Temporal and Spatial Characteristics of Localized Rainfall on 26 July 2012 Observed by Phased Array Weather Radar

Fusako Isoda¹, Shinsuke Satoh¹, and Tomoo Ushio²

¹National Institute of Information and Communications Technology, Koganei, Tokyo, Japan

²Tokyo Metropolitan University, Hino, Tokyo, Japan

Abstract

On 26 July 2012, localized rainfall from four isolated convective cells was observed by the Phased Array Weather Radar (PAWR) located in Osaka, Japan. The PAWR can observe fine three-dimensional features of precipitation every 30 seconds. In this paper, we investigated the evolution of localized isolated convective cells using the PAWR data.

The first echoes appeared at around 5 km altitude, and light rain (25 dBZ) near the ground started in 3 to 5 minutes after the first echo. Heavy rain (50 dBZ) started in 9 to 15 minutes after the first echo. The lifespan of four convective cells was from 40 to 70 minutes.

The reflectivity centroid over 25 dBZ (C25) of the first echo in developing stage descended first and then ascended within the several minutes. The behavior of the first echo motion looked complicated and it is difficult to be explained by the traditional conceptual model. In dissipation stage, the descending C25 was stopped by an alternation of precipitation core.

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1. Introduction

Localized heavy rainfall caused by isolated cumulonimbi or isolated convective storms can often cause disastrous floods because the precipitation intensity increases rapidly, causing sudden swelling in rivers and groundwater. Prediction of the occurrence and development of localized heavy rainfall will help avoid flood related disasters. Radar observations are frequently used when studying severe rainfall. For example, conventional C-band weather radar (Ishihara 2012) and X-band multi parameter (MP) radar (Kato and Maki 2009; Hirano and Maki 2010; Kim et al. 2012) observed local heavy rainfall. However, these radars only create full volume scan about every 5 to 10 minutes, which is not fast enough to capture the quickly evolving storms producing localized heavy rainfall. Because the time resolution was so not good, the details about formations and developing of isolated cumulonimbi were not revealed in previous studies. For example, Kim et al. (2012) describe the replacement of precipitation core by using every 5 min data. The more rapid scan investigation (in every 2 min) of localized heavy rainfall was done by Shusse et al. (2015) which revealed the relationship between the precipitation core and ground level precipitation. In comparison with traditional radars, the Phased Array Weather Radar (PAWR) developed by National Institute of Information and Communications Technology (NICT), Osaka University and Toshiba can produce a full volume scan every 30 seconds (Ushio et al. 2013; Yoshikawa et al. 2013). Until now short-term events such as microburst and miso-cyclone (Adachi et al. 2016a, 2016b) were reported by using PAWR observation data.

The purpose of this study is to leverage the high temporal

resolution and the dense three-dimensional measurement of the PAWR to reveal the details of these quickly evolving localized heavy rainfall events. To do so, we will present observations of four localized heavy rainfall events which occurred on 26 July 2012.

2. Data and method

The PAWR is an X-band weather radar operating since May 2012 at the Osaka University Suita campus. Main specifications of the PAWR were listed in Adachi et al. (2016a). Its high spatial and temporal resolution is realized using transmitting of fan-beams and receiving by digital beam forming (DBF) technique (Yoshikawa et al. 2013; Ushio et al. 2015). The technique allows the volume scan within a range of 60 km, up to 14 km altitude for 100 different elevation angles every 30 seconds.

In our analysis, the polar coordinate data is interpolated onto a 250 m vertical and horizontal mesh using the Cressman scheme (Cressman 1959). To identify the event of localized heavy rainfall from the 2012 summer data, a high reflectivity part more than 50 dBZ and a small rainfall area less than about 200 km² (8 km radius) are adopted. Once an event was identified, a three-dimensional animation was made.

The ‘first echo’, the echo that precedes localized heavy rainfall, is determined by playing 3D animations backwards. After choosing a horizontal projection area relative to the first echo, precipitation tracking begins. To track the rainfall area, the position of the rectangular region surrounding radar reflectivity over 25 dBZ at 1 km and higher altitude at a time t is recorded. Here, the analysis is limited to altitudes above 1 km to suppress the effect of ground clutter. The threshold of 25 dBZ was selected to identify the precipitation echoes considering the range dependent noise level of the PAWR. At the time $t + 30$ sec. the rectangular region is searched again. If the subsequent horizontal projection area overlaps any of part of the previous region at time t , then the two regions are considered a part of the same convective cell. This procedure is repeated until the time when the overlap area is not seen, and here the tracking is finished. By tracking the rainfall area, we derive the time of the first echo observed, the first time of light rainfall (the reflectivity of 25 dBZ corresponding to 1.3 mm h⁻¹) and heavy rainfall (the reflectivity of 50 dBZ corresponding 50.0 mm h⁻¹) reached at a height of 1 km, the 3D position of the 25 dBZ centroid (C25, three dimensional center of mass weighted by the reflectivity of the radar echo region with reflectivity over 25 dBZ), the maximum reflectivity, the end time of rain echo, and the maximum echo top. By tracking the C25, the movement of the convective cell is deduced every 30 sec.

On 26 July 2012, four cases of localized heavy rainfall were observed by the PAWR. The cumulonimbi which produced the localized heavy rainfall were well separated, were not organized with other rainfall, had a lifetime of several tens of minutes. The radar observation indicated heavy rainfall, but only one rain-gauge (Kyotanabe) recorded 0.5 mm h⁻¹ in 10 minutes. The convective available potential energy (CAPE) at Shionomisaki (140 km south of Osaka) were 19.41 (J kg⁻¹) at 0900 JST and 1133 (J kg⁻¹) at 2100 JST. The level of free convection (LFC) were 508.0 (hPa) at 0900 JST and 703.9 (hPa) at 2100 JST.

Corresponding author: Fusako Isoda, National Institute of Information and Communications Technology, 4-2-1, Nukui-Kitamachi, Koganei, Tokyo 184-8795, Japan. E-mail: f.isoda@nict.go.jp.

Table 1. Features of four isolated rainfall.

	CASE 1 (15:52:16)		CASE 2 (16:43:46)		CASE 3 (17:30:16)		CASE 4 (18:04:16)	
First Echo	0:00:00	4.0–5.75 km	0:00:00	1.5–5.5 km	0:00:00	4.0–6.5 km	0:00:00	5.25–6.0 km
Light Rainfall at 1 km	0:04:00		0:03:00		0:05:00		0:03:00	
Heavy Rainfall at 1 km	0:13:00		0:15:00		0:09:00		0:15:00	
Maximum Reflectivity	0:17:00	64.6 dBZ at 5.75 km	0:15:30	61.9 dBZ at 3.5 km	0:19:00	66.1 dBZ at 7.5 km	0:12:30	66.0 dBZ at 3.75 km
End Time	0:40:00		0:50:00		0:55:00		1:10:00	
Maximum Echo Top	0:21:30	13.75 km	0:24:00	12.75 km	0:12:30	11.50 km	0:29:30	12.00 km

Fig. 1. 3D visualization of the lifetime of rainfall by isolated cumulonimbus observed by PAWR every 6 min in CASE 4. Five isosurfaces are used for the visualization of reflectivity.

3. Results

3.1 Time and spatial changes in heavy rainfall by isolated cumulonimbus

Various characteristics of the four convective cells are shown in Table 1. The first echoes tended to be vertically elongated, so the altitude of the top and bottom of the first echoes are listed. The first echo heights are comparable to those reported in previous studies (Kobayashi et al. 2009; Nakakita et al. 2010). Light rainfall started 3 to 5 minutes after the first echoes were observed. Heavy rainfall started 9 to 15 minutes after the first echoes were observed. The lifespan of the rainfall events was from 40 to 70 minutes, similar or little longer to the 30 to 60 minutes reported in previous studies (Biondini 1976; Weisman and Klemp 1986). CASE 4 had a lifespan of 70 minutes, but is considered long lived in comparison to the other precipitation events in this study. Here we showed CASE 4 because its time evolution was the longest and it has variety of interesting characteristics described later.

The CASE 4 rainfall event is shown in Fig. 1, rendered in 3D using 5 isosurfaces from 25 to 50 dBZ every 6 min. The first echo is seen in Fig. 1a at an altitude of between 4.25 and 5.75 km. Six minutes later in Fig. 1b, the echo grew in size, and the 25 dBZ isosurface reached ground level. This indicates that by the time shown in Fig. 1b, light rain (1.3 mm h^{-1}) had already started. The reflectivity of the echo grew to 50 dBZ by the time shown in Fig. 1c, indicating heavy rain at ground level. In Fig. 1d, upward growth of the convective cell can be seen. Figures 1b, 1c, and 1d show the system in the developing stage; the mature stage is seen in Figs. 1e, and 1f. By the time shown in Fig. 1g, the echo had

begun to reduce in size, a trend which continues in Fig. 1j. Figures 1g, 1h, 1i, and 1j show the convective cell in the dissipation stage. Figure 1 shows the time evolution of the convective cell in 6 minutes intervals; a movie showing the progression in 30 second intervals is included as Supplement 1.

3.2 Horizontal movement of the 25 dBZ centroid

To track the motion of the convective cells, the C25 position was calculated for every radar scan (every 30 seconds). The C25 is useful and easy to calculate position and movement for the isolated convective cell. The horizontal movements for CASES 1–4 are plotted in Fig. 2 with colors representing the altitude of the C25s, and arrows along the direction of motion. For CASE 3, the horizontal motion was very small, so no direction is indicated. The path traversed by CASE 4 is longer than those by other CASES. The C25 of CASE 1 seems to move across the mountain. The C25 of CASE 4 moves along the foot of the mountains, while CASES 2 and 3 are isolated convective systems in the flat lands. The directions of movement of the C25 are South-East for CASE 1 and 2, and South for CASE 4. The movements of CASES 1 and 4 seem to be affected by the topography.

3.3 Vertical movement of the 25 dBZ centroid

a. Behavior of the first echo (Developing stage)

Figure 3 shows the vertical changes in the C25s as a function of time. The behavior of the C25s for the first several minutes of the precipitation events are remarkable. In CASES 1–3, the altitude of C25s descends for the first 5 to 8 minutes, and then rises to above or the same altitude of the first echo. In CASE 4, the C25 falls for the first 1 minutes, then rises until 7 minutes after the first

Fig. 2. Satellite view of radar observation area (a circle of 60 km radius) and tracking of the 25 dBZ centroid in 4 rainfall cases. Colors indicate the altitudes of the centroid. Arrows indicate the directions of rainfall events. In CASE 3, there is no arrow because the horizontal movement is small. The background gray scale color represents the altitude of the ground over the observation area.

echo, then falls and rises again.

Vertical cross sections of the first echoes for CASE 1 and CASE 3 are presented in Fig. 4 and Fig. 5. For CASE 1, the first echo is descending for Figs. 4a, 4b, 4c, 4d, and 4e but in Fig. 4f, a high reflectivity region appears higher than the first existing echo. For CASE 3, the first echo goes down but another echo appears on the left side in Fig. 5c. When the first echo is descending and reach the ground, the second echo grows up and it becomes dominant. Because the C25 is calculated above the horizontal projection area, the C25 with such a dual core shows the averaged features.

b. Alternation of precipitation core (Dissipating stage)

In the Dissipation stage, the altitude of the C25 gradually descends in all the four cases (Fig. 3). However, the descending of the C25 stopped in the CASE 1 (after 30 min) and CASE 4 (after 40 min). To understand what occurs during a subsequent stopping descending in the dissipation stage, detailed cross sections of the precipitation core in CASE 4 for the time period indicated by an arrow in Fig. 3d are shown in Fig. 6. This figure contains the east-west vertical cross section at the center of the precipitation core every 30 seconds. The precipitation core is defined as the part having an echo stronger than 45 dBZ, therefore the contours are drawn every 5 dBZ starting at 45 dBZ. Figures 6a and 6b show a strong reflectivity area at 2 to 4 km altitude and 10 to 12 km to the east of the radar, this region is considered to be the main core. A branch region to the west of the main core at an altitude of 4 km can also be seen. After that the main core continues to descend, and the branch reflectivity becomes stronger. In Fig. 6e,

Fig. 3. Time changes of the altitudes of the 25 dBZ centroids (solid line) for the four cases in this study. Dashed line and dot line indicate echo bottom and top respectively. The arrow in (d) indicates the start time of the branching off of a precipitation core. Red lines indicate the maximum reflectivity height.

Fig. 4. West-east vertical cross sections of first echoes of CASE 1 (a) every 2 min. Contour lines are drawn above 25 dBZ every 5 dBZ.

Fig. 5. West-east vertical cross sections of first echoes of CASE 3 (a) every 2 min. Contour lines are drawn above 25 dBZ every 5 dBZ.

Fig. 6. West-east vertical cross section of the precipitation core (> 45 dBZ) in the dissipation stage of CASE 4 every 30 s. Filled contour lines are drawn every 5 dBZ starting at 45 dBZ.

the extent of the main core falls to 2 km altitude, and the branch grows vertically with increasing reflectivity. In Fig. 6f, the branch extends vertically to 6 km. The reflectivity of the branch echo remains higher than the reflectivity of the main core until 18:44:16 JST (Fig. 6g). As the main core fades away, the branch increases in reflectivity and altitude, becoming dominant. Every 30 second animation (Supplement 2) includes the state after Fig. 6. This is similar to the alternating precipitation cores described in a previous study (Kim et al. 2012).

4. Discussion

4.1 Horizontal movement of the 25dBZ centroid

The horizontal movement of the convective cells shown in Fig. 2 indicate that CASEs 1–3 had short footprints. In contrast, the CASE 4 convective cell moved a long distance to the south. The motion of convective cells with echo top heights lower than 12 km is affected by the horizontal wind lower than 5 to 7 km (Weisman and Klemp 1986). The echo top height for all four cases are not very different from 12 km. Therefore, the Japan Meteorological Agency Meso Scale Model (JMA-MSM) for horizontal wind from 5 to 7 km altitude can be used to interpret the motion of CASEs in this study. The nearest data point for CASEs 2 and 3 at 15:00 JST around 5.5 km altitude indicates south-westward wind with a speed of about 2 m s^{-1} . Similarly, the nearest data point for CASE 4 at 18:00 JST indicates south-westward wind with a speed of about 3 m s^{-1} . There was no significant difference in the background horizontal wind from about 5.5 km altitude. The convective cell in CASE 4 moved to the south at an average speed of 5 m s^{-1} , higher than the environmental wind speed. This indicates that a special reason might be affecting the motion of the CASE 4 system. Doppler data may be useful to understand the relationship with the wind. However, during the early stage in operation of the PAWR, Doppler velocity data was not recorded in this case unfortunately.

4.2 Vertical movement of the 25 dBZ centroids

a. Behavior of first echo (Developing stage)

In the traditional conceptual model of convective cloud, the precipitation core is generated at the higher part of convection (about 5 km) in the develop stage. After that, the precipitation core goes down and it rains strongly at the ground in the mature stage (See Fig. 10 of Kim et al. 2012). The PAWR observed more complicated movement of the C25 which is not represented the precipitation core but movement of whole precipitation echo can be revealed. The C25 of first echo falls in first several minutes. After the weak rain starts on the ground level, the C25 grows upward. The C25 also goes up to about 5 km. After that the strong rainfall maintains for several ten minutes. The C25 is useful to see the movement of a whole of convective cells, but for details it is necessary to examine the precipitation core itself.

b. Alternation of precipitation core (Dissipating stage)

In the dissipation stage of an isolated heavy rainfall event, the altitude of the C25 gradually descends as shown in Fig. 3. However, in CASE 1 and CASE 4, the descending the C25 stopped after 30 or 40 minutes. As mentioned in Section 3.3.b, the subsequent stopping descending seems to be due to the creation and growth of a new precipitation core, leading to the alternation of precipitation cores in the cell.

Kim et al. (2012) presented a mechanism to explain precipitation core alternation for a convective cell with multiple precipitation core by analysis of Doppler velocity of radars. The mechanism presented by Kim et al. (2012) was the following: horizontal wind at ground level toward the established core and humidity created by evaporating rainfall generate an updraft and new precipitation core. This mechanism may work for the precipitation cells observed in this study, however it is not possible to discuss the mechanism really worked for our cases because Doppler velocity data were not obtained in this study.

Initially, the new core seems to branch off the existing precipitation core as shown in Fig. 6. The development of a new pre-

precipitation core is very rapid, taking only about 3 minutes for the alternation, meaning that it would be difficult to see the detailed time evolution of the replacement by conventional radar observations.

5. Summary

Observations of high spatial and temporal resolution made by the PAWR reveal several new aspects of localized rainfall from isolated convective cells on 26 July 2012. On this day, four localized heavy rainfall events were observed. By tracing the rectangular region surrounding radar reflectivity over 25 dBZ, it was found that rainfall near the ground (1 km altitude) began 3 to 5 minutes after the appearance of the first echo, and heavy rainfall was observed 9 to 15 minutes after the first echo. The convective cells lasted from 40 to 70 minutes. The motion of the convective cells were found by tracking the centroid over 25 dBZ (C25) of each radar scan (every 30 seconds). The difference in the horizontal motion could not be accounted for by the environmental wind. In the developing stage of the convective cells for all four cases, the altitude of the centroid of the precipitation echo first descended and then ascended within the first several minutes. The behavior of the C25 corresponds the behavior of precipitation core such that grow upward after descending of the precipitation core. The behavior of first echoes looked complicatedly and it is difficult to explain by the traditional conceptual model, which shows the first echo appears at a middle level, and it expands both upward and downward. During the dissipation stage of convective cells, the 25 dBZ centroid gradually descends, but is seen to stop. From the investigation of the vertical cross section of the precipitation core for one of these subsequent stops, the new precipitation core was observed to become dominant in just a few minutes. An alternation of precipitation made longer the lifespan of convective cell.

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Supplements

Supplement 1. The movie of an event CASE 4 observed by Osaka PAWR. The echo intensities are expressed 5 isosurfaces from 25 dBZ to 50 dBZ. The vertical scale is relatively multiplied 4 times to horizontal scale.

Supplement 2. The movie of cross sections of the precipitation core for CASE 4 of later of convective cell. The contour lines are drawn over 45 dBZ and every 5 dBZ.

Supplement 3. The same with Supplement 1 but for CASE 2.

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