Polarimetric Radar Observation of the Melting Layer in a Convective Rainfall System during the Rainy Season over the East China Sea

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ABSTRACT

During the rainy season over the East China Sea, convective rainfalls often show melting layer (ML) characteristics in polarimetric radar variables. In this research, the appearance ratio of the ML (the ratio of rainfall area accompanied by polarimetric ML signatures) and the variation in height of the level of the ML signature maximum (MLSM level; defined by the level of the $\rho_{HV}$ minimum in the ML) in a convective rainfall region in a rainfall system over the East China Sea observed on 2 June 2006 were studied using C-band polarimetric radar (COBRA). For this analysis, a method of rainfall type classification that evaluates the presence of an ML in addition to providing conventional convective–stratiform classification using range–height indicator (RHI) observation data was developed. This rainfall type classification includes two steps: conventional convective–stratiform separation using the horizontal distribution of $Z_h$ at 2-km altitude, and ML detection using the vertical profile of $\rho_{HV}$ at each horizontal grid point. Using a combination of these two classifications, the following four rainfall types were identified: 1) convective rainfall with an ML, 2) convective rainfall with no ML, 3) stratiform rainfall with an ML, and 4) stratiform rainfall with no ML. An ML was detected in 53.9% of the convective region in the rainfall system. Using the same definition, an ML was detected in 83.1% of the stratiform region. The ML in the convective region showed a marked decrease in $\rho_{HV}$ coincident with an increase in $Z_{DR}$ around the ambient 0\degree C level, as did that in the stratiform region. Melting aggregated snow was the likely cause of the ML signature in the convective region. The average height of the MLSM level in the convective region was 4.64 km, which is 0.46 km higher than that in the stratiform region (4.18 km) and 0.27 km higher than the ambient 0\degree C level (4.37 km).

1. Introduction

Numerous previous studies have classified rainfall mainly into convective and stratiform types to characterize rainfall systems. Representative classification methods are based on ground-based measurements such as radar reflectivity data (e.g., Steiner et al. 1995; Rosenfeld et al. 1995), wind profiler data (e.g., Williams et al. 1995), disdrometer measurements (e.g., Tokay and Short 1996), and a combination of disdrometer and wind profiler measurements (e.g., Tokay et al. 1999). These classification techniques and the studies in which they have been applied have contributed greatly to many meteorological fields such as quantitative rainfall estimation, diabatic heating profile evaluation, and understanding the growth process of hydrometeors in precipitation systems. However, we still do not fully understand the microphysical structure of each rainfall type. For example, hydrometeor types around the 0\degree C level and their spatial distribution in convective rainfall regions are necessary for upgrading rain retrieval algorithms for spaceborne radars and microwave radiometers [e.g., the Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Measurement (GPM)].

Polarimetric radar measurements have been used to examine microphysical properties within precipitation...
systems. Some of the measurements show robust signatures of the presence of a melting layer (ML) (e.g., Bringi et al. 1986; Zrnić et al. 1993; Brandes and Ikeda 2004; Tabary et al. 2006; Giangrande et al. 2008). For example, the correlation coefficient between horizontal and vertical polarization signals ($\rho_{hv}$) decreases markedly and the linear depolarization ratio (LDR) increases in a region of melting hydrometeors with a large distribution of axis ratios, shapes, and/or canting angles. A bright band in the radar reflectivity ($Z_h$) and a peak in the differential reflectivity ($Z_{DR}$) are also common features of the ML in stratiform regions, which is usually associated with melting aggregated snow.

Several observational studies of the ML using polarimetric radars have been published recently (e.g., Brandes and Ikeda 2004; Ikeda et al. 2005; Tabary et al. 2006; Giangrande et al. 2008), some of which proposed an ML detection algorithm using polarimetric radar measurements. Many of these studies focused mainly on the ML in stratiform regions. Giangrande et al. (2008), however, suggested the possibility of ML detection using polarimetric radar variables in convective rainfalls, which are usually not accompanied by a bright band in $Z_h$. Recently, Shusse et al. (2009) showed that embedded convective rainfall, which was one of the rainfall types observed in a rainfall event over the East China Sea, was accompanied by obvious ML signatures in vertical profiles of $\rho_{hv}$ and $Z_{DR}$. Teshiba et al. (2009) also showed polarimetric ML signatures in a convective rainfall area in a mesoscale convective system in central Oklahoma. These studies clearly indicate that the appearance of polarimetric ML signatures in convective rainfalls is not unusual. In addition, Teshiba et al. (2009) presented a vertical change in the height of the polarimetric ML signatures in the convective rainfall area. An investigation of the appearance ratio of the ML and the variation in height of the MLSM level (defined by the level of $\rho_{hv}$ minimum in the ML) in the convective rainfall region of this rainfall system using the RHI scan data. The characteristics of the ML in the convective rainfall region are compared with those in the surrounding stratiform rainfall region. To conduct these analyses, a rainfall type classification method that evaluates the presence of the ML in addition to providing conventional convective–stratiform separation is developed using polarimetric radar information.

1. Observation and data

Figure 1 shows the surface weather map at 0900 LST (LST = UTC + 9 h) 2 June 2006. A cold front was located around Okinawa Island, where the COBRA is installed (26°35′11″N, 128°03′50″E). The temperature and water vapor mixing ratio near the surface were 26.6°C and 20.9 g kg$^{-1}$, respectively, and the 0°C level was about 4.37 km from the upper-air sounding launched at 0900 LST at Naha (see Fig. 2a for the location).

A convective rainfall system accompanying this cold front was observed by the COBRA. Figure 2 shows the horizontal distribution of $Z_h$ at 2-km altitude at 0800 and 0900 LST. A line of intense echo consisting of convective cells extended from the southwest to the northeast. This convective rainfall region moved into the COBRA observation area (120 km in radius during this observation) around 0700 LST and generally propagated southeastward, as shown in Fig. 2. It passed over the COBRA...
The convective cells moved at about 15 m s\(^{-1}\) toward the northeast along the line of the convective region. The stratiform rainfall region appeared on both the front (southeast) and back (northwest) sides of this convective rainfall region.

The COBRA was operated with 14 plan position indicator (PPI) scans from 0.5\(^{\circ}\) to 20.5\(^{\circ}\) and 1 RHI scan every 6 min during this observation. The azimuth angle of the RHI scan was set as 330\(^{\circ}\), which is the direction almost perpendicular to the line of convective rainfall. The transmitting polarization was +45\(^{\circ}\)-tilt linear, and H- and V-independent digital receivers were used. The pulse width 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 and 1.5 rpm for RHI scans. The number of integration pulses was 48 for PPI scans and 128 for RHI scans.

RHI scan data during the 3 h from 0700 to 1000 LST were mainly used in the following analysis because high-resolution data in the vertical direction are required for the present ML analysis. The polarimetric variables obtained by RHI scans were interpolated at grid points with horizontal intervals of 0.5 km and vertical intervals of 0.25 km. For this interpolation, measurements were averaged along the beam within a distance of 1.5 km in the horizontal direction using a Cressman weighting function (Cressman 1959) and then linearly interpolated in the vertical direction using data from two elevation angles (just above and below each grid point). The values of \(\rho_{hv}\) were corrected for signal-to-noise ratio (SNR) using the method of Shusse et al. (2009) before the interpolation of observational data to grid points. Low-SNR data of less than 10 dB were removed from the analysis. Rainfall attenuation in \(Z_h\) and \(Z_{DR}\) was corrected using the combined \(\phi_{DP}-Z_{DR}\) constraint (Bringi and Chandrasekar 2001).

3. Rainfall type classification

To analyze the appearance ratio of the ML and the variation in height of the MLSM level in a convective rainfall system, we first develop a method of rainfall type classification that evaluates the presence of the ML in addition to providing conventional convective–stratiform classification using RHI observation data. The rainfall type classification includes two steps: conventional convective–stratiform separation using the horizontal distribution of \(Z_h\) at 2-km altitude, and ML detection using the vertical profile of \(\rho_{hv}\) at each horizontal grid point. Using a combination of these two classifications, the following four rainfall types are identified: 1) convective rainfall with an ML (CML), 2) convective rainfall with no ML (CNL), 3) stratiform rainfall with an ML (SML), and 4) stratiform rainfall with no ML (SNL). This classification method is applied within the horizontal ranges between 25 and 60 km from the COBRA radar, as described later. The following subsections present the detailed algorithm used for this rainfall classification.

a. Convective–stratiform separation

In this study, the method of Steiner et al. (1995), with slight modifications, is employed for the separation into
convective and stratiform regions. Convective–stratiform separation is performed on gridpoint \( Z_h \) data at 2-km altitude derived from the RHI scan data. Local peaks in the 1D horizontal field of \( Z_h \) at 2-km altitude are identified as convective areas, and the remaining reflectivity echo greater than 15 dBZ is identified as a stratiform area (as described later in detail). The altitude of 2 km is sufficiently below the ambient 0°C level, and no ground- and/or sea-clutter echoes appear at that altitude in this case.

We use two criteria for identifying convective centers in this study, as in Steiner et al. (1995). First, any grid point with \( Z_h \) not less than 40 dBZ is labeled a convective center. The threshold value of 40 dBZ is the same as that in Steiner et al. (1995). In addition, stratiform rainfalls with \( Z_h \) larger than 40 dBZ were not observed at 2-km altitude in this study. Second, any grid point with a reflectivity difference (\( \Delta Z_h \); dB) between \( Z_h \) at an individual grid point and the local background reflectivity (\( Z_{h/bg} \); dBZ) larger than the convective center criterion defined below is identified as a convective center. In this study, \( Z_{h/bg} \) is determined as the linear average of \( Z_h \) data within a distance of 11 km from each grid point. The criteria in \( \Delta Z_h \) for the detection of a convective center are depicted in Fig. 3. The curve is given by

\[
\Delta Z_h = \begin{cases} 
6 & Z_{h/bg} < 30, \\
8.5 \sqrt{1 - \left( \frac{Z_{h/bg}}{42.43} \right)^2} & 30 \leq Z_{h/bg} < 42.43, \\
0 & Z_{h/bg} \geq 42.43.
\end{cases} 
\]  

Once convective centers have been detected, grid points within a certain distance of them are classified as a convective area. The distance is determined according to the “small” distance in Fig. 6b in Steiner et al. (1995).

The \( \Delta Z_h \) criteria in Eq. (1) are modified from those in Steiner et al. (1995). In this study, some areas of strong stratiform rainfall under the rain streak accompanied by an obvious bright band in \( Z_h \) tend to be classified into the convective rainfall region when using the \( \Delta Z_h \) criteria in Steiner et al. (1995). This misclassification seems to be attributed to the different data dimensions used for convective–stratiform separation: a 2D (horizontal) distribution in Steiner et al. (1995) and a 1D (range) profile in the present study. Consequently, the \( \Delta Z_h \) criteria in Steiner et al. (1995) have been adjusted for the present study to reduce these misclassifications.

\section*{b. Detection of the ML and definition of the MLSM level}

Tabary et al. (2006) reported the vertical profiles of polarimetric variables using 20 episodes of stratiform rainfall observed by C-band polarimetric radar. They concluded that \( \rho_{hv} \) decreases to 0.93 on average in the middle of the bright band. On the other hand, \( \rho_{hv} \) values above and below the ML are usually larger than 0.98. The ML thickness presented in Fig. 6 in Tabary et al. (2006) was about 1 km. Taking their results into consideration, an ML detection algorithm was developed using the vertical profile of \( \rho_{hv} \) with a vertical grid interval of 0.25 km at each horizontal grid point in this study.

A model profile of \( \rho_{hv} \) in the region with the ML is shown in Fig. 4 to illustrate the ML detection algorithm. This profile is based on the work of Tabary et al. (2006) and Brandes and Ikeda (2004). For illustration purposes, a level of \( \rho_{hv} \), minimum of 4.0 km and an ambient 0°C level of 4.37 km are assumed in Fig. 4.

First, the \( \rho_{hv} \) minimum (\( \rho_{hv, min} \)) is detected in the 3-km-thick layer centered around the ambient 0°C level (2.87–5.87-km altitude in Fig. 4). Grid points with \( Z_h \) of less than 15 dBZ, however, are not considered in the search for \( \rho_{hv, min} \) to eliminate data with low SNR from the analysis. Then, the mean \( \rho_{hv} \) (\( \rho_{hv, mean} \)) of values at levels 1 km above and below the level of \( \rho_{hv, min} \) is calculated. The \( \rho_{hv} \) difference (\( \Delta \rho_{hv} \)) between \( \rho_{hv, mean} \) and \( \rho_{hv, min} \) is used to evaluate the presence of an ML. Any horizontal grid point with \( \Delta \rho_{hv} \) greater than or equal to 0.02 is identified as an area with an ML. Any horizontal grid point with \( \Delta \rho_{hv} \) less than 0.02 is identified as an area with no ML. The level of \( \rho_{hv, min} \) in the ML is defined as the MLSM level.

In this study, we use the threshold of \( \Delta \rho_{hv} \) instead of the value of \( \rho_{hv, min} \) to detect an ML, as stated above.
because the values of $\rho_{hv_{\text{min}}}$ detected by the above procedure are not always the local minimum values in the vertical profiles of $\rho_{hv}$. Using $\Delta \rho_{hv}$ for the threshold is a simple fitting method to detect the local minimum value of $\rho_{hv}$ with a layer structure. For example, in the case of $\rho_{hv}$ values of 0.99 at 1 km above and below the height of $\rho_{hv_{\text{min}}}$, which is a typical value in the areas above and below the ML in this observation, the $\rho_{hv_{\text{min}}}$ value in the ML is less than or equal to 0.97 with a threshold value of 0.02 in $\Delta \rho_{hv}$ for ML detection. A $\rho_{hv}$ value of 0.97 in the ML corresponds to the upper $\rho_{hv}$ threshold in the ML detection algorithm in Giangrande et al. (2008), which is based on the best separation in $\rho_{hv}$ values of wet snow from dry snow and rain. In addition, the variation in $\Delta \rho_{hv}$ values was surveyed in the stratiform region with an obvious bright band in $Z_h$ in this rainfall event, where wet snow should be contained within the ML. Figure 5 is an example of RHI displays of $Z_h$ and $\rho_{hv}$, and the range distribution of $\Delta \rho_{hv}$ in the stratiform rainfall region. In most parts of this section, a bright band is observed in the $Z_h$ field (Fig. 5a). A layer of low $\rho_{hv}$ is also clearly found near the brightband level (Fig. 5c). As Fig. 5d shows, the $\Delta \rho_{hv}$ value fluctuates between 0.02 and 0.05 in this section. Only a few $\Delta \rho_{hv}$ data are lower than 0.02 at around $x = 30$ km, where the brightband signature in $Z_h$ is clearly weaker than in surrounding areas. These spatial distributions of $\rho_{hv}$, $Z_h$, and $\Delta \rho_{hv}$ indicate that the $\Delta \rho_{hv}$ threshold of 0.02 for ML detection in this study is adequate to detect an ML associated with melting aggregated snow.

Several previous studies noted that the favorable elevation angle for ML observation is limited (e.g., Tabary et al. 2006; Ryzhkov 2007; Giangrande et al. 2008). At elevation angles lower than 4°, ML signatures are smeared and widened, mainly because of beam broadening. On the other hand, at elevation angles greater than 10°, the number of range gates within an ML range decreases. Ground-clutter contamination is also likely at higher elevation angles. Thus, elevation angles between 4° and 10° are considered adequate for ML observation. Considering the ambient 0°C level of 4.37-km altitude in this study, horizontal ranges between 25 and 60 km from the radar are adequate for ML analysis. For this reason, the rainfall type classification algorithm in this study is applied within the horizontal ranges between 25 and 60 km from the COBRA.

c. Examples of rainfall type classification

Figures 6 and 7 present examples of rainfall type classification for the convective rainfall system. In the $Z_h$ field at 0835 LST (Fig. 6a), a strong echo area appears at around $x = 50.0$ km and is identified as a convective area (Fig. 6b). The 40-dBZ echo-top height of this convective rainfall is 5.25-km altitude. Its surroundings are identified as stratiform areas (Figs. 6a and 6b). A bright band in $Z_h$ is found in the stratiform areas around 4-km altitude, but it is not remarkable in the convective area (Fig. 6a). In the $\rho_{hv}$ field (Fig. 6c), a low $\rho_{hv}$ layer is found not only in the stratiform areas but also in the convective area. The low $\rho_{hv}$ layer in this convective rainfall area is contiguous to those in the surrounding stratiform rainfall areas. Most of the rainfall region in Fig. 6 is identified as having an ML (Fig. 6b). The MLSM level corresponds roughly to the brightband level and the ambient 0°C level (4.37-km altitude) in the stratiform areas. Note that the ML in the convective area in Fig. 6c is clearly elevated. The RHI display of $Z_{DR}$ is also presented in Fig. 6d, although $Z_{DR}$ is not used for rainfall classification in this study. Around the ambient 0°C level, $Z_{DR}$ enhancement is observed in both the stratiform and
convective regions, the height of which is almost coincident with the MLSM level in Fig. 6c.

Figure 7 shows another example of a convective rainfall area at 0859 LST. The convective area is located at around $x = 47$ km, which is almost the same distance from the radar as the convective area in Fig. 6. However, the two convective cells in Figs. 6 and 7 are different cells, since convective cells in the rainfall system moved toward the northeast, nearly perpendicular to the vertical cross sections in Figs. 6 and 7. A low $\rho_{hv}$ layer is observed in a wide range in Fig. 7 as well as in Fig. 6. However, the decrease in $\rho_{hv}$ at around the ambient 0°C level is not significant in the central part of the convective area in Fig. 7 (from $x = 45$ km to $x = 50$ km), which is identified as having no ML. In the $Z_{DR}$ field (Fig. 7d), $Z_{DR}$ enhancement around the 0°C level is generally observed in the stratiform region but is not obvious in the convective region. A $Z_{DR}$ column below the 0°C level is a distinctive structure in the convective region in Fig. 7.

To illustrate the discriminative vertical structures in the SML, CML, and CNL areas, selected vertical profiles of $Z_h$, $\rho_{hv}$, and $Z_{DR}$ in Figs. 6 and 7 are shown in Fig. 8. In the SML area at $x = 30$ km in Fig. 7, a bright band in $Z_h$ is obvious at around the ambient 0°C level (Fig. 8a). The MLSM level (the level of $\rho_{hv,min}$) is seen at 4.0-km altitude (Fig. 8b), which is slightly lower than

![Fig. 5](http://journals.ametsoc.org/doi/pdf/10.1175/2010JAMC2469.1)
the level of the bright band in $Z_h$. The level of the maximum $Z_{DR}$ is close to the MLSM level determined by the vertical profile of $\rho_{hv}$ (Fig. 8c). These vertical profiles in the SML area are typical ML signatures in stratiform rainfalls (e.g., Brandes and Ikeda 2004).

In the CML area at $x = 50.5$ km in Fig. 6 and the CNL area at $x = 47$ km in Fig. 7, the brightband signatures in $Z_h$ are not obvious (Fig. 8a). However, the existence of the ML in the CML area is confirmed by the decrease in $\rho_{hv}$ at 5.5-km altitude (Fig. 8b). An increase in $Z_{DR}$ is found at the same altitude as $\rho_{hv,\text{min}}$ in the CML area (Fig. 8c), which also supports the existence of the ML in the CML area. These vertical profiles in $\rho_{hv}$ and $Z_{DR}$ clearly illustrate that the MLSM level of 5.5-km altitude in the CML area in Fig. 6 is 1.5 km higher than that in the SML area in Fig. 7 (Figs. 8b and 8c).

The absence of the obvious bright band in $Z_h$ in the CML area illustrated in Fig. 8a is a common feature in

Fig. 6. (a) RHI display of $Z_h$ at 0835 LST. (b) Rainfall types identified by the algorithm in section 3; red—convective rainfall area, blue—stratiform rainfall area, green—area with melting layer, and gray—area with no melting layer. (c) RHI display of $\rho_{hv}$ (shading) at 0835 LST. (d) RHI display of $Z_{DR}$ (shading) at 0835 LST. The $Z_h$ contours are also drawn every 5 dB from 15 dBZ for reference. The location of the vertical profile in Fig. 8 is indicated (x = 50.5 km).
the CML region in this rainfall system. To show this
generality, a scatterplot of $Z_h$ at the MLSM level and at
1 km below the MLSM level for the whole CML region
is presented in Fig. 9a. The $Z_h$ values at the two levels
are generally comparable in the CML region. The av-
erage $Z_h$ at the MLSM level in the CML region is
40.0 dB$_Z$, which is 0.5 dB smaller than that at the level
1 km below the MLSM level (40.5 dB$_Z$). It is reasonable
to say that the bright band in $Z_h$ is not obvious in the
CML region in this rainfall system. The same analysis
was conducted for the SML region for comparison (Fig.
9b). The $Z_h$ values at the MLSM level are generally
larger than those at the level 1 km below the MLSM
level. The average $Z_h$ at the MLSM level in the SML
region is 37.7 dB$_Z$, which is 4.8 dB larger than that at the
level 1 km below the MLSM level. Unlike the CML re-

gion, the bright band in $Z_h$ is dominant in the SML region.

In contrast to the SML and CML areas, no dramatic
change in $\rho_{hv}$ is found at any altitude in the CNL area at
$x = 47$ km in Fig. 7 (Fig. 8b). In addition, $Z_{DR}$ increases
steadily with decreasing altitude and does not show a
marked increase around the ambient 0°C level in the

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{As in Fig. 6, but for 0859 LST. The locations of the vertical profiles in Fig. 8 are indicated ($x = 30$ km and $x = 47$ km).}
\end{figure}
CNL area (Fig. 8c). It is reasonable to say that melting aggregated snow is not a major constituent of hydrometeors around the ambient 0°C level in the CNL area in Fig. 7.

As shown in Figs. 6–8, rainfall areas with an ML are identified independently from the convective and stratiform separation using the vertical distributions of $r_{hv}$. This enables the estimation of the appearance ratio of the ML in the convective rainfall region. Another remarkable feature is the significant vertical change in the MLSM level in the convective region. The following section presents these overall features of the ML in this rainfall system.

4. Characteristics of the ML in the convective rainfall region

a. Appearance ratio of the ML in the convective rainfall region

The appearance ratio of the ML in the convective region was derived using the data from 31 RHI scans during the 3 h from 0700 to 1000 LST in the range between 25 and 60 km from the COBRA, where the rainfall type classification was applied. The total observation length for this analysis was 1100.5 km. Of this length, the precipitation region with $Z_h$ larger than 15 dBZ at 2-km altitude was 838.0 km. The total convective region was 168.0 km and covered 20.0% of the precipitation region. Table 1 summarizes the appearance frequency of each rainfall type. The CML region was 90.5 km and constituted 53.9% of the total convective rainfall region. The CNL region was 67.5 km and constituted 40.2% of the total convective rainfall region. The other 6.0% of the total convective region was the area eliminated from the rainfall type classification analysis because of its low SNR around the ambient 0°C level, as stated in section 3b.

The appearance frequency of each rainfall type in the stratiform rainfall region is also shown in Table 1 for reference. The SML and SNL regions covered 83.1% and 14.8% of the total stratiform rainfall region, respectively. One example of the SNL region, the area with a weaker brightband signature in $Z_h$ than the surroundings, is already presented in Fig. 5.

b. MLSM level in the convective rainfall region

Figure 10 shows the relative frequency distributions of the MLSM level in the convective and stratiform regions. The frequencies of the MLSM level in the convective and stratiform regions are shown for the CML (168.0 km) and SML (670.0 km) areas. The MLSM levels are widely distributed around the ambient 0°C level between 3.5- and 5.5-km altitude. However, a statistical difference in the MLSM levels between the convective and stratiform regions is clearly seen. The MLSM level in the convective region is generally higher than that in the stratiform region. The modes of the MLSM levels in the convective and stratiform regions are 4.5 and 4.0 km, respectively. Closer examination of the figure reveals that in the convective region, the area with an MLSM level lower than the mode value of that in the stratiform region is small. This indicates that depression
of the MLSM level in the convective region was not predominant in this rainfall system. Consequently, the average height of the MLSM level is 4.64-km altitude in the convective region, which is 0.46 km higher than that in the stratiform region (4.18 km) and 0.27 km higher than the ambient 0°C level (4.37 km).

5. Discussion

a. Hydrometeors at around the 0°C level in the CML region

This study shows that 53.9% of the convective rainfall region was accompanied by an ML and was identified as a CML region using RHI observational data. As depicted in Figs. 6 and 8, the CML region shows the ML signature of marked decrease in $\rho_{hv}$ coincident with an increase in $Z_{DR}$ around the ambient 0°C level, although the bright band in $Z_h$ is not obvious (Fig. 9a). The foregoing features of vertical profiles of polarimetric radar variables have also been reported in embedded convective rainfalls in Baiu front events during the rainy season in East Asia (Shusse et al. 2009; Oue et al. 2010).

Several previous studies have presented polarimetric radar signatures of melting hydrometeors in convective rainfalls. For example, Bringi et al. (1986) studied graupel melting in Colorado convective storms using an electromagnetic backscatter model as well as polarimetric radar and aircraft measurements. In their study, an LDR bright band due to soaked, water-coated conical graupel was manifested. The LDR is also sensitive to the presence of large mixed-phase hydrometeors; the response to mixed-phase hydrometeors in LDR shows the opposite sign to that of $\rho_{hv}$. Bringi et al. (1986) also presented a steady increase in $Z_{DR}$ with decreasing altitude in the LDR bright band, which corresponded to the onset and progression of the melting of graupel into

![TABLE 1. Appearance length and ratio of each rainfall type in the convective and stratiform rainfall regions.](image1)

<table>
<thead>
<tr>
<th>Type</th>
<th>Length (km)</th>
<th>Appearance ratio to the convective portion (%)</th>
<th>Appearance ratio to the stratiform portion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convective</td>
<td>168.0</td>
<td>53.9</td>
<td>83.1</td>
</tr>
<tr>
<td>Stratiform</td>
<td>670.0</td>
<td>40.2</td>
<td>14.8</td>
</tr>
</tbody>
</table>

![FIG. 10. Scatterplots of $Z_h$ at the MLSM level and at 1 km below the MLSM level for the (a) CML and (b) SML regions.](image2)

![FIG. 10. Relative frequency distribution of the height of the MLSM level in the CML and SML regions.](image3)
raindrops. In the CML region in this study, however, a marked increase in \( Z_{DR} \) was observed at almost the same altitude as the decrease in \( r_{hv} \) around the ambient 0°C level. These features of the vertical profiles of \( Z_{DR} \) and \( r_{hv} \) are more similar to the polarimetric ML signatures in stratiform rainfalls, where melting aggregated snow should be contained within the ML (Ryzhkov and Zrnić 1998; Brandes and Ikeda 2004; Ikeda et al. 2005; Shusse et al. 2009).

Ryzhkov et al. (2008) presented modeling results in which the profiles of polarimetric radar variables around the ML are sensitive to the degree of riming of melting hydrometeors. A deeper \( r_{hv} \) minimum is simulated for unrimed and low-density snow (as in the pure stratiform case), and a shallower \( r_{hv} \) minimum is simulated for heavily rimed snow (i.e., graupel). Figure 11a presents the normalized histogram of \( r_{hv,\text{min}} \) for the CML and SML regions in this study. The mode value of \( r_{hv,\text{min}} \) in the CML region (0.94) is lower than that in the SML region (0.96), which should be associated with melting aggregated snow. The mean value of \( r_{hv,\text{min}} \) in the CML region (0.94) is also lower than that in the SML region (0.95). The normalized histogram of \( Z_{DR} \) at the MLSM level for the CML and SML regions is also shown in Fig. 11b. The mean value of \( Z_{DR} \) in the CML region (1.09 dB) is larger than that in the SML region (0.95 dB). These data support the idea that melting low-density snow is a major component of the mixed-phase layer in the CML region. It is reasonable to say that melting aggregated snow is more likely than melting graupel to cause the ML signature in the CML region.

In this rainfall system, the stratiform rainfall region was observed on both the front and back sides of the convective rainfall region (Fig. 2). The convective cells in the present convective rainfall system appeared and developed in an embedded situation in the widespread stratiform rainfall region. It is considered that preexisting aggregated snow at upper levels in the rainfall system can be fed to produce the polarimetric ML signature in this convective rainfall region.

**b. Vertical change in height of the MLSM level in the CML region**

The average height of the MLSM level in the convective region was 0.46 km higher than that in the stratiform rainfall region, as described in section 4b. Horizontal distributions of elevated MLs in the convective areas were clearly observed in the RHI data, as shown in Fig. 6, whereas significant depression of the MLSM level was rarely observed (Fig. 10). As discussed in section 5a, the dominant hydrometeors in the ML are likely to be melting aggregated snow in the CML region as well as in the surrounding stratiform region. It seems reasonable to suppose that this upward shift of the MLSM level in the convective region corresponds to local temperature variations.

To check the possible range of upward shift of the local 0°C level in the updraft areas in this rainfall system and consider the reasonability of the presence of melting aggregated snow in the ML in the CML region, the vertical profile of ambient temperature \( T_{\text{amb}} \) and the temperature of a rising air parcel from near the surface \( T_{\text{par}} \) estimated from sounding data observed at Naha at 0900 LST 2 June 2006 are shown in Fig. 12. The level of 0°C in \( T_{\text{amb}} \) was 4.37 km, as stated earlier. On the other hand, the level of 0°C in \( T_{\text{par}} \) was 5.62 km, which is 1.25 km higher than for \( T_{\text{amb}} \).

The average height of the MLSM level in the CML region was 4.64 km, which is 0.27 km higher than the level of 0°C in \( T_{\text{amb}} \) (4.37 km). However, the average height of the MLSM level in the CML region is 0.98 km lower than the level of 0°C in \( T_{\text{par}} \) (5.62 km). The maximum height of the MLSM level in the CML region was 5.5 km in this study (Fig. 10). It tended to appear around the center of the convective cells (Figs. 6 and 8), where
the influence of entrainment is relatively small. Even this highest MLSM level in the CML region was still lower than the level of 0°C in $T_{\text{par}}$ (5.62 km). The $T_{\text{par}}$ value at the maximum height of the MLSM level in the CML region was 0.66°C. From the above analysis of sounding data and simple parcel theory, the polarimetric MLS signatures in the CML region are considered to have occurred in convective updraft areas and at positive temperatures where aggregated snow can melt, although the MLSM level in the CML region was generally higher than the ambient 0°C level.

In contrast to this study, Teshiba et al. (2009) have reported an obvious depression of the ML in a convective downdraft region in a mesoscale convective system in central Oklahoma using the vertical $Z_{\text{DR}}$ and $\rho_{\text{hv}}$ profiles. They also showed the possible presence of graupel and/or small hail above the ML by vertically pointed wind profiler data. Their study attributed the depression of the ML to a downdraft combined with cooling by melting graupel/hail below the ambient 0°C level. In this study, significant depression of the ML was rarely observed, as stated above. This indicates that cooling by melting hydrometeors below the 0°C level was not effective in the CML area. This also supports the idea that the dominant hydrometeors in the ML in the CML area in this study are melting aggregated snow, which has smaller terminal velocities than melting graupel/hail.

c. Hydrometeors at around the 0°C level in the CNL region

The ML signature in $\rho_{\text{hv}}$ was not obvious in 40.2% of the convective rainfall region in the present rainfall system. This region was identified as the CNL region. The 15-dBZ echo-top height in the CNL area in Fig. 7 reached an altitude of 8 km (around −18°C). This implies that mixed-phase hydrometeors probably exist around the 0°C level in the CNL area. However, a significant decrease in $\rho_{\text{hv}}$ and increase in $Z_{\text{DR}}$ were not observed around the ambient 0°C level, as depicted in Figs. 7 and 8. Thus, melting aggregated snow is not a major constituent of hydrometeors around the ambient 0°C level in the CNL region.

One possibility for the dominant mixed-phase hydrometeors in the CNL region is melting graupel, as in the case of Bringi et al. (1986). A steady increase in $Z_{\text{DR}}$ with decreasing altitude around the ambient 0°C level was observed in the CNL area in this study (Fig. 8c), which is similar to the vertical profile of $Z_{\text{DR}}$ in the melting graupel region in Bringi et al. (1986). Bringi et al. (1986) also showed a model result in which LDR values depend on the median particle diameter of melting graupel. A smaller change in $\rho_{\text{hv}}$ around the ambient 0°C level in the CNL areas in this study might imply smaller melting graupel in this convective rainfall system.

Another possibility for the mixed-phase hydrometeors in the CNL region is partially frozen raindrops in updrafts, although partially frozen raindrops can be responsible for depression of $\rho_{\text{hv}}$ around the tops of vertical columns of positive $Z_{\text{DR}}$ (e.g., Bringi et al. 1997; Gibson and Stewart 2007). Smith et al. (1999) reported, for a model of the freezing of drops in updraft regions, that the required freezing time and the final diameter in the updraft region are functions of initial raindrop size. In this study, the values of $Z_{\text{DR}}$ around the ambient 0°C level are approximately 1 dB in the CNL area in Fig. 7, as seen in Fig. 8c, and do not exceed 1.5 dB in any CNL area. These $Z_{\text{DR}}$ values are smaller than those in the $Z_{\text{DR}}$ columns of the convective cells in Florida in Bringi et al. (1997). The smaller drops around the ambient 0°C level in the CNL region may have a smaller effect on the $\rho_{\text{hv}}$ values during freezing. For further discussion of the hydrometeors at around the 0°C level in the CNL area

Fig. 12. Vertical profile of temperature observed at Naha at 0900 LST 2 Jun 2006 (dashed line). Solid line indicates the temperature of a rising air parcels at 1000 hPa (59-m altitude) of the sounding.
in this study, in situ observations of hydrometeors are needed in the future in addition to the polarimetric radar observations.

6. Summary

This paper describes the appearance ratio of the melting layer and the variation in height of the level of the ML signature maximum (defined by the level of \( \rho_{hv} \) minimum in the ML) in a convective rainfall region in a rainfall system during the rainy season over the East China Sea using C-band polarimetric radar. The convective rainfall system consisted of a line of convective rainfall and widespread stratiform rainfall regions, which spread both ahead of and behind the convective region, RHI scan data were obtained at 6-min intervals in the direction perpendicular to the line of convective rainfall during the 3-h observation of the system.

For the analysis, we first developed a method of rainfall type classification that evaluates the presence of the ML in addition to providing conventional convective–stratiform classification using the RHI observation data. The rainfall type classification includes two steps: conventional convective–stratiform separation using the horizontal distribution of \( Z_h \) at 2-km altitude, and ML detection using the vertical profile of \( \rho_{hv} \) at each horizontal grid point. Four rainfall types are identified by a combination of these two classifications: 1) convective rainfall with an ML (CML), 2) convective rainfall with no ML (CNL), 3) stratiform rainfall with an ML (SML), and 4) stratiform rainfall with no ML (SNL). This classification method is applied within the horizontal ranges between 25 and 60 km from the COBRA.

In this study, the CML region covered 53.9% of total convective region; that is, the ML was detected in 53.9% of the convective region in the precipitation system. The ML was detected in 83.1% of the stratiform region. The ML in the convective region showed a marked decrease in \( \rho_{hv} \) coincident with an increase in \( Z_{DR} \) around the ambient 0°C level, as did that in the stratiform region, although the bright band in \( Z_h \) was not obvious. Melting aggregated snow is likely the cause of the ML signature in the convective region of this study. The average height of the MLSM level was 4.64 km in the convective region, which is 0.46 km higher than that in the stratiform region (4.18 km) and 0.27 km higher than the ambient 0°C level (4.37 km). However, the polarimetric ML signatures in the convective region are considered to have occurred at positive temperatures in the convective updraft areas, where aggregated snow can melt, through the analysis of sounding data and simple parcel theory. These results suggest that an ML model with melting aggregated snow should be considered not only in the stratiform rainfall region but also in the convective rainfall region in rain retrieval algorithms for spaceborne radars and microwave radiometers.

The appearance ratio of the ML and the variation in height of the MLSM level in convective rainfalls should be closely related to the microphysical and dynamical structures of convective clouds and environmental atmospheric conditions. The characteristics of the ML in convective rainfall systems in different seasons and climate regions should be investigated and compared in the future. This will be helpful for characterizing the microphysical properties of the ML and developing practical ML models in convective rainfalls for rain retrieval algorithms for spaceborne radars and microwave radiometers.

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