Dual Doppler Radar Observation of a Tropical Rainband Developed from Two Convective Clouds

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Abstract

The structure and evolution of a small, isolated convective rainband, which developed over the warm pool between January 5 and 6, 1993, were examined in detail using sounding and dual-Doppler radar data from Manus Island, Papua New Guinea, during the TOGA-COARE IOP. The rainband developed from two small convective cells and decayed within the dual-Doppler radar coverage area.

The rainband was oriented parallel to the low-level environmental shear with a lower magnitude of $2.5 \times 10^{-3} \text{ s}^{-1}$ and the CAPE was as small as 342 J kg^{-1} . It moved from 320° to 140° at a speed of 5.5 m s^{-1} . During its mature stage, it was 30 km long and 15 km wide. Rain water within the rainband was mainly concentrated below the 3.0 km level and decreased rapidly with height. The maximum updraft was about $4\sim 5 \text{ m s}^{-1}$ and the maximum radar reflectivity was about 35–40 dBZ.

The number of convective cells changed with time as follows: two at the initial stage, five at the developing stage, and one at the mature stage. The low-level front inflow was lifted upward within the cells, formed the main updrafts over the reflectivity cores, and then moved toward the trailing region. There were no strong downdrafts below the heavy rainfall area, and there was no widespread stratiform region behind the convective region. Convective-scale rear inflows were observed in the early stage. These rear inflows aggregated with each other, increased in area and depth, and developed into a flow like a gravity current. The aggregated rear inflow with a gravity current “head” moved faster than the rainband, caused strong low-level convergence, and triggered explosive development of a convective cell in the mature stage, according to a detailed analysis of the dual Doppler radar data. The aggregation of convective-scale rear inflows appears to be important in the organization of a rainband.

1. Introduction

It has been recognized that the tropical western Pacific Ocean (warm pool) releases a great deal of energy into the atmosphere as heat and moisture, and that convective activities over this warm pool play an important role in climatic fluctuations and remote changes in atmospheric circulation (Nitta, 1987). Hamilton and Archbold (1945) were the first to describe tropical squall lines. Satellite imagery and radar data confirmed that most clouds are organized into mesoscale systems in the tropics (Houze and Cheng, 1977; Leary and Houze, 1979). Radar echoes associated with tropical convection in GATE have revealed a hierarchy of scales, from the cumulus scale to the synoptic scale. Radar echoes of all sizes in GATE were found to move slowly, except in relatively rare squall-line situations. Small echoes were

the most common, but large echoes accounted for most of the precipitation area (Houze and Cheng, 1977).

The primary vertical air circulation in the squall line consists of ascending front-to-rear inflow, convective-scale downdraft cores in areas of heavy rain, and mid-level mesoscale rear-to-front inflow descending to the low level (Zipser and LeMone, 1980). It is generally recognized that convective-scale downdrafts contribute significantly to feeding the low-level cold air. Potentially cool mid-tropospheric air is initially dragged downward by heavy precipitation, and cools evaporatively before spreading near the ground in a shallow layer measuring only a few hundred meters in depth (Zipser, 1969 and 1977). This shallow layer of cold air moves forward by means of a density-current propagation mechanism, which creates new convective cells ahead of the system. Therefore, the long-lasting feature of convective systems, such as super-cell storms or squall lines, is generally considered

1 GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment
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to be the result of a three-dimensional feedback between the convective-scale updrafts and downdrafts (Zipser, 1977).

Using Doppler radar data, Chong *et al.* (1987) found that rear inflow in a tropical squall line plays an important role in the generation of convective updrafts along the leading gust front. The relatively strong inflow coming from the rear of the convective region suggests that the trailing anvil region also plays an important role in feeding the deep, cold air. Lafore and Moncrieff (1989) and Zhang and Gao (1989) used numerical simulations to show that rear inflow has a significant effect on the convective region by increasing the low-level convergence and the mass in the cold pool. Using three-dimensional simulations, Weisman (1992) found that rear inflow can either remain elevated near the leading edge of the line or descend and spread along the surface well behind the leading edge of the system. For a squall line with descending rear inflow, the gust-front lifting is not strong nor deep enough to regenerate new convective cells and the mesoscale circulation slowly weakens. However, in a squall line with an elevated rear inflow, the system tends to be longer-lived as strong convective cells are regularly regenerated by the deeper gust-front lifting.

Much research has been focused on understanding the interaction between the narrow band of the system, which dominates the early portion of the system's life, and the wide band of more gradual ascent and stratiform precipitation that develops behind the convective line, and which dominates the later portion of the system's life. Experimental cloud simulations by Weisman *et al.* (1988) and Weisman (1992) showed that the CAPE directly controls the maximum amount of buoyancy that can be realized by a parcel lifted from near the surface, while the vertical wind shear controls the characteristics of the lifting produced near the leading edge of the system, thereby controlling the magnitude of the buoyancy perturbations that are actually realized both aloft and within the cold pool. Zhang and Gao (1989) suggested that there were three different scales of dynamic processes involved in the development of the rear inflow: the large-scale baroclinity which produces strong rear inflow within the upper half of the troposphere, the mesoscale response to the convective development which enhances the mid-level trailing inflow, and the moist downdrafts responsible for the descending portion of the rear inflow close to the leading line. From numerical simulations, Lafore and Moncrieff (1989) showed that horizontal potential temperature gradients generated by a combination of latent heat release in the convective region, and unsaturated mesoscale descent—both modulated by evaporation—cause a horizontal pressure gradient and generate horizontal, line-parallel vorticity. The rear inflow is a consequence of these

processes.

Although it is less spectacular than squall-line cluster, non-squall-line cluster has been reported to be the most common feature of tropical convective activities (Houze and Cheng, 1977; Martin and Schreiner, 1981). Tropical non-squall-line cluster often consists of one or more rainbands which are aligned approximately parallel to a weak low-level shear vector. Despite their different environmental conditions, the tropical non-squall line sometimes shares many features with the squall line (Zipser *et al.*, 1981). By using aircraft data, Zipser *et al.* (1981) found that front-to-rear inflow was lifted by a weak gust front and flowed out of the rear portion of the rainband. The gust front was less well marked than most squall gust fronts in terms of the vector wind change and temperature drop, and the change in equivalent potential temperature was found to be extremely small. The mesoscale downdraft computed to the rear of the system was mostly in the rain area and therefore appears to be in agreement with expectations based on previous work on squall lines by Newton (1963), Houze (1977), and Zipser (1977).

New squall lines tend to become organized when cumulonimbus cells form along or just ahead of the edges of dense downdraft air from older cloud clusters (Houze, 1977; Houze and Betts, 1981). The line's organization cannot be explained by the mesoscale downdraft that spreads out below the squall's trailing anvil cloud, at least not in the initial stages of the line, since the arc-shaped squall line takes shape well before the development of a significant anvil structure (Houze, 1977; Fortune, 1980). The mechanism of organization can only be understood by observing a cloud system from the developing stage to the mature stage.

The present paper presents a case study of a tropical convective rainband observed by a dual-Doppler radar system, which was deployed and operated on Manus Island (2°S, 147°E), Papua New Guinea, during the Intensive Observation Period (IOP) of TOGA-COARE (from Nov., 1992 to Feb., 1993). The case presented here concerns a small rainband which developed from two shallow convective cells. The rainband was observed between January 5 and 6, 1993 and revealed detailed kinematic structures, as measured by the dual-Doppler radar system. The rainband was small and isolated, moved slowly, and entirely developed and decayed within the dual-Doppler radar coverage area. The rainband showed interesting similarities to and differences from a typical squall line. Convective cell interactions and aggregations were observed to occur within the rainband, however, the mechanism responsible for the rapid growth seems different from that described in previous studies. There were no strong downdrafts below the heavy rainfall area and there was

Fig. 1. Selected low-elevation PPIs (the time interval is about 30 minutes). Contours correspond to levels 1 (~10 dBZ, light stipple), 2 (~20 dBZ, vertical hatch), 3 (~30 dBZ, heavy stipple) and 4 (~35 dBZ, horizontal hatch). The outline of Manus Island is shown by a dotted line.

Fig. 2. Skew T-log p profiles of temperature and dewpoint temperature (thick, solid line) before the rainband. The path of a parcel lifted from the surface without mixing is indicated by a thin, solid line. The lifting condensation level (LCL) and the level of free convection level (LFC) are also shown in the figure.

no widespread stratiform region behind the convective region. Most observational and numerical studies have not described an organization mechanism for squall lines that lack these features.

The purpose of this study is to investigate the structure and organization processes of the rainband over the warm pool. Following a brief description of the method of analysis (Section 2), we will present an overview of the rainband and environmental conditions (Section 3). Sections 4 and 5 describe the general features of the rainband and describe its kinematic structure in detail. Section 6 contains a discussion of the organization processes of the rainband and Section 7 concludes the chapter.

2. Data and method of processing

Data were collected using radio sondes and a dual-Doppler radar system during the IOP. The observational systems of the IOP of TOGA-COARE and the characteristics of the radars have been described in detail by Uyeda *et al.* (1995). Data from the radar system were collected by performing full 360° plan position indicator (PPI) volume scans. The time interval of the volume scans was about 15 minutes, which is suitable for slow-moving systems. The time interval varied from 9 to 17 minutes in actuality, for the volume scans were made manually.

The Doppler velocity data utilized in the dual-

Fig. 3. Coordinate system used in this paper. The X-axis and the Y-axis were defined as parallel and normal to the elongated direction of the rainband, respectively. The direction of the movement of the rainband was also parallel to the Y-axis.

Doppler synthesis were edited in radar coordinates to remove noise and to correct folded Doppler velocities. The edited data were then interpolated to Cartesian grids using the Cressman scheme (Cressman, 1959), with a grid interval of 1.0 km in the horizontal axis and 0.5 km in the vertical axis. Horizontal wind velocity was calculated from the radial velocity and was filtered to retain scales in the velocity fields greater than 4.0 km. The vertical wind velocity was then obtained indirectly by integrating the anelastic equation of mass continuity from the sea surface, assuming a vertical velocity of zero at both top and bottom boundaries. The middle time of a volume scan was used to indicate the time of a synthesized field.

3. Overview of the rainband and environmental conditions

Figure 1 shows some selected low-elevation (1°) PPIs of the radar at Momote airport. The rainband appeared to the northwest of the radar site before 22:30 LST but data recording started at 22:30 LST on January 5. The rainband was oriented from southwest to northeast and moved on an average from 320° to 140° at 5.5 m s⁻¹. As it moved toward the radar, the rainband developed and became organized at about 23:33 LST, with a maximum length and width of about 30 km and 15 km, respectively. The convective region was found clearly, and the

Fig. 4. Vertical profiles of wind component parallel (U) (a) and normal (V) (b) to the rainband observed by the radio sonde at Momote airport. The radio sonde was released at 22:00 LST on Jan. 5, just before the arrival of the rainband at Manus airport.

area of weak and uniform echo behind it was small in the rainband. By 00:02 LST on January 6, the rainband began to decay and disappeared at 02:01 LST. Figure 1 indicates that it lasted over a 3-hour period, which was much longer than the isolated convective echoes that were observed within the radar observational area. The rainband developed and matured within the region where three-dimensional air circulations is synthesized by dual-Doppler radar observation.

Figure 2 shows sounding data collected at 22:00 LST from Momote airport. The rainband was located about 40 km northwest of Momote airport at this time and the data represent the environmental conditions ahead of the rainband. A shallow temperature inversion was found in the lowest 11 hPa (indicated by an arrow). The dew-point profile shows that the atmosphere was wet in the lower troposphere (below 600 hPa), while it was dry in the mid-troposphere. The air was extremely dry at 500 hPa (5.9 km). The freezing level was identified at 560 hPa (5.0 km). The lifting condensation level (LCL) and level of free convection (LFC) were 948 hPa (0.55 km) and 660 hPa (3.6 km), respectively, as determined by a parcel having its mixing ratio and temperature extrapolated from the top of the inversion to the sea surface. When the air parcel was lifted to LFC, it ascended to 200 hPa (12.4 km) in the absence of mixing with the environment. However, the maximum temperature excess was only 2°C near 350 hPa and the CAPE was only about 342 J kg⁻¹.

Figure 3 shows the coordinate system used for the following determinations. The X-axis was defined as parallel to the rainband; the Y-axis was defined as normal to the rainband. The direction of the movement of the rainband was also parallel to Y-axis. Figure 4 shows vertical profiles of environmental wind components parallel (U) and normal (V) to the rainband observed by the radio sonde at Momote airport (22:00 LST). The propagation speed of the rainband is indicated by a thick vertical line (Fig. 4b). The normal component of the system-relative wind was obtained by subtracting its velocity from the wind velocity. The magnitudes of the two horizontal wind components were nearly identical throughout the troposphere, but the vertical shears were markedly dissimilar. Except in the lowest layer, the normal wind velocity (V) changed little with height up to 600 hPa, but the parallel wind velocity (U) changed markedly. Therefore, the wind shear was mainly caused by the U component and the rainband was almost parallel to the wind shear of the U component. Turpeinen (1982) defined the mean wind shear vector as the vector obtained by subtracting the lower-level (450 m) wind from the upper-level (3450 m) wind. In this case, the magnitude of the shear was about $2.5 \times 10^{-3} \text{ s}^{-1}$ from 950 hPa (552 m) to 700 hPa (3165 m). The system-relative wind (V) blew from front to rear only in the lower troposphere (below 950 hPa) and was nearly stagnant between 950 and 600 hPa. The system-relative U component blew from positive (northeast) to negative (southwest) X-direction below 870 hPa.

Fig. 5. Three-dimensional display of 30 dBZ reflectivity factor surfaces. The X- and Y-axes were shifted so that the position of the rainband existed in the center of each figure. Each alphabet letter corresponds to a convective cell. The direction of the true north is also shown in each figure.

(1.3 km) and from the opposite direction between 850 and 470 hPa.

Barnes and Sieckman (1984) reported that non-squall lines or ordinary rainbands in GATE were characterized by weak low-level shear and were parallel to the direction of the shear vector. This result is in agreement with our own. It should be noted that, in our study, the magnitude of the line-normal wind was different from that in GATE. Compared with the line-parallel component, both the wind speed and wind shear of the line-normal component were small at the low and middle levels for the non-squall line in the GATE area. In our case, the wind shear of the normal component V was nearly zero at the low and middle levels, but the magnitude of the normal component V was nearly identical to that of the parallel component. The normal wind at the low and middle levels was equal to the movement speed of the rainband (Fig. 4b).

4. General features of the rainband

Figure 5 presents three-dimensional displays of radar reflectivity greater than 30 dBZ showing the evolution of convective cells within the rainband. In this study, the convective cell was defined subjectively as the region having a radar reflectivity greater than 30 dBZ. It will be shown in Section 5 that the defined convective cell corresponds well to the updraft core.

At 22:32 LST, the rainband was composed of only two small cells, designated A and B, respectively, which were separated by about 10 km. As the rainband moved, new cells (Cells C and D) developed near Cells A and B. At 23:37 LST, a fifth cell (Cell E) was detected in the middle of the rainband. After 23:37 LST, convective cells (A, C and E) developed explosively in the middle of the rainband and merged with each other. It is important that the

Fig. 6. Time evolution of maximum echo top (thick, solid line), total rain water content (dash line), and echo area (thin, solid line) at the 1.0 km level. The attached number means the number of convective cells.

Fig. 7. The change with time of the vertical profile of rain water content.

number of convective cells did not change from two to one, but did change with time in the rainband as follows: two at the initial stage, five at the developing stage, and one at the mature stage. Figure 5i shows that the final cell was much larger than any other cell.

Figure 6 shows the time change of the echo top level defined by 10 dBZ, total rain water content, and the area of the echo greater than 10 dBZ at the 1.0 km level. The rain water content was calculated by using the following relationship of Z to the liquid-

water content (M) (Douglas, 1964). All echoes were considered to be from raindrops, because it was difficult to distinguish between rain and snow using only radar echoes.

$$Z = 2.4 \times 10^4 M^{1.82}$$

The total water content and the echo area gradually increased with time. In contrast, the level of the radar echo top did not change gradually or smoothly, but intermittently. Before 00:06 LST, it took about 1.5 hours for the echo top to develop to 9.0 km. Thereafter, the echo top rapidly developed up to 13.5 km, which was close to the parcel equilibrium level estimated from the sounding data shown in Fig. 2. This successive development of convective echoes suggests that the rainband needed some period of time to gain sufficient potential energy to develop up to the parcel equilibrium level. The maximum value of total rain water content appeared after the echo top reached its highest level; the maximum value of the radar echo area at the 1.0 km level appeared thereafter. All three values decreased rapidly after 1:00 LST.

Figure 7 shows the vertical profiles of rain water content at different times. The maximum of rain water was found between the 1.0 km and 1.5 km levels. Although the level of the echo top increased with time, most of the rain water remained concentrated below 3.0 km where the temperature was about 10°C. The rain water decreased dramatically above this level. This feature is very similar to that found by Leary and Houze (1979), Zipser and LeMone (1980), and Szoke and Zipser (1986) in the GATE area, and indicates that the warm rain process was dominant inside the rainband.

Figure 8 shows vertical profiles of the mean divergence at different times. It should be noted that the

Fig. 8. Same as in Fig. 7, but for divergence averaged horizontally within the rainband.

divergence was calculated and averaged only for the echo area. Low-level convergence and upper-level divergence were evident; the maximum convergence was about $4 \times 10^{-4} \text{ s}^{-1}$ near the sea surface and was much smaller than the divergence (about 10^{-3} s^{-1}). Also evident was a deepening of the low-level convergence layer with time: the depth of the convergence layer increased from 1.5 to 3.5 km. Figure 9 shows the change with time of the vertical profiles of minimum (downdraft) and maximum (updraft) vertical velocities within the rainband. The maximum updraft found within the rainband was weak, only about $4\sim 5 \text{ m s}^{-1}$. The result was similar to the weak updraft in GATE found by LeMone and Zipser (1980). The small updraft velocity is attributed to the low convective potential energy available, as suggested by Zipser and LeMone (1980). Although the level where the peak of the maximum updraft velocity appeared moved upward with time, the peak value of the maximum updraft velocity was nearly unchanged. The deepening of the low-level convergence layer was responsible for the upward movement of the peak of the maximum updraft velocity. The magnitude of the maximum downdraft was about half that of the maximum updraft, being about $-2\sim -3 \text{ m s}^{-1}$. The level at which the maximum downdraft appeared was always lower than that at which the maximum updraft appeared.

Fig. 9. Same as in Fig. 7, but for minimum (downdraft) and maximum (updraft) vertical velocities.

5. Kinematic structure

A total of five volume scans (between 23:04 and 00:06 LST) were performed to measure the horizontal wind field using dual-Doppler radar measurements during the developing and mature stages of the rainband. In Fig. 10, system-relative streamlines are superimposed on the echo intensity at the 1.0, 2.0 and 3.0 km levels. The general system-relative flow at the 1.0, 2.0 and 3.0 km levels was easterly, southeasterly, and southerly, respectively. This general flow corresponds well to the upper air sounding data observed at 22:00 LST (Fig. 4). The location of the rear inflow and its evolution at the 1.0 km level is noteworthy. At 23:04 LST, three regions of rear inflow were noted behind only three of the convective cells. In contrast, the easterly flow passed directly through the middle part of the rainband, where the radar reflectivity was weak. By 23:21 LST, two regions of the rear inflow aggregated with each other. After 23:37 LST, the rear inflow was united and concentrated into the middle part of the rainband. The area of the rear inflow increased with time from 23:04 LST to 23:51 LST, and decreased thereafter both at the 1.0 and 2.0 km levels. That the area of the rear inflow at the 2.0 km increased means the increase in depth of the rear inflow. In short, the rear inflows existed separately at the developing stage, and increased their areas and depth as aggregated with each other at the mature stage.

Fig. 10. Time evolution of system-relative streamlines with radar reflectivities superimposed at the 1.0, 2.0, and 3.0 km levels. Reflectivity contours are depicted at 10, 20, 30, 35, and 40 dBZ. The rear inflow regions are stippled. The X- and Y-axes were shifted so that the position of the rainband existed in the center of each figure. The vertical bar beside the Y-axis shows the width in which data were averaged to make the vertical cross sections shown in Fig. 11. The vertical bars with adjacent letters in the upper-left panel show the lines along which the vertical cross sections in Fig. 12 were made.

These data indicate that the rear inflow was organized and developed within the rainband.

Figure 11 shows southwest-northeast cross sections of echo intensity, and vertical and system-relative horizontal wind. The direction is parallel to the rainband. The vertical bar beside the Y-axis in Fig. 10 shows the width along which data shown in these sections were averaged. For every period of time, the wind generally blew from right to left below the 1.5 km level and left to right above it, which corresponded well to the upper air sounding data in Fig. 4a. There was a clear correspondence evident between the updraft cores and the strong echo regions. At 23:21 LST, an updraft core began to develop and Cell E appeared in the middle of the rainband. The updraft became stronger and expanded, becoming higher. As exemplified at $X = 8\sim 10$ km at 23:37 and 23:51 LST, horizontal wind having an opposite direction (that is, left to right in the figure) from the air sounding data was seen only near the center of the updrafts at the lower levels. This indicates that strong convective cells attracted the surrounding air and changed its wind direction. This effect is clearly shown in Fig. 10 (see the stream lines of the front inflow at 00:06 LST). It is noteworthy that there were no downdrafts from the old cells at two sides of the middle part of the rainband during the rapid development of convection in the middle of the rainband. This suggests that the strong updraft and the strong convective echo for Cell E were not caused by convergence between the downdrafts, even though they formed between two convective cells.

Figure 12 shows southeast-northwest vertical cross sections of echo intensity, and vertical and system-relative horizontal wind. The direction is normal to the rainband. Each cross section was selected so as to cut the center of Cells A~E. The developing and mature stages of these convective cells share some common features. First, the low-level air entering from the front was lifted, and it flowed out at the middle and upper levels. Second, the maximum updrafts were found just above the echo cells. No downdrafts were found beneath the echo cells and no gust fronts were found. Furthermore, no new cells developed in front of the old cells. Third, radar echoes in the rear side were eroded at the middle levels, where the downdrafts were found.

Although the downdrafts were found in the rear portion of the rainband, the rear inflow was not induced by a divergence of the downdrafts at the low levels. There are several reasons for this. The rear inflow appeared not only in front of the downdraft (Figs. 12a, 12b, and 12d) but also behind it (Figs. 12c and 12e), and some rear inflow appeared in the regions where no downdraft was noted at the low levels. The evolution of the rear inflow seems to be important in the rapid development of the rainband. After the aggregation of the rear inflow at

Fig. 11. Rainband-parallel vertical planes of the vector wind and reflectivity obtained through averaging with respect to Y among the region illustrated in the left panels in Fig. 10. Levels of reflectivity contours (thick line) are the same as those in Fig. 10. Vertical velocity (thin line) is contoured every 0.7 m s^{-1} . Downdraft regions are stippled while updraft regions are illustrated by alternating hatched-unhatched regions.

Fig. 12. Rainband-normal vertical planes of the vector wind and reflectivity obtained through the hearts of Cells A~E as shown in the upper-left panel in Fig. 10. Levels of reflectivity contours (thick line) are the same as those in Fig. 10. Vertical velocity (thin line) is contoured every 1.0 m s^{-1} . The lightly shaded region shows the rear inflow.

23:37 LST (Fig. 10), the rear inflow behind Cells C and E became thicker. The thick rear inflow had a “head” and looks like a gravity current, which is clearly seen at 23:51 LST in Figs. 12c and 12e. As the moving speed of the “head” in the rear inflow

was estimated to be 6.8 m s^{-1} and moved faster than the convective cells, the rear-inflow caused the low-level convergence. Thus, the development of these cells was associated with the deepening and movement of the rear inflow. The “head” of the rear

Fig. 12. (Continued)

inflow eroded after the development of the strong-convective cells, as seen at 00:06 LST in Figs. 12c and 12e. The erosion of the “head” would be caused mainly by the following two processes: entrainment into the developing cell which is suggested from the upward movement of air in the “head”, and mixing due to Kelvin-Helmholtz instability as suggested by

Thorpe (1973) and Britter and Simpson (1978). The relationship between the development of the convective cells and the rear inflow will be discussed in detail in the next section.

Fig. 12. (Continued)

6. Discussion

As shown in Fig. 1, only the analyzed convective system developed into a meso- β -scale rainband, although there were some convective clouds around it. Only the convective system composed of two small convective cells was able to develop and become organized for several reasons which will be discussed

below.

6.1 The lack of a strong downdraft

The interactions of clouds and the rapid growth of the convective system by aggregation of individual convective cells are common features of the evolution of tropical rainbands. These are important organization processes in the upscale development of convection in a tropical, non-squall line cluster (Houze and Cheng, 1977; Turpeinen, 1982). Simpson (1980) proposed that the collision of downdraft outflows from old cells can lead to the growth of a new cell between them. The new cell, called a "bridge", fills the gap between the old cells and promotes their merging. From the results of three-dimensional simulations, Tao and Simpson (1989) found that new convective cell, a precipitating cloud merger, and vigorous development of the system were associated with increasing low-level convergence, resulting from the cloud downdrafts and their associated cold outflows at the each side of the new cell. This study suggests that the primary initiating mechanism for the occurrence of a precipitating cloud merger is the cloud downdrafts and their associated cold outflows. Such an organization process was also discussed in a numerical study by Misumi *et al.* (1994) as one of three mechanisms that form vigorous and long-lasting convective storms. However, this and other theories concerning cloud merging (Orville *et al.*, 1980; Tripoli and Cotton, 1980; Cunning *et al.*, 1982; Turpeinen, 1982; Westcott, 1984; Westcott and Kennedy, 1989) are not applicable to the present case for the following reasons: no downdrafts were found within the convective cells at two sides of the rainband (Fig. 11); no strong convergence was found between the two convective cells; there was no relative motion between the cells; and the number of convective cells did change with time in the rainband, from two at the initial stage, to five at the developing stage, and finally to one at the mature stage.

The fact that downdrafts were not found under the reflectivity cores cannot be accounted for by the poor measurements of the divergence field in the boundary layer, because the rainband over the sea was close to the radar systems during the period of wind-synthesis. Ulanski and Garstang (1978) found that slowly moving systems have no gust fronts. Warner *et al.* (1980) stated that a gust front was associated with "one of" the cloud bands. Nicholls *et al.* (1988) showed that the density current strength is significantly reduced when the mid-levels are moist or when the CAPE is small. In our case, the lower cloud base, the moist sub-cloud layer, the weak vertical wind shear, and the warm rain process would explain the lack of strong downdraft within the convective cells and the absence of a strong outflow or gust front in front of

Fig. 13. Time-evolutions of the volume of low-level rear inflow and maximum echo top.

the rainband. The cloud updrafts were not tilted, since the storm was developing in a weak-sheared environment; therefore, precipitation did not descend completely outside the region in which upward motion was occurring. Similar observations were made by Jorgensen *et al.* (1991) in an oceanic convective line during TAMEX². They reported an organized convective system having no distinct low-level rear inflow nor strong convective-scale downdrafts. They attributed the lack of a persistent gust front to the near-moist-adiabatic lapse rate and the near-saturation of the sounding.

6.2 Development of convective cells in the small CAPE environment

As shown in Fig. 6, the level of the echo top had been below 6.0 km by 23:04 LST. The convective system was observed by the Momote radar before 22:00 LST, although the data were not recorded. Therefore, the level of the echo top of the convective system was less than 6.0 km for at least 1 hour. The levels of the echo top of the surrounding convective clouds were also less than 6.0 km. These facts suggest that there was not enough potential energy in the boundary layer to make a cloud develop up to the level of the calculated equilibrium (~ 12.4 km). As shown in Fig. 2, the atmosphere was dry above 900 hPa and driest at 500 hPa. Turpeinen and Yau (1981) reported that a cloud cannot develop to the parcel equilibrium level in a dry atmosphere; the dry air should have a large effect on the rainband development. Warner *et al.* (1980) stated that cumulonimbus clouds reaching 15 km only grew out of an environment already moistened by lesser clouds. Yanai *et al.* (1973) pointed out that water vapor and liquid water which are detrained from the shal-

low clouds can moisten the lower troposphere. If a number of small convective cells develop and decay repeatedly in a small region, the amount of potential energy in the region would become larger than that in the surrounding region. This process which accumulates larger CAPE in a limited small region than that in the surrounding region could explain why only the analyzed convective system developed, though the reason why two small convective cells accidentally developed close together is not clear.

The level of the echo top of Cell B remained unchanged after it reached 9.0 km. Cell E then rapidly increased up to 13.5 km (see Fig. 5). The second development could not be explained by the above process for the following reasons: the number of convective cells decreased after 23:37 LST; the development of Cell E occurred within 15 minutes after termination of Cell B development, which is too little time for further potential energy to accumulate in the lower troposphere. Another process is needed for Cell E to develop. As indicated by Figs. 10 and 12, development of the rainband was accompanied by enhancement of the low-level rear inflow in the middle part of the rainband. Figure 13 clearly shows that the enhancement of the rear inflow promoted the development of the rainband. After the volume of the rear inflow reached its maximum, the level of the echo top extended rapidly upward. In other words, the rear inflow enhanced first, before the rainband developed. The formation and evolution of the low-level rear inflow may play an important role in the development of the rainband.

6.3 Developing processes of the rear inflow

As shown in Fig. 10 (23:04 LST), the rear inflow was noted only in the small region behind each convective cell. Thereafter, three small regions of rear inflow merged and became concentrated in the mid-

dle of the rainband, and its covering area increased with time. These facts demonstrate that the low-level rear inflow was produced in the convective-scale at first, and then developed to the mesoscale. Ulanski and Garstang (1978) noted the inflow at the rear and side of a developing cell. Zipser *et al.* (1981) also noted rear inflow in a restricted area, and concluded that this feature is induced by pressure gradients inside the convective band itself as did Brown (1979) for a similar feature in another model. A possible mechanism of convective-scale rear inflow is the lower pressure disturbance induced by the convection. Such pressure perturbation is formed by hydrostatic and dynamic effects (Schlesinger, 1980), resulting in attraction of air by the updraft of the developing convection and the low-level rear inflow formed behind the convection (see Figs. 10 and 12).

As indicated in Fig. 12, radar echoes in the downwind, rear side of convective cells were eroded at the middle levels, where downdrafts were found. The erosion of the radar echo was attributed to evaporation of precipitation particles. The front inflow carried precipitation particles rearward, where the air was dry and evaporation occurred. According to the numerical results of Brown (1979), the downdraft is induced mainly by evaporation of precipitation particles. The evaporation in the rear portion of the rainband also cools the air significantly.

The cooled air in the rear side of a convective cell would remain even after a convective cell decayed. The observed small wind speed near the sea surface is favorable to a longer life due to the low exchange rate of latent and sensible heat between the air and the sea surface. When a new convective cell develops near an old one, the new cell would attract the old cooled air and would cool the air further by the same process stated above. Thus, the volume of the cooled air would increase with time. In addition, the remaining cooled air would aggregate if a number of convective cells developed and decayed in a small region. Cooled air exists behind a convective cell would be attracted to the center of the updraft, and so the cooled air would always be moving rear to front. Also the air in the front side of the rainband would be attracted by the developing convection, which means the increase in the convergence. As explained above, Cell B developed rapidly after 23:04 LST, and consumed the accumulated potential energy. Cell B was large and had a wider region of rear inflow than the smaller cells, A and D (Fig. 12). Cell B would have made a wider area of cooled rear inflow which would have attracted other cooled air to the center of its updraft. Therefore, aggregation of the rear inflow was promoted by the formation of the convective Cell B. This process would explain why the rear inflow was organized into the mesoscale in the later stage.

As the depth of the cooled air increased, the low-

level rear inflow would begin to move like a gravity current. Figures 12c and 12e show a "head" in the rear inflow that reached about 2.0 km. The mean propagation speed of the "head" of the low-level rear inflow was estimated to be 6.8 m s^{-1} . When we substitute the temperature data before (26.3°C) and within (26.0°C) the rainband observed by the radio sondes into the theoretical expression of the gravity current propagation speed (Benjamin, 1968), the propagation speed is found to be 6.3 m s^{-1} . There is good agreement between the observed phenomenon and the theory. Since the propagation speed of the low-level rear inflow was faster than that of the propagation speed of the rainband (5.5 m s^{-1}) and the speed of the front inflow increased due to attraction by developing cells, the low-level convergence was enhanced, which promoted rapid development of cells in the middle of the rainband.

If this organized rear inflow maintained its depth and penetrated into convectively unstable air, the cold outflow moves in a downshear direction faster than the rising air parcels, and an upshear-tilting updraft is built as discussed by Misumi *et al.* (1994), an organized rainband would be formed. In the present case, however, the rainband was short lived. The "head" of the rear inflow was lowering at 00:06 LST (Fig. 12) due to entrainment into the convective cells and mixing, and the volume of the rear inflow decreased rapidly (Fig. 13). Further, the amount of potential energy in the lower troposphere was small. Taken together, these facts could account for why the rainband was short lived.

The measured time change of the air temperature suggests that evaporative cooling and subsidence warming occurred behind the convective region of the rainband, although a lack of humidity data precludes a conclusive finding. Figure 14 shows a time-height cross section of the air temperature measured at 30-min. intervals using a NOAA radio-acoustic sounding system (RASS) at Momote airport. As shown in Fig. 1, the leading edge of the westernmost part of the system arrived at the station at about 00:06 LST and passed at 00:30 LST. The air temperature showed the minimum value below 350 m just behind the convective region (soon after 00:32 LST), though data was lack owing to the noise of rain below 250 m, and showed the maximum at the rear portion of the rainband (soon after 01:02 LST). As the western edge of the rainband passed through the RASS site as seen in Fig. 1, the depth of cold air in Fig. 14 would be less than that in Fig. 12. In his numerical study, Brown (1979) showed that mesoscale downdrafts can result in adiabatic warming that exceeds the cooling of evaporation, thus leading to a warm and dry lower troposphere. Leary (1980) expanded on concepts presented by Betts and Silva Dias (1979), to develop a one-dimensional steady state, hydrostatic model

Fig. 14. Time-height cross section of air temperature ($^{\circ}\text{C}$) measured with RASS at Momote airport.

of a downdraft containing a realistic spectrum of evaporating raindrops. Leary (1980) showed that the soundings below anvils result from an imbalance between the evaporation of the falling precipitation particles, which acts to increase the relative humidity, and the subsidence, which warms and dries the air.

6.4 Conceptual model

Figure 15 presents a conceptual model of rainband evolution. During the moistening stage, the rainband consists of several convective cells and accumulates potential energy in the lower troposphere. Each cell induces low-level rear inflow in its downwind side. At this stage, the rear inflow is shallow and is in the convective scale. Meanwhile the rear inflow is cooled by the evaporation of precipitation particles carried by front inflow into the dry atmosphere. Once a cell develops, having largely consumed the accumulated potential energy, it causes wider rear inflow, attracts other cooled air and promotes aggregation of a number of cooled air masses (aggregation stage). The aggregated rear inflow becomes deeper and evolves into a gravity current. The resulting gravity current moves fast, and causes strong convergence and updraft at the leading edge, thus causing explosive development of a new cell in the rainband (mature stage). The rainband then decays due to mixing and entrainment of cooled air into updraft air, which causes lowering of the gravity current head, and due to extreme consumption of

potential energy remained in the lower atmosphere (decaying stage).

7. Conclusions

We analyzed the structure and evolution of a convective rainband that developed over the warm pool between January 5 and 6, 1993. The details of the rainband were analyzed using sounding and data derived from a dual-Doppler radar system. The rainband was small and isolated, and it moved slowly, allowing its kinematic structure to be fully resolved from development to maturity.

Like most rainbands observed in other tropical regions, the present rainband was oriented parallel to the mean low-level environmental shear. The magnitude of wind shear was $2.5 \times 10^{-3} \text{ s}^{-1}$ and the CAPE was as small as 342 J kg^{-1} . It moved from 320° to 140° at a speed of 5.5 m s^{-1} and was 30 km long and 15 km wide at maturity. Rain water within the rainband was concentrated below 3.0 km and decreased rapidly at higher elevations. A warm rain process is supposed to have dominated in the rainband. Due to the small CAPE, the updraft within the rainband was lower, being about $4\sim 5 \text{ m s}^{-1}$ at maximum. The maximum radar reflectivity was about 35~40 dBZ.

The theories concerning cloud merging presented so far are not applicable to the present case for the following reasons: no downdrafts were found within the convective cells at two sides of the rainband; no

Fig. 15. Conceptual model of the evolution of the rainband. Convective-scale rear inflows are attracted by the developed cell and aggregate with each other to form a flow like a gravity current. A strong convective cell explosively develops at the leading edge of the “head”.

strong convergence was found between the two convective cells; there was no relative motion between the cells; and the number of convective cells changed with time in the rainband, to become two at the initial stage, five at the developing stage, and one at the mature stage.

The level of the echo top of the convective system was less than 6.0 km for at least 1 hour. The levels of the echo top of surrounding convective clouds were also less than 6.0 km. These facts suggest that there was insufficient potential energy in the boundary layer to make a cloud develop to the calculated equilibrium level (~12.4 km). If a number of small

convective cells develop and decay repeatedly in a small region, the amount of potential energy in the region would become larger than that in surrounding region. This process could explain why only the analyzed convective system developed.

After the level of the echo top of Cell B reached 9.0 km, it remained unchanged for some period of time, and then Cell E rapidly increased to 13.5 km. The second development could not be explained by the above process. Development of the rainband was accompanied by the enhancement of the low-level rear inflow in the middle part of the rainband. After the volume of the rear inflow reached its maximum,

the level of the echo top extended rapidly upward. In other words, the rear inflow enhanced first, before the rainband developed. The low-level rear inflow was first produced in the convective-scale, and then developed to the mesoscale. A possible mechanism of convective-scale rear inflow is the lower pressure disturbance induced by the convection. As a result, the air was attracted by the developing convection and the low-level rear inflow formed behind the convection.

Radar echoes in the downwind, rear side of the convective cells were eroded at the middle levels, where downdrafts were found. The erosion of the radar echo was attributed to evaporation of precipitation particles. The front inflow carried precipitation particles to rearward, where air was dry and evaporation occurred. When a new convective cell develops near an old cell, the new cell would attract the old cooled air and cool further. Thus, the volume of the cooled air would increase with time. In addition, the remaining cooled air would aggregate, if a number of convective cells develop and decay in a small region. Cell B rapidly developed after 23:04 LST, and consumed the accumulated potential energy. Cell B would have made a wider, cooled rear inflow and attracted other cooled air to the center of updraft. Therefore, aggregation of the rear inflow was promoted by the formation of the convective Cell B. This process would explain why the rear inflow was organized into the mesoscale in the later stage.

As the depth of the cooled air increased, the low-level rear inflow began to move like a gravity current. Its propagation speed was 6.8 m s^{-1} , which agrees well with the theoretical value. As the propagation speed of the low-level rear inflow became faster than that of the rainband, the low-level convergence was enhanced in conjunction with the attracted front inflow, which promoted rapid development of Cell E. The "head" of the rear inflow was lowering at 00:06 LST due to mixing and entrainment into the convective cells. Further the amount of potential energy in the lower troposphere was small. These facts could account for why the rainband was short lived.

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熱帯域で二つの対流性エコーから発達したレインバンドの デュアルドップラーレーダー観測

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TOGA-COARE IOP 期間中の 1993 年 1 月 5 日から 6 日にかけてパプアニューギニアのマヌス島で観測した、孤立した小規模な対流性のレインバンドの構造と発達過程を、ゾンデデータとデュアルドップラーレーダーデータを用いて詳細に解析した。このレインバンドは、2 台のドップラーレーダーによる解析範囲の中で、2 つの小さな対流セルから発達して衰弱した。

レインバンドは、 342 J kg^{-1} と小さい CAPE を持つ環境場の中で発達し、成熟期には長さが 30 km で幅が 15 km に達した。バンドは $2.5 \times 10^{-3} \text{ s}^{-1}$ の大きさを持つ下層の平均シアーとほぼ平行な走向を持ち、 320° から 140° の方向に毎秒 5.5 m で移動していた。雨水は高度 3 km 以下に集中し、それより上空では急激に減少した。最大上昇流は毎秒 4~5 m で、レーダー反射強度は最大で 35~40 dBZ であった。

レインバンドを構成する対流セルの数は、発生初期では 2 つ、成長期には 5 つ、そして成熟期には 1 つと、時間と共に変化した。前方下層からレインバンドに流入した空気は対流セルの中で上空に持ち上げられ、強いエコー域の真上で上昇流となった後、後方に抜けて行った。強い降雨域の真下には強い下降流が存在せず、また、対流域の風下に於ける層状域の面積は小さかった。発達初期には、対流セルの中心に向かう後方から前方への対流スケールの流れが見られた。これらの後方から前方に向かう流れは、相互に併合して面積と厚みを増し密度流を形成した。この密度流はレインバンドよりも速い速度で移動することにより下層に強い収束を生じさせ、成熟期には密度流の“ヘッド”部で強い対流セルを発達させていたことが、2 台のドップラーレーダーを用いた詳細な解析から明らかになった。対流スケールで形成された後方から前方に向かう流れの併合過程が、このレインバンドの組織化にとって重要であることが示唆された。