Mammatus-Like Echo Structures Along the Base of Upper-Tropospheric Outflow-Layer Clouds of Typhoons Observed by Cloud Radar

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Abstract Upper-tropospheric clouds in the outflow layer of typhoons can affect the track of typhoons (tropical cyclones) through radiation effects. In this study, the microstructure of the outflow-layer clouds of several typhoons was examined. Cloud radar observations of three typhoons around Japan revealed numerous protuberances in echoes along the base of the upper-level clouds, which are referred to as mammatus-like echoes. The horizontal and vertical scales of these mammatus-like echoes were 0.5–3.0 and 0.3–1.5 km, respectively. Vertical observations revealed downward (upward) Doppler velocities in (between) the hanging echo regions. Upward and downward velocity maxima were estimated at 3 m s−1 around the mammatus-like echoes. Neutral stratification developed in the dry layer beneath the cloud base in which the mammatus-like echoes formed. These mammatus-like structures may promote mixing along the cloud base that contributes to dissipation of the outflow-layer clouds.

Plain Language Summary Heating and cooling due to radiative effects associated with upper-level clouds spreading from a typhoon have been reported to have an impact on the actual track of the typhoon. Therefore, it is important to clarify the processes of formation and dissipation of the upper-level clouds of typhoons. However, observations of such clouds, which are formed from relatively small ice particles, are scarce and the process of their dissipation is not well understood. In this study, we used cloud radar, which can detect clouds formed of small ice particles, to observe the upper-level clouds of three typhoons that approached Japan. At the base of the upper-level clouds, we found many protuberance structures with 0.5–3.0 km width and 0.3–1.5 km depth. These protuberance structures were accompanied by relatively large vertical motions of approximately 3 m s−1. The temperature and water vapor distributions near the base of the upper-level clouds of the studied typhoons were conducive to these vertical motions. The small-scale protuberance structures might promote dissipation of upper-level clouds along their base.

1. Introduction

Tropical cyclones (TCs), especially typhoons and hurricanes, represent a frequent cause of natural disasters. Therefore, it is important to understand the processes that determine the track and intensity of TCs. The upper-tropospheric outflow-layer clouds of TCs have been found to play important roles in the processes that determine the track (Bu et al., 2014; Cao et al., 2011; Fovell et al., 2009, 2010; Fovell & Su, 2007) and intensity (e.g., Trabing et al., 2019) of TCs. In particular, Fovell et al. (2016) clearly showed that radiative forcing effects of outflow-layer clouds are related to the processes that determine the path of a TC. Therefore, it is important to clarify the structures in and around outflow-layer clouds, as well as the processes of formation, maintenance, and dissipation.

The outflow layer of a TC has high potential for turbulence generation (Molinari et al., 2014). Duran and Molinari (2016) used radiosonde data to investigate the occurrence of a low Richardson number ($K_r$), which is an indicator of turbulence generation, in the upper troposphere around TCs. They found that the frequency of occurrence of $K_r$ values below the critical value was largest at the height of 13.5 km and within a radius of 200 km of the storm center. This peak remained evident more than 1,000 km from the TC center. Molinari
et al. (2014) examined $K_i$ values only below a height of 13 km (flight levels) in Hurricane Ivan (2004) using dropsonde observations from an aircraft. They found three layers with $R_i$ below the critical value of 0.25, which is very likely related to turbulence. One of the three layers, which was present at the cloud base near the edge of the central dense overcast clouds, was accompanied by a very dry underlying layer (relative humidity <40%). A similar arrangement of a layer of low $K_i$ values with a very dry underlying layer was also observed in TCs studied by Braun et al. (2016), Kudo (2013), and Molinari et al. (2019). Kudo (2013) reported that many commercial aircraft encountered moderate turbulence below the upper-level clouds. This region of turbulence was found to extend more than 1,500 m below the sharp temperature inversion corresponding to the base of the upper-level clouds. Ohigashi et al. (2020) reported the presence of saw-like echoes along the base of TC outflow-layer clouds. However, because they used a C-band (5.5 GHz, 5.5 cm wavelength) precipitation radar, which can detect relatively large hydrometeors, the detailed structure of the saw-like echoes could not be elucidated.

The Ka-band (34.9 GHz, 8.6 mm wavelength) cloud radar of Nagoya University (Japan) has been used over several years to observe clouds associated with typhoons around Japan. In comparison with radars that target precipitation, this radar is more sensitive to smaller particles, such as cloud droplets, drizzle, and early ice crystals (Kollas et al., 2007; Maesaka, 2018), and has a narrower beam width that is suitable for observing the microstructure of outflow-layer clouds. This radar detected numerous protuberances in echoes along the base of upper-tropospheric outflow-layer clouds associated with three typhoons. In this study, we investigated the details of these echo structures and examined their formation processes.

### 2. Observations and Data

Cloud observations were conducted using the Ka-band cloud radar of Nagoya University. The specifications and settings of the radar are summarized in Table S1. The maximum observation range was 30 km. The range and azimuth resolutions were 75 m and 0.35°, respectively. The radar was deployed at two sites: Sesoko station of the University of the Ryukyus (26.64°N, 127.87°E, height: 24 m) in 2016 and 2019, and at Kobe International University (34.68°N, 135.27°E, height: 26 m) in 2018. The cloud radar was used to observe three typhoons during the observation period: Chaba (2016), Cimaron (2018), and Neoguri (2019). Plan position indicator (PPI) and range-height indicator (RHI) scans were performed during all the observation periods. Additionally, in 2018 and 2019, observations at the elevation angle of 90° were also performed to obtain 2 min vertical Doppler velocity ($v_d$).

In 2016, five sounding observations using radiosondes (Vaisala, RS92-SGP) were performed during 02:36–10:52 UTC on October 3, 2016 at the Okinawa Electromagnetic Technology Center, National Institute of Information and Communications Technology (NICT; 26.50°N, 127.84°E). To relate altitude to temperature, we used upper-air sounding data from Shionomisaki (33.45°N, 135.76°E) for 2018 and from Minamidaitojima (25.83°N, 131.23°E) for 2019, obtained during routine observations conducted by the Japan Meteorological Agency (JMA). Himawari-8 geostationary meteorological satellite data (Bessho et al., 2016; Yamamoto et al., 2020) were used to determine the extent of cloud development around the radar observation ranges. The location and pressure of the center of each typhoon were obtained from the Regional Specialized Meteorological Center Tokyo best track data.

### 3. Results

Figure 1 shows infrared images acquired by the Himawari-8 satellite, vertical cross-sections of the equivalent radar reflectivity ($Z_{eq}$) obtained by RHI scans, and PPI images of $Z_{eq}$ at high elevation angles for Chaba (2016), Cimaron (2018), and Neoguri (2019). The PPI observations for Chaba (2016) are not shown because the PPI scan at the highest elevation angle (18.1°) did not reach the upper-level clouds within the observation range. The position and pressure of the typhoon centers, the distance between the typhoon centers and the cloud radar, and the minimum pressure during the lifetime of each typhoon are summarized in Table S2. These radar echo snapshots show the upper clouds of the typhoons at distances of several hundred kilometers from the centers of the typhoons. The clouds for Chaba (2016) were observed when the typhoon was in its most developed phase with central pressure of 905 hPa (Table S2). The cloud top temperatures around the cloud radar site were very low (−80°C to −70°C in Figure 1a). During the observation periods,
both Cimaron (2018) and Neoguri (2019) had intermediate central pressures (990 and 975 hPa, respectively, Table S2), and the cloud top temperatures around the radar sites were −50°C to −40°C (Figures 1c and 1f). Thus, the three typhoons were observed at different intensities.

Vertical cross-sections of Z obtained by the RHI observations show upper-level clouds. Shallow convective echoes below the height of ~5 km were seen in Chaba (Figure 1b) and Neoguri (Figure 1g), but not in Cimaron (Figure 1d). The heights of the base of the upper-level clouds were ~10 km (Figure 1b) for Chaba (2016), ~8.5 km (Figure 1d) for Cimaron (2018), and ~5 km (Figure 1g) for Neoguri (2019). These heights correspond to temperatures of ~28°C (10:52 UTC on October 3, 2016) at NICT, ~19°C (00 UTC on August 24, 2018) at Shionomisaki, and ~2°C (00 UTC on October 20, 2019) at Minamidaitojima. Therefore, the upper-level clouds, located in regions with temperatures below 0°C, consisted mainly of ice-phase particles.
Protuberance echoes were found along the base of the upper-level clouds. These protuberance echo structures were evident over a wide region, although they were not present at the base of all upper-level clouds. There were periods for Chaba (2016) when the protuberance echoes were seen throughout the entire range of RHI observations from 0° to 180° elevation (distance: \( \sim 55 \) km). Additionally, including the period when the protuberance structures were seen only in part of the cloud bases, the protuberance structures were observed almost continuously during 04–20 UTC on October 3, 2016 for Chaba (2016). This corresponds to a distance of \( \sim 290 \) km, given the distance that the center of the typhoon moved.

The PPI images at high elevation angles (Figures 1e and 1h) show a complicated echo structure in the innermost part of the upper-level clouds. These echoes appear as numerous projections rather than a wavelike (2-dimensional) structure with no variation in any one horizontal direction, and they appear similar to the form of mammatus clouds often observed visually along the base of anvil clouds extending from deep convective clouds (e.g., Schultz et al., 2006). As no visual observations were recorded in this study, these echoes are referred to as mammatus-like echoes.

Enlarged images of the mammatus-like echoes corresponding to Figures 1b, 1d, and 1g are shown in Figures 2a–2c, respectively. The mammatus-like echoes are \( 0.5–3.0 \) km in width and \( 0.3–1.5 \) km in depth. The maxima of \( eEZ \) are located slightly above the base of the clouds. The maximum \( eEZ \) increases with decrease in the height of the maxima, corresponding to the increase in temperature, shown in Figures 2a–2c. Moreover, the scale of the variability of the mammatus-like echoes appears to increase and the echoes show transition from relatively smooth (Figure 2a) to complex structures (Figure 2c).

The time-height cross sections of \( eEZ \) and \( dEV \) obtained from 2 min vertical PPI observations from 20:17:22 UTC on August 23, 2018 are illustrated in Figure 3. Positive values of \( dEV \) indicate upward motion. The observation time was approximately the same as that shown in Figures 1c–1e and 2b for Cimaron (2018). A layer of enhanced \( eEZ \) exceeding 15 dBZ is present in the height range of 9.3–9.6 km, and structures with unevenness in the vertical direction, corresponding to the mammatus-like echoes, are present in the region beneath (Figure 3a). In the upper part of the upper-level clouds, where \( eEZ < \sim 0 \) dBZ, \( V_d \) is slightly negative (\( >-0.5 \) m s\(^{-1}\)), but becomes less than \(-1 \) m s\(^{-1}\) as \( eEZ \) increases to a maximum at the height of around 9.5 km (Figure 3b). Below this \( eEZ \) maximum layer, the mammatus-like structures show large vertical motion in a very thin layer of \( \sim 1 \) km, which is completely different from the motion in the upper layers. The \( V_d \) pattern around the mammatus-like echoes was also different from the wavy pattern explained by the Kelvin-Helmholtz instability in Luce et al. (2010, their Figure 5), which extended over several kilometers in the vertical direction. When the standard deviation of \( V_d \) was calculated at each altitude, its maximum value at heights of 9.3–13.0 km was \( 0.3 \) m s\(^{-1}\) at a height of 9.3 km. On the other hand, in the height range of 8–9.3 km, the maximum value was \( 1.7 \) m s\(^{-1}\) at a height of 9.1 km. The time variations of these \( V_d \) values within the mammatus-like echo structures were considerably large.

In the layer of the mammatus-like echoes, downward (upward) Doppler velocities were present in (between) the hanging echo regions. This is similar to the characteristics of mammatus echoes (Kollias et al., 2005; Schultz et al., 2006). The range of \( V_d \) is from \(-4 \) to \( 2 \) m s\(^{-1}\). Assuming that the maximum absolute values of upward and downward velocities produced in association with the mammatus-like echo structures were comparable, the maximum/minimum vertical air motion in these large variations can be estimated at \( \pm 3 \) m s\(^{-1}\), while the sum of the terminal fall velocity of snow particles and the vertical air velocity of the mean field can be determined as \(-1 \) m s\(^{-1}\).

Figure 2. Close-up range-height indicator images of mammatus-like echoes for: (a) Chaba (2016), (b) Cimaron (2018), and (c) Neoguri (2019). The display ranges in (a–c) correspond to the rectangles shown in Figures 1b, 1d, and 1g, respectively.
In 2016, five radiosondes were released into Chaba (2016) from NICT in Okinawa (blue “+” mark in Figure 1a) at the time when the mammatus-like echoes were seen. The observation results of the radiosonde released at 10:52 UTC on October 3, 2016 are illustrated in Figure 4. The horizontal position of this sonde (blue closed circle) at 11:30 UTC, when the sonde was located at a height of 10.6 km near the base of the outflow-layer clouds, and the cloud distribution at the same time are shown in Figure 1a. At heights below ~10 km, the difference between the temperature \( T \) and the dew-point temperature \( T_d \) increased downward, indicative of dry air (Figure 4a). At heights between 9.3 and 10.0 km, there was little change in the virtual potential temperature \( \theta_v \), indicating neutral stratification. Conversely, at heights above ~10 km, the difference between \( T \) and \( T_d \) was smaller. Moreover, at heights between 10.0 and 10.8 km, \( \theta_v \) increased substantially with height, indicating stable stratification. For the discussion of static stability in saturated air, it is accurate to use the moist Brunt-Väisälä frequency (Durran & Klemp, 1982; Kirshbaum & Durran, 2004), which takes into account the effects of total mixing ratio (water vapor and hydrometeors). However, it is difficult to estimate the mixing ratio of hydrometeors from observations in this study. Therefore, the static stability was discussed using \( \theta_v \), which considers the effect of only the water vapor mixture ratio. As expected from the values of \( T \) and \( T_d \), the ice supersaturation ratio \( S_i \), defined by the ratio of excess from saturated water vapor pressure to ice, decreased markedly downward below ~10 km. Around the height of 9.0 km, \( S_i = -0.8 \) (i.e., relative humidity with respect to ice was 20%), indicating very dry air (Figure 4b). Conversely, \( S_i \) was close to 0 above the height of ~10 km, indicative of saturation with respect to ice. When cloud base was set at \( S_i = -0.1 \), the height of the base of the upper-level clouds was 10.1 km (Table S3).
The radial ($v_r$) and tangential components ($v_t$) of wind velocity relative to typhoon motion are shown in Figure 4c. It can be seen that $v_r$ is 10–15 m s$^{-1}$ and that its variation with height is relatively small. Conversely, $v_t$ is larger (approximately 30 m s$^{-1}$) below the base of the clouds, indicating cyclonic flow in the lower levels of the typhoon. Above the base of the clouds, $v_t$ largely decreases, which indicates that the cyclonic flow weakens with height, as seen in the general structure of typhoons (e.g., Izawa, 1964; Frank, 1977).

Vertical profiles of $R_i$, the squared Brunt-Väisälä frequency $N^2$, and squared vertical shear of horizontal wind $\mathbf{V}^2$ are presented in Figure 4d. The definitions of these parameters are provided in Text S1 in the Supporting Information S1. A value of $R_i < 0.25$ is considered the critical value of turbulence generation. A layer with $R_i$ values of <0.25 is present at the height of 9.7–9.8 km. Smaller values of $R_i$ reflect smaller values of $N^2$. The maximum value of $\mathbf{V}^2$ is present at the height of 10.6 km, located 0.5 km above the base of the clouds. This is attributable to the large vertical shear of $v_t$ (Figure 4c). However, owing to the large increase in height of $\theta_i$ (Figure 4a), which is indicative of high stability (Figure 4d), $R_i$ is 0.7, i.e., not <0.25. In the height range of ±1 km from the base of the clouds for the five sondes, $N^2$ minima are observed in the range of 170–450 m below the base of the clouds (Table S3). The minimum values of $N^2$ at 02:36 and 06:28 UTC are negative, indicative of absolute instability. Layers with values of $R_i < 0.25$ are present around the $N^2$ minima in the observations of all sondes except the sonde released at 04:31 UTC (Figure S1). At heights of 500–940 m above the base of the clouds, there are large shear layers where the maximum values of $\mathbf{V}^2$ (exceeding 2.5 × 10$^{-4}$ s$^{-2}$) are present (Table S3). In these large shear layers, $N^2$ also tends to be larger. Consequently, there is no shear layer with $R_i < 0.25$ in the height range of 1 km above the base of the clouds (Figure S1).

4. Discussion

From the sounding observations, sublimation cooling of ice particles falling into a very dry layer below the cloud base is considered to cause the neutral layer ($N^2 \approx 0$) just below the cooling layer with $R_i < 0.25$. Convective motions within this layer are considered responsible for the formation of the mammatus-like echoes. Molinari et al. (2014) showed that the region with low $R_i$ values was located in the same layer as the unstable layer ($N^2 \approx 0$) associated with sublimation of snow below the base of the clouds, and at a different location from the strong vertical shear layer slightly above the base of the clouds. Through consideration of convection generation based on the Rayleigh number, Kudo (2013) used numerical simulations to show that convection cells below the base of the clouds were caused by Rayleigh-Bénard convection. In their sensitivity experiments, precipitation became stronger in higher air temperatures, which resulted in a larger temperature decrease attributable to enhanced sublimation cooling. Consequently, convection beneath the cloud base was intensified. In this study, when the cloud base temperature was higher in the order of Neoguri (2019), Cimaron (2018), and Chaba (2016), the maximum $\theta_i$ just above the cloud base and the depth of the mammatus-like echoes were larger in the same order. This result, which is consistent with the sensitivity experiments performed by Kudo (2013), supports the idea that buoyant convection in the unstable layer formed by sublimation cooling caused the mammatus-like echoes.

Among the sounding observations released in Chaba (2016), $R_i$ did not reach the critical value below the cloud base for one profile (04:31 UTC, Figure S1b). This is because the vertical shear was too small, despite the weak static stability. This may explain the lack of mammatus-like echo structures in certain regions.

5. Conclusions

The present study used a Ka-band cloud radar to observe the outflow-layer clouds of three typhoons: Chaba (2016), Cimaron (2018), and Neoguri (2019). Cloud echoes in the upper levels of the typhoons were present in regions where the temperature was <0°C. Values of $\theta_i$ increased toward the lower levels and showed maxima at several hundred meters above the base of the clouds. An echo structure with numerous protruberances was observed along the base of the clouds, which was referred to as a “mammatus-like echo.” The mammatus-like echoes were 0.5–3.0 km in width and 0.3–1.5 km in depth. Echoes from the high-elevation PPI scans showed that the mammatus-echoes extended horizontally. The vertical Doppler velocities $v_d$ during Cimaron (2018) revealed downward motions in the downward-projecting echoes and upward
motions in the upward-recessed areas. The maximum values of upward and downward velocity variation associated with the mammatus-like echoes were estimated to be 3 m s\(^{-1}\). Five radiosonde observations were performed for Chaba (2016). The outflow-layer clouds corresponded to the ice-saturated layer, with a very dry layer beneath. Layers of weak static stability \(N^2\) were found in the range of 170–450 m below the base of the clouds, and \(K_v\) values below the critical value of 0.25 were found around the minima in four of these cases. Cooling by sublimation of ice particles occurred just below the cloud base, corresponding to the upper part of the mammatus-like echoes. This cooling, which led to neutral stratification and the small values of \(K_v\), caused vertical mixing evidenced by the mammatus-like echoes. In this study, the cloud radar clearly showed that mammatus-like echo structures with vertical motion of a few meters per second existed in the layer with low \(K_v\) values along the base of outflow-layer clouds of multiple typhoons. The mammatus-like structure leads to increased surface area. This may enhance mixing between the clouds and the underlying air and promote sublimation of the outflow-layer clouds which plays an important role in the process of dissipation and radiation of outflow-layer clouds of TCs. Numerical simulations are needed to reveal more accurately the horizontal extent and duration of the mammatus-like structure, and the cloud dissipation rate.

Data Availability Statement
Cloud radar and sounding observation data released at NICT, Okinawa, Japan, are available online (https://doi.org/10.5281/zenodo.5173188). Upper-air sounding data obtained by the JMA are available from the website of the University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html). Himawari-8 satellite data can be obtained from the Center for Environmental Remote Sensing, Chiba University (http://www.cr.chiba-u.jp/databases/GEO/H8_9/FD/index.html). The Regional Specialized Meteorological Center Tokyo best track data are available from the website of the JMA (https://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/trackarchives.html).

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