X-Band Dual-Polarization Radar Observations of Precipitation Core Development and Structure in a Multi-Cellular Storm over Zoshigaya, Japan, on August 5, 2008

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Abstract

A multi-cellular storm over the Zoshigaya area of Tokyo, Japan (5 August 2008) was observed by two X-band dual-polarization radars, and this paper aims to investigate the structure of the precipitation cores within its individual precipitation cells. The precipitation cell and core are defined here on the basis of liquid water content (LWC).

The storm comprised 20 precipitation cells, each with a precipitation core. Of these, 17 cells were characterized by a single precipitation core (single-core cells) and lasted for less than 30 minutes (5–25 minutes). In contrast, the other three cells consisted of several auxiliary precipitation cores (multi-core cells) that were produced in succession and descended to the ground each lasting approximately 15 minutes, the cells themselves were relatively long-lived (≥40 minutes). Single-core cells developed via updrafts driven by low-level convergence that persisted for approximately 10 minutes before being converted to a downdraft by precipitation loading. Without the supporting updraft, the precipitation core fell to the ground 5–25 minutes after its first appearance. In contrast, replacement of precipitation cores in multi-core cells during their mature stage was driven by periodic strong updrafts associated with a low-level southeasterly inflow that supplied warm, moist air to the precipitation cell.

The results of a statistical analysis of precipitation cell and core are presented. The rainfall amount from each precipitation cell was proportional to the cell’s lifetime, with a slope of 0.89 for the relationship and a correlation coefficient of 0.95. The average updraft and downdraft velocities of multi-core cells (7.9 and 4.7 m s\(^{-1}\), respectively) were stronger than in the single-core cells (5.2 and 3.7 m s\(^{-1}\), respectively). The average liquid water content of precipitation cores in single-core cells was 4.0 g m\(^{-3}\), whereas the multi-core cells averaged 5.3 g m\(^{-3}\). The average formation heights of single- and multi-core cells were 4.7 km and 4.6 km, respectively. The intensity and formation height of the precipitation cores are approximately proportional to each other.

Kanto Plain of Japan, generating heavy rainfall that may cause urban flooding and landslides, especially when the storm cells are mature and slow moving. A multi-cellular storm is defined as a storm comprising several precipitating convective cells which may persist for several hours due to the periodic appearance of new cells. The individual embedded cells are generated from a quasi-steady updraft cell located over the leading edge of the density current (Lin et al. 1998)

1. Introduction

Multi-cellular storms often develop over the southern
and are normally short-lived, lasting about 15–30 min (Browning et al. 1976; Hobbs and Locatelli 1978; Warner et al. 1980; Takeda and Seko 1986). Although most cells are short-lived, some may persist for several hours or more. To determine the influence of vertical wind shear on the motion, structure, evolution, and longevity of convective storms, numerous workers have considered the relationship between storm type (multi-celled and supercell storms), vertical buoyancy and wind shear through empirical studies (Marwitz 1972a, b, c; Peterson 1984; Westcott 1994; Rasmussen and Blanchard 1998; Evans and Doswell 2001; Markowski et al. 2003; Shusse et al. 2005), theoretical studies (Moncrieff and Green 1972; Davies-Jones 1984; Lilly 1986a, b; Rotunno et al. 1988), and numerical simulations (Klemp and Wilhelmson 1978a, b; Weisman and Klemp 1982; Weisman and Klemp 1984; Misumi et al. 1994; McCaul and Weisman 2001). A comprehensive review of this work is outside the scope of this paper.

To describe the behavior and structure of precipitating convective cells that develop in multi-celled and supercell storms, the terms “precipitation area (or cell)” and “precipitation core” (a greater precipitation area) are often loosely interchanged with “radar reflectivity area (radar echo or cell)” and “reflectivity core” respectively, and there appears to be no clear definition of these terms. Previous studies have equated the reflectivity core to the precipitation core (Kropeli and Miller 1976; Wakimoto and Bringi 1988; Stalker and Knupp 2002; Wiens et al. 2005). Hobbs and Locatelli (1978) use radar reflectivity measurements, supported by airborne and ground observations, to define precipitation cores as small mesoscale regions of precipitation within a rainband (a large mesoscale region of precipitation within the storm). Kingsmill and Wakimoto (1991) identified individual convective cells from distinct areas of maximum radar reflectivity, and the precipitation core within each cell was defined as the region of 60 dBZ (or greater) reflectivity within the dominant cell. Wakimoto and Lew (1993) defined the precipitation core as the region of 50 dBZ reflectivity, and they showed a descending precipitation core in a waterspout. However, it may not be appropriate to define a precipitation core based solely on radar reflectivity because reflectivity does not always equate directly to precipitation intensity. At the Rayleigh limit, the radar backscatter cross-section of a raindrop is proportional to the sixth power of the drop diameter; consequently, a large number of small drops can produce the same radar reflectivity as a small number of large drops. Tuttle et al. (1989) showed that rainfall rates estimated from radar reflectivity could be as much as 200% larger than those estimated from one-way specific attenuation and differential reflectivity if the precipitation contained a low concentration of large raindrops, resulting in low rainfall rates but moderate radar reflectivity. This result demonstrates some of the inherent difficulties associated with attempting to identify precipitation cores based solely on radar reflectivity.

We present here a case study of a multi-cellular storm observed over the Zoshigaya area of Tokyo, Japan on August 5, 2008. This storm produced localized, severe rainfall, and resulted in five sewer workers being swept away by a flash flood (Kato and Maki 2009; Hirano and Maki 2010). A unique aspect of this study is that the precipitation cells and cores are defined by LWC (liquid water contents) which was estimated from dual-polarization measurements made using X-band wavelength radar. The aim of this study is to investigate the precipitation core structure of the individual precipitation cells within this storm by analyzing these radar measurements.

The remainder of the manuscript is organized as follows. The analytical data are described in Section 2, and the atmospheric conditions are briefly explained in Section 3. Section 4 outlines the characteristic of the precipitation cells, the three-dimensional wind structure (as obtained from dual-Doppler analysis), and the precipitation core structure, followed by a statistical summary of the precipitation cores. Finally, a summary and discussion of the results are presented in Section 5.

2. Data acquisition and processing

Two X-band dual-polarization radars (at Ebina and Kisarazu), operated by the Japanese National Research Institute for Earth Science and Disaster Prevention (NIED), were used to observe a storm over Tokyo, Japan (Fig. 1). Upper air information was obtained from the Tateno Aerological Observatory of the Japanese Meteorological Agency (JMA). These radars simultaneously transmit and receive horizontally and vertically polarized signals at frequencies of 9.375 GHz (Ebina) and 9.709 GHz (Kisarazu).

The polarimetric variables measured by these radars were the radar reflectivity factor at horizontal polarization ($Z_H$), differential reflectivity ($Z_{DR}$), copolar correlation coefficient ($\rho_{HH}$), differential phase shift ($\Phi_{DP}$), Doppler velocity ($V_D$), and spectral width ($W_S$). The polarimetric variables $Z_H$, $Z_{DR}$, and the specific differential phase shift ($K_{DP}$) obtained from Ebina were used primarily to analyze the structure of the storm. Velocity data obtained from both radars were used to analyze the kinematic structure of the storm. Polarimetric variables and Doppler velocity data were recorded at 5 minute
intervals using consecutive volume scans comprising 12 elevation angles (0.7°, 1.2°, 1.7°, 2.2°, 2.7°, 3.3°, 3.9°, 4.7°, 5.7°, 6.9°, 8.4°, and 10.4°) with a range resolution of 100 m and an azimuthal resolution of 1°. Filtering algorithms were used to process the measured polarimetric variables to eliminate high-frequency random fluctuations from gate to gate. The variables $Z_H$ and $Z_{DR}$ were processed using the infinite-impulse response (IIR) filter of Hubbert et al. (1993). The range profiles of the total differential phase ($\phi_{DP}$) were iteratively filtered in the range using the finite-impulse response (FIR) filter proposed by Hubbert and Bringi (1995), which separates the scattering differential phase ($\delta$) from the $\phi_{DP}$ profiles and then extracts the filtered differential propagation phase, $\Phi_{DP}$. After the filtered $\Phi_{DP}$ range profiles had been extracted, $K_{DP}$ was computed using the procedures described by Maesaka et al. (2011). The $Z_H$ and $Z_{DR}$ biases of Ebina were estimated to be $-5.6$ dBZ and $+1.44$ dB respectively, according to the method of Gorgucci et al. (1999). The observed $Z_H$ and $Z_{DR}$ were also corrected for rain attenuation using the attenuation correction algorithm (SSCM: Shifted Self-Consistent Method) proposed by Kim et al. (2008, 2010), which considers variability in the optimum coefficient $\alpha (A_H = aK_{DP})$ along the radar slant-range. Using the vertical incidence observations (Liu et al. 1993), the accuracy of $K_{DP}$ was estimated to be $0.3° \text{ km}^{-1}$. The accuracy of $K_{DP}$ (i.e., $0.3° \text{ km}^{-1}$) is the statistical error derived from analysis of the experimental data. The majority of the $K_{DP}$ data (>90%) has a standard deviation $< 0.3° \text{ km}^{-1}$, which is appropriate for the estimation error of $K_{DP}$ associated with the data used here, in particular for the estimation of LWC (or rain rate) and classification of the noise element of the attenuation correction.

The precipitation cells were identified on the basis of their LWC estimated from $K_{DP}$, mainly in convective echo, as well as $Z_H$. LWC is a measure of the water mass in a cloud and is roughly proportional to the precipitation rate. Using observed drop size distribution (DSD), Maki et al. (2005) examined the dependency of $K_{DP}$, $Z_H$, rain rate ($R$), and LWC on DSD. They showed that the maximum contribution of raindrops to $R$ and LWC was closer to $K_{DP}$ than $Z_H$. Consequently, LWC and $R$ estimated from $K_{DP}$ are less sensitive to variations in DSD than to that in $Z_H$. Another important reason for using $K_{DP}$ values is that they are much larger for X-band radar than for longer wavelengths. Scattering simulations indicate that $K_{DP}$ at X-band is 1.5–3.0 times larger than at C- and S-bands for the same rain rate (Zmić and Ryzhkov 1996; Maki et al. 2005; Bringi and Chandrasekar 2001); this may be useful when studying weak rainfall events. $K_{DP}$ is also relatively immune to beam-blockage, independent of radar power calibrations, and unaffected by attenuation due to heavy rain (Bringi et al. 1990; Smyth and Illingworth 1998; Carey et al. 2000). A composite method was used to derive LWC from scattering simulations performed at a temperature of 15°C using the Andsager drop shape (Maki et al. 2005) as follows:

$$LWC(Z_H; K_{DP}) =
\begin{cases}
0.00393Z_H^{0.55} & \text{for } K_{DP} \leq 0.3 \text{ deg km}^{-1} \text{ or } Z_H \leq 35 \text{ dBZ} \\
0.991K_{DP}^{0.713} & \text{for } K_{DP} > 0.3 \text{ deg km}^{-1}
\end{cases}
$$

When $K_{DP} > 0.3° \text{ km}^{-1}$, which is the estimated standard error of $K_{DP}$, the LWC–$K_{DP}$ relationship can be used to calculate LWC. However, for $K_{DP} \leq 0.3° \text{ km}^{-1}$ or $Z_H \leq 35$ dB, the LWC–$Z_H$ relationship is used because $K_{DP}$ is noisy.

For the same reason, the following composite radar-rainfall estimators (Maki et al. 2005) were used:
\[ R(Z_{HI}; K_{DP}) = \begin{cases} 0.0229 Z_{HI}^{0.673} & \text{for } K_{DP} \leq 0.3 \text{ deg km}^{-1} \text{ or } Z_{HI} \leq 35 \text{ dBZ} \\ 19.63 K_{DP}^{0.823} & \text{for } K_{DP} > 0.3 \text{ deg km}^{-1} \end{cases} \] (2)

The Doppler radar data were interpolated into a Cartesian coordinate system with a horizontal grid interval of 0.5 km, and a vertical grid interval of 0.25 km (CAPPI dataset). To account for advection during each volume scan, the location of the binned data was shifted according to the storm’s movement (Gal-Chen 1982). A Cressman-type weighting function was used for interpolation and the effective radius of influence in the weighting function was fixed at 1 km. We conducted a dual-Doppler analysis using the variation method proposed by Gao et al. (1999). The terminal fall velocities of rain, snow, and graupel were adapted from Shimizu et al. (2008) as shown below:

\[
W = \begin{cases} -0.75 \left( \frac{\rho}{\rho_0} \right)^{0.4} Z_e^{0.0714} & \text{for snow} \\ -3.80 \left( \frac{\rho}{\rho_0} \right)^{0.4} Z_e^{0.0714} & \text{for rain} \\ -1.23 \left( \frac{\rho}{\rho_0} \right)^{0.4} Z_e^{0.103} & \text{for graupel} \end{cases} \] (3)

Here, \( Z_e \) (mm\(^6\) m\(^{-3}\)) indicates the equivalent reflectivity factor, while \( \rho \) and \( \rho_0 \) indicate the air density and surface air density, respectively.

Three components of wind were calculated in the Cartesian coordinate system within the dashed circles in Fig. 1 (the intersection angle is less than 30°). Boundary conditions of \( w = 0 \text{ m s}^{-1} \) at \( z = 0.5 \text{ km} \) and the storm top were employed. The mean error of wind velocity was evaluated using the root-mean-squared error (RMSE) between the analyzed and observed radial velocity, as defined by Shimizu et al. (2008). In this study, RMSE was roughly 1.0 m s\(^{-1}\), and less than 0.5 m s\(^{-1}\) below 5 km above sea level (ASL).

3. Brief description of the atmospheric condition

The surface weather map for 0900 LST (LST = UTC + 9 hours) August 5, 2008 is shown in Fig. 2a. Relative humidity (RH) at 900 hPa and the surface wind vectors (Fig. 2b) were obtained from the Japanese Meteorological Agency’s (JMA) Regional Objective Analysis (RANAL) dataset and are shown in Fig. 2b. A stationary front was located over the southern part of the Tohoku region in northeastern Japan (Fig. 2a); the edge of this front was lying over the northern part of Tokyo (our observation area). Relative humidity in Tokyo was >90% and over the ocean to the south was >80%, while the ocean surface temperature was >28°C. Consequently, warm and humid air flowed towards the front from the ocean south of Tokyo, and a cold northeasterly flow prevailed over the northern part of Tokyo. As the stationary front moved north, by 0600 LST the predominant wind direction over north Tokyo had changed to an easterly.

Figure 3 shows the upper-air sounding taken at Tateno 3 hours before the development of the storm. The 0°C isotherm was located at 550 hPa (about 5.2 km ASL). Below 850 hPa, there was a very moist layer (RH 90%–97%) and a deep moist layer with RH > 80% extended from the surface to 450 hPa. The precipitable water (PW) from the surface to 300 hPa was 65.38 km\(^2\). The lifting condensation level (LCL)
and the level of free convection (LFC) were 0.95 and 1.36 km respectively, and the convective available potential energy (CAPE) was 516.67 J kg\(^{-1}\). This low value of CAPE at 0900 LST was not sufficient to support the formation of a multi-cell storm, but by 1200 LST, when a multi-cell storm developed over the Zoshigaya district of Tokyo, CAPE (calculated from RANAL vertical data) had increased to 1135 J kg\(^{-1}\) due to surface heating (not shown). This increased value of CAPE (1135 J kg\(^{-1}\)) is still smaller than that of a typical multi-cell (or supercell) environment over the Great Plains (e.g., 2022 J kg\(^{-1}\) for a multi-cell, Skalka and Knupp 2002; 2542 J kg\(^{-1}\) for an Oklahoma super-cell, Bluestein and Jain 1985). However, according to Shimizu et al. (2008), who investigated the frequency distribution of CAPE at Tateno in May between 1990 and 1999, a value of 1000 J kg\(^{-1}\) was the 10th highest value in those 10 years. Very weak vertical wind shear (7.9 \(\times\) 10\(^{-4}\) s\(^{-1}\)) existed from the surface to 6 km ASL. Consequently, the bulk Richardson number (BRN) was 253 (>200 at 1200 LST) because of the weak vertical wind shear. In general, values of BRN > 45 favor multicellular type storms (Weisman and Klemp 1982, 1984; Peterson 1984; Bluestein and Jain 1985). These high values of CAPE and BRN suggest that the atmosphere was capable of supporting the formation of multi-cell storms.

4. Results

4.1 Characteristic of analyzed precipitation cells

a. Definition of precipitation cell and core

In this study, a precipitation cell is defined as the region enclosing a single peak in LWC > 1 g m\(^{-3}\) in a 3D distribution at all heights up to the echo top. A precipitation core is defined by the region where LWC exceeds 80% of the maximum LWC within each precipitation cell because the maximum LWC in the developing and dissipating stages of each precipitation cell averaged 80% of maximum lifetime LWC in the present study. However, if two descending precipitation cores in the upper levels merge within 5 minute, the result is regarded as a single precipitation cell.

Figure 4 shows an example of the 3D precipitation cell distribution. Between 1155 and 1200 LST, six precipitation cells were classified. The strong precipitation core of cell \(PC_1\) (LWC > 5.25 g m\(^{-3}\)) is clearly distinguishable, and the precipitation core with LWC > 3 g m\(^{-3}\) in cell \(PC_{10}\) descended from a height of around 5 to 2 km within 5 minutes (1155–1200 LST). In the horizontal distribution of LWC at a height of 1 km, each classified precipitation cell corresponds with those in the 3D LWC distribution at 1200 LST.

b. Lifetime, rain amount, and dimensions of precipitation cells

During the period between 1100 and 1305 LST, multi-cellular storms over the study area were monitored and 20 precipitation cells (\(PC_1\)–\(PC_{20}\)) were identified. The trajectories of each precipitation cell (Fig. 5) were derived from the maximum LWC at any height. Cells \(PC_1\) and \(PC_2\) moved northeastward at speeds of 1.1 and 2.2 m s\(^{-1}\) respectively; they covered approximately 5 and 7 km in diameter during their lifetimes, but even though these cells moved a distance of 5–8 km, they were in effect stationary. The other cells trav-
eled in various directions and also remained almost stationary.

The lifetimes of each precipitation cell are shown in Table 1. These lifetimes refer only to the period when LWC was detected by the radar; they are not the entire lifetime of the precipitation cell including the cumulus stage. Seventeen of the cells ($PC_4$–$PC_{20}$) had a lifetime of 5–25 minutes, with an average of 16 minutes. These lifetimes are similar to those typically observed; e.g., 23 minutes (Battan 1953), 21 minutes (Foote and Knight 1979), 30 minutes (Warner et al. 1980), and less than 30 minutes (Henry 1993). In contrast, cell $PC_1$ was accompanied by heavy rainfall over the Zoshigaya area, and its lifetime of 100 minutes is approximately 6 times longer than the average of cells $PC_4$–$PC_{20}$. Cells $PC_2$ and $PC_3$ had lifetimes of 40 and 45 minutes, respectively.

The dimensions and rainfall amounts associated with each precipitation cell calculated in a Lagrangian frame are also shown in Table 1. The dimensions of
the precipitation cells were defined as the largest area where LWC > 1.0 g m$^{-3}$ during its lifetime while rainfall amounts were the maximum accumulated rainfall from each precipitation cell during its lifetime. Average rainfall amounts and the cell dimensions of PC$_{4}$–PC$_{20}$ (lifetime ≤ 30 minutes) were 12.5 mm and 13.2 km$^2$, respectively. In contrast, 100.6 mm of rain fell from cell PC$_{1}$ and covered an area of 48.8 km$^2$; these values are 8 and 3.7 times larger respectively, than those recorded from cells PC$_{4}$–PC$_{20}$. Cells PC$_{2}$ and PC$_{3}$ also generated relatively large amounts of rainfall, but had similar dimensions to cells PC$_{4}$–PC$_{20}$.

For all precipitation cells, rainfall amounts were proportional to the cell’s lifetime with a slope of 0.89 (Fig. 6a) and a correlation coefficient of 0.95. The lifespan of the majority (85%) of the precipitation cells was short; i.e., <30 minutes (Fig. 6b).

c. Time evolution of precipitation cells

Figure 7 follows the overall evolution of the precipitation cells by plotting the LWC distributions at a height of 1 km between 1130 and 1245 LST. The names and dotted rectangles in Fig. 7 refer only to a height of 1 km, not all heights; therefore the lifetimes of each precipitation cell in Fig. 7 differ from those in Table 1. The first precipitation cell (PC$_{4}$), with LWC > 1.5 g m$^{-3}$, formed (but is not shown) at about 1105 LST, and this cell developed as it moved very slowly to the northeast. Cell PC$_{1}$ formed in the upper levels (5 km) at 1125 LST (not shown), and appears at a height of 1 km at 1130 LST. At the same time (1130 LST), two new precipitation cells (PC$_{5}$ and PC$_{6}$) begin to form at its northern and southern margins. Over a period of 20 minutes, these two cells dissipated and partly merged with the main precipitation cell, PC$_{1}$. During the developmental stage of PC$_{1}$ (1125–1145 LST), its precipitation core became stronger, wider, and moved northeastward. From 1150 LST, the core of PC$_{1}$ reached 6 g m$^{-3}$ LWC and the cell, which was over 8 km in diameter, remained almost stationary until 1240 LST. Cells PC$_{2}$ at 1145 LST and PC$_{8}$ at 1155 LST appeared to the west of PC$_{2}$ and dissipated within 40 and 20 minutes, respectively. Following the dissipation of PC$_{8}$, further new precipitation cells PC$_{15}$, PC$_{17}$, and PC$_{20}$ formed at almost the same position as PC$_{8}$ after 1220 LST. Farther to the southwest, cells PC$_{7}$, PC$_{10}$, and PC$_{11}$, each having a lifespan of around 20 minutes, formed sequentially.

4.2 Three-dimensional structure of precipitation cells PC$_{7}$, PC$_{8}$, PC$_{10}$, and PC$_{11}$

a. Temporal change of precipitation cores

To investigate the temporal development of the precipitation cells, time series of the vertical profiles of the maximum LWC, updraft, and downdraft velocities were calculated for each cell, and the results from four of the short-lived (≤30 minutes) cells PC$_{7}$, PC$_{8}$, PC$_{10}$, and PC$_{11}$ are shown in Fig. 8. Locations and ranges for each time period were selected to ensure that the strongest echoes at each height were included in the analysis. Maximum LWC values of 3.0–4.5 g m$^{-3}$ typically occurred below a height of 4 km, and the precipitation cores gradually descended and reached the ground within 15–20 minutes. The rate of descent of these cores was 3.5–7.5 m s$^{-1}$. Updrafts >3.0 m s$^{-1}$ were observed above 3 km during the developmental stage, but as the cores strengthened, stronger updrafts (>5.0 m s$^{-1}$) developed below 3 km. The strong updrafts associated with the appearance of precipitation cores at upper levels showed a weakening during the dissipation stage. Downdrafts, which first appeared during the developmental stage, also weakened but remained active during the dissipation stage. Similar patterns of temporal evolution were observed in the other cells among PC$_{4}$–PC$_{20}$ (data not shown) showing that all of these cells had only one precipitation core which was generated by a strong low-level updraft, the cells were later dissipated by a downdraft.

The internal wind and LWC structure of cell PC$_{10}$ between 1150 and 1205 LST, when the precipitation core descended, is shown in detail in Fig. 9. The storm-relative inflow at a height of 1 km blew into cell PC$_{10}$ from the south during this 15 minute (1150–1205
Table 1. List of analyzed cells that developed in the study area (see the solid box in Fig. 1) between 1100 and 1305 LST. The table also shows rainfall amounts, and cell dimensions calculated from the area where LWC > 1.0 g m⁻³ at a height of 1 km.

<table>
<thead>
<tr>
<th>Name of cell</th>
<th>Lifetime of precipitation cell</th>
<th>Rain Amount (mm)</th>
<th>Dimension (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC₁</td>
<td>100 min (1125–1305 LST)</td>
<td>100.62</td>
<td>48.75</td>
</tr>
<tr>
<td>PC₂</td>
<td>40 min (1145–1225 LST)</td>
<td>26.96</td>
<td>8.25</td>
</tr>
<tr>
<td>PC₃</td>
<td>45 min (1210–1255 LST)</td>
<td>37.19</td>
<td>24.75</td>
</tr>
<tr>
<td>PC₄</td>
<td>25 min (1100–1125 LST)</td>
<td>17.01</td>
<td>9.50</td>
</tr>
<tr>
<td>PC₅</td>
<td>25 min (1125–1150 LST)</td>
<td>18.53</td>
<td>12.25</td>
</tr>
<tr>
<td>PC₆</td>
<td>15 min (1130–1145 LST)</td>
<td>13.02</td>
<td>12.34</td>
</tr>
<tr>
<td>PC₇</td>
<td>20 min (1140–1200 LST)</td>
<td>11.54</td>
<td>9.50</td>
</tr>
<tr>
<td>PC₈</td>
<td>20 min (1155–1215 LST)</td>
<td>11.37</td>
<td>14.00</td>
</tr>
<tr>
<td>PC₉</td>
<td>10 min (1155–1205 LST)</td>
<td>11.64</td>
<td>9.50</td>
</tr>
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<td>PC₁₀</td>
<td>20 min (1150–1210 LST)</td>
<td>15.17</td>
<td>18.25</td>
</tr>
<tr>
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<td>15 min (1205–1220 LST)</td>
<td>9.97</td>
<td>13.75</td>
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<td>PC₁₂</td>
<td>15 min (1205–1220 LST)</td>
<td>12.77</td>
<td>8.00</td>
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<td>PC₁₃</td>
<td>10 min (1205–1215 LST)</td>
<td>9.88</td>
<td>6.25</td>
</tr>
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<td>20 min (1215–1235 LST)</td>
<td>16.93</td>
<td>10.25</td>
</tr>
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<td>PC₁₅</td>
<td>5 min (1220–1225 LST)</td>
<td>3.53</td>
<td>11.50</td>
</tr>
<tr>
<td>PC₁₆</td>
<td>5 min (1220–1225 LST)</td>
<td>3.52</td>
<td>9.00</td>
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<tr>
<td>PC₁₇</td>
<td>15 min (1225–1240 LST)</td>
<td>16.28</td>
<td>16.25</td>
</tr>
<tr>
<td>PC₁₈</td>
<td>10 min (1225–1235 LST)</td>
<td>5.87</td>
<td>7.25</td>
</tr>
<tr>
<td>PC₁₉</td>
<td>20 min (1235–1255 LST)</td>
<td>17.26</td>
<td>26.25</td>
</tr>
<tr>
<td>PC₂₀</td>
<td>25 min (1240–1305 LST)</td>
<td>18.94</td>
<td>30.25</td>
</tr>
</tbody>
</table>

Fig. 6. (a) The relationship between precipitation cell lifetime and rainfall amounts. (b) Distribution of precipitation cell lifetimes.
LST) period. While cell $PC_{10}$ was not observed at 1 km, cell $PC_{10}$ with a high LWC (>3.0 g m$^{-3}$), formed at a height of 6 km (red dotted rectangle). In the upper levels, a strong updraft (>4.0 m s$^{-1}$) was observed at 1150 LST, and the southerly wind recorded at 1150 LST in the southern section of the cell became a northwesterly from 1155 LST. At 1155 LST, a downdraft was observed at the center of cell $PC_{10}$ at a height of 4 km, and the precipitation core had more than 4.0 g m$^{-3}$ of LWC, corresponding to a rainfall intensity of approximately 100 mm h$^{-1}$. The precipitation cell remained almost stationary throughout its lifetime and was less than 5 km in diameter. In vertical cross-section, two distinct precipitation cores appear at heights

Fig. 7. Horizontal distributions of LWC at 1 km ASL from 1130 to 1245 LST on August 5, 2008. The boxes indicate the analysis areas of the vertical profiles of each precipitation cell.
Fig. 8. Temporal change in vertical profiles of maximum LWC (top panel), maximum updraft (middle panel), and maximum downdraft (lower panel) for cells PC_7, PC_8, PC_10, and PC_11.
of 6 and 8 km (Fig. 9c) at 1150 LST. The upper core (above 8 km) was too high to be detected by the radar scanner. Within 5 minutes, the 2 cores had merged and started to descend before finally reaching the ground 10 minutes later at 1205 LST. During the short developmental stage (1150–1155 LST), updraft was observed throughout the cell with a maximum updraft velocity of 6.5 m s\(^{-1}\). From 1200 LST, a downdraft developed within the precipitation core (not shown), and at 1205 LST precipitation cell \(PC_{10}\) began to dissipate as the weak downdraft became dominant within the whole layer.

**b. Schematic picture of a single-core cell**

The life cycle and precipitation core of cells \(PC_4–PC_{20}\) with a lifetime of less than 30 minutes is shown schematically in Fig. 10. A significant feature of such short-lived cells is that they all contained only one precipitation core (hereafter, single-core cell), and this reached the ground within 25 minutes. These single-core cells follow the life cycle of a typical cell as suggested by Chisholm and Renick (1972). In the early stages of growth, updraft associated with low-level convergence (or thermal forcing) is strong enough to carry the growing cloud drops upwards. As they are carried upwards, these cloud drops begin to condense...
until they become heavy enough to overcome the updraft and begin to fall relative to the ground. The first precipitation core (>2.0 g m⁻³) observed by radar denoting the presence of numerous, sizable water drops appears and expands within 5–10 minutes in the updraft core. The updraft usually persists for about 10 minutes, and then a strengthening downdraft develops driven by the precipitation loading. Without the supporting updraft, the precipitation core falls to the ground 10–25 minutes after its first appearance. After dissipating the original updraft, a new single-core cell develops with a new updraft, considered to be a discrete, closed system.

4.3 Three-dimensional structure of precipitation cell \( PC_1 \)

a. Temporal change of precipitation core

The temporal change in the vertical profiles of maximum LWC, updraft, and downdraft for cell \( PC_1 \) are shown in Fig. 11. At least five precipitation cores can be identified between 1125 and 1305 LST (Fig. 11a). These cores recur every 15 minutes, and most were associated with the strong updraft in the low-level atmosphere. At 1125 LST, the first precipitation core appears at around 4.5 km, and grows slowly for the next 15 minutes before developing rapidly due to a strong updraft at 1145 LST. During the mature stage (1145–1245 LST), 4 precipitation cores (C2–5) formed. Of these, 3 (C2–4) had a high LWC (>5.0 g m⁻³), almost 1.5 times that of a single-core cell. LWC was slightly lower (<5.0 g m⁻³) in the last core (C5), although this is still relatively high compared with single-core cells. These precipitation cores may have descended repeatedly, but it was difficult to distinguish each one clearly, especially between 1155 and 1210 LST as the temporal resolution of the radar observations was too low. During this period (1155–1210 LST) one precipitation core descended toward the ground while a second was simultaneously forming in the upper levels. Generation of precipitation cores C1–C5 in the upper levels during the developing and mature stages coincided with an increasing updraft at lower levels. During these stages (1125–1140 LST), oscillations in the intensity of the downdraft, as well as the updraft, were also observed at lower levels caused by substituting precipitation cores. In cell \( PC_1 \), the downdraft was strengthened by the precipitation loading of an old precipitation core, and at the same time, a new precipitation core associated with the strong updraft in the low-level atmosphere formed in the upper levels. Therefore, a strong updraft and downdraft were observed at the same time. The detailed structure of the wind regime is shown in Fig. 12. Cell \( PC_1 \) then dissipated slowly, over about 20
minutes, as the updraft weakened and the downdraft strengthened.

The substitution process from precipitation core C2 to C3 in cell PC₁ is shown in Fig. 12. At a height of 1 km, the wind blew into cell PC₁ from the north, south, and east. A lower-level southeasterly wind continued to blow into the cell throughout its mature stage, as well as 1145–1155 LST, and the updraft strengthened periodically on the south and east sides of the cell. At 4 km, the dominant wind direction did not differ greatly on the north (northerly wind) or the east sides of the cell (easterly wind), whereas a north-northwest wind was predominant on its south side. A new precipitation core (C3) was generated by an increasing updraft at 1150 LST at heights of 1 and 4 km (Figs. 12d, e) on the upwind side of a southeast wind, and this core strengthened with LWC > 5.5 g m⁻³ and descended to 1 km height within 5 minutes (Fig. 12g). A low-level southeasterly wind is considered to have been the main supplier of warm, moist air from the ocean to precipitation cell PC₁.

The structures of the updraft, downdraft, and precipitation core are clearly shown in the vertical cross-sections along line A in Fig. 12c, 12f, and 12i. A precipitation core was located at a height of 3.5 km at 1145 LST, and part of this core reached the ground 5 minutes later (1150 LST). A new precipitation core, C3 (4–7 km distant), developed close to the southeastern side of the previous core (C2) with a strong updraft (6.0 m s⁻¹) from the southeast (Fig. 12f) although this new core was not identified as a separate entity. At 1155 LST, downdraft predominated in core C2, while core C3 grew up to 6 km in height with a strong updraft. The maximum LWC in core C3 was more than 6.0 g m⁻³ at around 2 km. This process continued for cores C4 and C5, and precipitation cell PC₁ was maintained for 100 minutes.

**b. Schematic picture of a multi-core cell**

The life cycle and precipitation core of cell PC₁ is schematically depicted in Fig. 13. The development and dissipation processes of cell PC₁ are similar to those of the single-core cells despite its longer lifespan. Cell PC₁ was characterized by several repeating precipitation cores (hereafter, multi-core cell), comparative longevity, and a high LWC. During the mature stage, three precipitation cores regenerated successively in the vicinity of the previous core. On each occasion a strong updraft appeared with approximately the same velocity and in the same relative position (southeast) in the cell and the horizontal wind field showed only minor variations. In addition, the cell was almost stationary during its mature stage (60 minutes). A new precipitation core developed following a new updraft surge associated with the southeasterly wind in the lower region (below 3 km) of the cloud (Fig. 13a). This low-level southeasterly flow advected warm, moist air from the ocean, which was lifted to its LFC (<1.5 km). This southeasterly inflow is considered to have been the main supplier of warm, moist air to the precipitation cell as it penetrated into the updraft.

**4.4 Statistical summary of precipitation cores**

Table 2 summarizes, for each precipitation cell, the characteristics of the precipitation core (number, intensity, and height) and the maximum updraft and downdraft velocity at lower levels (below 3 km). The
The intensity of the precipitation core was derived from the maximum LWC in each precipitation cell during its lifetime. The numbers of precipitation cores in the long-lived (>40 minutes) cells $PC_1$, $PC_2$, and $PC_3$ were 5, 2, and 3, respectively; however, all of the short-lived (<30 minutes) cells had single-core cells.

The intensity of the precipitation cores in multi-core cells $PC_1$, $PC_2$, and $PC_3$ was 6.0, 3.8, and 6.1 g m$^{-3}$ respectively, whereas the average intensity of the single-core cells was 4.0 g m$^{-3}$. The average formation height of the precipitation cores in all cells was 4.7 km, and this height as almost the same in both the multi-core (4.6 km) and single-core cells (4.7 km). However, the intensity of the precipitation cores during the developmental stage was different: 4.2 g m$^{-3}$ in the multi-core cells but only 3.2 g m$^{-3}$ in the single-core cells (not shown). The maximum updraft and downdraft velocities at lower levels (below 3 km) for the multi-core cells averaged 7.9 and 4.7 m s$^{-1}$ respectively, whereas those for the single-core cell were 5.2 and 3.7 m s$^{-1}$, respectively. Although, the updraft and downdraft velocities of the multi-core cells were stronger than those in the single-core cells, the values in several single-core cells (e.g., $PC_6$, $PC_8$, and $PC_{10}$) are comparable to the multi-core cells. This may indicate that the position of the updraft (or downdraft), and its interaction with adjacent inflows, could be more important than its intensity in facilitating the development and maintenance of precipitation cells over long periods.

Scatter plots of precipitation core intensity against
formation height and occurrence frequency by core intensity are shown in Fig. 14. The intensity and formation height of the precipitation cores were roughly proportionally related (slope 0.6, Fig. 14a), 60% of precipitation cores had a core intensity of 4.0–5.0 g m\(^{-3}\) (the modal value was approximately 4.6 g m\(^{-3}\)), but more data are required to reach a statistically significant conclusion.

5. Summary and discussion

This paper presents the structure and developmental mechanisms of precipitation cores with differing life cycles and their statistical properties. The case analyzed was a localized convective storm that produced 120 mm of rainfall during 2 hours, causing flooding in the Zoshigaya area of Tokyo, Japan on August 5, 2008. After the precipitation cell and core had been defined by the distribution pattern of the LWC as estimated from X-band dual-polarization radar measurements, the structures of precipitation cores within the individual precipitation cells were investigated.

Three-dimensional analysis of the LWC showed that the storm was of a multi-cellular type and it was subdivided into 20 precipitation cells. Seventeen precipitation cells (\(PC_4\)–\(PC_{20}\)) were characterized by a single precipitation core, and these cells had lifespans of less than 30 minutes. In contrast, the precipitation cell \(PC_1\), which lasted for 100 minutes and produced the heavy rainfall over the Zoshigaya area, consisted of five precipitation cores that were produced successively and descended to the ground, each lasting approximately 15 minutes. The other multi-core cells (\(PC_2\) and \(PC_3\)) had at least two precipitation cores, as well as comparatively long lifetimes of 40 and 45 minutes.

The developmental mechanisms of precipitation cores in single- and multi-core precipitation cells were
Table 2. Intensity and formation height of the precipitation cores (PCO) in each precipitation cell. Also shown are the maximum updraft (UW) and downdraft (DW) velocities below a height of 3 km.

<table>
<thead>
<tr>
<th>Name of cell</th>
<th>Number of PCO (lifetime)</th>
<th>Intensity of PCO (g m(^{-3}))</th>
<th>Formation Height of PCO (km)</th>
<th>Max UW (m s(^{-1})) of Height ≤ 3.0 km</th>
<th>Max DW (m s(^{-1})) of Height ≤ 3.0 km</th>
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Fig. 14. (a) Relationship between precipitation core intensity and formation height. (b) Distribution of precipitation core intensity.
revealed by dual-Doppler radar analysis. The precipitation cores in the single-core cells appeared as each precipitation cell developed via updrafts associated with low-level convergence. The precipitation core fell to the ground within 5–25 minutes in the absence of a supporting updraft. In contrast, the replacement mechanism of precipitation cores in the multi-core cell $PC_1$ was driven by periodic updrafts associated with a low-level southeasterly inflow that supplied warm, moist air to the precipitation cell. However, the substitution mechanism of cells $PC_2$ and $PC_3$ is different from that of cell $PC_1$. Further studies are required in this regard.

The statistical properties of the precipitation cells and cores, as obtained in the present study, are summarized as follows. The longest-lived multi-core cell $PC_1$ covered an area of 48.7 km$^2$ and produced 101 mm of rainfall, while the single-core cells covered an average area of 13.2 km$^2$ and produced an average of 12.5 mm of rainfall. These rainfall amounts are proportional to the lifetimes of the precipitation cells with a slope of 0.89 for the relationship. The average updraft velocities at lower levels (below 3 km) for the single- and multi-core cells were 5.2 and 7.9 m s$^{-1}$, respectively, and the average downdraft velocities were 3.7 and 4.7 m s$^{-1}$, respectively. The intensity and formation height of the precipitation cores were similar for both precipitation cell types (average 4.7 km). These results of the present statistical analysis will improve nowcast and short-time forecast models of localized severe rainfall.

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of PCO (km)

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| Max UW (m s–1) | 113 | 125 |
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