Relationship between Growing Speed and Turret Development

Fumiaki Kobayashi¹, Akihito Katsura¹ and Takumi Ookubo¹

¹ Department of Geoscience, National Defense Academy, Yokosuka, 239-8686, Japan

Abstract. On the basis of conducting simultaneous observations of cumulonimbi using the X-band radar, and photogrammetry, several cases of cumulonimbus initiations were observed during the mid-summer days from 2010 to 2011 in the southern Kanto region of Japan. The relationship between the maximum growing speed and the maximum height of 40 turrets was almost linear. The average maximum growing speed was 7 m/s. Turrets were categorized into two groups based on their growing speed, relative to this value. The first, named the “inactive” group, consists of turrets that have a relatively low growing speed with a maximum growing speed that is less than 8.5 m/s, and reach up to 8 km AGL. Another group is the “active” group, in which the turrets develop vertically (10 km or more AGL) with a larger maximum growing speed (> 8.5 m/s). In the active group, some turrets grew with a maximum growing speed that was greater than 15 m/s and had a maximum height that was recorded as greater than 10 or 15 km AGL. The turrets that developed over the Boso Peninsula, Japan, during the observation period indicated that the generation area moved northward as time progressed and turrets eventually developed in the northern regions of the Boso Peninsula.

Keywords: cumulonimbus turret, convection initiation, X-band Doppler radar

1. Introduction

The understanding of the cumulonimbus (Cb) generation process (convection initiation) and the fine structure of Cb is of great importance not only for scientific purpose, but also for the mitigation of heavy rainfall disasters and high winds. Cb cloud turrets, which are bulbous Cb inner structures with a horizontal scale of 1 to 3 km and represent overturning air, develop continuously. Tufts are the smallest features of Cb clouds and have a horizontal scale of approximately 100 m (Fig. 1, Kobayashi et al. 2012). Generally, a turret is organized by many tufts and Cb is organized by several turrets. The development of Cb may be influenced by the activity of each tuft or turret. The multi-scale structure of Cb, turrets and tufts would be a key concept for understanding the cumulus convections. The structure and development process of turrets and tufts remain uncertain due to the lack of observational data.

In the previous paper (Kobayashi et al. 2012), on the basis of simultaneous observations of cumulonimbi using the 95-GHz FM-CW cloud radar (FALCON-I), the NDA (National Defense Academy) X-band radar, and photogrammetry, several cases of Cb initiations on 24 July, 23 August 2010 and 7 August 2011 in the Kanto region of Japan, were presented.
The generation of the Cb was initiated by cloud turrets. The Cb was organized by the continuous generation of some distinct turrets. The growing speeds of turrets were quite different 2 m/s to 13 m/s among the life cycle of the Cb. The time relationship between the generation of Cb clouds and the vertical growth of turrets to the cloud top is different in the cases.

Sakurai et al. (2012) demonstrated the process of Cb initiation and development by conducting simultaneous observations using a Ka-band Doppler radar and an X-band polarimetric Doppler radar in the Kanto region of Japan. They showed a misoscale convective echo development during the lifetime of a Cb cloud. In the first half of its development stage, a misoscale convective echo appeared between 2 and 5 km AGL. Furthermore, during the second half of the development stage, an additional misoscale convective echo appeared between 5 and 12 km AGL. They concluded that the ascent of the convective echo height is one of the key factors in the prediction of deep convection.

Saito et al. (2013) demonstrated the formation process of an isolated Cb cloud, while using MTSAT-1R satellite rapid scan data, which generated during the afternoon on a fine mid-summer day. An isolated Cb developed suddenly near the observation site in Chiba, Japan, and the first echo (Kobayashi and Inatomi 2003) appeared at 4 km AGL. After 40 min since cloud generation, turrets developed vertically and an anvil formed. The lifetime of the Cb was approximately two hours. The features of the cumulus and Cb clouds in the early stage of the Cb were detected by visible brightness data. The temporal change of visible brightness suggested the evolution of Cb turrets and the temporal and spatial structures of the anvil were also provided. It was shown that the generation, development and decaying of an isolated Cb on a fine mid-summer day can be recognized by utilizing MTSAT-1R rapid scan data.

The purpose of the current study is to clarify the average growing speed of Cb turrets using the X-band Doppler radar and photogrammetry. This paper presents the growing speeds of 40 turrets that were observed during the summers of 2010 and 2011 in the southern Kanto region of Japan, and describes the temporal and spatial relationships between the growing speed and the turret development.

2. Observation methods

An X-band Doppler radar was installed at the National Defense Academy (NDA) of Yokosuka (100 m ASL), Japan, to observe the development of Cbs around a metropolitan area. The Doppler radar was operated at 9.7 GHz, and with a wavelength of 3 cm, a beam width of 1°, a minimum detection reflectivity signal of 16 dBZ, a radial resolution of 125 m, a Nyquist velocity of 16 m/s, and an antenna scan rate of 6 rpm. The plan position indicator (PPI) volume scan with a 14-step (from 0.5 to 19.5°) mode observation was conducted at 5-min intervals. This radar had a radial maximum range of 64 km. Daytime cloud images were captured via a time-lapsed video and still photography during the periods of Cb development.

In this study, the elevation and azimuth of each turret top was observed by a theodolite. Figure 1 shows the observation method using a theodolite. The position of the first echo (X) was detected by the X-band radar. Generally, Cb turrets develop vertically in the early
stages of Cb development, so the horizontal differences between each turret top and the first echo are quite small. The height of each turret top (\( h \)) was then calculated using the turret top’s elevation (\( \theta \)) and position of the first echo (\( X \)). Moreover, the isolated turrets, which generated vertically under the conditions of fine and calm days in mid-summer, were selected in this paper. The accuracy of turret position is assumed to be several tens of meters. The observational errors of cloud top height were estimated on the order of 10 m (Fig. 2). This spatial resolution is sufficient for the discussion of the cloud height on the order of 1 km. In this paper, the growing speed of a turret is defined as the growth rate of the turret during 1 min.

Simultaneous observations using the X-band radar and the theodolite have been conducted during two summer months in 2010 and 2011. Cb turrets generated in the afternoon on a fine mid-summer day were observed during 100 days in 2011 and 2012. The height of each turret was estimated geometrically using the theodolite observation and the analysis of video image. Theodolite observations were conducted from 09:00 to 17:00 JST (Japan Standard Time) on fine days. In this study, 40 turrets were selected by the following conditions: 1) the Pacific high over east Japan, 2) clear sky over the southern Kanto region, 3) by noon, the temperature in Tokyo and Chiba had exceeded 30 °C at Ootemachi and Chiba AMeDAS (Automated Meteorological Data Acquisition System) stations, 4) a wind speed at 12 JST at Ootemachi of less than 2.5 m/s to allow for the onset of local circulation (sea breeze). In particular, isolated turrets, which developed vertically on fine days were analyzed for evaluation.

Fig. 1. Schematic view of the theodolite observation method.
Fig. 2. The observational errors of cloud top height (m) of the theodolite observation method shown in Fig. 1. Errors of height are indicated by every theodolite elevation angle.

3. Relationship between growing speed and maximum height of turrets

Figure 3 denotes the relationship between the maximum growing speed and maximum height of 40 turrets, which were observed during the mid-summer days of 7 August 2010, 1, 2, 12, 17, 19, 30 August 2011. The maximum heights of the turrets ranged from 3 to 17 km AGL, the maximum growing speeds varied from 2 to 23 m/s. As the maximum growing speed increases, maximum height also increases, on average. The relationship between the maximum growing speed (and averaged growing speed) and the maximum height is almost linear. The average value of the maximum growing speed is 7 m/s.

Figure 4 shows the height of each turret when the maximum growing speed was observed. For turrets with a maximum growing speed of less than 8.5 m/s, the height of each turret is 8 km or less AGL. In contrast, for turrets with a maximum growing speed that is greater than 8.5 m/s, the height of each turret is greater than 8 km AGL, except for one data. This tendency also appears in Fig. 3. So, turrets were categorized into two groups based on their growing speed, relative to this value. The first, named the “inactive” group, consists of turrets that have a relatively low growing speed with a maximum growing speed that is less than 8.5 m/s, and grow up to 8 km AGL. Another group is the “active” group, in which the turrets develop vertically (10 km or more AGL) with a larger maximum growing speed (> 8.5 m/s). In the active group, some turrets grew with a maximum growing speed that was greater than 15 m/s and had a maximum height that was recorded as greater than 10 or 15 km AGL. The peak maximum growing speed was 23 m/s, in which the turret reached 18 km AGL. In the active group, more than half of the turrets were recorded in altitude more than 10 km AGL, the maximum growing speed observed both the relatively lower speed (8-12 m/s) and the relatively higher speed (more than 20 m/s), respectively.
Fig. 3. Relationship between maximum growing speed and maximum height of each turret (top) and averaged growing speed and maximum height (bottom).

Fig. 4. Height of each turret when the maximum growing speed was observed.
4. Conditions of turret generation

Figure 5 shows a histogram of turret occurrence time for the case presented with 40 turrets. No turret generated until noon in this study and was observed after 16 JST in the mid-summer days. The most active period of turret generation was between 13 and 14 JST. Relationship between generation time and maximum height of each turret and maximum growing speed are shown in Fig. 6. Most turrets appeared from 3 to 8 km in height, in contrast, the maximum height of the turrets, which ascended to 10 km AGL, rose gradually between 12 and 16 JST. This result indicates that, in this case, the turrets developed later in the afternoon. In the same way, the maximum growing speed of most turrets ranged from 2 m/s to 11 m/s, three turrets which exceeded 15 m/s of the maximum growing speed, observed 16 m/s at 13:00 JST, 17 m/s at 14:40 and 23 m/s at 15:50, respectively.

Relationship between the instability of upper air (CAPE and CIN) and maximum growing speed of each turret are shown in Fig. 7. The thermodynamic parameters were calculated at the sounding station at Tateno that were released from three to five hours before (09 JST) and after (21 JST) the generation of the Cb turrets and approximately 60 km away from the Cb generation point. The value of CAPE (convective available potential energy) varied from zero to 1900 J/Kg, and CIN (convective inhibition) was from zero to 240 J/kg, respectively. The large number of CAPE and small value of CIN close to zero suggest the active of thermal convection. The turrets of the active group, in which the turrets develop vertically (> 10 km AGL) with a larger maximum growing speed (> 8.5 m/s), show the large values of CAPE (400~1900 J/Kg) and the small values of CIN (0~120 J/Kg), respectively. In particular, the maximum growing speed more than 15 m/s was observed under the large number of CAPE more than 1500 J/Kg in Kanto, Japan (e.g., Taguchi et al. 2002; Chuda and Niino 2005).

![Fig. 5. Histogram of turret occurrence time for 40 turrets.](image)
Fig. 6. Relationship between generation time and maximum height of each turret (left) and generation time and maximum growing speed (right).

Fig. 7. Relationship between CAPE and maximum growing speed of each turret (left) and CIN and maximum growing speed (right).

5. Discussion

In this section, we will discuss the spatial distribution of 40 turrets described in the previous sections, the environmental features of the generation of turrets. Figure 8 shows the distribution of the turrets that developed over the Boso Peninsula during the observation period. The area of turret generation moved northward as time progressed from 12 to 16 JST. Furthermore, the inactive turrets, which had a maximum height of less than 8 km AGL (a relatively low growing speed (maximum growing speed of less than 8.5 m/s)), appeared in the southern regions of the turret generation area, and the active turrets with a maximum height of more than 10 km (maximum growing speed of more than 8.5 m/s) appeared in the northern regions (including two turrets generated in Kanagawa prefecture in the figure). It is assumed that the turrets, which all formed over the southern regions of the Boso Peninsula, all generated in the early afternoon. After developing, the turrets gradually became organized and eventually began to actively develop over the northern areas of the Boso Peninsula in the late afternoon.

Kobayashi et al. (2011) denoted the development of an isolated Cb cloud above the cloud radar (FALCON) site on 24 July 2010, using the 95-GHz cloud profiling radar, the X-band radar, and photogrammetry on a mid-summer day. A continuous generation of turrets was
observed and a total of four turrets developed at the same location for approximately one hour. The growing speeds were calculated to be approximately 10 m/s (Turret 1), 8 m/s (Turret 2), 13 m/s (Turret 3) and 7 m/s (Turret 4), based on the temporal change of each turret. The first echo appeared at a height of 3 km, which developed rapidly and had an echo core region of 30 dBZ at 16:35 JST. The height of the cloud top in the generation stage was estimated to be 4 km AGL at 16:25 JST. The maximum height of the X-band echo was 10 km AGL at 16:50 JST. Turret 3, which had the largest value of vertical growth rate, appeared after the maximum height of Turret 2 (16:48 JST) and reached at a height of 11 km AGL at 16:58 JST. These results suggest that the turrets developed gradually in the life cycle of Cb evolution.

The features in Fig. 8 indicate some patterns of Cb turret development. Cb turrets often develop to large Cbs and organized to multi-cell or supercell in the lifetime. The behavior and evolution of turrets are influenced by environmental conditions, such as local circulations, topography and upper air stability. Further studies are needed to observe the inner structure of turrets and Doppler velocity fields detected by both X-band (micro wave) and W-band (mm wave) radars for understanding the development of Cb turrets.

Fig. 8. Distribution of the turrets that generated over the Boso Peninsula during the observation period. Colors indicate generation time (left) and maximum height of the turrets (right), respectively.

6. Conclusions

On the basis of conducting simultaneous observations of Cbs using the X-band radar and photogrammetry, growing speeds of Cb turrets in the southern Kanto region of Japan were presented. The relationship between the maximum growing speed and maximum height of 40 turrets, which were observed during the mid-summer days from 2010 to 2011, were discussed in this paper. Conclusions of this study are as follows:

(1) The relationship between the maximum growing speed (and averaged growing speed) and the maximum height of turrets is almost linear. The average value of the
maximum growing speed is 7 m/s.

(2) It is recognized that two groups exist according to this value, the “inactive” group that consists of turrets that have a relatively low growing speed (maximum growing speed of less than 8.5 m/s) and ascend up to 8 km AGL. Another group is the “active” group, which the turrets develop vertically (10 km or more AGL) with a larger maximum growing speed (> 8.5 m/s). In the active group, some turrets grew with a maximum growing speed of 15 m/s or greater and had a recorded maximum height of greater than 10 or 15 km AGL.

(3) The turrets that generated over the Boso Peninsula during the observation period indicated that the area of generation moved northward as time progressed and the turrets developed in the northern regions of the Boso Peninsula.

Acknowledgments The authors would like to thank the Japan Meteorological Agency (JMA) and the University of Wyoming for providing the meteorological data. This study was partly supported by a Grant-in-Aid for Scientific Research (C) 23510232.

References

Chuda, T. and H. Niino, 2005: Climatology of environmental parameters for mesoscale convections in Japan. J. Meteor. Soc. Japan, 83, 391–408.

Kobayashi, F. and N. Inatomi, 2003: First radar echo formation of summer thunderclouds in southern Kanto, Japan. J. Atmos. Electr., 23, 9–19.

Kobayashi, F., A. Katsura, Y. Saito, T. Takamura, T. Takano and D. Abe, 2012: Growing speed of cumulonimbus turrets. J. Atmos. Electr., 32, 13–23.

Kobayashi, F., T. Takano and T. Takamura, 2011: Isolated cumulonimbus initiation observed by 95-GHz FM-CW radar, X-band radar, and photogrammetry in the Kanto region, Japan. SOLA, 7, 125–128.

Saito, Y., F. Kobayashi, A. Katsura, T. Takamura, T. Takano, and T. Kurino, 2013: The lifetime of an isolated cumulonimbus observed by weather satellite (MTSAT-1R) rapid scans. Tenki, 60, 247–260.

Sakurai, N., K. Iwanami, T. Maesaka, S. Suzuki, S. Shimizu, R. Misumi, D. Kim and M. Maki, 2012: Case study of misoscale convective echo behavior associated with cumulonimbus development observed by Ka-band Doppler radar in the Kanto region, Japan. SOLA, 8, 107–110.

Taguchi, A, K. Okuyama and Y. Ogura, 2002: The thunderstorm activity observed by SAFIR and its relation to the atmospheric environment over the Kanto area in the summer. Part II: Thunderstorm prediction by stability indices. Tenki, 49, 649–659.

(Received October 23, 2017; accepted March 12, 2019)