relatively low peak height of 4–7 km is consistent with the results from the CloudSat CPR, which revealed that the cloud-top heights of tropical and subtropical mesoscale convective systems are typically much higher than 10 km, but that they exhibit a bottom-heavy echo structure (Yuan et al. 2011). Another interesting feature is that the detectability enhancement better captures a situation where anvil clouds overshadow shallow cumulus clouds (Fig. 11d), which is sometimes depicted in typical squall-line structures (e.g., Leary and Houze 1979; Zipser et al. 1981).

4. Discussion

In the previous subsection, we examined the validity of considering 12–18-dBZ signals as meaningful precipitation echoes. Here we further discuss the validity from different viewpoints.

The actual performances of KuPR and KaPR are better than the initial design specification. From laboratory tests before the launch of the GPM core observatory, Kojima et al. (2012) showed that the actual minimum detectable rainfall rates of KuPR and KaPR matched scans are 0.30 mm h$^{-1}$ (corresponding reflectivity of ~14.53 dBZ) and 0.38 mm h$^{-1}$ (~16.32 dBZ), both of which are beyond the design specifications.

Moreover, the definition of minimum detectable reflectivity is a little too conservative for some meteorological analyses. The minimum detectable reflectivity for DPR is defined to ensure that the precipitation detection algorithm works properly, by suppressing false positives as much as possible but avoiding excessive rejection of true precipitation signals as noise. However, it is readily understood that such definition may reject many true echoes below the threshold from light precipitation as noise. Figure 12 shows received power $P_r$ and noise power $P_n$ versus reflectivity for KuPR for an orbit. If $P_r$ is

\[ P_r = P_{tot} - P_n \]

where $P_{tot}$ is the total received power, and $P_n$ is the noise power. The system noise of the GPM DPR is mainly attributed to the thermal noise of the receiver and background radiation from the earth’s surface, water vapor, etc. For GPM KuPR and KaPR, $P_n$ is measured when the transmitters are turned off, independently of $P_r$. Both $P_r$ and $P_n$ are stored in “1BKa” and “1BKu” products, as the average values of ~100 and ~900 samples for $P_r$ and $P_n$, respectively.

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significantly larger than $P_n$, then $P_r$ can be considered to contain true precipitation echo with a statistical confidence level. Note that in this case the uncertainty is not the sample standard deviation of $P_n$, $\sigma_n$, but that coupled with the sample standard deviation of $P_r$, $\sigma_r = \sqrt{\sigma_r^2 + \sigma_n^2}$, since echo power $P_e$ is estimated by $P_e = P_r - P_n$. Both over land and the oceans, there is still likely to be significant separation between $P_r$ and $P_n$ below 14.5 dBZ down to $\sim$12 dBZ and $\sim$13 dBZ over the oceans and land, respectively. Although depending on the intended application, one may still use reflectivity in this range as the true precipitation signal, at the risk of increased false positives with lowering threshold reflectivity.

5. Concluding remarks

Using 6 months of observations from the first spaceborne dual-frequency precipitation radar on board the GPM core observatory, the impact of its detectability enhancement over the TRMM PR was demonstrated. A comparison between the differences in precipitation occurrence and volume is performed using two datasets based on the same DPR product but with different thresholds—that is, 12 and 18 dBZ— that correspond to the minimum detectable reflectivities of the GPM DPR and TRMM PR, respectively.

The overall increments of near-surface precipitation occurrence and volume following the detectability enhancement are $\sim$21.1% and $\sim$1.9% between 40°S and 40°N with the maximum increase over the oceans. The increments show significant regional variation and have the largest impact over arid and convection-suppressed regions, such as the Sahara and eastern parts of subtropical oceans. These results are expected to advance the understanding of precipitation characteristics over these regions (e.g., Kelley 2014; Wood et al. 2011).
There are two distinct kinds of increments revealed in the precipitation profiles following the detectability enhancement. The first is a lower-tropospheric increment with a maximum echo-top height occurrence at 1–2 km. This increment is most significant for shallow convective precipitation over the oceans, indicating that the GPM DPR is effective in resolving shallow and light precipitation over convection-suppressed regions. The second increment has a maximum occurrence at 6–7 km and consisted mainly of the precipitation type other, demonstrating that the GPM DPR can detect light precipitation in the lower levels of anvil clouds. These results are expected to further advance the understanding of the characteristics of organized precipitation systems in the tropics and subtropics by detecting light precipitation, such as those related to anvil and shallow clouds, which could not be observed by the TRMM PR.

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of the Environment, Japan. Figures have been produced using the GFD DENNOU Library, the Grid Analysis and Display System (GrADS), and the VAPOR software (www.vapor.ucar.edu).

APPENDIX A

Comparison of Precipitation Types between TRMM PR and GPM DPR

Since the algorithms for determining precipitation types are different between the TRMM PR and GPM DPR, their results should be compared to know how they correspond with each other. We use 14 matchup observations between the TRMM PR and GPM DPR from March to July 2014 to make a contingency table between precipitation types in two datasets. These matchup observations consist of a variety of precipitation scenes, such as mesoscale organized precipitation systems and isolated convection, with a wide range of precipitation rates. We selected matchup pixel pairs for which both contain nonzero and nonshallow precipitation echoes, the distance between the two is less than 2 km, the temporal difference is less than 3 min, and the angle bins are between 13 and 37 for both the TRMM PR and GPM DPR.

The contingency table is shown in Table A1. There is little difference between land and the oceans (not shown). Stratiform precipitation determined by the GPM DPR algorithm mostly corresponds to stratiform precipitation determined by the TRMM PR algorithm. About 10% of stratiform precipitations in the GPM DPR are categorized as the precipitation type other in the TRMM PR, but this may be interpreted as a weak precipitation echo that is under the detection limit of the TRMM PR.

More than half of convective precipitations determined by GPM DPR are determined as stratiform precipitation in the TRMM PR. This is probably due to the difference between two algorithms in examining vertical echo profiles: the TRMM PR algorithm utilizes only one vertical reflectivity profile observed at Ku band (Awaka et al. 1997), whereas the GPM DPR dual-frequency algorithm utilizes the difference between two vertical reflectivity profiles observed at Ku and Ka.

Table A1. The number of matchup pixels between TRMM PR and GPM DPR, categorized according to precipitation types determined by two datasets. The numbers in parentheses are frequencies relative to the total for each GPM DPR precipitation type (%).

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<thead>
<tr>
<th></th>
<th>TRMM PR</th>
<th>GPM DPR</th>
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<tbody>
<tr>
<td></td>
<td>Stratiform</td>
<td>Convective</td>
</tr>
<tr>
<td>Stratiform</td>
<td>2275 (79.6)</td>
<td>235 (8.2)</td>
</tr>
<tr>
<td>Convective</td>
<td>260 (58.8)</td>
<td>151 (34.2)</td>
</tr>
<tr>
<td>Other</td>
<td>130 (39.8)</td>
<td>8 (2.4)</td>
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</table>
bands (Le and Chandrasekar 2013; Iguchi et al. 2015). Overall, the ratio between the stratiform and convective precipitation types for the GPM DPR for these matchup cases is 86:14, being marginally different from that for the TRMM PR, 87:13, since more than half of the convective precipitation in the TRMM PR is determined as stratiform precipitation in the GPM DPR. An example of matchup observation is shown in Fig. A1. Organized mesoscale convective systems are observed by both satellites. However, distributions of convective precipitation pixels are considerably different between the two: Convective pixels for the GPM DPR (Fig. A1b) in the inner swath are somewhat scattered compared to the TRMM PR (Fig. A1a). Note that the precipitation-type distributions correspond reasonably with each other in the outer swath, since the method for precipitation-type classification in the outer swath of the GPM DPR is based on the same principle as for the TRMM PR. Such a large difference might require considerable attention when examining the GPM DPR datasets based on the knowledge of the TRMM PR, and it needs further investigation to clarify the factors that contributed to the difference in precipitation types.

The precipitation type other in the GPM DPR generally corresponds to the precipitation type other in the TRMM PR. About 40% of the precipitation is determined as stratiform precipitation in the TRMM PR, but this is acceptable since almost all of the stratiform precipitation in the TRMM PR has no or very weak surface precipitation (not shown).

APPENDIX B

Latitudinal Sampling Characteristics of GPM DPR

Because of the orbital characteristics of the GPM core observatory, a number of observations have latitudinal dependence similar to TRMM. Figure B1 shows the latitudinal distribution of the number of monthly total observation pixels for KuPR, at a certain 0.25° × 0.25° grid box. A number of observations show a rapid increase around 50° and a sharp peak around 64°. The ratio of pixel counts to that at the equator increase to

![Fig. A1. An example of matchup observation between the TRMM PR and GPM DPR at 0907 UTC 24 Mar 2014. Colors show precipitation types determined by (a) TRMM PR and (b) GPM DPR classification algorithms. Black lines indicate the inner swath region of GPM DPR observation.](image)

![Fig. B1. Latitudinal dependence of the number of the monthly total (with and without precipitation) of observation pixels for KuPR at 0.25° spatial resolution. Bottom and top horizontal axes indicate the pixel counts at each latitude and ratio to the pixel counts at the equator, respectively.](image)
REFERENCES


