1. Introduction

Meteorological radars are used to observe hydrometeors such as cloud and precipitation particles. However, radar echoes can appear even in clear weather. Clear-air echoes (CAEs) can be used as an atmospheric tracer in regions where there are no hydrometeors (Achtemeier 1991), but when targeting hydrometeors,
CAEs represent a contaminating signal. Therefore, it is important to distinguish CAEs and hydrometeors in radar echoes.

Rauber and Nesbitt (2018) listed ground clutter, echoes from biological sources (e.g., insects, birds, and bats), debris, dust, smoke, chaff, aircraft, and Bragg scattering as causes of CAEs. Bragg scattering and biological echoes occur frequently and are difficult to distinguish from hydrometeor echoes using only radar reflectivity. Usually associated with turbulence, Bragg scattering occurs when marked variations in atmospheric density are present on a scale of half the wavelength of the radar (Rauber and Nesbitt 2018), and it shows substantial radar reflectivity at longer wavelengths (Knight and Miller 1998; Martin and Shapiro 2007). Knight and Miller (1993) examined the early stage of precipitation formation in clouds and highlighted that Bragg scattering can affect the equivalent radar reflectivity \(Z_e\) and highlighted that Bragg scattering can affect the equivalent radar reflectivity \(Z_e\) at magnitudes of \(< 10, 0, \text{and } -10 \text{ dBZ for } \text{S- (10-cm), C- (5-cm), and X-band (3-cm) radars, respectively.}\)

Biological echoes have been observed to be associated with birds (Harper 1958; Russell et al. 1998; Diehl et al. 2003; Minda et al. 2008; Van Den Broeke 2013), bats (Horn and Kunz 2008; Pennisi 2011; Rauber and Nesbitt 2018; Meade et al. 2019), and insects (Glover et al. 1966; Riley 1975; Takeda and Murabayashi 1981; Kusunoki 2002). Birds and bats show characteristic circular echoes when leaving their roost (Pennisi 2011; Van Den Broeke 2013; Rauber and Nesbitt 2018), whereas a flock of migrating birds typically shows as an irregular line in a radar echo when in a V-shaped flight formation (Minda et al. 2008; Rauber and Nesbitt 2018). When birds and bats have high velocity relative to the ambient atmosphere, Doppler velocities show deviations from atmospheric wind velocities (Minda et al. 2008; Van Den Broeke 2013). Insect echoes appear widely within the radar observation range, except along gust fronts. When small insects fly randomly relative to the atmosphere, the bulk velocity of the insects relative to the atmosphere is negligible, and Doppler velocities obtained from radars reflect only atmospheric wind velocities (Achtmeier 1991). Thus, insect-derived Doppler velocities could be assimilated in models (Rennie et al. 2011).

The characteristics of CAEs have been observed using polarimetric radars. In observations of Bragg scattering by S-band radars, turbulent eddies are randomly oriented, indicating a differential reflectivity \(Z_{DP}\) of 0 dB (Melnikov et al. 2011; Richardson et al. 2017; Melnikov and Zrnić 2017; Hubbert et al. 2018), and the copolar correlation coefficient \(\rho_{hv}\) is close to unity (Melnikov et al. 2011; Melnikov and Zrnić 2017). With regard to biological echoes from birds (Zrnić and Ryzhkov 1998; Minda et al. 2008; Van Den Broeke 2013) and insects (Zrnić and Ryzhkov 1998; Browning et al. 2011; Melnikov and Zrnić 2017; Hubbert et al. 2018), the return signal is highly horizontally polarized \(Z_{\rho_{hv}} \approx 5 \text{ dB}, \text{sometimes more than } 10 \text{ dB}\), and the value of \(\rho_{hv}\) is typically small \((< 0.9)\) (Zrnić and Ryzhkov 1998; Minda et al. 2008; Van Den Broeke 2013; Hubbert et al. 2018). The total differential phase \(\Psi_{DP}\) contains the system differential phase \(\Psi_{sys}\), differential backscatter phase \(\delta\), and differential propagation phase \(\Phi_{DP}\) \(\Psi_{DP} = \Psi_{sys} + \delta + \Phi_{DP}\) (Melnikov et al. 2015). Except for \(\Psi_{sys}\), which is constant in a radar, \(\delta\) for insects and birds is large and represents a dominant contributor to \(\Psi_{DP}\) (Zrnić and Ryzhkov 1998). Meanwhile, \(\Phi_{DP}\), which is near zero in light rain, increases with distance from the radar in stronger rainfall (Dufton and Collier 2015; Hubbert et al. 2018). Large fluctuations in \(\Psi_{DP}\) indicate nonmeteorological scatterers. These characteristic features of polarimetric radar observations are useful for distinguishing echoes from hydrometeors, Bragg scattering, and biological echoes.

In 2015, the National Research Institute for Earth Science and Disaster Resilience (NIED) introduced five Ka-band scanning radars in the Tokyo metropolitan area of Japan. Three of these radars have dual-polarization capability, and the other two have single polarization. Millimeter-wavelength radars (Kollias et al. 2007; Maesaka 2018), which are also referred to as cloud radars, are more sensitive to smaller particles than radars using centimeter wavelengths, which mainly measure precipitation particles. One of the targets of the NIED cloud radars is early detection of cumulonimbus clouds that cause short-term heavy rainfall. Therefore, it is necessary to distinguish hydrometeor echoes and CAEs in the weak radar reflectivity observed in the early stage of cloud development. Several previous studies have observed CAEs using vertically pointing cloud (Ka- and W-band) radars (Yanagisawa 1970; Yanagisawa and Kanbayashi 1972; Geerts and Miao 2005; Luke et al. 2008; Kalapureddy et al. 2018). However, no scanning cloud radar observations of CAEs have been conducted to obtain polarimetric variables such as \(Z_{DP}, \rho_{hv}, \text{and } \Psi_{DP}\), which are expected to be effective in distinguishing CAEs and hydrometeor echoes. Therefore, this study investigated the characteristics of polarimetric variables for CAEs obtained using the NIED polarimetric cloud radar.
2. Observations

This study used the NIED polarimetric cloud radar (red dot in Fig. 1) deployed at Ota, Tokyo (35.58°N, 139.78°E; height: 38 m). The transmitting frequency of this radar is 34.8 GHz (Ka-band), which corresponds to a wavelength of 8.6 mm. The peak transmitting power of 3.0 kW is divided equally into horizontally and vertically polarized waves. The observation range is 30 km (red open circle in Fig. 1). At distances of more than 9 km, a pulse compression technique is applied on a 55-μs pulse (referred to as long pulse). In the long-pulse region, high sensitivity was achieved while maintaining the same range resolution as with a 1-μs pulse (referred to as short pulse), used at distances < 9 km. Therefore, the sensitivity (noise level of $Z_e$) significantly changed across the boundary at 9 km between short and long pulses. Data were recorded at 150-m intervals in the radial direction and every 0.35° in the azimuthal direction. Five plan position indicator (PPI) scans at elevation angles of 1.6, 4.5, 7.6, 10.6, and 15.0° and a range–height indicator (RHI) scan at the azimuth angle of 240.7° were repeated every 3 min. The two lowest PPI scans (1.6° and 4.5°) were limited on the landward side (205°–15°) to avoid large reflections from low-flying aircraft near the Tokyo International Airport. The differential reflectivity ($Z_{DR}$) bias was corrected as follows. Misumi et al. (2018) have classified in situ observational data of drop size distributions at the Tokyo Skytree (Sumida, Tokyo) into five categories. The $Z_{DR}$ data around the Tokyo Skytree were extracted for comparison within the time classified into the “CL” category, which indicates clouds that are not raining or drizzling, using the same approach as Misumi et al. (2018). The bias was corrected so that $Z_{DR}$ extracted within the time classified into the “CL” category had a value of 0 dB. No attenuation correction was applied for either $Z_e$ or $Z_{DR}$. As the correlation coefficient ($\rho_{hv}$) tends to decrease with a decrease in signal-to-noise ratio (SNR), a correction for $\rho_{hv}$ was applied according to the SNR (Schuur et al. 2003; Shusse et al. 2009; Section 6.7 in Ryzhkov and Zrnić 2019). In addition, to confirm the absence of clouds, Himawari-8 (Bessho et al. 2016) band 3 (visible, 0.64 μm) images acquired at 10-min intervals were used along with surface observations taken at the observation site of the Japan Meteorological Agency (JMA) in Tokyo (35.69°N, 139.75°E; the blue rectangle in Fig. 1), which is located 12.5 km north-northwest of the NIED polarimetric cloud radar (i.e., within the radar observation range).

3. Results

Figure 1a shows albedo in the band 3 (visible) image obtained by the Himawari-8 geostationary satellite. (a) Horizontal distribution at 12:00 JST on May 21, 2016. The red dot and red open circle indicate the Ka-band radar site at Ota (Tokyo) and its observation range with a radius of 30 km, respectively. The range of azimuth from 205° to 15° clockwise from north, which is indicated by the two white lines and a double-headed arrow, corresponds to the scanning range of sector PPI scans at an elevation angle of 1.6°. The blue rectangle indicates the Japan Meteorological Agency surface observation site in Tokyo. (b) Time–latitude cross section along 139.78°E through the cloud radar site from sunrise (04:30 JST) to sunset (18:50 JST) in Tokyo. The two red lines indicate the northern and southern limits of the radar observation range. White blank before 12:00 JST indicates no data.
The local mean time in Tokyo is close to JST (i.e., approximately 19 min ahead of JST). Albedo, which is the top-of-atmosphere reflectance defined as the ratio of reflected radiation to incident solar radiation, was small throughout the area, indicating cloud-free skies in the radar observation range. Figure 1b shows a time–latitude cross section of albedo along 139.78°E (crossing the radar site) from sunrise (04:30 JST) to sunset (18:50 JST) on May 21, 2016. From sunrise until around 13:30 JST, albedo remained low within the radar observation range between the two red lines. From around 14:00 JST to sunset, an area of cloud represented by the higher albedo extended from the northern end of the display area toward the south, reaching the northern part of the radar observation range.

Figure 2 shows hourly sunshine duration, defined as the ratio of direct normal irradiance of $\geq 0.12$ kW m$^{-2}$ h$^{-1}$ (Fig. 2a), and instantaneous cloud cover measured in tenths observed every 3 h (Fig. 2b), on May 21, 2016 at the JMA Tokyo observation site (blue rectangle in Fig. 1). Sunshine duration was 1.0 during 07:00–15:00 JST. Then, sunshine duration decreased to 0.9 at 16:00–17:00 JST and to 0.4 at 18:00 JST. On the following day, sunshine duration was 1.0 during 06:00–18:00 JST. The sunshine duration of 0.4, recorded at 18:00 JST on May 21, 2016, was due to the appearance of clouds, not the onset of sunset. Cloud cover was 0, 0′ (representing cover between 0 and 1), or 1 during each 3-h interval from 06:00 to 15:00 JST. At 18:00 JST, cloud cover was 10–, indicating cover between 9 and 10, i.e., the cloud covered most of the sky, but with some gaps. As observed at the JMA Tokyo observation site, the sky was almost cloud-free during 06:00–15:00 JST, following which clouds increased during 16:00–17:00 JST to cover most of the sky by 18:00 JST.

Figure 3 shows the horizontal distribution of $Z_e$ for each hour during 06:00–19:00 JST on May 21, 2016. The $Z_e$ value was obtained from the sector PPI scans at an elevation angle of 1.6°. The value of $Z_e$ at 06:00 JST is considered background noise because it varied randomly in the horizontal direction. A sharp change in the noise level can be seen at a distance of 9 km from the radar. This reflects the application of the pulse compression technique for a long pulse, which means weak values of $Z_e$ can be treated as a significant signal. In particular, at distances of between 9 and approximately 20 km from the radar within the long-pulse area, an increase of $Z_e$ from early morning to noon is evident. Given the surface observations from the JMA Tokyo observation site (Fig. 2), it is inferred that this increase was caused by CAEs, not by clouds. The CAEs then widely developed within the radar observation range. In the early afternoon, the maximum $Z_e$ value of the CAEs was $> -15$ dBZ. The clouds in the satellite image (Fig. 1b) moved southward to reach the latitude of the radar site (35.58°N) at around 15:30 JST. In the PPI scans at high elevation angles of 10.6° and 15.0°, an echo with moderately large $Z_e$ ($> 10$ dBZ) extended southward after 13:45 JST (not shown). RHI observations at the azimuth angle of 210.7° showed that this echo was present at heights of 4–8 km and did not reach the ground surface (not shown). Therefore, this echo at higher altitude could not be confirmed in the PPI images obtained at a
Fig. 3. Hourly equivalent radar reflectivity ($Z_e$, color scale, dBZ) from 06:00–19:00 JST on May 21, 2016 obtained by sector PPI scans at an elevation angle of 1.6°. Radar reflectivity at 06:00 JST was considered to be the background noise level because it varied randomly in the horizontal direction. The white lines indicate the azimuthal angle of RHI scans (240.7°) shown in Fig. 4.
low elevation angle of 1.6° (Fig. 3). The temporal variation of clouds in the satellite image (Fig. 1b) and the decrease in sunshine duration at Tokyo after 16:00 JST (Fig. 2a) were consistent with the appearance of the higher altitude clouds seen in the radar observations. Values of $Z_e > 15$ dBZ were observed at a low altitude in the north-northeast of the observation range at 18:00 JST and in the northern half of the observation range at 19:00 JST (Fig. 3). These echoes showed much higher values of $Z_e$ than the CAEs (i.e., $−15$ dBZ or less). These higher values of $Z_e$ at a low altitude were considered to reflect cloud and precipitation. The CAEs of $−15$ dBZ (or less) near the cloud and precipitation echoes decayed after 18:00 JST.

Vertical cross sections of $Z_e$ obtained by the RHI scans at the azimuth angle of 240.7° are shown in Fig. 4. The values of $Z_e$ at 06:00 JST also represent the background noise level. At 07:00–08:00 JST, $Z_e$ started to increase slightly in the lowest layer, which was particularly evident at distances of between 9 and approximately 20 km from the radar within the long-pulse area. Considering the satellite images and surface observations, the echoes in the lowest layer were considered CAEs. The CAEs in the lowest layer extended upward and reached a height of 1.5 km by 11:00 JST. Echo plumes with a horizontal scale of 1–3 km were especially pronounced during 12:00–13:00 JST. Subsequently, CAEs of $−20$ to $−15$ dBZ were present below a height of approximately 1 km until 18:00 JST. Echoes of 0 dBZ within a distance of 12 km from the radar at 19:00 JST were associated with cloud and precipitation, as confirmed by the PPI images (Fig. 3). At 19:00 JST, the CAEs had decayed further than the echoes of the cloud and precipitation area (> 12 km from the radar).

To examine the differences in polarimetric parameters between CAEs and cloud/precipitation echoes, Fig. 5 presents PPI scans of $Z_e$, $Z_{DR}$, $\rho_{hv}$, and $\Psi_{DP}$ obtained at an elevation angle of 1.6° at 18:00 JST. To remove signals around the noise level, only regions with SNR > 3 dB were examined. In a region including mainly cloud and precipitation echoes (CP region; Fig. 5a), shown by an arc shape surrounded by thick white lines at a distance of more than 14 km north of the radar, most values of $Z_{DR}$ were around 0–1 dB (Fig. 5b). As the axis ratio of small liquid particles is close to 1 (e.g., Pruppacher and Beard 1970; Beard et al. 2010), the $Z_{DR}$ value of small liquid particles is expected to be close to 0 dB. This indicates that the $Z_{DR}$ observed by the Ka-band radar was reasonable. In the region excluding the CP region, which mainly includes CAEs (CAE region), $Z_{DR}$ values showed a large variation from more than 3 dB to negative values. In the CP region, the $\rho_{hv}$ values were large (> 0.9) in most areas but small at the edges of the echoes. In the CAE region, most $\rho_{hv}$ values were < 0.9 (Fig. 5c). The variability of $\Psi_{DP}$ in the range direction was small in the CP region, whereas it increased in the CAE region (Fig. 5d). Prior to 18:00 JST, the $Z_{DR}$, $\rho_{hv}$, and $\Psi_{DP}$ values of CAEs showed similar characteristics (not shown).

The relative frequency distributions of polarimetric parameters are shown in Fig. 6. The relative frequencies are indicated by a common logarithm. The upper and lower panels show the CAE and CP regions, respectively. In the CAE region, most values of $Z_e$ were < $−15$ dBZ (Figs. 6a, b). On average, $Z_{DR}$ was positive (1.8 dB), although it exhibited very large variance with a standard deviation of 2.8 dB (Figs. 6a, c). Most $\rho_{hv}$ values were < 0.9 (Figs. 6b, c). In the distribution in the $Z_{DR}$–$\rho_{hv}$ space, the relative frequencies showed a remarkably wide distribution (Fig. 6c). In the CP region, $Z_{DR}$ was distributed around 0 dB, as shown in Fig. 6d. The average value and standard deviation were 0.4 dB and 1.4 dB, respectively. The dispersion of $Z_{DR}$ increased as $Z_e$ or $\rho_{hv}$ decreased (Figs. 6d, f). This is consistent in that the standard deviation of $Z_{DR}$ increases with decreasing SNR and $\rho_{hv}$ (Bringi et al. 1983; Melnikov and Zrnić 2004, 2007). Values of $\rho_{hv}$ were mostly > 0.9 when $Z_e > −10$ dB. However, the values were considerably < 0.9 when $Z_e < −10$ dBZ (Fig. 6e). The small values of $\rho_{hv}$ were considered to be partially caused by the larger dispersion in the small SNR with small $Z_e$ and by contamination of CAEs with small $\rho_{hv}$. In the $Z_{DR}$–$\rho_{hv}$ space (Fig. 6f), the areas with high frequency are concentrated around $Z_{DR} = 0$ dB and $\rho_{hv} > 0.9$.

4. Discussion

We discuss the scattering bodies that potentially cause CAEs. However, there have been no previous observations of CAEs using Ka-band dual-polarization radars. Therefore, the results obtained in this study are compared with observations derived using dual-polarization radars operating at other transmitting frequencies. Many CAE cases have been observed by S-band radars in the United States. Of the CAEs described by Rauber and Nesbitt (2018), we discuss the potential involvement of Bragg scattering and biological echoes. Bragg scattering shows significant radar reflectivity at longer wavelengths (Knight and Miller 1998; Martin and Shapiro 2007). A number of CAEs considered to reflect Bragg scattering have been observed by S-band radars, which have the
longest wavelength of meteorological radars used for measuring hydrometeors. Values of $Z_e$ for Bragg scattering observed in the S-band are typically $< 10$ dBZ and mostly $< 0$ dBZ (Knight and Miller 1993; Richardson et al. 2017). Echoes observed by C-band and X-band radars, which were probably due to Bragg scattering, have also been reported by Minda et al. (2010) for C-band radar and Knight and Miller (1998) for X-band radar. We assume that there exist turbulent eddies observable by two radars with different wavelengths and that Bragg scattering is observed by the radars. A formula for calculating the difference in $Z_e$ of Bragg scattering between two wavelengths (Knight and Miller 1993, 1998; Wilson et al. 1994; Gage et al.)
Fig. 5. (a) Equivalent radar reflectivity ($Z_e$, dBZ), (b) differential reflectivity ($Z_{DR}$, dB), (c) copolar correlation coefficient ($\rho_{hv}$, unitless), and (d) total differential phase ($\Psi_{DP}$, degree) at 18:00 JST on May 21, 2016, obtained by a sector PPI scan at the elevation angle of 1.6°. The arc-shaped region to the north of the radar surrounded by thick white lines indicates the main region of cloud and precipitation echoes (CP region). The black color within the observation range indicates a signal-to-noise ratio of < 3 dB.
The data in Canada and the United States, Kilambi et al. (2018) suggested thresholds of DR > −12 dB and \( Z_e < 35 \text{ dBZ} \) for nonmeteorological echoes. To exclude hail and melting graupel, which can exhibit values of DR > −12 dB, they used the threshold \( Z_e < 35 \text{ dBZ} \). However, no such large reflectivity was observed in the present case. The decibel values of DR are shown as contours in Figs. 6c and 6f. In the CAE (CP) region, most values of DR are > −12 (−12 dB). Therefore, it was considered that identification using the DR threshold works well for this Ka-band radar. In addition, Kilambi et al. (2018) reported that the identification skill was improved when a despeckling algorithm was used to remove false identification, i.e., if the identification of the central pixel differs from that of the majority comprising itself and the eight neighboring pixels, it is changed to reflect the majority. In addition, the difference in the variation of \( \Psi_{\text{DP}} \) in the range direction might be effective for distinguishing clouds and precipitation echoes and nonmeteorological echoes.

5. Summary

This study examined the characteristics of CAEs observed by the NIED polarimetric cloud radar at Ota in the Tokyo metropolitan area, Japan, on May 21, 2016. Based on images from the Himawari-8 geostationary weather satellite and surface observations recorded at the JMA Tokyo observation site, it was determined that almost no cloud was present during 06:00–15:00 JST within the radar observation range and that clouds extended southward within the radar range during 16:00–17:00 JST. By 18:00 JST, cloud covered most of the sky at the JMA Tokyo observation site, which is located 12.5 km north-northwest of the NIED polarimetric cloud radar within the radar observation range.

In the lowest layer, the \( Z_e \) values of the CAEs increased after sunrise. The largest \( Z_e \) values of the CAEs were > −15 dBZ. The CAEs extended upward with time from near the ground to reach a maximum height of 1.5 km. In the evening, the \( Z_e \) values of the CAEs decreased. In the CAE region at 18:00 JST, the average value of \( Z_{\text{DR}} \) was large and positive (1.8 dB) with a large standard deviation (2.8 dB), and the \( \rho_{hv} \) values were mostly < 0.9. The variability of \( \Psi_{\text{DP}} \) in the range direction was large. Conversely, in the CP region, the average value of \( Z_{\text{DR}} \) was close to 0 (0.4 dB), and the frequency was large at \( \rho_{hv} > 0.9 \), although \( \rho_{hv} \) at some points showed smaller values. The variability of \( \Psi_{\text{DP}} \) in the range direction was small in the CP region. The characteristics of \( Z_{\text{DR}}, \rho_{hv}, \) and
Ψ_{DP} in the CAE region were consistent with those associated with biological echoes observed by S-band radars in previous studies. When the maximum Z_{e} for Bragg scattering observed by S-band radar is 10 dBZ, the upper limit of the Bragg scattering observed by the Ka-band radar is estimated to be approximately −30 dBZ owing to the wavelength dependence of Bragg scattering. This indicates that Bragg scattering is hardly observed by the Ka-band radar. As the observed echoes were widely spread over the radar observation range, it was inferred that the scattering bodies were insects, not birds or bats. Most CAEs observed by Ka-band radars can be distinguished from clouds and precipitation echoes using the threshold of DR > −12 dB, as suggested by Kilambi et al. (2018). The polarimetric variables, which can be obtained by scanning radar, are useful in distinguishing between CAEs and meteorological echoes in Ka-band radar signals.

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References

Achtemeier, G. L., 1991: The use of insects as tracers for “clear-air” boundary-layer studies by Doppler radar. J. Atmos. Oceanic Technol., 8, 746–765.

Beard, K. V., V. N. Bringi, and M. Thurai, 2010: A new understanding of raindrop shape. Atmos. Res., 97, 396–415.

Bessho, K., K. Date, M. Hayashi, A. Ikeda, T. Imai, H. Inoue, Y. Kumagai, T. Miyakawa, H. Murata, T. Ohno, A. Okuyama, R. Oyama, Y. Sasaki, Y. Shimazu, K. Shimoji, Y. Sumida, M. Suzuki, H. Taniguchi, H. Tsuchiyama, D. Uesawa, H. Yokota, and R. Yoshida, 2016: An introduction to Himawari-8/9—Japan’s new-generation geostationary meteorological satellites. J. Meteor. Soc. Japan, 94, 151–183.

Bringi, V. N., T. A. Seliga, and S. M. Cherry, 1983: Statistical properties of the dual-polarization differential reflectivity (ZDR) radar signal. IEEE Trans. Geosci. Remote Sens., GE-21, 215–220.

Browning, K. A., J. C. Nicol, J. H. Marsham, P. Rogberg, and E. G. Norton, 2011: Layers of insect echoes near a thunderstorm and implications for the interpretation of radar data in terms of airflow. Quart. J. Roy. Meteor. Soc., 137, 723–735.

Diehl, R. H., R. P. Larkin, and J. E. Black, 2003: Radar observations of bird migration over the Great Lakes. The Auk, 120, 278–290.

Dufton, D. R. L., and C. G. Collier, 2015: Fuzzy logic filtering of radar reflectivity to remove non-meteorological echoes using dual polarization radar moments. Atmos. Meas. Tech., 8, 3985–4000.

Gage, K. S., C. R. Williams, W. L. Ecklund, and P. E. John-200GH, 1999: Use of two profilers during MCTEX for unambiguous identification of Bragg scattering and Rayleigh scattering. J. Atmos. Sci., 56, 3679–3691.

Geerts, B., and Q. Miao, 2005: The use of millimeter Doppler radar echoes to estimate vertical air velocities in the fair-weather convective boundary layer. J. Atmos. Oceanic Technol., 22, 225–246.

Glover, K. M., K. R. Hardy, T. G. Konrad, W. N. Sullivan, and A. S. Michaels, 1966: Radar observations of insects in free flight. Science, 154, 967–972.

Harper, W. G., 1958: Detection of bird migration by centi-metric radar—A cause of radar ‘angels’. Proc. Roy. Soc. B, Biol. Sci., 149, 484–502.

Horn, J. W., and T. H. Kunz, 2008: Analyzing NEXRAD Doppler radar images to assess nightly dispersal patterns and population trends in Brazilian free-tailed bats (Tadarida brasiliensis). Integr. Comp. Biol., 48, 24–39.

Hubbert, J. C., J. W. Wilson, T. M. Weckwerth, S. M. Ellis, M. Dixon, and E. Loew, 2018: S-Pol’s polarimetric data reveal detailed storm features (and insect behavior). Bull. Amer. Meteor. Soc., 99, 2045–2060.

Kalapureddy, M. C. R., P. Sukanya, S. K. Das, S. M. Desh-
Melnikov, V., and D. S. Zrnić, 2017: Observations of convective thermals with weather radar. J. Atmos. Oceanic Technol., 34, 1585–1590.

Melnikov, V. M., R. J. Doviak, D. S. Zrnić, and D. J. Stensrud, 2011: Mapping Bragg scatter with a polarimetric WSR-88D. J. Atmos. Oceanic Technol., 28, 1273–1285.

Melnikov, V. M., M. J. Istok, and J. K. Westbrook, 2015: Asymmetric radar echo patterns from insects. J. Atmos. Oceanic Technol., 32, 659–674.

Minda, H., F. A. Furuzawa, S. Satoh, and K. Nakamura, 2008: Bird migration echoes observed by polarimetric radar. IEICE Trans. Commun., E91B, 2085–2089.

Minda, H., F. A. Furuzawa, S. Satoh, and K. Nakamura, 2010: Convective boundary layer above a subtropical island observed by C-band radar and interpretation using a cloud resolving model. J. Meteor. Soc. Japan, 88, 285–312.

Misumi, R., Y. Uji, Y. Tobo, K. Miura, J. Uetake, Y. Iwamoto, T. Maesaka, and K. Iwanami, 2018: Characteristics of droplet size distributions in low-level stratiform clouds observed from Tokyo Skytree. J. Meteor. Soc. Japan, 96, 405–413.

Pennisi, E., 2011: Researchers use weather radar to track bat movements. Science, 331, 998, doi:10.1126/science.331.6020.998.

Pruppacher, H. R., and K. V. Beard, 1970: A wind tunnel investigation of the internal circulation and shape of water drops falling at terminal velocity in air. Quart. J. Roy. Meteor. Soc., 96, 247–256.

Rauber, R. M., and S. W. Nesbitt, 2018: Radar Meteorology: A First Course. John Wiley & Sons Ltd, 488 pp.

Rennie, S. J., S. L. Dance, A. J. Illingworth, S. P. Ballard, and D. Simonin, 2011: 3D-Var assimilation of insect-derived Doppler radar radial winds in convective cases using a high-resolution model. Mon. Wea. Rev., 139, 1148–1163.

Richardson, L. M., J. G. Cunningham, W. D. Zittel, R. R. Lee, R. L. Ice, V. M. Melnikov, N. P. Hoban, and J. G. Gebauer, 2017: Bragg scatter detection by the WSR-88D. Part I: Algorithm development. J. Atmos. Oceanic Technol., 34, 465–478.

Riley, J. R., 1975: Collective orientation in night-flying insects. Nature, 253, 113–114.

Russell, K. R., D. S. Mizrahi, and S. A. Gauthreaux, 1998: Large-scale mapping of Purple Martin pre-migratory roosts using WSR-88D weather surveillance radar. J. Field Ornithol., 69, 316–325.

Ryzhkov, A., P. Zhang, Q. Cao, S. Matrosov, V. Melnikov, and M. Knight, 2014: Measurements of circular depolarization ratio with the radar with simultaneous transmission/reception. Proceeding of eighth European Conference on Radar in Meteorology and Hydrology, Garmisch-Partenkirchen, Germany, ERAD, 10 pp. [Available at https://www.pa.op.dlr.de/erad2014/programme/ExtendedAbstracts/232_Ryzhkov.pdf].

Ryzhkov, A. V., and D. S. Zrnić, 2019: Radar Polarimetry for Weather Observations. Springer, 486 pp.

Ryzhkov, A., S. Y. Matrosov, V. Melnikov, D. Zrnić, P. Zhang, Q. Cao, M. Knight, C. Simmer, and S. Troemel, 2017: Estimation of depolarization ratio using weather radars with simultaneous transmission/reception. J. Appl. Meteor. Climatol., 56, 1797–1816.

Schuur, T., A. Ryzhkov, P. Heinselman, D. Zrnić, D. Burgess, and K. Scharfenberg, 2003: Observations and classification of echoes with the polarimetric WSR-88D radar. National Oceanic and Atmospheric Administration/National Severe Storms Laboratory and University of Oklahoma, 46 pp. [Available at https://arrc.ou.edu/~guzhang/Polarimetry/img/class/Schuur2003.pdf].

Shusse, Y., K. Nakagawa, N. Takahashi, S. Satoh, and T. Iguchi, 2009: Characteristics of polarimetric radar variables in three types of rainfalls in a Baiu front event over the East China Sea. J. Meteor. Soc. Japan, 87, 865–875.

Takeda, T., and S. Murabayashi, 1981: Observation of clear-air echoes with 3.2-cm radars. J. Meteor. Soc. Japan, 59, 864–875.

Van Den Broeke, M. S., 2013: Polarimetric radar observations of biological scatterers in Hurricanes Irene (2011) and Sandy (2012). J. Atmos. Oceanic Technol., 30, 2754–2767.

Wilson, J. W., T. M. Weckwerth, J. Vivekanandan, R. M. Wakimoto, and R. W. Russell, 1994: Boundary layer clear-air radar echoes: Origin of echoes and accuracy of derived winds. J. Atmos. Oceanic Technol., 11, 1184–1206.

Yanagisawa, Z., 1970: The observation of angel echoes by a 8.6 mm cloud detection radar (I). Tenki, 17, 434–440 (in Japanese).

Yanagisawa, Z., and K. Kanbayashi, 1972: The observation of angel echoes by a 8.6 mm cloud detection radar (II). Tenki, 19, 423–429 (in Japanese).

Zrnić, D. S., and A. V. Ryzhkov, 1998: Observations of insects and birds with a polarimetric radar. IEEE Trans. Geosci. Remote Sens., 36, 661–668.