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Ground Validation of GPM DPR Algorithms

by Hydrometeor Measurements and Polarimetric Radar Observations of Winter Snow Clouds:

A Case Study on 4 February 2018

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Abstract

Two products from the Global Precipitation Measurement (GPM) Dual-frequency Precipitation Radar (DPR) algorithms, a flag of intense solid precipitation above the –10°C height (“flagHeavyIcePrecip”) and a classification of precipitation type (“typePrecip”) were validated by ground-based hydrometeor measurements and X-band
multi-parameter (X-MP) radar observations of snow clouds on 4 February 2018. Contoured frequency by altitude diagrams of the X-MP radar reflectivity exhibited a significant difference between footprints flagged and unflagged by the “flagHeavyIcePrecip” algorithm, which indicated that the algorithm is reasonable. The hydrometeor classification (HC) by the X-MP radar, which was confirmed by microphysical evidence from ground-based hydrometeor measurements, suggested the existence of graupel in the footprints with “flagHeavyIcePrecip”. In addition, according to the information of the GPM DPR, the “flagHeavyIcePrecip” footprints were characterized by not only graupel but also large snowflakes. According to the information of X-MP radar HC, the “typePrecip” algorithm by the detection of “flagHeavyIcePrecip” was effective in classifying precipitation types of snow clouds, whereas it seems that there is room for improvement in the “typePrecip” algorithms based on the extended-\(DPR_m\)-method and H-method.

1. **Introduction**

   The Global Precipitation Measurement (GPM) core observatory carries the Dual-frequency Precipitation Radar (DPR), which was successfully launched on 28 February 2014 (Hou et al. 2014; Skofronick-Jackson et al. 2017). The GPM DPR provides some products associated with the microphysical structure of precipitating clouds. The product “typePrecip” is a classification of precipitation types based on the vertical and horizontal microphysical structures of the precipitation system obtained from the GPM DPR (Awaka et al. 2016). Another product “flagHeavyIcePrecip”, which indicates intense ice precipitation above the \(-10^\circ C\) height, was added in the DPR Level-2A product (2ADPR) version 05A to determine convective clouds in winter and
to improve the accuracy of precipitation type classification (Iguchi et al. 2018a).

The “typePrecip” algorithm classifies precipitation types into convective, stratiform, and other types. One effective method for precipitation type classification is to detect the bright band in clouds by radar. However, radar cannot detect it in winter snow clouds in which only solid hydrometeors exist from the ground to the cloud top. The GPM DPR often observes such snow clouds at high latitudes because the GPM DPR has an orbit inclination of 65 degrees. Thus, it is necessary to validate “typePrecip” of winter snow clouds by ground-based measurement.

Suzuki et al. (2019) conducted hydrometeor measurements of winter snow clouds in the coastal region of the Japan Sea using the Ground-based Particle Image and Mass Measurement Systems (G-PIMMSs; Suzuki et al. 2016). Simultaneous observations by the GPM DPR and G-PIMMSs made it possible to validate the “typePrecip” algorithm. The G-PIMMS located at which “typePrecip” indicated convective and stratiform precipitations observed graupel and snow, respectively. From the viewpoint of microphysics, the existence of graupel suggests that supercooled water droplets necessary for the riming growth of graupel are lifted by updrafts in the convective clouds. Therefore, they concluded that the “typePrecip” algorithm is reasonable. However, they just evaluated the GPM DPR and G-PIMMS data qualitatively, which have quite different horizontal resolutions: the GPM DPR footprint with a diameter of 5 km versus the small sampling area (3 cm × 3 cm) of the G-PIMMS.

The ground-based multi-parameter (MP) radar is effective for ground validation of the GPM DPR algorithms because it gives us a wide range of microphysical information in precipitating clouds. In addition, the validation of “flagHeavyIcePrecip”, which means detection of intense solid precipitation in the upper layer of clouds, is possible
because the radar can also provide the three-dimensional structure of precipitating clouds.

The X-band MP (hereinafter referred to as X-MP) radars had been deployed nationwide as the Extended Radar Information Network. In recent years, a hydrometeor classification (HC) technique using X-MP radar polarimetric variables has been developed (Kouketsu et al. 2015). The HC techniques show what kind of hydrometeors (i.e., rain, graupel, snow, ice crystals and so on) is dominant within each radar bin and provide the three-dimensional distribution of hydrometeor types. Therefore, it is possible to validate the GPM DPR algorithms by comparing the GPM DPR products with the hydrometeor distributions obtained from the X-MP radar HC that was evaluated by ground-based hydrometeor measurements by G-PIMMSs.

In the present study, we conducted a statistical comparison between the GPM DPR products (“flagHeavyIcePrecip” and “typePrecip”) and the hydrometeor types obtained from the X-MP radar HC technique in the case of 4 February 2018, using hydrometeor information observed by the G-PIMMSs as a reference. Focusing on the existence of graupel in clouds, we defined the graupel dominance ratio and validated the GPM DPR algorithms according to the following procedure: 1) evaluate the X-MP radar HC by hydrometeor measurements with the G-PIMMS, and 2) validate “flagHeavyIcePrecip” and “typePrecip” using the validated X-MP radar information.

2. Data and methodology

2.1 Hydrometeor measurements by G-PIMMSs

Suzuki et al. (2019) conducted ground-based hydrometeor measurements in the 2017-2018 winter season using the G-PIMMSs installed at Kanazawa University (Site
A: 36.544°N, 136.705°E) and Ishikawa Prefectural University (Site B: 36.509°N, 136.599°E), as shown in Fig. 1a. Particles having diameter more than 0.5 mm were used for analysis due to the limitation of the infrared sensor of the G-PIMMSs. The G-PIMMSs can capture nondestructive images of particles and provide information on particle size, shape, and type. Solid particle images were classified into graupel and snow (ice crystals and snowflakes) based on the description by Suzuki et al. (2019). In the case of 4 February 2018, raindrops and melting particles were not observed by the G-PIMMSs.

2.2 GPM DPR products “flagHeavyIcePrecip” and “typePrecip”

The GPM DPR passed northeastward from the southwest over the G-PIMMS observation sites at 0624 JST (Japan Standard Time: JST = UTC + 9 hours) on 4 February 2018. The orbit number is 022359. The DPR consisting of Ka-band radar (35.5 GHz) and Ku-band radar (13.6 GHz) provides the dual-frequency ratio (DFR), which can be used to estimate information associated with microphysical structures. “flagHeavyIcePrecip” and “typePrecip” are built into the Classification Module of the GPM DPR 2ADPR V06A products (Iguchi et al. 2018b). “flagHeavyIcePrecip” indicates the possibility that there is intense solid precipitation above the −10°C height. Iguchi et al. (2018a) defined “flagHeavyIcePrecip” by a large measured radar reflectivity (\(Z_m\)) and/or large measured DFR (\(DFR_m\)). “flagHeavyIcePrecip” was detected with the following conditions in the analysis area: \(Z_m > 27\) dBZ and \(DFR_m > 7\) dB at the same range bin above the −10°C height.

2.3 Hydrometeor classification by X-MP radar

Two X-MP radars (Table S1 in Supplements) at Nomi (36.459°N, 136.523°E) and Mizuhashi (36.706°N, 137.279°E) covering our observation sites were used. The X-MP
radar scans 12 elevation angles every 5 minutes. The polar coordinates of the X-MP
c Radar data were converted to three-dimensional rectangular coordinate data using the
Cressman interpolation (Cressman 1959). Data of two radars within an influence sphere
with a radius of 1 km were weighted and averaged to determine grid point values on the
Cartesian coordinate system. For beam height, the curvature of the earth was considered.
In this study, we used the first of several low elevation PPI scans to create the Constant
Altitude Plan Position Indicators (CAPPIs). The CAPPIs having a horizontal resolution
of 500 m were created at vertical intervals of 250 m from the X-MP radar observations
and the CAPPIs at 0620 JST were created using the X-MP radar data observed from
0620 to 0625 JST. We used the HC algorithm developed by Kouketsu et al. (2015).
Although the HC algorithm classified the hydrometeors into eight categories (drizzle, rain, wet snow, dry snow, ice crystals, dry graupel, wet graupel, and rain-hail mixture),
we adopted only two categories, graupel (including wet and dry graupel) and snow
(including wet and dry snow and ice crystals) in the present study to compare them with
hydrometeor types obtained from the G-PIMMS. The vertical profile of temperature
obtained from an upper air sounding (09 JST on 4 February 2018) at Wajima (37.385°N,
136.886°E; Fig. 1a) was used for the X-MP radar HC.
As shown in Fig. 1b, the X-MP radar CAPPI pixels (each of them is a square of 500
m × 500 m in this study), of which the centers are located within a GPM DPR footprint
with a diameter of 5 km, were used for the comparison.

2.4 Definition of $G_{ratio}$
In this study, the graupel dominance ratio ($G_{ratio}$) for each footprint is defined as
follows:
\[ G_{ratio} = \frac{N_{graupel}}{N_{graupel} + N_{snow}}, \]

where \( N_{graupel} \) and \( N_{snow} \) are the numbers of the XMP-graupel and XMP-snow pixels within a single footprint of the GPM DPR, respectively. Here, the XMP-graupel and XMP-snow pixels are defined as the pixels including graupel and snow classified by the X-MP radar HC at the height of 1500 m, respectively. Each footprint has approximately 80 pixels, which change depending on the location. Footprints with less than 15 pixels, which is equivalent to 3.75 km\(^2\) in area, were excluded from the \( G_{ratio} \) calculation.

3. Results and discussion

3.1 Evaluation of a hydrometeor classification using X-MP radar observations

Figure 1a shows the X-MP radar echoes at 0620 JST. The surface air temperature at Site A was 0.3°C at 0630 JST. According to the upper sounding (09 JST) at Wajima, the height of \(-10°C\) was equivalent to approximately 1.5 km in altitude (Fig. S1).

The G-PIMMS at Site A observed solid precipitation without completely or partially melted particles from 0620 to 0645 JST (Fig. 2b). The observed major particles were graupel for the first 10 minutes and changed to snowflakes after 0630 JST. Before/after 0630 JST, the averaged diameter and circularity of particles (Muramoto et al. 1993) changed from 0.95 mm and 0.71 to 1.02 mm and 0.62, respectively. The vertical cross section of the X-MP radar HC at 0620 JST showed that graupel was detected near the center of a snow cloud (Fig. 2a). The propagation speed along the east-west direction (X-Y in Fig. 1a) of the snow cloud was estimated to be approximately 13 m s\(^{-1}\) according to the time series of the X-MP radar HC cross section. Based on the propagation speed and horizontal scale of the snow cloud considered herein, the
graupel-observed period by the G-PIMMS at Site A from 0620 to 0630 JST corresponded well with the graupel region classified by the X-MP radar HC. In addition, the G-PIMMS mainly captured snowflakes in the snow region classified by the X-MP radar HC in the rear for the snow cloud. These features indicate that the X-MP radar HC used in the present study is appropriate to identify hydrometeors in the snow cloud although it is noted that the rain/drizzle region is due to an error of the temperature estimation in the HC algorithm and graupel may be classified as snow in the case that the radar reflectivity is weak.

3.2 Validation of “flagHeavyIcePrecip”

We validated the “flagHeavyIcePrecip” algorithm using X-MP radar reflectivity ($Z_H$) and its HC information, which was evaluated by G-PIMMS hydrometeor measurements as mentioned above.

Figure 3 shows contoured frequency by altitude diagrams (CFADs) of $Z_H$ for the DPR-flagged and DPR-unflagged footprints. Here, the DPR-flagged and DPR-unflagged footprints are defined as footprints with and without “flagHeavyIcePrecip”, respectively. At the DPR-flagged footprints, the concentration of large $Z_H$ extended vertically up to the height of 2.5 km. In contrast, the CFAD of $Z_H$ at the DPR-unflagged footprints was distributed broadly around the height of 1.5 km. The averaged $Z_H$ at the height of 1500 m was 27 dBZ for DPR-flagged footprints and 19 dBZ for DPR-unflagged footprints, and there was a statistically significant difference at a significance level of 5%. These features indicated that the “flagHeavyIcePrecip” algorithm is reasonable.

We compared the distributions of the DPR-flagged footprints and the XMP-graupel pixels at the height of 1.5 km (approximately –10°C height). They overlapped mostly
although there were some exceptions, which are that some DPR-flagged footprints were found in the XMP-snow pixel regions (Figs. 4a and 4b). It seems that “flagHeavyIcePrecip” was related to the presence of graupel.

In this case, there were 56 DPR-flagged footprints and 464 DPR-unflagged footprints in the analysis region. The averaged $G_{ratio}$ ($\overline{G_{ratio}}$) of the DPR-flagged and DPR-unflagged footprints were 28.9% and 4.9%, respectively. Figure 4c shows normalized histograms of $G_{ratio}$ for the DPR-flagged and DPR-unflagged footprints. About 53% of DPR-flagged footprints had $G_{ratio}$ of 10% or more. This indicated the presence of graupel. On the other hand, about 87% of DPR-unflagged footprints had $G_{ratio}$ of 10% or less.

Figure 5 shows the vertical profiles of the $Z_m$ and $DFR_m$ obtained from the GPM DPR at DPR-flagged (R and S) and DPR-unflagged (T and U) footprints. Their locations are shown in Fig. 3b. The footprints R and T (S and U) were chosen as typical points having high (low) values of $G_{ratio}$. In a comparison of the vertical profiles of $Z_m$ at footprints R and T, where the X-MP radar HC indicated the existence of graupel, footprint R had larger $DFR_m$ and higher $Z_m$ than footprint T at almost all levels. These features suggest that footprint R was a typical DPR-flagged footprint characterized by the existence of graupel. In contrast, “flagHeavyIcePrecip” was not detected at footprint T despite its high $G_{ratio}$. According to Iguchi et al. (2018a), the $DFR_m$ exhibits large values when precipitation particles are large. The small $DFR_m$ (< 7 dB) and smaller $Z_m$ than footprint R above the height of 2 km at footprint T leads to our presumption that small precipitation particles were dominant aloft.

For the footprints having low $G_{ratio}$, footprint U characterized by small $DFR_m$ and low $Z_m$ was a typical point unflagged by “flagHeavyIcePrecip”. On the other hand,
footprint S having XMP-snow pixels was flagged by “flagHeavyIcePrecip” and it was characterized by a smaller $Z_m$ than footprint R above the height of 2 km but large $DFR_m$ below the height of 3 km (Figs. 5a and 5b). Tyynelä and Chandrasekar (2014) showed that a large DFR indicates the existence of large snowflakes. Thus, it seems that the existence of large snowflakes was responsible for “flagHeavyIcePrecip” at footprint S.

3.3 Validation of “typePrecip”

The GPM DPR product “typePrecip” was validated from the point of view of cloud microphysics. The existence of graupel suggests that supercooled droplets necessary for riming growth are lifted by strong updrafts in convective clouds. Such a strong updraft is one of the most prominent features of a convective cloud (Houze 1994). Therefore, we believe that the existence of graupel is a proxy for convective precipitation.

In this case, precipitation was classified by three algorithms: the detection of “flagHeavyIcePrecip”, the extended-$DFR_m$-method, and the horizontal profile method (H-method: Awaka et al. 2016). The extended-$DFR_m$-method is examining $DFR_m$ near the storm top in the vicinity of the DPR-flagged footprints for the detection of winter convection (Iguchi et al. 2018b).

In this study, the footprints classified as convective by the GPM DPR “typePrecip” algorithm (hereinafter referred to as DPR-convective footprints) are divided into two types (DPR-flagged-convective and DPR-unflagged-convective) in consideration of "flagHeavyIcePrecip". Figure 6 shows the GPM DPR “typePrecip” map. The DPR-convective footprints tend to be distributed at the XMP-graupel pixels and their surrounding points (Fig. 4a), whereas some differences are found.

Table 1 shows the $G_{ratio}$ of DPR-convective footprints and the footprints classified as stratiform by the “typePrecip” algorithm (hereinafter referred to as DPR-stratiform...
footprints). Since all DPR-flagged footprints were classified into convective precipitation by the detection of “flagHeavyIcePrecip”, there were no DPR-flagged-stratiform footprints. In addition, the DPR-flagged-convective footprints had much larger $G_{ratio}$ than the DPR-unflagged-convective footprints. In other words, DPR-flagged-convective footprints well suggested the existence of graupel. Thus, the detection of “flagHeavyIcePrecip” is useful for the detection of convective footprints. However, footprints with large snowflakes might be classified as convective because “flagHeavyIcePrecip” might also reflect large snowflakes as mentioned in section 3.2.

On the other hand, among the DPR-unflagged-convective footprints with small $G_{ratio}$, 78 footprints out of a total of 83 were classified as convective by the extended-$DFR_m$-method. The extended-$DFR_m$-method is applied in the neighboring area within ±3 scans of detected “flagHeavyIcePrecip”. Considering the small horizontal scale of winter snow clouds, it is necessary to reconsider the parameters and applicable areas of the extended-$DFR_m$-method.

All DPR-unflagged-stratiform footprints in this case were classified as stratiform by the H-method in the single-frequency module, which is based on a horizontally uniform distribution of the attenuation-corrected radar reflectivity factor (Awaka et al. 2016). There are no significant differences of $G_{ratio}$ between DPR-unflagged-stratiform footprints and DPR-unflagged-convective footprints. The current algorithm classifying precipitation into the DPR-unflagged-convective/stratiform does not consider the microphysical features, so it might have something to improve in microphysics.

4. Summary

In this study, two GPM DPR products, “flagHeavyIcePrecip” and “typePrecip”, for a
winter snow cloud on 4 February 2018 were validated quantitatively using three-dimensional hydrometeor distributions by the X-MP radar, which were confirmed by microphysical evidence obtained from ground-based hydrometeor measurements by a G-PIMMS.

The CFAD of $Z_H$ at the DPR-flagged footprints showed a concentration of high reflectivity extending vertically up to the height of 2.5 km. In contrast, the CFAD of $Z_H$ at DPR-unflagged footprints exhibited a broad distribution with low reflectivity. This clear difference indicated that the “flagHeavyIcePrecip” algorithm is reasonable.

The X-MP radar HC information suggested that “flagHeavyIcePrecip” was strongly related to the existence of graupel. In addition, the vertical profiles of $Z_m$ and $DFR_m$ of the GPM DPR indicated that “flagHeavyIcePrecip” might be attributed to the existence of large snowflakes as well as graupel.

“flagHeavyIcePrecip” in the “typePrecip” algorithms was also useful to determine precipitation types in winter snow clouds. The DPR-convective footprints by the detection of “flagHeavyIcePrecip” were characterized by high $G_{ratio}$, which suggested the existence of graupel. On the other hand, most of the DPR-unflagged-convective (DPR-unflagged-stratiform) footprints were classified by the extended-DFRm-method (H-method), which does not consider the existence of graupel directly. On this point, there may still be room for improvement in the algorithm, and the accumulation of case studies will help to further improve the GPM DPR algorithm.

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Supplements

Table S1: Specification of the X-MP radars at Nomi and Mizuhashi.

Figure S1: Vertical profiles of temperature and relative humidity at Wajima at 09
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Fig. 1: (a) Radar reflectivity (CAPPI at a height of 500 m) obtained from X-MP radars at 0620 JST on 4 February 2018. A and B denote the locations of G-PIMMSs. W indicates the launching site of the upper sounding at Wajima. The two large circles indicate the observation range of X-MP radars. The red line (X-Y) denotes the direction of vertical cross section shown in Fig. 2. The small gray dots are footprints of GPM DPR. (b) Schematic diagrams of a single GPM DPR footprint with a diameter of 5 km and X-MP radar pixels (500 m × 500 m).

Fig. 2: (a) Vertical cross section of hydrometeor classification by X-MP radars at 0620 JST on 4 February 2018 along X-Y in Fig. 1a. Orange, green, and gray colors indicate graupel, snow, and drizzle/rain, respectively. (b) Time-size diagram of hydrometeors obtained from G-PIMMSs. Red and blue symbols indicate graupel and other solid particles, respectively.

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Fig. 6: GPM DPR “typePrecip” products considering the detection of  
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Table 1: Averaged $G_{ratio}$ for DPR-flagged and DPR-unflagged footprints in convective or stratiform precipitation.

<table>
<thead>
<tr>
<th>“flagHeavy IcePrecip”</th>
<th>Convective</th>
<th>Stratiform</th>
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<tr>
<td></td>
<td>$G_{ratio}$ (%)</td>
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<tr>
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</tr>
<tr>
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<td>85</td>
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N_{footprint}: number of footprints for each category