Structure and Evolution of a Convective System with Bow Echo Associated with Terrain on Jeju Island, Korea

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Abstract

On July 13, 2012, a bow echo was observed over the lee side of the Mt. Halla (1,950 m above sea level) on Jeju Island, Korea. Three-dimensional (3D) wind-field and surface observation analyses were carried out to understand the structure and evolution of convective systems with a bow echo on a bell-shaped terrain. A northeastward-moving convective system passed over the approximately bell-shaped isolated mountain with a mean speed of 17 m s\(^{-1}\). On the windward side of the mountain, the convective system developed by the inflow of unstable warm air from the ocean and terrain-induced upward motion, even with a low convective available potential energy value of 511 J kg\(^{-1}\). When passing the lee side of the mountain, a bow echo was formed in the convective system by the strongest winds behind the bow echo. Behind the leading edge of the bow echo, the strengthened rear-inflow jet descended with relatively dry air along the surface, resulting in enhancing evaporative cooling. The precipitation-induced downdrafts generated a cold pool on the lee side of the mountain. The development of an rear-inflow jet and cold pool formation both contributed to the evolution of the bow echo. In addition, the isolated bell-shaped terrain had a major indirect influence on the evolution of the convective system with a bow echo in this event.

Keywords bow echo; rear inflow jet; cold pool; terrain

1. Introduction

Bow echoes typically occur during the warm season over the Great Plains in the United States, producing severe weather phenomena such as damaging downburst winds, tornadoes, and heavy rainfall (Klimowski et al. 2004; Davis et al. 2004; Atkins et al. 2005;
Keene and Schumacher 2013). Severe bow echo events can cause significant damage to human lives and property (e.g., Johns and Hirt 1987; Przybylinski 1995; Weisman 2001; Trapp et al. 2005; Peng et al. 2013).

Bow echoes, which are characterized by a bow shape on radar echo patterns, were first detailed by Fujita (1978). He examined the morphological evolution of bow echoes using a conceptual model based on radar reflectivity. As shown in Fig. 5.2 in the paper by Fujita (1978), the temporal stages of an evolving bow echo can be classified into a strong tall echo, a bow echo, and a comma echo. Bow echoes are observed to have lifespans ranging from tens of minutes to several hours, with spatial extents ranging from tens to a few hundreds of kilometers (Fujita 1978; Klimowski et al. 2004; Trapp et al. 2005). At an early stage, a convective system begins to develop from single convective cells that are either isolated or embedded within a larger system, such as a squall line. The convective system then evolves into a bow-shaped line segment associated with strong surface winds. At its greatest intensity, the convective system exhibits a bow-shaped echo, forming a cyclonic circulation (CC) and an anticyclonic circulation (AC) on the bookends. At the final stage, the bow echo develops into a comma echo, which maintains a CC at one edge point and a weak AC at the other bookend of the bow echo.

The kinematic features of bow echoes are the tilted updrafts and downdrafts, midlevel rear-inflow jets (RIJs), gust fronts, and a low-level cold pool. Weisman (1993) used idealized simulations of bow echoes to explore the development of tilted updrafts and downdrafts, midlevel RIJ, in response to the aloft buoyant front-to-rear ascending current, and the backward-spreading cold pool at the surface. In favorable long-lived bow echoes, a convective cell develops in the unstable atmospheric condition (convective available potential energy (CAPE) > 2,000 J kg⁻¹) as well as within the strong low-level vertical wind shear (> 20 m s⁻¹ below 2.5 km) (e.g., Weisman 2001). As a result, the RIJ can reach a remarkable strength and descend behind the gust front, resulting in straight-line winds of up to 30–50 m s⁻¹. However, the environment described above is not a strict requirement, as bow echoes can also form in the presence of a lower instability (e.g., Jorgensen et al. 1997).

Additionally, cyclonic and anticyclonic vortices in the middle troposphere are unique features across the RIJ behind the bow-shaped line segment (referred to as “bookend vortices”; Weisman 1993). During the mature stage of a bow echo, the counterrotating circulations are the result of baroclinically generated vortices at the bookends of the leading edge of the cold pool. This pair of vortices strengthens the RIJ and initiates the bending process. Because of the Coriolis effect, the cyclonic (anticyclonic) vortex becomes dominant (suppressed) within a few hours, leading to a comma shape at a later stage.

In recent studies, it has been actively investigated how bow echoes interact with mountains (Keighton et al. 2007; Letkewicz and Parker 2010), since complex terrains play an important role in the enhancement and dissipation of bow echoes. In one study, it was reported that mesoscale convective systems (MCSs) that crossed the Appalachian Mountains caused severe weather on the lee side of the terrain (Letkewicz and Parker 2010). MCSs can also dissipate on encountering the mountains, depending on the environmental conditions. Letkewicz and Parker (2010) analyzed the difference of environmental characteristics between “crossing” and “noncrossing” MCSs (including bow echo cases) as they encountered the Appalachian Mountains. Analysis of radiosonde data revealed that crossing cases were characterized by an environment with a higher instability for the maintenance of MCSs. The crossing cases also tended to occur when vertical wind shear and mean wind were weak on the downstream side.

Although the kinematic features of bow echoes have been actively investigated in recent decades, most of these studies have been based on events in the United States during the warm season. Few studies have been performed on the environmental features of bow echoes in East Asia. Chen et al. (2007) investigated the environment and evolution of a wintertime bow echo near Taiwan using a single-Doppler radar. The evolution of the bow echo in the subtropical and maritime environment was generally consistent with the results of Weisman (1992, 1993), although it was characterized by a moderate instability (with a CAPE of 1,288 J kg⁻¹) and by strong low-level vertical wind shear (28 m s⁻¹ at a height of 0–3 km). Peng et al. (2013) studied a bow echo that occurred in Southern China. Their analysis of the bow echo structure confirmed the appearance of an RIJ; however, no bookend anticyclonic feature was clearly present during the lifecycle. As for the structure of the bow echo, a warm, moist southwesterly low-level jet (LLJ) converged with the cold air, which was associated with a low-level shear line or a cold front, under the unstable environmental condition. Although certain studies have reported on the structure and environmental characteristics of bow echoes, studies on bow echoes...
with topography in East Asia are relatively scarce.

In this paper, we analyzed the structure and evolution of a convective system with a bow echo on Jeju Island. At 12:40 LST (LST = UTC + 9 h) on 13 July 2012, the part of the convective system that should become a bow shape was observed in a northeastern area of Jeju Island (width: 35 km; length: 78 km; height: 1,950 m), Korea. The convective system moved from the southwest to the northeast on Jeju Island. Heavy rainfall was caused by the convective system on the windward side of Mt. Halla, and a bow echo and strong gust (17.9 m s\(^{-1}\)) were observed while the convective system with a bow echo was passing over Mt. Halla. The length of the bow echo at 12:40 LST was about 60–80 km (meso-ß scale). The environmental features of this convective system with a bow echo that interacts with local terrain were investigated using observational data. As far as the authors know, this is the first report showing the structure of a convective system with a bow echo in Korea.

The rest of this paper is organized as follows. The data and analysis methods are summarized in Section 2, and an overview of the synoptic environment is described in Section 3. In Section 4, we discuss the radar echo characteristics. The surface weather conditions are investigated in Section 5. The kinematic structure of the convective system with a bow echo is presented in Section 6, and the enhancement and maintenance of the bow echo are described in Section 7. A discussion and summary of the results are presented in Section 8.

2. Data and analysis methods

2.1 Data

A detailed analysis of the synoptic conditions in this study was performed using observational and model-based data. The synoptic conditions were described using the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) global reanalysis dataset from July 13, 2012, which contains measurements taken every 6 h at 03:00, 09:00, 15:00, and 21:00 LST with 2.5° × 2.5° horizontal resolution and 17 vertical levels (Kalnay et al. 1996). In addition, hourly infrared images from the Multifunctional Transport Satellite (MTSAT-IR) were obtained from the Weather Satellite Image Archive at Kochi University and used to examine the features of convection distribution with a grid spacing of 0.05° × 0.05° (Kochi University 2001). The surface weather map was provided by the Japan Meteorological Agency (Japan Meteorological Agency 2012).

The primary datasets used in this study were provided by operational S-band Doppler radars of the Korea Meteorological Administration (KMA), which are installed at Gosan (GSN, 33.29°N, 126.16°E, 103 m above sea level (a.s.l.)) and Seongsanpo (SSP, 33.38°N, 126.88°E, 72 m a.s.l.). Both radars provide volumetric distributions of reflectivity and radial velocity at an interval of 10 min. The Nyquist velocities of the radars are 15.91 m s\(^{-1}\) (GSN) and 16.31 m s\(^{-1}\) (SSP), covering an observation radius of 150 km at a height of 2.5 km on Jeju Island.

Radar volume scans were taken at 15 elevation angles (0.5°, 0.6°, 0.8°, 1.0°, 1.5°, 2.0°, 2.5°, 3.5°, 4.5°, 6.0°, 7.8°, 10.5°, 13.7°, 18.1°, and 24.0°) and interpolated onto a Cartesian coordinate system with horizontal and vertical grid intervals of 1 km and 0.25 km, respectively. A Cressman-type weighting function was used for the interpolation (Cressman 1959). The SSP radar was located at 66.64 km east and 10.3 km north of the GSN radar. The domain had dimensions of 361 × 361 km\(^2\) and 61 levels in both horizontal and vertical directions. The locations and observation radii of the radar are indicated in Fig. 1.

Surface weather data from 23 KMA stations, one Pukyong National University (PKNU) station, and surface rain gauges from 13 PKNU stations on and around Jeju Island were collected during the field observation period (locations shown in Fig. 2). Surface observations of rainfall, temperature, wind, and humidity were available at 1 min intervals.

In addition, upper-air sounding observations were performed at GSN to investigate the atmospheric thermodynamic conditions around Jeju Island. We calculated various atmospheric parameters including CAPE, convective inhibition (CIN), lifting condensation level (LCL), precipitable water (PW), and the Froude number (\(F_r\)) (Table 1). \(F_r\), a parameter describing the flow stability over topography, was obtained from the relation \(F_r = U/Nh\), where \(U\) is the vertical mean wind speed perpendicular to the main axis of a mountain (from the ground surface to the peak of Mt. Halla), \(h\) is the maximum terrain height, and \(N\) is the Brunt–Väisälä frequency. \(N\) is defined as
\[
N^2 = (g/\partial \theta/\partial z),
\]
where \(\theta\) is the potential temperature, \(g\) is the local gravitational acceleration, and \(z\) is the geometric height. When \(F_r\) is higher than 1.0, the airflow can easily rise and move over the slope of the mountain, but when it is lower than 0.5, the airflow becomes blocked and is diverted around the mountain (Smolarkeiwicz et al. 1988; Smolarkeiwicz and Rotunno 1989, 1990).

2.2 Three-dimensional (3D) variation method

A dual-Doppler synthesis between the GSN and
SSP radars was performed to obtain the 3D wind fields of the convective system with a bow echo as it passed over Jeju Island. A variational method by Gao et al. (1999, 2004) was used to estimate 3D wind components from the radial velocity data of two Doppler radars. This method computes the optimal $u$, $v$, and $w$ components at the minimum cost function without taking into account the effects of topography. Thus, this method cannot be applicable for analyzing low-level updrafts in this case event. To obtain a 3D wind field that includes vertical velocities in high-terrain regions and along the baseline that is difficult to recover wind fields, we adopted a newly designed algorithm that was developed by Liou and Chang (2009) and Liou et al. (2012) using dual-Doppler radar observational data and outputs from a mesoscale model (Cloud-Resolving Storm Simulator (CReSS); Tsuboki and Sakakibara 2002) as background wind. Liou and Chang (2009) developed a multiple-Doppler radar wind synthesis method in which the 3D wind information is obtained at two time levels by minimizing a cost function through repeated variations. The main constraints placed on this cost function are the multiple-radar radial velocity observations, an inelastic continuity equation, a vertical vorticity equation, a background wind field, top and bottom boundary conditions for the winds, and a smoothing filter. The background wind field, which can be obtained from CReSS outputs, is used to fill in radar data void regions. Liou and Chang (2009) demonstrated that this method can recover the wind fields along and near the radar baselines (an imaginary line connecting two radars) and conducted a vorticity budget analysis. The extension of the immersed boundary method (IBM)
based on a variational multiple-Doppler radar wind synthesis algorithm to construct 3D wind fields over a complex topography (Liou et al. 2012) was also adopted in this study. The IBM can represent realistic topographic forcing without the need to convert the Cartesian coordinates into a terrain-following coordinate system, while retaining the advantages of a multiple-Doppler radar wind synthesis method. Experiments using numerical and observational data (Liou and Chang 2009; Liou et al. 2012) showed that this method was capable of retrieving accurate horizontal winds and reasonable vertical velocity structure.

3. Synoptic environment

In this section, the synoptic conditions under which the convective systems with a bow echo occurred around the mountain on Jeju Island are described. The surface weather map at 09:00 LST on July 13, 2012, with satellite–IR blackbody temperature ($T_{\text{BB}}$) is presented in Fig. 3. The region of deep convection can be defined by cloud-top temperatures of $\leq 230$ K, corresponding to satellite–IR blackbody temperature ($T_{\text{BB}}$) data (Sakurai et al. 2005). Jeong et al. (2016a) showed that the region of deep convection with $T_{\text{BB}} \leq 230$ K developed along the Changma front (Meiyu in China and Baiu in Japan). In this case, the Changma front of 126.5°E was oriented east–westward along 36°N, and the deep convection with $T_{\text{BB}} \leq 230$ K appeared south of Changma front and west of Jeju Island.

The NCEP-NCAR reanalysis at the surface at 09:00 LST on July 13 indicated that a southwesterly low-level flow ($\geq 8$ m s$^{-1}$) existed with a confluence between the low pressure and the subtropical high at the western Pacific extension over the South China Sea (Fig. 4a). This pressure pattern is indirectly related to a strong monsoonal southwesterly low-level flow with a confluence between the deepening low and the anticyclonic flow along the border of the subtropical high. At 850 hPa (Fig. 4b), an intense southwesterly flow with speeds exceeding 12.5 m s$^{-1}$, which is often used as a threshold value of LLJs, appeared (e.g., Chen and Yu 1988). The warm southwesterly monsoon flow was supplied to the region around Jeju Island by an LLJ. The temperature advection ($> 3 \times 10^{-4}$ K s$^{-1}$) around Jeju Island was higher than that in the surrounding areas and appeared to be continuously supplied with warm air from low latitudes. In addition, relatively strong west–southwesterly prevailing winds ($> 14$ m s$^{-1}$) according to the increasing geopotential height gradient appeared near eastern South Korea and Japan at 500 hPa (Fig. 4c). At 300 hPa, a westerly upper-level jet (ULJ) streak of $\geq 30$ m s$^{-1}$ was found along about 38°N near eastern South Korea and Japan (Fig. 4d). The region around Jeju Island was located at the southern side of the entrance region of the ULJ. A direct thermal circulation was generated by the upward motion caused by warm air of the southwestern LLJ from the south and by the downward motion of relatively cold dry air originating from the westerly ULJ from the north (Uccellini and Johnson 1979). This environment is a favorable synoptic condition for convection development.

The GSN sounding station is located on the western edge of Jeju Island (marked in Fig. 2). Prior to the convective system arrival on Jeju Island at 09:00 LST on July 13, 2012, CAPE and CIN values of 511 J kg$^{-1}$ and 93.2 J kg$^{-1}$, respectively, were recorded. These values are relatively smaller than those reported in previous studies. Weisman (1993) reported that the shape of convective cells is likely to form bow-shaped echoes in an environment with a large CAPE ($> 2,000$ J kg$^{-1}$) in idealized modeling studies. The relatively low CAPE in this case suggests that the thermodynamic conditions were obviously different from those of previous bow echo cases. The LCL was relatively low at the 946.2 hPa level, and the PW value calculated between the surface and the top of the sounding was high at 69.77 kg m$^{-2}$ (Table 1). In addition, the $Fr$ value obtained from the GSN soundings was about 0.27 with $U = 7.67$ m s$^{-1}$, $N = 1.4 \times 10^{-2}$ s$^{-1}$, and $h = 1,950$ m. In previous studies, the environment flow with low $Fr$ (0.2, 0.4, 0.55) was investigated to analyze terrain-induced airflows on Jeju Island (Lee et al. 2010, 2012, 2014). Jeju Island has an isolated elliptically shaped terrain (oriented west–southwest to east–northeast), and Mt. Halla is located at the center of the
idealized experiment results show that if \( Fr > 0.2 \) in a moist environment with southwesterly winds at low altitudes, a low-level flow will pass around the mountain and a terrain-induced dry descending air mass will exist in the northeastern area (lee side) of Jeju Island (Lee et al. 2014). This result suggests that the isolated elliptically shaped terrain influences the rainfall distribution around Mt. Halla. (Lee et al. 2014).

Figure 5 shows the distribution of accumulated rainfall amounts (mm) on Jeju Island from 11:00 LST to 13:59 LST on July 13, observed from the rain-gauge network (marked in Fig. 2). The largest accumulated rainfall of 30 mm was located near the summit of Mt. Halla on Jeju Island. As mentioned, the Froude number on the windward side of Mt. Halla was as small as 0.27. However, once condensation occurs due to the topographic effect, it might cause an updraft, even if the Froude number is small. Namely, intense rainfall can occur by condensation in the windward side of Mt. Halla. Most of the accumulated rainfall over 20 mm was concentrated in the southwestern area of Jeju Island (marked by white-dashed lines in Fig. 5). Additionally, more than 20 mm of accumulated rainfall was recorded on the northeastern partial area. These relatively small rainfalls on the northeastern side of Mt. Halla suggest that the bow echo moved with a high speed there.

4. Radar echo characteristics

On July 13, 2012, a convective system with a bow echo was observed by composited radars on Jeju Island. To clearly explain the characteristics of the bow echo on Jeju Island, the morphological evolution
of the convective system with a bow echo was presented using time sequences of the horizontal reflectivity in Section 4.1 and the cyclonic and anticyclonic vortices associated with bow echoes were analyzed using radial velocity in Section 4.2.

4.1 Evolution of the convective system

The time sequences of the horizontal reflectivity fields at an elevation of 2.5 km are presented in Fig. 6 to illustrate the morphological evolution of the convective system with a bow echo. During an early stage at 11:00 LST, a convective system with an isolated echo with a horizontal scale of 10–35 km was observed on the southwestern side of Jeju Island.

The northeastward-moving isolated echo approached the southwestern shore of Jeju Island (11:30 LST, Fig. 6) and became more intense and extended the convective area (above 45 dBZ) at the southwestern areas of Jeju Island (12:00 LST, Fig. 6). At 12:40 LST, while passing the lee side of Mt. Halla, a bow echo was clearly observed with a scale of about 60–80 km (see the dotted box, Fig. 6). The area of reflectivity exceeding 45 dBZ had a bow-shaped pattern. After passing through Jeju Island, the convective system with a bow echo began to decay as it moved oceanward over the northeastern side of Jeju Island (13:30 and 14:10 LST, Fig. 6). The evolution features of the convective system with a bow echo around Jeju Island are morphologically consistent with those of Fujita’s conceptual model presented in Fig. 5.2 in the research by Fujita (1978).

4.2 Bookend vortices in the bow echo

A distinctive characteristic associated with bow echoes is a pair of midlevel cyclonic and anticyclonic vortices, known as “bookend vortices” (e.g., Weisman 1992, 1993; Weisman and Davis 1998). To examine
these features (the bow echo at 12:40 LST), a 2.5 km CAPPI radial velocity obtained by the SSP radar was analyzed (Fig. 7). The small circle on Jeju Island marks the position of the SSP radar. In this chart, red colors (positive values from 1 to 23 m s\(^{-1}\)) indicate winds moving away from the SSP radar (outbound wind) and blue colors (negative values from \(-1\) to \(-23\) m s\(^{-1}\)) represent winds moving toward the radar (inbound wind).

Two inbound and outbound relative velocity maxima appeared at the northwestern and southeastern bookends of the bow echo. At the northwestern bookend, a yellow region (1 ~ 7 m s\(^{-1}\)) was adjacent to a bright-blue region (\(-7\) to approx. \(-1\) m s\(^{-1}\)). This is a clear indicator that cyclonic rotation CC was present. A relatively bright-blue region (\(-3\) to approx. \(-9\) m s\(^{-1}\)) appeared around the darker-blue region (\(-9\) to approx. \(-18\) m s\(^{-1}\)) at the southeastern bookend. Although the anticyclonic rotation was relatively weak, the couple of weak inbound wind of \(-5\) m s\(^{-1}\) and intense inbound wind of \(-10\) m s\(^{-1}\) was discernible.

The conceptual model of bow echo presented by Fujita (1978) contains a pair of distinct cyclonic and anticyclonic vortices; however, the composite radar analysis in this study detected a dominant CC and a weaker AC. Contrary to Fujita’s conceptual morphology, this observational result indicates that bow echoes do not necessarily have a clear pair of vortices (Davis et al. 2004; Peng et al. 2013). Davis et al. (2004) observed a bow echo that lacked a dominant CC in the Doppler analysis. Additionally, Peng et al. (2013) used Doppler radar analysis to investigate a case in which no AC appeared at the bookend of a bow echo.

5. Surface weather conditions

To investigate the formation characteristics of the bow echo in the northwestern area of Jeju Island, the time series of surface meteorological observations was analyzed at the Seonheul site (marked in Fig. 2), which was at the lee side of Mt. Halla (Fig. 8). The time series of surface meteorological observations revealed that the surface wind direction changed from northerly to westerly after the passage of the gust front of a bow echo. At 12:40 LST (the observed time of the bow echo, e.g., Fig. 7), the mean wind speed rapidly increased from 1.6 m s\(^{-1}\) (12:34 LST) to 12.6 m s\(^{-1}\) (12:41 LST) with a wind gust of 17.9 m s\(^{-1}\), and a sudden drop in the surface temperature from 25.8°C (12:25 LST) to 21.3°C (12:49 LST) was observed. This is consistent with other cases shown by Davis et al. (2004), Wakimoto et al. (2006), and Chen et al. (2007), which discussed the characteristics of producing strong gusts, shifting wind direction, increasing wind speed, and falling temperature during the passage of a bow echo at a surface station.

6. Kinematic structure of convective system with bow echo

The kinematic characteristics of the convective system with a bow echo were investigated using dual-Doppler radar analysis. Figures 9 and 10 illustrate the vertical structure and horizontal fields of the system-relative winds, horizontal divergence, and reflectivity at 12:00 and 12:40 LST on July 13. At 12:00 LST, the convective system moved to the western area of Jeju Island. The relative winds within the convective system at 2.5 km a.s.l. on the windward side of Mt. Halla were mostly southwesterly (Fig. 9a). Figures 9c and 9d display the vertical sections, of which directions are nearly parallel to the moving direction of the convective system (along A–A’ in Fig. 9a). The top of
Fig. 8. Time series of temperature (°C), mean wind speed (m s$^{-1}$), and wind direction from the Seonheul automated weather station. The peak gust speed is shown by the star. Wind speed is reported as 1 min running averages based on data collected every second. The peak wind gust is the highest 5 s average of wind speed values over the preceding 5 min. The area shaded in light gray represents the primary period of change.

Fig. 9. Horizontal distributions of (a) system-relative winds (arrows) and reflectivity (shading) and (b) divergence (shading) and reflectivity (contour intervals of 5 dBZ starting from 35 dBZ) at a height of 2.5 km and vertical cross sections of (c) system-relative winds (arrows) and radar reflectivity (shading) and (d) divergence (shading) and reflectivity (contour intervals of 5 dBZ starting from 35 dBZ) along A–A’ at 12:00 LST on July 13, 2012.
the convective system with $Z > 40$ dBZ reached 7 km a.s.l. (Fig. 10c). The low-level warm southwesterly flow from the ocean southwest of Jeju Island was converged near the leading edge of the convective system (Fig. 9c). In addition to the airflow near the surface, the RIJ whose speed exceeds 8 m s$^{-1}$ was found between the heights of 1 and 3 km (Fig. 9c). Convergence with magnitude of less than $-3 \times 10^{-3}$ s$^{-1}$ was found at ~ 500 m a.s.l. and $x = 30$–35 km on the windward side of Mt. Halla (Fig. 9d). The position of this convergence suggests that the development of the convective system was mainly caused by the low-level southwesterly wind and that the convergence was enhanced by the terrain effects.

In Fig. 10a, the horizontal $Z$-distributions at 12:40 LST clearly show the leading convective line in the form of a bow shape with stratiform regions behind. The strong horizontal convergence along the leading edges with high $Z$-values of $> 40$ dBZ can be seen in Fig. 10b. In the vertical section (B–B$'$), which shows a slice across the center of the bow echo in Fig. 10c, the ascending front-to-rear flow from $x = \sim 32$ km to the rear side above $\sim 6$ km a.s.l. can be clearly observed. The descending RIJ toward the leading edge of the bow echo was found below 4 km a.s.l. at $x = 25$–30 km. Also noticeable is the vertical cross section in Fig. 10d, which shows that the maximum convergence reached $-4 \times 10^{-3}$ s$^{-1}$ at the 2.5 km level. This position suggests that the convergence was caused by the RIJ. These bow echo features identified in this study were similar to those depicted in Fujita’s conceptual model.

A previous idealized modeling study showed that the development of a midlevel RIJ is associated with creating a horizontal vorticity balance (Weisman 1993). The bookend vortices acted to accelerate the RIJ and focus the system’s RIJ, which led to a gust front of the bow echo (Weisman 1993; Schenkman and Xue 2016). In an observational study (Bow Echo and Mesoscale Convective Vortex Experiment, BAMEX), the development of the RIJ was concurrent with the formation of a bow echo, bookend vortices, and an increased dynamic pressure gradient beneath the rearward-tilted updraft (Davis et al. 2004; Grim et al. 2009). The system-relative winds in this case
were strongest behind the leading edge of the bow echo, and the development of a midlevel RIJ was concurrent with a CC and an AC on the bookends, respectively (Figs. 10a, c). These features obtained in this study were consistent with the results of previous studies.

7. Enhancement and maintenance of the bow echo

To understand the enhancement and maintenance mechanisms of the bow echo, surface weather data are examined in more detail. Behind and within the areas of the bow echo, precipitation-induced downdrafts can generate evaporative cooling and spread cold air over the surface, resulting in a cold pool (e.g., Weisman and Klemp 1986; Rotunno et al. 1990; Weisman et al. 1988; Weisman 1993; Keene and Schumacher 2013; Jeong et al. 2016b).

Figure 11a indicates the 1 min surface relative humidity distribution obtained by the horizontal interpolation of Automatic Weather System (AWS) data at 12:40 LST while the bow echo passed over Jeju Island. The relative humidity distribution in the northeastern area of Jeju Island was relatively lower than in the southwestern area of Jeju Island. This indicated that the dry air in the northeastern area of Jeju Island was produced by the descending airflow of RIJ. A previous idealized modeling study associated with Jeju Island showed that the northeastern area of Jeju Island has a relatively drier environment than the southwestern area of Jeju Island under the influence of prevailing southwesterly moist flows with relatively low $Fr$ ($0.2 < Fr < 0.55$, e.g., Table. 1; Lee et al. 2014). Moreover, numerical modeling studies showed that relatively dry environments favor intense cold-air production and strong cold pool development (Gilmore and Wichker 1998; James et al. 2005). The midlevel RIJ entrains relatively dry air into the downdraft, resulting in enhancing evaporative cooling (Goff 1976; Davis et al. 2004; Keene and Schumacher 2013). Therefore, the relatively dry air in the northeastern side of Mt. Halla played an important role in forming a cold pool through the evaporative effect.

Figure 11b shows the change in surface temperature with time using interpolation over AWS stations during the passage of the bow echo over Jeju Island. As mentioned in Section 5, the surface temperature decreased where the bow echo passed. The largest drop in surface temperature occurred in the northeastern part of Jeju Island, as shown in Fig. 11b. The surface temperature drop in this region was found to be above 5°C from 11:00 LST to 13:59 LST. The maximum drop was 6.5°C, which was observed at the Seonheul station (marked in Fig. 2). Therefore, it is certain that a cold pool existed over this area.

To examine the dynamic role of the cold pool in influencing the bow echo, we utilized the Rotunno–Klemp–Weisman (RKW) theory (Rotunno et al. 1988). The RKW theory explains how the environmental vertical wind shear ($\Delta u$) and a cold pool can affect the bow echo structure and intensity. Yu and Tsai (2013) also studied cold pool dynamics using a diagnostic tool based on radar and surface observational data,
originally suggested by Rotunno et al. (1988). They noted a relatively strong horizontal vorticity generated by the buoyancy gradient across the leading edge of a cold pool, as well as $\Delta u$, which is an important factor in producing the degree of tilting of the leading updraft. In this study, to further investigate the relative importance of the buoyancy gradient between the cold pool and ambient vertical wind shear ($\Delta u$), we used the equation below developed by Yu and Tsai (2013). The buoyancy-generated vorticity ($C$) is formulated as

$$C = \sqrt{\frac{g}{\theta_0} \Delta \theta_{\text{min}} H},$$

where $\theta_0$ is the base-state potential temperature, $\Delta \theta_{\text{min}}$ is the surface cold pool potential temperature difference relative to the environment, and $H$ is the cold pool depth. The vorticity induced by environmental shear can be represented by the vertical wind shear ($\Delta u$) over the cold pool depth. Based on the study of Rotunno et al. (1988), when the magnitude of $C$ is approximately equal to $\Delta u$ ($C \approx \Delta u$), the cold pool and horizontal vorticity produced by environmental vertical shear will balance out each other, generating upright and deep updrafts with strong vortex stretching. When the magnitude of $C$ is larger than $\Delta u$ ($C > \Delta u$), the cold pool is more effective than environmental shear, and thus the leading updrafts will tilt upshear. However, for $C < \Delta u$, the cold pool has a weaker effect than the environmental shear, and thus the updrafts will tilt downshear.

In this study, the dynamic role of the cold pool was investigated using surface station data of Seonheul and the 3D wind field. Because the region around Seonheul is almost flat even on the lee side of the mountain, the RKW theory is applicable there. The synoptic and mesoscale analysis showed that a stationary front was located over the Southern Korean Peninsula and that monsoonal southwesterly flows from low latitudes transported warm air toward Jeju Island, Korea. The supply of warm air by the southwesterly LLJ played a significant role in enhancing the convective system with a bow echo. The region around Jeju Island is located in the southern side of the entrance region of ULJ. In the region, a direct vertical circulation with warm ascent in the south and cold descent in the north could be formed and given a favorable synoptic condition for the convection development. The CAPE value $(511 \text{ J kg}^{-1})$ was relatively lower than $2,000 \text{ J kg}^{-1}$ in previous bow echo events (Weisman 1993; Davis et al. 2004) in upper sounding data. This indicated that the thermodynamic conditions were different from previous bow echo events.

3D wind fields and surface weather data are examined to explain the structure and evolution of convective systems with a bow echo in Jeju Island. The northeastward-moving convective system passed over the approximately bell-shaped isolated mountain with a mean speed of $17 \text{ m s}^{-1}$. The convective system was developed by the inflow of unstable warm air from the ocean and terrain-induced upward motion on the windward side of the mountain (12:00 LST). On the lee side of Mt. Halla (12:40 LST), the bow echo formed in the convective system and the strongest winds were seen behind the bow echo. In addition, a dominant CC and a weak AC were observed at the bookends of the bow echo. Behind the leading edge of the bow echo, the intense RIJ descended along the surface, in a relatively dry environment on the lee side of Mt. Halla. As a result of precipitation-induced downdrafts, a cold pool formed on the lee side of Mt. Halla. The development of an RIJ and cold pool contributed to the evolution of the bow echo. This process of the bow echo enhanced by the terrain effect is the first analyzed result in Korea obtained only by observational data.

8. Discussion and summary

The structure and evolution of a convective system with a bow echo on Jeju Island, Korea, on July 13, 2012, were investigated using a dual-Doppler radar and surface observations. The environmental conditions and characteristic results of this study are summarized and discussed below.

The structure and evolution of a convective system with a bow echo in Jeju Island. The development of an RIJ and cold pool contributed to the evolution of the bow echo. This process of the bow echo enhanced by the terrain effect is the first analyzed result in Korea obtained only by observational data.
The kinematic features of the bow echo determined in this study were in general agreement with the result of previous bow echo events (Davis et al. 2004), although the unstable environmental conditions were different from most US cases. In this study, the isolated bell-shaped terrain oriented from west–southwest to east–northeast is a crucial factor for the evolution of a convective system with a bow echo. The RIJ in the system passing over the center of the island can get to strength on the lee side and descend with relatively dry air along the surface behind the bow echo. This evolution of the convective system with a bow echo was consistent with that reported by Lee et al. (2014), in which the topographic effects were explained using numerical simulations. Namely, terrain had a major indirect influence on the evolution of a convective system and the bow echo in this event. Future studies using numerical models are required to understand the role of terrain in the evolution of bow echoes in various environments.

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