## RAINFALL-TYPE CLASSIFICATION BY POLARIMETRIC RADAR

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## 1. INTRODUCTION

Several previous studies presented that shallow convective rainfalls, which were characterized by low altitude of radar reflectivity peaks and large decrease of reflectivity with height above the 0°C level, are one of the main structures and have large contribution to the rainfall amount during the rainy season over East Asia (e. g., Chen et al. 2003; Zhang et al. 2006). Spatial distribution of hydrometeors in such rainfall systems is essential information to understand rain formation processes and also to upgrade rain retrieval algorithms from spaceborne radars and microwave radiometers (e.g., TRMM and GPM). However, little is known about such cloud microphysical properties in the shallow convective rainfall, mainly due to the inadequacy of those measurements.

Polarimetric radar measurements have been exploited to examine microphysical properties within precipitation systems. Some of the measurements are sensitive to the presence of large wet particles. For example, the cross-correlation coefficient ( $\rho_{hv}$ ) and linear depolarization ratio (LDR) show the robust signatures for the melting-layer in the stratiform rainfall (e.g., Herzegh and Jameson 1992; Brandes and Ikeda. 2004). These polarimetric measurements can give the signature of mixed-phase hydrometeors also in convective rainfall. Many previous studies, however, have focused on the presence of large, tumbling nonspherical particles such as irregular hail or graupel in wet growth in severe thunderstorm (e. g., Herzegh and Jameson 1992; Bringi et al. 1997).

Only a few studies examined the polarimetric measurements in shallow convective rainfalls. Shusse et al. (2006) compared the polarimetric measurements between two shallow convective rainfalls with almost the same echo-top height, one was isolated and the other was embedded in the preexisting stratiform rainfall. The melting layer signature of low  $\rho_{hv}(0)$  was observed in the embedded-type convective rainfall, which was closely related to the preexisting stratiform rainfalls accompanied with abundant snow aggregates above 0°C level. On the other hand, the melting signature was not observed in the isolated-type convective rainfall. This difference indicates that the conventional convective-stratiform classification based on the radar reflectivity field is insufficient for cloud microphysical characterization of the shallow

convective rainfall systems. The spatial distribution of melting layer should be one factor to characterize these rainfall systems.

In this study, the rainfall-type classification method which gives a judgment of the presence of the melting layer in addition to a conventional convective-stratiform classification is developed using the C-band polarimetric radar, CRL Okinawa bistatic polarimetric radar (COBRA) (Nakagawa et al. 2003). This method is applied to a rainfall system consisting of shallow convective rainfalls and broad stratiform rainfall region during the rainy season over East China Sea, which is called Baiu season in Japan. Using this rainfall-type classification, we estimate the appearance ratio of the melting layer and the level of melting layer in the convective rainfall region.

### 2. OBSERVATION AND DATA

On 2 June 2006, a rainfall system accompanied with the cold front was observed by the COBRA radar which is installed in Okinawa Island, Japan (128° 03' 50" E, 26° 35' 11" N). Figure 1 shows the horizontal distribution of radar reflectivity factor (Z<sub>hb</sub>) at 2-km altitude. Linear intense echo region which was consisted of convective cells extended from the southwest to the northeast. This convective rainfall region moved into the COBRA observation area (120km in radius during this observation) around 07 LST (LST = UTC + 9h) and generally propagated southeastward. It passed over the COBRA site at 10 LST and continued to propagate southeastward with maintaining its intensity. The convective cells moved at about 15 m  $\rm s^{-1}$  toward to the northeast within the linear convective region. The observed convective rainfall in the system were relatively shallow. The stratiform rainfall region was found both in the northwest and southeast sides of this convective



Fig. 1. Horizontal distribution of  $Z_{hh}$  at 0800 LST and 0930 LST. The contours of  $Z_{hh}$  are drawn every 5 dB from 15 dBZ. The solid lines indicate the azimuth direction of 330° of RHI scans.

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rainfall region. This type of rainfall system is often observed in the rainy season in this area.

The temperature was  $26.6^{\circ}$ C and the water vapor mixing ratio was  $20.9 \text{ g kg}^{-1}$  near the surface at 0900 LST at Naha, Okinawa. The 0°C level was about 4.3 km.

The COBRA radar was operated with 14 plan position indicator (PPI) scans, and one range height indicator (RHI) scan in 6 minutes during this observation. The elevation angles of the PPI scans were from 0.5° to 20.5°. The azimuth angle of the RHI scan was set at 330°, which is the direction perpendicular to the linear convective rainfall region.

The transmitting polarization was +45-degrees-tilt linear, and H- and V-independent digital receivers were used. The pulsewidth was 2  $\mu$ s, and the resolution of the radar data was therefore 300 m in the radial direction. The antenna scan speeds were 2.4 rpm for PPI scans and 1.5 rpm for RHI scans. The numbers of integration pulses were 48 for PPI scans and 128 for RHI scans. Low-SNR data of less than 15 dB were removed for the analysis of  $\rho_{hv}(0)$ . The values of  $\rho_{hv}(0)$  were corrected for low-SNR bias before the interpolation to grid points.

In the present study, the RHI scan data during 3 hours from 07 LST to 10 LST were mainly used in the following analysis because vertical resolution of at least several hundred meters is required for the detection of melting layer. The RHI scan data of  $Z_{hh}$  and  $\rho_{hv}(0)$  were interpolated at grid points with horizontal intervals of 1.0 km and vertical intervals of 0.25 km. For this interpolation, the measurements were averaged along the beam over a radius of 2 km in the horizontal direction using a Cressman weighting function (Cressman 1959), and then linearly interpolated in the vertical direction using 2 elevation angle data just above and below each grid point.

## 3. RAIN-FALL TYPE CLASSIFICATION

The rainfall-type classification in the present study includes two following steps: 1) conventional convective-stratiform separation using the horizontal distribution of  $Z_{hh}$  at 2km-altitude and 2) melting layer detection using the vertical profile of  $\rho_{hv}(0)$  at each horizontal grid point. Four rainfall types are identified by a combination of these two classifications: 1) convective rainfall with melting layer, 2) convective rainfall with no melting layer, 3) stratiform rainfall with melting layer, and 4) stratiform rainfall with no melting layer. These classification methods were applied within the ranges between 10 km and 80 km from the COBRA radar.

## 3.1 Convective-stratiform separation

Basically, the method of Steiner et al. (1995) was applied for the separation into convective and stratiform regions. But the method was slightly modified. The separation in this study is performed



Fig. 2. Peakedness criteria in the reflectivity difference used for convective center identification in the present study (solid line). The peakedness criteria used in Steiner et al. (1995) is also indicated (dashed line).

on gridded reflectivity data derived from the RHI data (1-km horizontal resolution) at 2-km altitude, which is sufficiently below the 0°C level. Any ground-clutter echoes do not appear at this level. The local 1D peakedness in the horizontal reflectivity field is identified as convective area and the remaining reflectivity echo greater than 15 dBZ as stratiform area.

Convective centers are identified when a grid point was at least 40 dBZ in  $Z_{hh}$ , or when the reflectivity difference ( $\Delta Z$  in desibel) between the reflectivity of an individual grid point and the local background reflectivity ( $Z_{bg}$  in dBZ) exceeds convective center criteria. In this study,  $Z_{bg}$  is determined as the linear average of the radar echoes within a radius of 11 km from the grid point. The criteria in  $\Delta Z$  for the detection of a convective center are depicted in Fig. 2. The curve is given by

$$\Delta Z = \begin{cases} 6, & (Z_{bg} < 30) \\ 8.5^2 \sqrt{1 - (\frac{x}{42.3})^2}, & (30 \le Z_{bg} \le 42.3) \\ 0, & (Z_{bg} \le 42.3). \end{cases}$$
(1)

Once convective centers have been identified, grid points within a certain distance from the convective center are classified as convective area. The distance is determined according to the Fig. 6b in Steiner et al. (1995). The relation of small distance is selected for the present analysis. These convective-stratiform separation criteria have been adjusted to match the manual identification as closely as possible.

## 3.2 Detection of melting layer and definition of melting-layer level

The melting layer is identified by using vertical profile of  $\rho_{h\nu}(0)$  (0.25-km vertical resolution) at each horizontal grid point. Figure 3 illustrates a model profile of  $\rho_{h\nu}(0)$  in the area with melting layer.  $\rho_{h\nu}(0)$ 

usually shows the value almost 1 for raindrops and ice crystals. But for melting aggregates such as wet snow,  $\rho_{hv}(0)$  can be less than 0.9 (Doviak and Zrnic 1993). Low  $\rho_{hv}(0)$  with layered structure is identified and detected as the melting layer signature by the following way.

First, the level with the lowest  $\rho_{hv}(0)$  is searched in the 3-km thick layer centering around the 0°C level. But the grid points with Z<sub>hh</sub> less than 15 dBZ were not considered in this search because their low values in  $\rho_{hv}(0)$  might be due to their low SNR. Then, the mean  $\rho_{hv}(0)$  of values at the levels 1 km above and below the lowest  $\rho_{hv}(0)$  level is calculated. The  $\rho_{hv}(0)$ difference ( $\Delta \rho_{hv}(0)$ ) between the mean  $\rho_{hv}(0)$  and the lowest  $\rho_{hv}(0)$  is used for identification of the melting layer. Any horizontal grid point that  $\Delta \rho_{hv}(0)$  is greater than or equal to 0.02 is identified as the area with melting layer. Any horizontal grid point that  $\Delta \rho_{hv}(0)$  is less than 0.02 is identified as the area with no melting layer. The level of the lowest  $\rho_{hv}(0)$  in the area with melting layer is defined as the melting-layer level.

The values of lowest  $\rho_{hv}(0)$  in the melting layer tend to artificially increase with the distance from the radar because of the smoothing by the beamwidth (0.91 degree). Interpolation of the measurements to grid points is also contributes to the smoothing. These smoothing effects have close relationship with the criterion in  $\Delta \rho_{hv}(0)$  for the detection of melting layer. In the present analysis, the criterion of 0.02 in  $\Delta \rho_{hv}(0)$  was enough small to detect the melting layer signature at the maximum range of 80 km, which was subjectively judged by the distribution pattern of  $\rho_{hv}(0)$  in the vertical section.

#### 3.3 Result of the rainfall-type classification

Figures 4 and 5 show examples of the rainfall-type classification. In the  $Z_{hh}$  field in Fig. 4,



Fig. 3. Model profile of  $\rho_{h\nu}(0)$  in the area with melting layer. The arrow indicates the range for searching the lowest  $\rho_{h\nu}(0)$  in the detection of melting layer.



Fig. 4. Vertical cross sections of  $Z_{hh}$  and  $\rho_{h\nu}(0)$  at 0835 LST. Top: Vertical distribution of  $Z_{hh}$ . The contours are drawn every 5 dB from 15 dBZ. Bottom: Vertical distribution of  $\rho_{h\nu}(0)$  (shadings). The contours of  $Z_{hh}$  are also drawn every 5 dB from 15 dBZ for reference. The areas identified as convective (C) and stratiform (S) rainfalls are labelled by red and blue bars under the top figure. The areas with melting layer (M) and with no melting layer (N) are labelled by green and gray bars above the bottom figure.



Fig. 5. As in Fig. 4, but for at 0923 LST.

convective area was shown at around x=50 km. The surroundings of the convective area were identified as stratiform rainfall areas. The bright band was found in the stratiform areas around 4-km altitude but was not remarkable in the convective area.

In the  $\rho_{h\nu}(0)$  field in Fig. 4, the layer of low  $\rho_{h\nu}(0)$  was observed almost all the range in the figure, where was identified as the area with melting layer. The melting-layer levels roughly corresponded with the levels of BB in the stratiform areas. It is noted that the melting layer moved upward in the convective area.

In Fig. 5, convective area was shown at around x=65 km. The decrease in  $\rho_{hv}(0)$  was not observed around the 0°C level in the convective area, where is identified as the area with no melting layer.

During the analysis period, precipitation region with larger than 15 dBZ at 2-km altitude was 1737 km. Convective region covered almost 23 % (396 km) of the precipitation region. The melting layer was detected in the 41 % of the convective region. The



Fig. 6. Normalized frequency distribution of melting-layer levels in convective and stratiform rainfall regions.

area with no melting layer was 57 % in convective region. Other 2% regions of convective region were eliminated from the analysis due to their low SNR around 0°C level as stated in section 3.2.

# 3.4. Melting-layer level in convective rainfall region

Figure 6 shows the frequency distribution of the melting-layer levels in the convective and stratiform regions. In this figure, the frequency of melting-layer levels was normalized in the convective with melting layer region (163 km) and in the stratiform with melting layer region (1055 km). The melting-layer levels widely distributed at around the 0°C level between 3 to 5.25-km altitudes. However, statistical difference was clearly found between in the stratiform and in the convective regions. The melting-layer levels in the convective region generally higher than those in the stratiform region. The convective and stratiform modes were at 4.25 and 3.75 km, respectively. The averaged level of melting layer was 4.1-km altitude in the convective region. This is 0.3 km higher than that in the stratiform region (3.8 km) and 0.2 km lower than the ambient 0°C level (4.3 km).

## 4. DISCUSSION

The frequency distributions of echo-top heights of 35 dBZ in the areas with melting layer and with no melting layer in the convective rainfall region are compared to discuss the convective activity (Fig. 7). The echo-top heights of 35 dBZ both in the convective areas with melting layer and with no melting layer peak at around the 0°C level (4.3 km). There is no significant difference in the frequency distribution of the echo-top heights of 35 dBZ between these areas. It seems that there was no large difference in the convective activity between in the areas with melting layer and with no melting layer. Both types could appear even in the same echo-top



Fig. 7. Frequency distribution of echo-top height of 35 dBZ in the areas with melting layer (WML) and with no melting layer (NML) in the convective rainfall region.

height for shallow convective rainfall.

Shusse et al. (2006) reported that the presence of a melting layer in shallow convective rainfalls had closely related to the preexisting stratiform rainfalls accompanied with abundant snow aggregates above 0°C level. In the present study, most of the melting layer in the convective rainfall was observed in the convective area which appeared in the preexisting stratiform rainfall (e.g., Fig. 4) as in Shusse et al. (2006). In addition, a melting layer was hardly observed in isolated convective cells as seen in Fig. 5. It is reasonable to say that, in the present rainfall system, the melting snow aggregates relating to the preexisting stratiform rainfall is an important factor to form mixed-phase layer in the convective area instead of the large nonspherical hail or graupel. A cold-rain process due to these melting snow aggregates appears to be more effective in the convective area with melting layer rather than in the convective area with no melting layer.

The averaged level of melting layer in the convective region was 0.3 km higher than that in the stratiform rainfall region. Air temperature in the updraft region is usually higher than that in the surrounding area. It seems reasonable to suppose that the difference in the vertical profile of temperature between in the convective area and surrounding stratiform area could result in the statistical ascent of the melting layer in the convective region. It is also noted that any significant descent of the melting layer was not observed in the convective rainfall region. This suggests that the downdrafts around the melting-layer level were weak in such shallow convective rainfalls.

Some areas with no melting layer were also observed around the center part of convective rainfalls appeared in the preexisting stratiform rainfall (not shown). It is considered that the melting-layer in these areas vanished as the convective cell developed. For these convective rainfalls, life stages of convective cells would be closely related to the characteristics of melting layer. The detailed time evolution of melting layer in the convective rainfall should be helpful to understand the microphysical properties in these areas.

In the rainfall retrievals by spaceborne radars and microwave radiometers, the assumption of the melting-layer model is closely related to the amount of retrieved surface rainfall. The stronger surface rainfall rate is estimated by the algorithm without the melting-layer model than by the algorithm with the melting-layer model. In the TRMM 2A25 algorithm (Iguchi et al. 2000), the melting-layer model based on the bright-band structure is introduced in stratiform rainfall region. In contrast, in the convective rainfall, any model for the melting hydrometeors is not introduced. However, the melting layer was detected in the 41 % of the convective region in the rainfall system in this study. This result suggests that the melting-layer model should be introduced not only in the stratiform rainfall but also in the shallow convective rainfall. The statistical studies for the spatial distribution of mixed-phase hydrometeors in convective rainfalls in various regions and seasons are useful to upgrade the rain retrieval algorithms for spaceborne radars and microwave radiometers.

## 5. SUMMARY

The rainfall-type classification method which gives a judgment of the presence of the melting layer in addition to a conventional convective-stratiform classification was developed using the C-band polarimetric radar. The convective-stratiform separation was conducted based on the horizontal distribution of  $Z_{hh}$  at 2 km-altitude. The melting layer was detected using the vertical profile of  $\rho_{hv}(0)$ . This method is applied to a rainfall system consisting of shallow convective rainfalls and broad stratiform rainfall region during the rainy season over East China Sea.

The melting layer was detected in the 41 % of the convective region in the rainfall system. This result suggests that the melting-layer model should be introduced not only in the stratiform rainfall but also in the shallow convective rainfall to upgrade the rain retrieval algorithms for spaceborne radars and microwave radiometers. Most of the melting layer in the convective rainfall was observed in the convective area which appeared in the preexisting stratiform rainfall. The averaged level of melting layer in convective region was 4.1-km altitude. This is 0.3 km higher than that in the stratiform region (3.8 km) and 0.2 km lower than the ambient 0°C level (4.3 km).

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## References

- Brandes, E. A., and K. Ikeda, 2004: Freezing-level estimation with polarimetric radar, *J. Appl. Meteor.*, 43, 1541–1553.
- Bringi, V. N., K. Knupp, A. Detwiler, L. Liu, I. J. Caylor, and R. A. Black, 1997: Evolution of a Florida thunderstorm during the Convection and Precipitation/Electrification Experiment: The case of 9 August 1991. *Mon. Wea. Rev.*, **125**, 2131–2160.
- Chen, J., H. Uyeda, and D. -I. Lee, 2003: A method using radar reflectivity data for the objective classification of precipitation during the Baiu season. *J. Meteor. Soc. Japan*, **81**, 229–249.
- Cressman, G. P., 1959: An operational objective analysis system. *Mon. Wea. Rev.*, **87**, 367–374.
- Doviak, R. J., and D. S. Zrnić, 1993: *Doppler Radar and Weather Observations.*, Academic Press., 562 pp.
- Herzegh, P. H., and A. R. Jameson, 1992: Observing precipitation through dual-polarization radar measurements. *Bull. Amer. Meteor. Soc.*, **73**, 1365–1374.
- Iguchi, T., T. Kozu, R. Meneghini, J. Awaka, and K. Okamoto, 2000: Rain-profiling algorithm for the TRMM precipitation radar. *J. Appl. Meteor.*, **39**, 2038–2052.
- Nakagawa, K., H. Hanado, S. Satoh, N. Takahashi, T. Iguchi, and K. Fukutani, 2003: Development of a new C-band bistatic polarimetric radar and observation of typhoon events. *Proc.* 31<sup>st</sup> Conf. on *Radar Meteor.*, Seattle, Amer. Meteor. Soc., 863–866.
- Shusse, Y., K. Nakagawa, N. Takahashi, S. Satoh, and T. Iguchi, 2006: Characteristics of polarimetric radar variables and their precipitation type dependence on a highly humid oceanic region. *Proc. 4th European Conference on Radar in Meteorology and Hydrology*, Spain, Barcelona, 57-60.
- Steiner, M., R. A. Houze Jr., and S. E. Yuter, 1995: Climatological characterization of three-dimensional storm structure from operational radar and rain gauge data. *J. Appl. Meteor.*, **34**, 1978–2007.
- Zhang, C. -Z., H. Uyeda, H. Yamada, B. Geng, and Y. Ni, 2006: Characteristics of mesoscale convective systems over the east part of continental China during the meiyu from 2001 to 2003. J. Meteor. Soc. Japan, 84, 763–782.