Evaluation and Validation of GPM Dual-Frequency Classification Module after Launch

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ABSTRACT

The Dual-Frequency Precipitation Radar (DPR) on board the Global Precipitation Measurement (GPM) Core Observatory has reflectivity measurements at two different frequencies: Ku and Ka bands. The dual-frequency ratio from the measurements has been used to perform rain type classification and microphysics retrieval in the current DPR level 2 algorithm. The dual-frequency classification module is a new module in the GPM level 2 algorithm. The module performs rain type classification and melting region detection using the vertical profile of the dual-frequency ratio. This paper presents an evaluation of the performance of the GPM dual-frequency classification module after launch. The evaluation process includes a comparison between the dual-frequency classification results and the TRMM legacy single-frequency results, as well as validation with ground radars.

1. Introduction

The Global Precipitation Measurement (GPM) Core Observatory was successfully launched on 27 February 2014 in Japan. The GPM is a science mission with application goals for advancing the knowledge of more accurate and frequent measurements of global precipitation than the Tropical Rainfall Measuring Mission (TRMM). The GPM Core Observatory is equipped with a Dual-Frequency Precipitation Radar (DPR) operating at Ku (13.6 GHz) and Ka (35.5 GHz) bands. The DPR aboard the GPM Core Observatory improves our knowledge of precipitation processes relative to the single-frequency (Ku band) radar used in TRMM. New Ka-band channel observation of the DPR helps improve the detection thresholds for light rain and snow relative to TRMM’s precipitation radar (Hou et al. 2014). The Ku- and Ka-band reflectivity measurements are two independent observations offered by DPR on board the GPM. Measurements from both frequency bands suffer from attenuation when a radar beam propagates through precipitation, such as the melting layer and moderate to heavy rain. However, attenuation from the Ka band is larger than from the Ku band. Non-Rayleigh scattering occurs in precipitation at both Ku and Ka bands. However, non-Rayleigh scattering is more severe at Ka band than at Ku band. This makes the difference between these two DPR measurements a viable parameter for making inferences about the profile.

The difference in the measured radar reflectivity at the two frequencies is a quantity often called the measured dual-frequency ratio (DFR$_m$), defined as

$$\text{DFR}_m = 10 \log_{10} \left[ \frac{Z_m(K_u)}{Z_m(K_a)} \right] = 10 \log_{10} \left[ \frac{Z_m(K_u)}{Z_m(K_a)} \right],$$

where $Z_m$ is the measured equivalent radar reflectivity factor in linear scale. The term DFR$_m$ is in decibel scale.

Two aspects that control the shape of the DFR$_m$ vertical profile are 1) the non-Rayleigh scattering effect and 2) the path-integrated attenuation (PIA) difference between two frequency channels. In the ice phase, the PIA difference (or $\delta$PIA) is negligible. The DFR$_m$ is mainly controlled by the non-Rayleigh scattering effect. In the melting region, the change in the dielectric constant due to the melting of the particles has different effects on the Ku and Ka bands. Meanwhile, the path-integrated attenuations are cumulative and become more obvious for a mixed-phase medium. Both non-Rayleigh scattering effects and $\delta$PIA play a role in the melting region. The DFR$_m$ is mainly controlled by $\delta$PIA in the rain region. Therefore, the vertical profile of DFR$_m$ is determined by the difference in the absorption and scattering properties of two different frequencies on ice: mixed phase and rain. This makes the DFR$_m$...
profile a good indication of precipitation type and different hydrometer phases. Figure 1 shows a typical vertical profile of DFRm for stratiform rain. An obvious DFRm “bump” between 4 and 5 km indicates the melting of precipitation particles.

In section 2, a brief review of dual-frequency classification method is provided. Section 3 is the evaluation and comparison of dual-frequency classification results with TRMM legacy methods as well as ground validation radar results. Section 4 is the enhancement of the dual-frequency classification method, which includes potential application of surface snowfall detection. The summary and conclusions are in section 5.

2. Brief review of dual-frequency classification module

This section briefly summarizes the dual-frequency classification module. The dual-frequency classification module is a new module in the GPM DPR level 2 algorithm. The module is developed using observations from both Ku and Ka bands; thus, it is applied only to the GPM DPR inner swath. The outputs of the module follow the legacy format used for TRMM PR. They include two parts, namely, precipitation type classification and melting layer detection. Instead of referring to “bright band” detection in the TRMM PR algorithm, we use the term “melting layer” detection in the GPM DPR dual-frequency classification module. Figure 2 shows the flowchart of the GPM DPR level 2 algorithm. From the figure, the outputs of the classification module determine the nature of microphysical models and algorithms to be used in the retrievals (Iguchi et al. 2015).

a. Precipitation type classification

The measured dual-frequency ratio and its vertical variation compose the main parameters used in the
To quantify the features of DFR\textsubscript{ml}, a set of indices are defined. Let \( V_1 \) be
\[
V_1 = \frac{\text{DFR}\textsubscript{ml}(\text{max}) - \text{DFR}\textsubscript{ml}(\text{min})}{\text{DFR}\textsubscript{ml}(\text{max}) + \text{DFR}\textsubscript{ml}(\text{min})}. \tag{2}
\]

The terms DFR\textsubscript{ml}(max) and DFR\textsubscript{ml}(min) are shown in Fig. 1. The term DFR\textsubscript{ml} used in (2) means DFR\textsubscript{ml} in linear scale. Let \( V_2 \) be the absolute value of the mean slope for DFR\textsubscript{ml} below the local minimum point,
\[
V_2 = \text{abs}[\text{mean(DFR}_{m}\text{ slope})]. \tag{3}
\]

The DFR\textsubscript{ml} slope is defined as the difference of DFR\textsubscript{ml} values between two successive DPR range bins, divided by range resolution. The parameters of \( V_1 \) and \( V_2 \) are normalized and are not dependent on the height or depth of the melting layer. In general stratiform rain has a larger \( V_1 \) value than convective rain, while convective rain has a larger \( V_2 \) value than stratiform rain. To further enlarge the difference between stratiform and convective rain types, a third index—\( V_3 \)—is defined as
\[
V_3 = \frac{V_1}{V_2}. \tag{4}
\]
The V3 is an effective parameter and provides a separable threshold for performing precipitation type classifications. Extensive statistical studies are performed on V3 using GPM DPR real data. The cumulative density function (CDF) of V3 is calculated for convective rain. The 1-CDF of V3 is calculated for stratiform rain. Different rain type databases are separated using a Ku-only classification algorithm (Awaka et al. 1997). The separable thresholds of C1 and C2 can be found on V3 for two rain types with around 70% of CDF. In other words, for stratiform rain: V3 > C2; convective rain: V3 < C1; and transition: C1 ≤ V3 ≤ C2. C1 is smaller than C2. “Transition” is neither a stratiform nor a convective rain type. The histogram of V3 and its cumulative density functions are shown in Fig. 3. The calculation is based on data from 73 storms with 121 859 vertical profiles in total. The thresholds of C1 and C2 used in the current version (version 4) are C1 = 0.18 and C2 = 0.20. Further adjustment of C1 and C2 might be needed in future versions. Figure 4 illustrates the flowchart of the precipitation type classification method in the dual-frequency classification module. Details of the algorithms can be found in Le and Chandrasekar (2013b).

b. Melting layer detection

Another function of the dual-frequency classification module is to detect the melting layer on a profile basis. The detection includes the melting layer top (MLT) and bottom heights. When the DFRm bump is detected, as shown...
in Fig. 1, the melting layer top is defined as the height at which the slope of the DFR\(_m\) profile hits a peak value. The melting layer bottom is defined as the height at which the DFR\(_m\) profile has a local minimum value. The dashed lines in Fig. 1 show an illustration of the melting layer top and bottom detected on a sample profile.

The criteria of the melting layer top and bottom defined above have been compared with other existing criteria in the literature using different radar parameters, including reflectivity-based criteria, linear depolarization ratio (LDR), and Doppler velocity-based criteria. Estimations from the DFR\(_m\) criteria have the smallest normalized bias when compared to velocity-based criteria. The normalized biases are 1.3% and 2.2% for the melting layer top and bottom height comparison, respectively. The DFR\(_m\) criteria compare well with the LDR-based criteria, using a \(\pm 28\)-dB threshold for LDR. The bias between these two criteria is around \(-2.8\%\). Figure 5 is the block diagram for the melting layer detection method implemented in the current version of the dual-frequency classification module. The details on melting layer detection can be found in Le and Chandrasekar (2013a).

3. Evaluation of dual-frequency classification module

Ever since the GPM launch, extensive evaluations have been made on the dual-frequency classification algorithm. Figure 6 is a block diagram that illustrates the validation procedure in this work. Results from the dual-frequency classification algorithm are compared with both the space radar algorithm and ground radar methods. The TRMM legacy single-frequency (Ku band) algorithm is applied to the full swath of the DPR overpass, while the dual-frequency algorithm is applied to the inner swath. It is critical to show the consistency of the classification results from the two different algorithms. We compare different

<table>
<thead>
<tr>
<th>Count</th>
<th>Dual-frequency method</th>
<th>TRMM legacy Ku only classification algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>82,199</td>
<td>18,833</td>
</tr>
</tbody>
</table>

### TABLE 2.

<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>No. of cases</th>
<th>Total case No.</th>
</tr>
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<td>Cyclone</td>
<td>HUDHUD</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>KATE</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NILOFAR</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Hurricane</td>
<td>ANA</td>
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<td></td>
<td>EDOUARD</td>
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<td>SIMON</td>
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</tr>
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<td>VANCE</td>
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<tr>
<td></td>
<td>PHANFONE</td>
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<tr>
<td></td>
<td>VONGFONG</td>
<td>7</td>
<td>27</td>
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rain type counts using both algorithms and perform a
statistics study on the melting layer top and bottom heights
using tropical storm datasets. Dual-polarization ground
radar is a powerful tool for cross validation of GPM DPR
algorithms. Results from the dual-frequency classification
algorithm are cross compared with those from ground
validation radars. Figure 7 is a cartoon illustration of the
cross comparison between spaceborne radar and ground
radar. Two kinds of ground validation radar are involved
in this study. They are Next Generation Weather Radar
(NEXRAD) and NASA’s S-band dual-polarimetric radar
(NPOL). Both of them are dual-polarized S-band radars.

### TABLE 3. Count of the melting layer top match between the dual-frequency method of the DPR and the Ku-only method using GPM DPR data from tropical storms, including cyclones, typhoons, and hurricanes.

<table>
<thead>
<tr>
<th>Count</th>
<th>Match of MLB? (Δ ≤ 0.25 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Cyclone</td>
<td>7234</td>
</tr>
<tr>
<td>Typhoon</td>
<td>37,137</td>
</tr>
<tr>
<td>Hurricane</td>
<td>19,278</td>
</tr>
</tbody>
</table>

### TABLE 4. Count of melting layer bottom match between the dual-frequency method and the Ku-only method using GPM DPR data from tropical storms, including cyclones, typhoons, and hurricanes.

<table>
<thead>
<tr>
<th>Count</th>
<th>Match of MLB? (Δ ≤ 0.25 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Cyclone</td>
<td>7406</td>
</tr>
<tr>
<td>Typhoon</td>
<td>37,950</td>
</tr>
<tr>
<td>Hurricane</td>
<td>19,736</td>
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</tbody>
</table>
NEXRAD has good coverage in the United States, which makes it easier to find overlap precipitation events between DPR and NEXRAD. NPOL has RHI scan information, which is convenient in direct comparison of the melting layer top and bottom heights. In this study, a total of five precipitation events are chosen to compare classification results from the dual-frequency classification algorithm and NPOL, as well as NEXRAD hydrometeor types.

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a. Comparison between dual-frequency and TRMM legacy single-frequency method

Table 1 is a contingency table summarizing a comparison of rain type counts between the dual-frequency classification method and the TRMM legacy Ku-only method using GPM data from a total of 15 orbits. The “S,” “C,” and “O” in the table represents stratiform, convective, and other rain types, respectively. The count of stratiform rain that was detected by both methods is 73190. The count for convective rain and other rain type is 14094 and 9414, respectively. With a total of 110794 rain type counts in this comparison, the percentage of

FIG. 9. (a) GPM and NPOL overpass on 21 May 2015. GPM orbit 6974. Dark green straight line represents the centerline of the DPR swath. Light green straight lines are the DPR inner and outer swaths. Red straight lines represent the GPM Microwave Imager swath. Pink dashed line is the location of the NPOL RHI scan. Black dashed line is the DPR vertical cut aligned with the NPOL RHI scan. (b) RHI scan of NPOL radar reflectivity at an azimuthal angle of 201°. (c) RHI scan of NPOL radar at an azimuthal angle of 201°. (d) Hydrometeor types of RHI scan of NPOL radar at an azimuthal angle of 201°.

FIG. 10. (a) Vertical cut of reflectivity at the aligned DPR vertical cut with the RHI scan shown in Fig. 9. (b) Vertical cut of the measured dual-frequency ratio. Dashed pink lines in (b) indicate the melting layer top and bottom.

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match between the dual-frequency method and the TRMM legacy Ku-only method is around 87.3%.

In addition to a general profile comparison, the evaluation is also performed on tropical storms. A total of 61 tropical storms, with 7 from cyclones, 27 from hurricanes, and 27 from typhoons, are used in the evaluation of the melting layer top and bottom between the dual-frequency classification method and the single-frequency approach. Table 2 shows the type, name, and number of cases of tropical storms used in the evaluation. A comparison of the results is shown in Fig. 8. Histograms for the melting layer top and bottom for these three storm types illustrate a similar range. The median value for the melting layer top and bottom is the same for the dual-frequency classification method and the Ku-only method for hurricanes and typhoons. For cyclones, the median value of the melting layer bottom from the dual-frequency classification method is a little lower than the estimations from the Ku-only method. We assume the results from both methods match if the absolute difference of the melting layer top (or bottom) between the two methods is within 0.25 km. We count the number of profiles that have a melting layer top (or bottom) match (or not match) for cyclone, typhoon, and hurricane storms. Table 3 and 4 summarize this comparison for the melting layer top and melting layer bottom, respectively. Shown in Table 3, we have 7234 of matched melting layer top detection out of 7407 cyclone profiles, while we have 37137 of matched melting layer top detection out of 37969 typhoon profiles and we have 19278 of matched detection out of 19747 hurricane profiles. The percentage of match for the melting layer top is higher than 97% for the different tropical storm types. Table 4 shows similar results for melting layer bottom detection. The percentage of match for the melting layer bottom is more than 99%.

From the histogram plots and tables shown above, the results from the dual-frequency classification method match well with the Ku-only method, which is the TRMM legacy method. In this way, consistency can be expected between the inner swath (where the dual-frequency classification method is applied) and the outer swath.

b. Validation with ground radar

GPM overpasses that have overlap with NPOL at the Wallops Precipitation Science Research Facility are studied. Two cases are shown in this research. Figure 9a shows one precipitation event that was observed by both GPM DPR (orbit 6974) and NPOL radar on 21 May 2015. The pink dashed line is the location of the NPOL RHI scan at an azimuthal angle of 201°. The black dashed line is the location of the DPR vertical cut that aligned with the RHI scan direction. The closest footprint from DPR that aligned best with NPOL data was chosen. Figures 9b and 9c illustrates an RHI scan of NPOL reflectivity as well as rhv at an azimuthal angle of 201°. A clear melting region can be observed at around 4 km. Figure 9d shows the hydrometeor types of the RHI scan. The bright red region at around 4-km height indicates wet snow, with around 45 km to NPOL. The algorithm used to perform hydrometeor type classification for NPOL is described in Bechini and Chandrasekar (2015). Figure 10 shows a vertical cut of reflectivity at Ku band and DFRm at the aligned direction of the NPOL RHI scan. The pink dashed lines in Fig. 10 are the melting layer top and bottom detected using the dual-frequency classification method. These lines show the melting region is around 3.5–4.2 km within nine DPR

<table>
<thead>
<tr>
<th>Range to NPOL (km)</th>
<th>MLB_DFRm (avg, km)</th>
<th>MLB_NPOL (avg, km)</th>
<th>Absolute in difference (km)</th>
<th>Match? (Δ ≤ 0.25 km)</th>
</tr>
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<tbody>
<tr>
<td>0−15</td>
<td>3.50</td>
<td>3.71</td>
<td>0.21</td>
<td>Yes</td>
</tr>
<tr>
<td>15−30</td>
<td>3.38</td>
<td>3.55</td>
<td>0.17</td>
<td>Yes</td>
</tr>
<tr>
<td>30−45</td>
<td>3.31</td>
<td>3.37</td>
<td>0.06</td>
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<tr>
<td>45−60</td>
<td>3.31</td>
<td>3.26</td>
<td>0.05</td>
<td>Yes</td>
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</table>
footprints from the origin of NPOL. The DPR footprint size is around 5 km. This result matches well with the observations in Fig. 9. In Table 5 and 6, we perform a quantitative comparison of the melting layer top and bottom for the estimations from the DPR and NPOL. Again, we say the results from both methods match if the absolute difference of the melting layer top (or bottom) between the two methods is within 0.25 km. We calculate the averaged estimations of the melting layer top (or bottom) within a certain range to NPOL. The number of footprints shown in Fig. 10 refers to the range to NPOL also. Table 5 shows that except for the range of 45–60 km, the absolute differences of melting layer top detection are all within 0.25 km. In Table 6, similar comparisons are performed for the melting layer bottom. In this comparison, estimations from two methods match for all the chosen ranges.

Another precipitation event that was observed by both GPM DPR (orbit 4745) and NPOL radar is on 29 December 2014, as shown in Fig. 11a. RHI scans of reflectivity and $r_{hv}$ are shown in Figs. 11b and 11c at an azimuthal angle of 198°. (a) Vertical cut of reflectivity at scan 4999. DPR radar footprint is around 5 km for each angle bin. (b) Vertical cut of the measured dual-frequency ratio. Dashed pink lines in (b) indicate the melting layer top and bottom.
azimuthal angle of 198°. **Figure 11d** is the hydrometeor type classified for the NPOL RHI scan. From **Figs. 11b** to 11d, the melting region is obvious and shallow at around 1.5 km. Accordingly, **Fig. 12** shows a vertical cut of reflectivity and DFRm for the inner swath at scan 4999. Pink dashed lines in the bottom plot of **Fig. 12** are around 1–2 km, which is a good match with the melting layer detected by NPOL.

NEXRAD is a network of 160 high-resolution S-band Doppler dual-polarized weather radars. It is a powerful ground validation system for GPM DPR. In this study, we show three precipitation events that were observed

![Fig. 13. DPR overpass with the KHGX radar at 1351:52 UTC 11 Jan 2015. (a) Overpass of GPM orbit 4946. Reflectivity at Ku band at the outer swath. (b) Reflectivity of the Ka band at the inner swath. Black circle in (a) and (b) indicates the range of NEXRAD. (c) Reflectivity of NEXRAD at 2-km height. (d) As in (a), but zoomed in. (e) Hydrometeor types classified for NEXRAD radar. Points A–C indicate the locations of the three vertical profiles in Fig. 14.](image-url)
by GPM DPR and the KHGX (Houston, Texas), KFWS (Dallas/Fort Worth, Texas), and KMLB (Melbourne, Florida) radars, respectively.

Figure 13 shows a DPR overpass (orbit 4946) of precipitation over the KHGX radar at 1351:52 UTC 11 January 2015. KHGX is one of the NEXRAD radars located in the Houston–Galveston area in Texas. Figure 13a illustrates reflectivity at Ku band from the DPR outer swath (~245 km). The black circle indicates the 100-km radius of the KHGX radar. Figure 13b shows the reflectivity of Ka band from the DPR inner swath (~120 km). The S-band reflectivity of the KHGX radar at 2 km is shown in Fig. 13c. Comparing S-, Ku-, and Ka-band reflectivity, a similar pattern of reflectivity can be found from space and ground radars. However, attenuations from the precipitation are obvious, especially for Ka band. Hydrometeor types are classified for the KHGX radar using an algorithm described in Bechini and Chandrasekar (2015). Figure 13e shows the hydrometeor types at a height of 2 km. To get a better vertical structure of the hydrometeor types, Fig. 14 illustrates the hydrometeor types of three randomly selected vertical profiles marked as A–C, respectively, in Fig. 13c. For a profile-based comparison, a volume-matching algorithm is applied (Schwaller and Morris 2011). Different colors represent different hydrometeor types with yellow indicating dry snow, green indicating wet snow, and blue for rain. Horizontal dashed lines in Fig. 14 are the melting layer top and bottom classified by the dual-frequency classification method in DPR. Two dashed lines matches well with the green region. In Fig. 14b, DPR shows a narrower melting region compared to the ground radar, but overall the comparison is reasonable.

Figure 15 shows another case with precipitation observed by both the DPR overpass and the KFWS radar. KFWS is one of the NEXRAD radars located in the Dallas–Fort Worth area in Texas. Figure 15a shows the
DPR Ku-band reflectivity at the outer swath with orbit 5970. The black circle indicates the 100-km-radius range of the KFWS radar. Figure 15b shows the S-band reflectivity of the KFWS radar at a height of 2 km. Hydrometeor types are classified for the KFWS radar and are shown in Fig. 15c. Three vertical profiles are randomly chosen to compare the hydrometeor types, and they are located at points A–C, respectively, in Fig. 15b. Figures 15d–f show a profile-based comparison of the hydrometeor types between the DPR and KFWS radars. Similar to the case shown in Fig. 14, green in Figs. 15d–f indicates wet snow from the KFWS radar. Horizontal black dashed lines are the melting layer top and bottom from the dual-frequency classification method. For all these profiles, the DPR results match well with ground radar classification.

Figure 16 illustrates an overlap precipitation event observed by the DPR overpass (GPM orbit 4970) and KMLB radar on 13 January 2015. KMLB is one of the NEXRAD radars located in Melbourne, Florida. Figure 16a shows DPR overpass 4970 with reflectivity at Ku band at the outer swath. The black circle indicates the range of the NEXRAD radar. Figure 16b is the reflectivity of NEXRAD at a height of 2 km. The hydrometeor type is classified for NEXRAD and is shown in Fig. 16c. Three vertical profiles, marked A–C, respectively, in Fig. 16c are shown in Figs. 16d–f, respectively. Block colors in Figs. 16d–f are hydrometeor types classified for the KMLB radar. Green indicates wet snow. The black dashed lines in Figs. 16d–f are the melting layer top and bottom detected using the dual-frequency classification method implemented in the DPR algorithm. The green regions are a little wider than the black-dashed-line region, but in general they match well. For three comparison cases between the DPR and NEXRAD, products of the melting layer top and bottom height from DPR radar show a good match with products from NEXRAD.

4. Validation of new experimental products

Surface snowfall detection

A new algorithm has been developed to separate snowfall and rain profiles on surfaces using information mainly from DFR\textsubscript{m}.

Figure 17a is a typical textbook case of an overpass (DPR overpass 000272) from GPM DPR that has snow,
stratiform, and convective rain precipitation within a 160 scan (around 800 km) range. To study the features of the vertical profiles for these three different precipitation types, we study their averaged profile of reflectivity and measured dual-frequency ratio. Figure 17b shows an averaged reflectivity profile at Ku and Ka bands, and the measured dual-frequency ratio profile for snow. As expected, the reflectivity at Ku band is, most of time, below 25 dBZ. However, the difference between Ku and Ka bands is obvious (in several decibels), even when the reflectivity at Ku band remains a small value. Figure 17c shows an averaged reflectivity profile for stratiform rain. Bright band is obvious for reflectivity at Ku band. Values of the DFR_m profile under the melting region (below bright band) are very small, indicating that attenuation at Ka band is very small when reflectivity is less than around 25 dBZ in the rain region. In contrast, DFR_m values above the melting layer are obvious (in several decibels), with the range similar to the snow case in Fig. 17b. For convective rain, as can be seen from Fig. 17d, the maximum of reflectivity at Ku band is equal or larger than 35 dBZ, while the DFR_m values are appreciable in the rain region. Large DFR_m values are contributed from large attenuation at Ka band. Comparing Figs. 17b and 17c, the DFR_m values are larger for snow than for stratiform rain even when the reflectivity values are in the same range. Comparing Figs. 17b and 17d, the DFR_m values for snow profiles are similar to convective profiles in the rain region. However, reflectivity at Ku band is much smaller for snow than for convective rain.

Though only an example is shown above, similar studies enable us to summarize the features of snow profiles as follows: (i) A DFR_m slope is obvious for snow (close to 0.8 dB km^{-1} in Fig. 17b) compared to stratiform rain, where the slope is close to 0 dB km^{-1}.FIG. 15. (Continued)
below bright band; (ii) the maximum of reflectivity for snow is less than 30 dBZ, while for convective rain it is around 35–40 dBZ; the snow profile also has a feature that has a (iii) the storm top height that is lower than convective rain, in general. Combing these features, we can design a surface snowfall index to perform the effective separation between snowfall and rain (includes stratiform and convective) on surface. A snow index (SI) is defined based on three ingredients: DFR$_m$ values, the maximum value of reflectivity at Ku band, and storm top height,

$$SI = \frac{\text{mean}[\text{abs}(\text{DFR}_m\text{slope})]}{\text{Zmku}_{\text{max}} \times \text{Storm\_top\_height}},$$  

Where the DFR$_m$ slope (dB km$^{-1}$) is used instead of DFR$_m$ value due to its immunity to calibration change. The term Zmku$_{\text{max}}$ (dBZ) represents the maximum value of reflectivity at Ku band along the profile. The term Storm_top_height represents the altitude of the storm top (km). This snow index can be used to effectively perform the separation of snowfall and rain profiles. This experimental product will be implemented in the next version of the GPM DPR algorithm.

The histogram of the snow index, defined in (5), is calculated for both snow and rain profiles of DPR overpass 000272 (overpass plot shown in Fig. 17a). For that specific case, the snow index can separate snow and rain at a CDF (dashed lines) of around 84%. Furthermore, a statistical study of the snow index is performed on large-scale GPM DPR vertical profiles. A total of 353,166 DPR rain profiles and 4,935 DPR snow profiles are involved in this study. Rain profiles are chosen from a tropical region during the summer season and snow profiles are chosen from northern Europe and the northern United States during the winter season. Information of the 0$^\circ$ isotherm is used in the profile selection. Figure 18 shows the histogram of the snow index defined in (5) in a large-scale analysis. It is shown that at around 85% of CDF, the SI index can separate snow profiles and rain profiles. In other words, 85% of the snow profiles have SI > 0.023, while 85% of the rain profiles have SI ≤ 0.023.

FIG. 16. DPR overpass with KMLB radar at 0225:17 UTC 13 Jan 2015. (a) Overpass of GPM orbit 4970. Reflectivity at Ku band at the outer swath. Black circle in (a) indicates the range of NEXRAD. (b) Reflectivity of NEXRAD at 2-km height. (c) Hydrometeor types classified for NEXRAD. (d–f) Hydrometeor types of three vertical profiles at locations A–C shown in (c). Horizontal dashed lines are MLT and bottom heights from DPR products. Red vertical profiles are measured reflectivity at Ku band from DPR.
A snow mask algorithm is developed upon this experimental product of the snow index and other information, such as clutter-free height. It needs to be pointed out that 0° height information is used as a sanity check in this algorithm—not as a major decision parameter. In other words, this algorithm relies on observations of reflectivity profiles to perform surface snowfall detection. Figure 19 shows a flowchart of the snow mask algorithm. Details of the algorithm can be found in Le and Chandrasekar (2015, manuscript submitted to IEEE Trans. Geosci. Remote Sens.). The snow mask algorithm has been evaluated and validated using many overlapping precipitation events observed by both DPR and NEXRAD. One example is shown in Fig. 20.

The KEAX radar is one of the NEXRAD network located in Kansas City, Kansas. Figure 20a shows a DPR overpass with the KEAX radar. Reflectivity at Ku band for DPR overpass 5263 on 31 January 2015 is illustrated. Black dashed lines in the plot indicate the boundaries of the DPR inner swath. Black solid lines are the center and boundaries of the DPR outer swath. The black circle is the 100-km range of the KEAX radar with the center marked by the black diamond. The snow mask algorithm in Le and Chandrasekar (2015, manuscript submitted to IEEE Trans. Geosci. Remote Sens.) is applied to the data from the DPR inner swath and the results are shown in Fig. 20b. Dark green in Fig. 20b indicates snow. Figure 20c shows the S-band reflectivity of the KEAX radar at the lowest PPI scan with an elevation angle of 0.48°. The black dashed line is the right boundary of the DPR inner swath. The black solid line is the center of the DPR overpass. In this case, the region we are interested
The reflectivity value of the S band is below 30 dBZ. The hydrometeor type classification algorithm described in Bechini and Chandrasekar (2015, manuscript submitted to IEEE Trans. Geosci. Remote Sens.) is applied to the PPI scan shown in Fig. 20c. Figure 20d shows the hydrometeor type of the KEAX radar. In between the solid and dashed black lines, the hydrometeor type is classified as dry snow (DS) for most of the overlapped area except for a little yellow, which indicates wet snow appears on the edge. This result matches well with the snow mask algorithm shown in Fig. 20b. More overlap cases similar to the one shown in Fig. 20 are evaluated, and satisfactory results are achieved. Details of the snow mask algorithm is described in Le and Chandrasekar (2015, manuscript submitted to IEEE Trans. Geosci. Remote Sens.).

5. Summary and conclusions

The dual-frequency classification method is implemented in the GPM DPR level 2 algorithm to perform rain type classification and melting region detection for the DPR inner swath. Extensive analysis has been done on evaluating the method ever since the GPM launch. The dual-frequency classification method is compared to the TRMM legacy Ku-only algorithm, and it shows reasonable agreement, which is of great importance for algorithm consistency between the inner and outer swaths. Melting layer detection from the dual-frequency
FIG. 18. Large-scale study of snow index using GPM DPR profiles. A total of 353,165 rain profiles and 4,935 snow profiles are used.

FIG. 19. Potential flowchart to perform snow–rain separation in the dual-frequency classification module of the GPM DPR level 2 algorithm.

FIG. 20. Overlap of DPR with the KEAX radar. Black dashed lines indicate the boundaries of the DPR inner swath. Black solid lines are the center and boundaries of the DPR outer swath. Black circle is the 100-km range of the KEAX radar with the center marked by the black diamond. (a) Reflectivity at Ku band for DPR overpass 005263 on 31 Jan 2015. (b) Snow mask for overpass shown in (a). Dark green is snow. (c) Reflectivity at S band of the KEAX radar at an elevation angle of 0.48°. Black dashed line is the right boundary of the DPR inner swath. Black solid line is the center of the DPR overpass. (d) Hydrometeor type of the KEAX radar at an elevation angle of 0.48°.
classification method is cross validated using ground validation radars, including NPOL and NEXRAD. A good match can be seen from validation cases. For enhancing of the dual-frequency classification method, a new experimental product (snow index) is used to perform the separation of surface snowfall and rain profiles. A snow mask algorithm has been developed and evaluated with NEXRAD. Preliminary comparisons show promising results.

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REFERENCES