X-Band Dual-Polarization Radar Observations of Snow Growth Processes of a Severe Winter Storm: Case of 12 December 2013 in South Korea

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ABSTRACT

The characteristics of microphysical processes of a severe winter storm that occurred on the Korean Peninsula on 12 December 2013 was studied in this work for the first time via X-band dual-polarization weather radar observations. A new range–height indicator (RHI) scan-based quasi-vertical profile methodology, in which polarimetric radar variables were averaged at each height of the RHI scan, was introduced to investigate the snow microphysics, and the obtained polarimetric radar signatures served as fingerprints of the dendritic growth, aggregation, and riming processes. Enhanced differential reflectivity (Z_{dr}) and specific differential phase shift (K_{dp}) bands were detected near the -15°C isotherm, which signified the growth of dendrites or platelike crystals. The observed correlation between the increases in the reflectivity factor at horizontal polarization Z_h and copolar correlation coefficient ρ_{hv} and the decreases in Z_{dr} and K_{dp} magnitudes at lower heights suggested the occurrence of the aggregation process. The combination of high Z_h and low Z_{dr} values with turbulent atmospheric conditions observed at the ground level indicated the occurrence of the riming process. In addition, the negative K_{dp} and Z_{dr} values combined with high Z_h and ρ_{hv} magnitudes (observed near the end of the snow event) indicated the formation of graupel particles. The polarimetric radar signatures obtained for the snow growth processes were evident from ground observations and agreed well with the results of the Weather Research and Forecasting Model and Modern-Era Retrospective Analysis for Research and Applications data. Furthermore, the spatial variability of Z_h methodology was implemented to describe both aggregates and rimed ice particles.

1. Introduction

Winter storms produce high socioeconomic impact on human lives and property. The heavy snowfall occurring during a winter storm is a serious threat to

transportation (especially aviation) and other related services. Snow growth processes affect the surface precipitation rate, which may have significant impact on the surface transportation (Juga et al. 2012) and agricultural activities. Therefore, monitoring and nowcasting of winter storms are important to provide early warnings. The proper interpretation of

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dual-polarization radar data plays a crucial role in describing the characteristics of the winter storm and making accurate predictions. Nevertheless, the latter remains a difficult task because of the uncertainty in interpreting the cloud composition and microphysics of snow growth processes (Schrom et al. 2015).

Ice particles can grow through the vapor deposition, aggregation, and riming processes (Houze 2014; Magono and Lee 1966; Pruppacher and Klett 1997; Wallace and Hobbs 2006). Further, ice multiplication is also an important process for ice growth in clouds (Hallett and Mossop 1974). Several researchers (Wolde and Vali 2001; Kennedy and Rutledge 2011; Andrić et al. 2013; Bechini et al. 2013; Griffin et al. 2014; Moisseev et al. 2015; Schrom et al. 2015; Kumjian et al. 2016; Kumjian and Lombardo 2017; Griffin et al. 2018) observed very interesting polarimetric radar signatures of the enhanced differential reflectivity (Z_{dr}) and specific differential phase (K_{dp}) layers located above the melting layer, which were related to the growth of dendrites and platelike crystals. Kennedy and Rutledge (2011) found pronounced Z_{dr} and K_{dp} signatures near the -15°C isotherm by conducting S-band radar observations during four different winter storm events. The authors also performed electromagnetic scattering simulations to describe the polarimetric radar signatures obtained by dendritic ice crystals. Bechini et al. (2013) conducted further analysis of the bands of high K_{dp} and Z_{dr} observed for stratiform precipitation events. They performed T-matrix electromagnetic scattering simulations at the C-band and X-band wavelengths to support the conclusion that the high values of K_{dp} aloft strongly correlated with heavy ground precipitation that was drawn by Kennedy and Rutledge in 2011. In another study, Andrić et al. (2013) observed enhanced layers of Z_{dr} and K_{dp} associated with low values of the copolar correlation coefficient ρ_{hv} , which appeared as isolated pockets during a winter storm. The enhanced signatures were explained using a one-dimensional microphysical model incorporating the ice initiation, vapor deposition, and aggregation processes. They concluded that the proposed model roughly reproduced both the profile and magnitudes of the reflectivity factor at horizontal polarization Z_h and ρ_{hv} as well as the correct shapes (but not the magnitudes) of the Z_{dr} and K_{dp} bands. The authors also reported that some important microphysical processes affecting the observed signatures, such as secondary ice production, were not included into the model. In another context, Moisseev et al. (2015) explored the relationship between the “seeder–feeder” process and

the values of K_{dp} and Z_{dr} . Strong bands of Z_{dr} without perceptible K_{dp} signatures were produced by the ice crystals grown by vapor deposition at low particle concentrations, which explained the existence of a vertical offset between the Z_{dr} and K_{dp} bands. Further, the enhanced K_{dp} bands indicated the onset of snow aggregation. Recently, Kumjian and Lombardo (2017) elucidated the mechanism of the seeder–feeder processes occurred during the northeastern U.S. coastal winter storms. In their study, it was documented that the strong K_{dp} bands observed near the -15°C isotherm indicated the presence of large concentrations of planar crystals, which suggested highly efficient snow aggregation. The authors also concluded that the enhanced Z_{dr} signature with low K_{dp} values denoted the start of the planar crystal growth process. Temperature is also an important parameter of winter storms that influences the snow growth mechanism (Wallace and Hobbs 2006; Griffin et al. 2018; Houze 2014; Dolan and Rutledge 2009). Schneebeli et al. (2013) characterized the ice/snow properties by studying the variabilities of Z_{dr} and K_{dp} with temperature. They observed the formation of pristine ice crystals at temperatures below -25°C (high altitudes), as indicated by the increases in these two parameters. The dendrites formed in the temperature range from -20° to -15°C were signified by the enhancement of the corresponding Z_{dr} bands. Finally, aggregates were observed at temperatures above -15°C (low altitudes), as indicated by the increase in Z_h and decrease in Z_{dr} .

During heavy riming, ice particles may lose their original shape and form rimed particles (graupel). Generally, graupel particles exhibit conical, hexagonal, and lump shapes (Knight and Knight 1973; List and Schemenauer 1971; Locatelli and Hobbs 1974; Magono and Lee 1966). Lump and hexagonal graupel particles are produced at near zero or small positive Z_{dr} and K_{dp} values (Aydin and Seliga 1984; Carey and Rutledge 2000; Vivekanandan et al. 1999). Knight and Knight (1973) provided a detailed description of the formation and growth of conical graupel particles, which exhibited low/negative Z_{dr} and negative K_{dp} polarimetric signatures because of their vertical orientations and small apex angles (Aydin and Seliga 1984; Evaristo et al. 2013; Homeyer and Kumjian 2015; Brangi et al. 2017). Oue et al. (2015) reported that prolate ice particles were characterized by negative K_{dp} and Z_{dr} values; conversely, positive K_{dp} and Z_{dr} magnitudes corresponded to large isometric or slightly oblate ice particles. Brangi et al. (2017) described the properties of graupel particles using the data obtained with an S-band polarimetric radar, a

two-dimensional video disdrometer (Schönhuber et al. 2008), and a multiangle snowflake camera (Garrett et al. 2012). The shape, orientations, and characteristics of graupel were determined via microwave backscattering calculations.

It is well known that rimed ice particles are denser and heavier and have higher terminal fall velocities than other ice particles (aggregates, dendrites, and pristine ones). Pristine ice crystals exhibit fall velocities less than 0.6 m s^{-1} , while aggregates of dendrites and densely rimed particles have fall velocities in the range of $0.7\text{--}1.5 \text{ m s}^{-1}$ (Locatelli and Hobbs 1974; Pruppacher and Klett 1997). The fall velocities above 1 m s^{-1} correspond to either aggregates or rimed particles. In some cases, it is difficult to classify the aggregation and riming processes according to vertical velocities W . Further, polarimetric radar signatures are not distinctive enough to differentiate between aggregates and rimed ice particles; instead, the spatial variability of Z_h (SVZ) factor related to particle size sorting and proportional to their fall velocity can be used for this purpose (Lim et al. 2013). The authors found that the rimed ice particles exhibited high Z_h values with large variabilities of Z_h as compared to those of aggregates. Moisseev et al. (2009) also showed that the smoothness of the reflectivity vertical profile of ice particles depended on their type. They reported that at lower heights, the large difference between $\max(Z_h)$ and $\min(Z_h)$ indicated rimed (dense) particles, while the opposite was true for aggregates.

Multiple research studies have been conducted to investigate the snow growth processes and ice particle habits (dendrites, aggregates, rimed particles, and graupel) in various regions of the world (Moisseev et al. 2015; Grazioli et al. 2015; Kouketsu et al. 2015; Oue et al. 2016; Brongi et al. 2017; Griffin et al. 2018). The topography of South Korea significantly differs from those of other countries. About 70% of its land is mountainous, especially in the northern and eastern parts. The eastern, western, and southern borders of South Korea are surrounded by the East Sea, Yellow Sea, and East China Sea, respectively. During winter, strong jet streams and orographic forcing can cause heavy snowfalls in this region. In the majority of studies conducted over different regions of South Korea, the snow growth processes were described by model-based scattering simulations. In this work, we cross validated the observed ice particle habits via the inferences of the Weather Research and Forecasting (WRF) Model (version 3.5.1), Modern-Era Retrospective Analysis for Research and Applications (MERRA) measurements, and ground observations.

Usually, winter storms in Korea do not produce graupel or heavy riming. The studied case represents an unusual/rare snowstorm event, during which large aggregates as well as heavily rimed and graupel particles were formed. No previous studies were conducted in the Korean Peninsula to describe the evolution of winter storms or variability of ice particles via dual-polarization radar measurements. Hence, this particular winter storm was investigated for the first time using high-spatiotemporal-resolution X-band polarimetric radar signatures. A new range–height indicator (RHI) scan-based quasi-vertical profile (R-QVP) methodology was utilized to determine Z_h , Z_{dr} , K_{dp} , ρ_{hv} , and spectrum width (SW) values and achieve a better understanding of the internal structure and evolution of the ice microphysical processes. The relation between the enhanced polarimetric radar signatures (such as large Z_{dr} and K_{dp} aloft values and high Z_h at lower heights) and the heavy snowfall on the ground was also established. At the end of the event, the negative K_{dp} and Z_{dr} magnitudes associated with high Z_h and ρ_{hv} in convective snow cells were examined. Additionally, the R-QVP method was applied to SVZ to distinguish between the aggregates and rimed ice particles.

This paper is organized as follows. Section 2 describes the R-QVP methodology for polarimetric variables. Observational data and synoptic conditions of the event are provided in section 3. The microphysics of the snow growth processes occurred during the winter storm on 12 December 2013 is interpreted in section 4 using X-band polarimetric radar signatures. Analysis of the entire snowfall event is conducted in section 5 using R-QVP vertical profiles. Finally, a summary and the conclusions of this study are presented in section 6.

2. R-QVP methodology

Ryzhkov et al. (2016) explored a new QVP method for polarimetric radar variables to elucidate the vertical and temporal evolutions of ice microphysical processes. In this method, the data of plan position indicator (PPI) scans are azimuthally averaged over 360° at a high fixed elevation angle ($>10^\circ$) for each time step. In our study, the PPI data recorded at only 5° and 6° elevation angles were utilized, while 10 RHI scans per volume were performed at fixed azimuthal angles from 0° to 360° and temporal resolution of 5 min (see Fig. 1). Therefore, we introduce a similar strategy exploiting RHI scans. A so-called R-QVP technique was used to calculate noise-reduced radar variables by the elevation-wise averaging of the

FIG. 3. Location of the KICT dual-polarization radar in South Korea and its coverage range circles with diameters of 20 and 40 km.

of 9.41 GHz and covers a range of 40 km. It operated in a dual-polarization mode, which was also known as the simultaneous transmit and receive mode (STAR). The scan schedule encompasses 6 PPI and 10 hemispheric (with elevation angles of 0° – 180°) RHI scans every 5 min. Over the duration of the winter storm event, the quasi-horizontal (PPI) data collection was performed by alternating between the elevation angles of 5° and 6° every minute at a range resolution of 60 m. RHI scans were conducted at 18° azimuth intervals. The main specifications of the KICT radar system and description of the utilized scanning strategy are provided in Table 1 and Fig. 1, respectively. The data collected by the KICT radar included the bias/error correction, attenuation correction for rain (performed by taking into account Φ_{dp}), data quality check (Scarchilli et al. 1996),

TABLE 1. Main specifications of the KICT radar.

Parameter	Value
Frequency	9410 ± 30 MHz
Peak power output	8.0 kW (per channel)
Maximum duty cycle	0.16%
Maximum coverage range	40 km
Gain	41 dB
Polarization	Dual linear, horizontal and vertical channels
Antenna type (diameter)	Front-fed parabolic (1.8 m)
Scan speed	Up to $60^{\circ} \text{ s}^{-1}$
Sampling resolution	1.2–192 m
Pulse repetition	2.0 kHz (maximum)
3-dB beamwidth	1.4°

TABLE 2. Configurations and physical parameters of the WRF Model.

Configuration	Outer domain	Inner domain
WRF version	V3.5.1	
Horizontal grids	382×373	400×382
Grid spacing (m)	5000	1000
Vertical grid	50 layers (top at 50 hPa)	
Integration time (s)	30	6
Initial boundary condition	Unified Model regional model forecast field (12-km resolution, KMA)	
Radiation	RRTM longwave and Dudhia shortwave radiation	
Microphysics	WDM 6-class	
Surface layer	Monin–Obukhov (Janjić) scheme	
Land surface	Unified Noah LSM	
Planetary boundary layer	Mellor–Yamada–Janjić TKE scheme, integration time: 5 min per step	
Cumulus	CPS	—
Land-use and topography data	30 s, USGS 33cat	

and K_{dp} estimation (Wang and Chandrasekar 2009) conducted using the algorithms described by Chen et al. (2017).

The MERRA data (obtained at 0300 and 0600 UTC 12 December 2013) were utilized to describe the atmospheric parameters of the studied event. It was generated by the Global Modeling and Assimilation Office (GMAO) of the National Aeronautics and Space Administration (NASA) for the Goyang region using the Goddard Earth Observing System, version 5 (GEOS-5), data assimilation system (Rienecker et al. 2011). The vertical velocity (W), cloud ice mixing ratio (QI), cloud liquid water mixing ratio (QL), environmental relative humidity (RH), and temperature (T) parameters were extracted to describe the growth of precipitation particles.

WRF is a state-of-the-art numerical weather prediction model widely used for operational forecasting and meteorological research (Skamarock et al. 2008). In this study, the WRF Model, version 3.5.1, was utilized to describe the microphysics of the snow growth processes. The nonhydrostatic incompressible model was developed by the National Center for Atmospheric Research (NCAR) in the United States. It used a one-way nested domain and was configured in the Lambert conformal map projection with the central latitude of 38°N and longitude of 126°E . The resolutions were 5 km with a 382×373 grid and 1 km with a 400×382 grid for the outer and inner domains, respectively. The inner domain covered Seoul metropolitan city and its surrounding areas. The outer

FIG. 4. Synoptic weather maps obtained at (a) 300 hPa, (b) 850 hPa, and (c) the surface at 0000 UTC 12 Dec 2013. (d) AWS hourly precipitation observed at 0700 UTC 12 Dec 2013. (e) Time series of the AWS observational data obtained for the Goyang City (37.6343°N, 126.8917°E). Denoted are the temperature (red line), humidity (blue line), wind direction (orange dots), wind speed (green line), precipitation (blue and pink shading), and time of occurrence (sky blue shading). The top axis shows the time (UTC).

FIG. 5. Vertical hydrometeor and temperature profiles obtained for Seoul from the WRF Model data at (a) 0400, (b) 0500, and (c) 0700 UTC.

domain passed down large-scale information to the inner domain and prevented the appearance of instabilities around the lateral boundary by creating a buffer zone for the artifacts entering into the inner domain. The physical parameterization procedure included the Yonsei University planetary boundary layer scheme, WRF double-moment 6-class microphysics scheme (WDM6), unified Noah land surface model (LSM), and Rapid Radiative Transfer Model (RRTM) longwave and Dudhia shortwave radiation schemes (WDM6 utilized two-moment schemes for rain and cloud and single-moment schemes for ice and snow). These schemes were found to be applicable to the East Asia region (Min et al. 2015), and their configurations and physical parameters are listed in Table 2.

b. Synoptic overview

Three hours before the snowstorm (at 0000 UTC 12 December 2013), a cutoff low was formed over northern China, and a circular jet stream with a velocity of 60 m s^{-1} was observed at 300 hPa (Fig. 4a). At 700–850 hPa, a broad upper-level trough has been identified west of the Korean Peninsula, which extended from the low pressure system located near the Sea of Okhotsk (Fig. 4b). This resulted in the formation of a surface cyclone over the Bay of Bohai, which brought relatively warm and humid air into the Seoul metropolitan area before the snowstorm (Fig. 4c). Later, a surface cold front was formed over the Yellow Sea, and the cold air moved toward the Seoul region. These two air masses (the warm air from the northwest and cold air from the

southwest) converged over the Seoul area leading to the development of a squall line (see the temperature profile depicted in Fig. 4e, which shows that the temperature was below 0°C at this particular time). The squall line was composed of an updraft ascending from the ground level to higher altitudes, which resulted in the condensation of water vapor and creation of a heavy snowfall. High rates of precipitation (up to 5.8 mm h^{-1}) were also observed on the ground (Fig. 4d). Figure 4e shows the temperature and humidity time series data obtained by the automatic weather station (AWS) located in Goyang City at a distance of about 13 km southeast of the KICT radar (37.6343°N, 126.8917°E; see Fig. 3), which was maintained by the Korea Meteorological Administration (KMA). Figure 4e shows that the humidity level was low ($<60\%$) until 0300 UTC and suddenly increased at 0330 UTC, which signified the convergence of the cold and warm humid airstreams. The humidity remained high until 0900 UTC conducive to the rapid growth of snow particles and decreased afterward.

4. X-band polarimetric radar observations of the winter snowstorm

This section describes the distinct polarimetric radar signatures of the studied storm from its development to the maturity and dissipation stages. The storm started at 0200 UTC, intensified between 0600 and 0800 UTC, and weakened afterward.

a. Dendritic growth of ice crystals and early aggregation

The vertical hydrometeor, snow growth, and temperature profiles obtained from the WRF Model data over Seoul are shown in Fig. 5. Figures 5a–c contain the profiles recorded at 0400, 0500, and 0700 UTC, respectively, indicating that the temperature at a height of 2.6 km was about -15°C . Figure 6a depicts the RHI scans of the Z_h , Z_{dr} , K_{dp} , ρ_{hv} , and SW parameters conducted at 0334 UTC. The distinctly high Z_{dr} and K_{dp} values were observed at an altitude of 2.6 km corresponding to a temperature of -15°C ; these were associated with the ρ_{hv} depression and a strong vertical gradient of Z_h , which suggested the growth of dendrites or platelike ice particles with low axis ratios and relatively high densities. This signature has been widely reported in the literature (see section 1). The R-QVP vertical extents of Z_h , Z_{dr} , K_{dp} , ρ_{hv} , and SW extracted from the 9–19-km range of the RHI scan (depicted in the red rectangular boxes in Fig. 6a) are illustrated in Fig. 6b (top row). The obtained

FIG. 6a. RHI scan obtained along the 306° azimuth for (top to bottom) Z_h , Z_{dr} , K_{dp} , ρ_{hv} , and SW at 0334 UTC to elucidate the dendritic growth mechanism. The dashed ellipses represent the dendritic growth zone. The horizontal line indicates the -15°C isotherm. The data in the rectangular boxes are used to obtain the averaged vertical profiles.

FIG. 6b. (top) R-QVP vertical profiles of (left to right) Z_h , Z_{dr} , K_{dp} , ρ_{hv} , and SW extracted from the 9–19-km range [red rectangular boxes in (a)] of the RHI scan obtained at 0334 UTC. (bottom) Profiles of (left to right) W, QI, QL, RH, and T obtained from the MERRA dataset at 0300 UTC. The horizontal dashed lines indicate the -15°C isotherm.

vertical profiles contain the distinct maxima of the Z_{dr} ($\sim 1.2\text{ dB}$) and K_{dp} ($\sim 0.86^{\circ}\text{ km}^{-1}$) bands. Thus, it can be hypothesized that ice particles fell into the moist layer with a temperature of around -15°C (corresponding to a height between 2 and 3.2 km) and started transforming into dendrite-like crystals that exhibited these dual-polarization signatures with enhanced Z_{dr} and K_{dp} values.

As the crystals fall toward the ground, the particle growth mechanism changes from the dendritic to aggregation (Houze 2014; Magono and Lee 1966). Figure 6b (bottom row) shows the vertical profiles of W, QI, QL, RH, and T obtained from the MERRA dataset. The high W and SW values observed at a height below 2.6 km indicate the existence of turbulence/updraft on the ground. The high liquid water content (LWC) (represented by

QL) associated with the high RH is also detected in this height range ($T > -15^{\circ}\text{C}$). The high updrafts (with large RH) can increase the LWC and amount of cloud ice (QI) aloft and initiate the growth of ice particles (Chu et al. 2018). As a result, the number of ice particle collisions increases in the turbulent layer at a height below 2.6 km, thus increasing the fall speed of precipitation particles and W magnitude. Additionally, the values of Z_h and W start to increase exactly at the height of the enhanced K_{dp} band, suggesting the transition of the hydrometeor. Further, Z_{dr} and K_{dp} maxima do not occur at the same height with the Z_{dr} maximum slightly above the maximum of K_{dp} . There may also be new ice crystals grown in this layer (Moisseev et al. 2015). At warmer temperatures ($> -15^{\circ}\text{C}$), dendrite-like crystals with multiple branches exhibit high sticking probabilities and, therefore, will form

early aggregates upon collision (Houze 2014; Magono and Lee 1966; Pruppacher and Klett 1997; Wallace and Hobbs 2006).

b. Heavy snowfall and dense aggregation

After obtaining the radar signatures with high Z_{dr} (~ 1.2 dB) and positive K_{dp} ($\sim 0.86^\circ \text{km}^{-1}$) values at around 0330 UTC, a heavy snowfall occurred on the ground, as indicated by the results of the AWS measurements (~ 0430 UTC shown in Fig. 4) and ground observations. The blue and pink shaded areas in Fig. 4e represent the high surface precipitation zones detected by the AWS. Furthermore, a moderate snowfall has been observed (Fig. 8) with a peak precipitation rate of 5.8 mm h^{-1} (Fig. 4d). Thus, it can be suggested that the enhanced (positive) K_{dp} band aloft is a precursor to heavy surface precipitation (Bechini et al. 2013; Kennedy and Rutledge 2011; Kumjian and Lombardo 2017; Moisseev et al. 2015; Schrom et al. 2015). The RHI scan taken at 0519 UTC (Fig. 7a) indicates that dense aggregation and heavy snowfall occurred on the ground. The high Z_{dr} and low Z_h values were found at a height above 2.5 km ($T < -15^\circ\text{C}$) within the 5–20-km range. Below this level, these variables exhibited the opposite trend. The negative correlation between the Z_h and Z_{dr} parameters indicates the aggregation of ice particles since the formed aggregates become bigger and less anisotropic. The R-QVP vertical profiles of Z_h , Z_{dr} , K_{dp} , ρ_{hv} , and SW (Fig. 7b) were extracted from the 8–18-km range of the RHI scan (depicted in the red rectangular boxes in Fig. 7a). The MERRA data were not available for this particular time. The measured values of Z_h (around 25 dBZ), ρ_{hv} (>0.98), and SW were higher than those obtained for dendritic particles, while the magnitudes of Z_{dr} (around 0.2 dB) and K_{dp} (around 0°km^{-1}) were relatively low, indicating the presence of low-density large aggregates (at a height below 2.5 km). The corresponding in situ photographs obtained at 0518 UTC (Fig. 8) show the reduction of visibility range due to the snowfall and formation of large aggregates.

c. Riming and graupel formation

The riming process occurs through the collision of ice particles with supercooled liquid water (SLW) drops below the freezing point as the drops impinge on the ice surface. The obtained RHI scan (Fig. 9a) shows that the high Z_h (30–40 dBZ) and ρ_{hv} (>0.98) values collocated with the low Z_{dr} (≤ 0 dB) and K_{dp} ($\leq 0^\circ \text{km}^{-1}$) magnitudes in the range between 5 and 15 km (at a height below 2.5 km), which may signify the riming process. Further, the high values of SW

FIG. 7a. RHI scan obtained along the 108° azimuth for (top to bottom) Z_h , Z_{dr} , K_{dp} , ρ_{hv} , and SW at 0519 UTC to elucidate the aggregation mechanism. The dashed ellipses represent the dendritic growth zone associated with aggregate embryos, and the dash-dotted ellipses denote the aggregation zone of ice crystals. The horizontal lines indicate the -15°C isotherm. The data in the rectangular boxes are used to obtain the averaged vertical profiles.

observed in this range are consistent with intense riming. It should be also noted that the Z_h values measured during the intense riming process are higher than those obtained in the periods of dendritic growth and aggregation. On the other hand, the magnitudes of Z_{dr} and K_{dp} are smaller than the values determined for the dendritic and aggregation processes. The riming process makes crystals more isotropic as indicated by the low Z_{dr} and high ρ_{hv} values. Figure 9b (top row) shows the R-QVP profiles of Z_h , Z_{dr} , K_{dp} , ρ_{hv} , and SW extracted from the 5–15-km range of the RHI

FIG. 7b. R-QVP vertical profiles of (left to right) Z_h , Z_{dr} , K_{dp} , ρ_{hv} , and SW extracted from the 8–18-km range [red rectangular boxes in (a)] of the RHI scan obtained at 0519 UTC. The horizontal dashed line indicates the -15°C isotherm.

scan (depicted in the red rectangular boxes in Fig. 9a). The vertical extents of W, QI, QL, RH, and T obtained from the MERRA data are also presented in Fig. 9b (bottom row). The observed high W ($>1\text{ m s}^{-1}$), SW ($>2\text{ m s}^{-1}$), and Z_h values suggest the relatively strong shear and turbulence on the ground that was likely caused by convection. In addition, Fig. 4 suggests that the convergence of the two air masses (the cold and warm streams) may be responsible for the measured W values. The updrafts associated with the convective instability are observed in the bottom part of the mixed-phase clouds, where liquid water coexists with ice (Michimoto 1991). Further, the large amounts of cloud ice and LWC collocated with the high RH at heights between 1.5 and 4 km (Fig. 9b), supporting the optimal riming conditions. Under these conditions, a larger number of SLW droplets likely freeze on the surface of ice particles. The riming process increases the density of precipitating particles, thereby raising their fall speed (as indicated by the observed increase in W). As a result, the rimed particles rapidly fall to the ground. The riming process consumed the entire liquid water (QL); therefore, the LWC is low or equals zero at lower heights.

Intense riming processes may produce graupel as was observed near the end of the storm. Figure 10 shows the PPI scan taken at 0647 UTC. Distinct SW and velocity features were observed at a distance between 20 and 28 km west (between -10 and 0 km south) from the radar. The region corresponding to $\text{SW} > 2.5\text{ m s}^{-1}$, $W > 12\text{ m s}^{-1}$, and $Z_h > 25\text{ dBZ}$ suggests that the convective turbulence associated with SLW droplets is ideal for graupel formation. Various shapes of graupel particles produce different polarimetric radar signatures, as has

been reported in the literature (see section 1). The high Z_h ($>30\text{ dBZ}$) and low Z_{dr} (from -0.2 to -0.5 dB) values combined with $\rho_{hv} \sim 0.99$ indicate the formation of prolate or conical graupel at a distance of around 18 km west (-12 km south) from the radar. Additionally, the high Z_h ($>30\text{ dBZ}$) and low but positive Z_{dr} ($>0.5\text{ dB}$) values measured at a 24-km distance west (-6 km south) from the radar suggest the formation of lump or hexagonal graupel, which can be indeed confirmed by ground observations. Figure 11a shows the rimed snow/graupel falling to the surface, whose shape is depicted in Fig. 11b. The corresponding RHI scan taken along the 125° azimuth is shown in Fig. 12. In the range between 15 and 18 km (with high Z_h , negative Z_{dr} , and negative K_{dp} values), conical graupel might be formed; while lump or hexagonal graupel were noticed at a distance of 18–20 km (with high Z_h , near zero or negative Z_{dr} , and positive K_{dp} values). Figure 5c (the WRF Model output) shows that the graupel features are predominant at 0700 UTC in the height range of 0.5–2.5 km. The polarimetric signatures depicted in Fig. 12 also contain the graupel signatures obtained at 0644 UTC in the height range of 0.5–2.5 km as discussed above. Thus, the experimental data are in good agreement with the results of the WRF Model.

5. Snowfall event interpretation: R-QVP vertical profiles

Figure 4e shows that at 0330 UTC, when the cold front reached the Goyang region, the sudden increase in humidity and small decrease in temperature resulted in a heavy snowfall, which lasted until

FIG. 8. Photographs illustrating the spatial visibility of the heavy snowfall and large aggregates on the surface at 0518 UTC.

0800 UTC and decreased afterward. Accordingly, the period between 0330 and 0730 UTC corresponds to the heavy snowfall event.

It is not possible to comprehensively describe the snow growth processes occurred throughout the entire event using only the RHI and PPI scans. Hence, the detailed illustration of the evolution of the ice growth processes for the total event was performed using the R-QVP methodology. The obtained R-QVP profiles clearly show the distinction of the snow habits and their growth through the spatial and temporal formats. The R-QVP profiles of Z_h , Z_{dr} , K_{dp} , ρ_{hv} , and SW related to the total snowfall event occurred in the Goyang region (at a 108° azimuth) are shown in Fig. 13. The total event was divided into three categories based on the polarimetric radar signatures: (i) the growth of platelike or dendritic ice particles (from 0330 to 0430 UTC), (ii) aggregation (from 0430 to 0515 UTC), and (iii) heavy riming associated with the graupel formation (from 0515 to 0730 UTC). The first two events (occurred from 0330 to 0515 UTC) are

FIG. 9a. RHI scan obtained along the 306° azimuth for (top to bottom) Z_h , Z_{dr} , K_{dp} , ρ_{hv} , and SW at 0559 UTC to investigate the riming process. The dashed ellipses represent the riming zone of ice crystals. The horizontal lines indicate the 15°C isotherm. The data in the rectangular boxes are used to obtain the averaged vertical profiles.

classified into the upper-level (above 2 km) and lower-level (below 2 km) precipitation.

The upper-level precipitation (from 0330 to 0515 UTC) exhibits low Z_h (<15 dBZ), low ρ_{hv} (<0.985), high Z_{dr} (>0.3 dB), and high K_{dp} ($>0.3^\circ\text{km}^{-1}$) values. The dendritic growth and onset of the aggregation process correspond to the strong Z_h gradient associated with the intense Z_{dr} and K_{dp} bands in the temperature range between -10° and -20°C (Ryzhkov et al. 2016). It is worth noting that during the third event (occurred from 0515 to 0700 UTC), the K_{dp} ($\geq 0.3^\circ\text{km}^{-1}$) and Z_{dr} (≤ 0.3 dB) values were not as high as those observed in the period from 0330 to 0515 UTC, which

FIG. 9b. (top) R-QVP vertical profiles of (left to right) Z_h , Z_{dr} , K_{dp} , ρ_{hv} , and SW extracted from the 5–15-km range [red rectangular boxes in (a)] of the RHI scan at 0559 UTC. (bottom) Profiles of (left to right) W, QI, QL, RH, and T obtained from the MERRA data at 0600 UTC. The horizontal dashed lines indicate the -15°C isotherm.

correlated with the low Z_h and ρ_{hv} magnitudes. Thus, we advocate that the high Z_{dr} and K_{dp} values observed during the first two events (with shallow clouds from 0330 to 0515 UTC) signify that the dendrites (D-type ice crystals) are the dominant species; while the moderate Z_{dr} and high K_{dp} magnitudes obtained for the third event (with deep clouds from 0515 to 0700 UTC) indicate that the isometric (I-type) ice crystals with an aspect ratio of around 0.6 are predominant (Schrom and Kumjian 2016; Griffin et al. 2018).

The lower-level precipitation (below 2 km) signifies the aggregation process. From 0330 through 0430 UTC (the first event), the Z_h values were below ≤ 21 dBZ, the magnitudes of Z_{dr} and K_{dp} were slightly positive ($< 0.3^{\circ}\text{km}^{-1}$), and $\rho_{hv} > 0.98$. These signatures indicate the reduction of particle anisotropy and initiation of the aggregation process (further, ice particles appear as

early snow aggregates). During the second event (from 0430 to 0515 UTC), the observed Z_h (> 20 dBZ) values are greater than those measured at the previous stage (from 0330 to 0430 UTC). On the other hand, Z_{dr} is slightly negative (close to zero), K_{dp} remains the same, and $\rho_{hv} > 0.985$. The large Z_h and low Z_{dr} and K_{dp} values suggest intensified aggregation and the formation of small clusters as dense aggregates. During the third event (from 0515 to 0700 UTC), very interesting signatures were observed. The period between 0515 and 0610 UTC exhibited high Z_h (mostly > 24 dBZ), negative Z_{dr} , and slightly negative K_{dp} values with $\rho_{hv} \geq 0.985$, indicating the formation of rimed ice crystals or rimed aggregates with small graupel due to heavy riming (Kouketsu et al. 2015). The spectrum width is also large during the process that riming becomes intense, which indicates intensified updraft and

FIG. 10. Radar PPIs representing the graupel signatures obtained at 0647 UTC for (top left) Z_h , (top right) Z_{dr} , (middle left) Φ_{dp} , (middle right) ρ_{hv} , (bottom left) SW , and (bottom right) velocity.

pumps a large number of SLW droplets for riming. Further, riming aloft is consistent with high LWC (see QL) depicted in Fig. 9b (Ryzhkov et al. 2016). Toward the end of the event, the rimed particles transformed into large graupel particles. The pronounced negative Z_{dr} (< -0.1 dB) and K_{dp} ($< 0^\circ \text{ km}^{-1}$) values associated with high Z_h (> 24 dBZ) and ρ_{hv} (> 0.985) magnitudes were observed from 0610 to 0700 UTC. These signatures signify the conical and complex shapes of graupel particles (Aydin and Seliga 1984; Locatelli and Hobbs 1974). The shape of the graupel was also evident from

the ground observations (see Fig. 11). Furthermore, the observed $W > 1 \text{ m s}^{-1}$ (Fig. 9b) may be indicative of the density and mass of the particles (Moisseev et al. 2015). Thus, we can state that the low Z_{dr} and near-zero K_{dp} values (0515–0610 UTC) are characteristics of rimed ice particles, while the high negative Z_{dr} and K_{dp} magnitudes (0610–0700 UTC) are typical for the large graupel particles with sizes of several millimeters. The evolution of the ice habits shown in Fig. 13 is in good agreement with the snow growth rates obtained via WRF Model simulations (Fig. 5 at 0400, 0500, and

FIG. 11a. Spatial visibility of the graupel falling to the surface at 0647 UTC.

0700 UTC). Table 3 lists various categories of microphysical species and the corresponding values of the polarimetric radar variables (Z_h , Z_{dr} , K_{dp} , ρ_{hv} , and SW) obtained from the visual representations for the studied event.

To classify the aggregation and riming processes, the variability factor Z_h was determined at lower and upper heights (here, the transition height at 2.5 km was taken as a reference) following the procedures developed by Moisseev et al. (2009) and Lim et al. (2013).

FIG. 11b. Different shapes of the graupel lying on the surface at 0647 UTC.

FIG. 12. Radar RHI scans representing the graupel signatures obtained along the 125° azimuth for (top to bottom) Z_h , Z_{dr} , K_{dp} , ρ_{hv} , and SW at 0644 UTC. The dashed ellipses denote the graupel regions, and the dashed horizontal lines indicate the -15°C isotherm.

This classification was performed based on the RHI scans presented in Fig. 6a (dendritic growth), Fig. 7a (aggregation), and Fig. 9a (riming) and the R-QVP profiles for the total event. The minimum and maximum values of Z_h have been identified for all heights separately (the vertically discretized heights in Fig. 6a were used for dendrites; similarly, the data presented in Figs. 7a and 9a were utilized for aggregates and rimed ice particles, respectively). The difference between $\max(Z_h)$ and $\min(Z_h)$ was calculated for each individual height and plotted in Fig. 14a (ΔZ_h). The ΔZ_h values obtained from their respective RHI scans ranged from 10 to 17 km (the red rectangular boxes in

FIG. 13. R-QVP vertical profiles of (top to bottom) Z_h , Z_{dr} , K_{dp} , ρ_{hv} , and SW obtained for the entire snowfall event.

Fig. 6a), from 8 to 18 km (the red rectangular boxes in Fig. 7a), and from 5 to 15 km (the red rectangular boxes in Fig. 9a) for the dendritic growth, aggregation, and riming processes, respectively. If ΔZ_h occupies a large range of values at low heights, it indicates riming. Similarly, if the range of ΔZ_h is large at upper heights, particle aggregation occurs (Moisseev et al. 2009). Figure 14a shows that the riming process generates a greater range of ΔZ_h at lower heights (below 2.5 km) as compared to that obtained at upper heights (above 2.5 km). In the case of dendrites and aggregates, the opposite is true (ΔZ_h is larger at upper heights as compared to that at lower heights). Interestingly, the ΔZ_h range for aggregates (at upper heights) is slightly greater than that for dendrites. It is well known that dendrites are more oblate than aggregates. Furthermore, dendrites or platelike crystals are more anisotropic and produce mostly identical Z_h values with a smaller difference between $\max(Z_h)$ and $\min(Z_h)$. On the other hand, aggregates are formed when the branches of dendrites or platelike crystals interact with each other and become entwined. They exhibit higher variability of shapes and sizes and thus generate a broad range of Z_h values. Therefore, we speculate that the range of ΔZ_h for dendrites is smaller than that for aggregates. However, the variance of ΔZ_h for dendrites is smaller than for other particles. To demonstrate this classification feature, the R-QVP of SVZ (containing ΔZ_h values obtained at all heights) is plotted for the entire event in Fig. 14b following the methodology illustrated in Fig. 2. It shows that ΔZ_h is larger (>12 dBZ) at upper heights (above 2.5 km) than that at lower heights (<12 dBZ) in the period from 0430 to 0515 UTC, indicating the presence of aggregates. On the other hand, from 0515 to 0700 UTC, the range of ΔZ_h at lower heights is larger (mostly ≥ 20 dBZ) than that obtained at upper heights (mostly < 20 dBZ), indicating the presence of rimed ice particles. Furthermore, at upper heights the ΔZ_h of aggregates (0430–0515 UTC) is slightly higher than the magnitude obtained for dendrites (0330–0430 UTC). Hence, it can be suggested that the range of ΔZ_h may be used to identify the ice particle category and differentiate between the aggregates and rimed ice particles. We are currently in the process of investigating this phenomenon in more detail, and related data will be discussed in future works.

6. Summary and conclusions

In this study, the characteristics of the severe winter storm occurred over the Korean Peninsula were

TABLE 3. Categories of various microphysical species and the corresponding values of the main parameters determined for the studied event.

Category	Z_h (dBZ)	Z_{dr} (dB)	K_{dp} ($^{\circ}\text{km}^{-1}$)	ρ_{hv}	SW (m s^{-1})	T ($^{\circ}\text{C}$)
Dendrites	10 to 30	0 to 1.4	0 to 2	~ 0.98	1 to 1.4	~ -15
Dendrites plus aggregate embryos	15 to 30	-0.3 to 1.4	0.4 to 1.1	~ 0.98	1 to 1.6	~ -15
Aggregates	18 to 30	-0.4 to 1.1	-0.2 to 0.2	> 0.98	1 to 1.8	> -15
Rimed ice crystals/rimed aggregates	13 to 40	-1.3 to 0.7	-1 to 0.2	> 0.98	1 to 3	> -15

examined for the first time by the KICT X-band dual-polarization radar. A new R-QVP methodology for analyzing polarimetric radar variables was proposed to comprehensively describe the microphysical processes of ice particles as well as the evolution of the storm and snow growth processes in the spatial and temporal forms. The maximum values of Z_{dr} and K_{dp} (obtained at 0334 UTC) associated with a high Z_h gradient and depressed ρ_{hv} were obtained at a temperature of around -15°C , indicating the dendritic growth of crystals similar to that observed in previous studies (Kennedy and Rutledge 2011; Bechini et al. 2013; Andrić et al. 2013). Below the maxima of Z_{dr} and K_{dp} , the magnitudes of W and Z_h increased toward the ground. The enhanced Z_{dr} values likely indicated the growth of planar crystals. The increase in W was observed exactly at the height (~ 2.6 km) of high K_{dp} suggesting the start of the new ice particle growth. The offset between the maxima of K_{dp} and Z_{dr} likely resulted from the presence of early aggregates. Further, the

combination of high Z_h and ρ_{hv} values with low Z_{dr} and K_{dp} magnitudes obtained at lower heights (below 2.5 km) indicated the existence of large aggregates. The low Z_{dr} (close to 0 dB) and high ρ_{hv} (> 0.98) values suggest that the formed ice clusters/aggregates were isotropic and possessed low densities. At upper heights (above 2 km), the enhanced Z_{dr} and K_{dp} signatures obtained from 0330 to 0515 UTC represent D-type crystals; while from 0515 to 0700 UTC, the high K_{dp} with moderate Z_{dr} values indicate the presence of I-type crystals [which were also observed by Schrom and Kumjian (2016) and Griffin et al. (2018)].

The riming phenomenon (observed at 0559 UTC) has been explored by examining the signatures containing high Z_h (> 25 dBZ) and slightly negative Z_{dr} values combined with the high ρ_{hv} (> 0.985) and low K_{dp} (near zero) magnitudes, which pertain to the local updraft. Both small ice crystals and dense aggregates act as targets for the riming process. During riming, the updraft or vertical motion lifts a larger LWC to upper heights; as a result, the higher number of SLW droplets freeze on the surface of small ice crystals and dense aggregates to produce rimed crystals/rimed aggregates and, ultimately, snowflakes or graupel. Near the end of the event, very interesting signatures of pronounced negative Z_{dr} (< -0.1) and K_{dp} (< 0) values associated with high Z_h (> 25 dBZ) and high ρ_{hv} (> 0.985) magnitudes were obtained at lower heights, which signified the

FIG. 14a. R-QVP vertical profiles of the differences between $\max(Z_h)$ and $\min(Z_h)$ obtained for the dendritic growth, aggregation, and riming processes. The horizontal dashed line indicates the -15°C isotherm.

FIG. 14b. R-QVP of SVZ obtained for the entire snowfall event to classify different ice particle types.

presence of graupel with conical and more complex shapes, as was also observed by Kouketsu et al. (2015) over Japan. Further, the high W values and ground observations confirm our interpretation. The classification of the obtained ice particles (aggregates, rimed snowflakes, and dendrites) was performed using the SVZ methodology. The R-QVP of SVZ was also utilized to distinguish between the aggregates and rimed ice particles. On the one hand, rimed ice covered a larger range of SVZ values at lower heights (as compared to that of aggregates). On the other hand, at upper heights, aggregates produced a larger range of ΔZ_h leading to higher SVZ relative to dendrites. Further, as the dendritic growth mechanism changed to aggregation growth, Z_h increased, Z_{dr} decreased, K_{dp} decreased, and ρ_{hv} increased [similar to the phenomenon observed by Vogel et al. (2015)]. The riming process produced high Z_h with low Z_{dr} and K_{dp} values as compared to those obtained during the dendritic and aggregation growths. The observed polarimetric signatures of various snow growth processes were compared with the microphysical output of the WRF Model and verified by ground observations. After the detection of the enhanced K_{dp} – Z_{dr} signatures at 0334 UTC, a heavy snowfall occurred on the ground about an hour later, at 0430 UTC. The beginning of the snowfall event exhibited high values of Z_h at lower heights (on the surface) for several hours, while the enhanced K_{dp} and Z_{dr} layers were linked to the heavy snowfall on the surface. The results obtained in this study can be used for the early warning of intense snowfall events and provide a foundation for the future studies aimed at investigating the finescale microphysics of winter storms occurring over this region in more detail.

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