The Mesoscale and Microscale Structure and Organization of Clouds and Precipitation in Midlatitude Cyclones. VII: Formation, Development, Interaction and Dissipation of Rainbands

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ABSTRACT

Mesoscale measurements on five Pacific cyclones are used to investigate the formation, movement, development, interaction and dissipation of warm-sector, prefrontal cold-surge, narrow cold-frontal, wide cold-frontal, wave-like and postfrontal rainbands.

Warm-sector rainbands formed near the leading edge of the cold front and often moved away from the front. Prefrontal cold-surge and wide cold-frontal rainbands formed aloft and behind the surface cold front and they also advanced relative to the front. The clearest interactions between rainbands occurred when wide cold-frontal rainbands overtook narrow cold-frontal rainbands; in this case the narrow cold-frontal rainband may be either temporarily or permanently dissipated, or the wide cold-frontal rainband may be dissipated, depending on the relative strengths of the rainbands. Wave-like rainbands, with very uniform properties, were initiated primarily in the vicinity of the cold front aloft; despite their small scale, these rainbands were relatively long-lived. Postfrontal rainbands, some of which contained oriented precipitation cores, moved with the winds within the postfrontal airmass, and exhibited a variety of lifecycles.

1. Introduction

It is well established that mesoscale rainbands are an important organized component of the precipitation associated with extratropical cyclones (e.g., Browning, 1974; Harrold and Austin, 1974; Hobbs, 1978; Matejka et al., 1980). In previous papers in this series (Hobbs et al., 1980; Herzegh and Hobbs, 1980, 1981; Houze et al., 1981; Hobbs and Persson, 1982; Rutledge and Hobbs, 1983; Parsons and Hobbs, 1983) we have described various aspects of these rainbands. In this paper we are concerned with observational information on the formation, development, interaction and dissipation of several types of rainbands.

2. Data base

The data to be discussed were obtained during the 1976–77 winter field season of the University of Washington's (UW) CYCLES (CYCLonic Extratropical Storms) Project. The facilities available in this project and the modes in which they were used have been described by Hobbs et al. (1980).

Five cyclonic storms were chosen for the present study. Each storm included a surface cold-frontal passage within the CYCLES network. A detailed synoptic and mesoscale analysis was performed on each case using satellite data, National Weather Service (NWS) synoptic measurements, CYCLES rawsonde ascents (up to 1 per hour), high-resolution data from ground stations, and information from the CP-3 Doppler radar. Since the CP-3 radar was located on the Washington Coast at Pt. Brown and had a range of 140 km, quantitative radar data were available over both water and land.

3. Synoptic situations

a. 14 November 1976

The cyclonic system that passed through the CYCLES network on this day originated nearly four days earlier as a small low-pressure center over the western Pacific Ocean. As this center moved toward the Gulf of Alaska, the system developed into a deep occlusion with a central low pressure at the surface of ~954 mb. As the system approached the Washington Coast, the central low pressure began to rise, indicating that the cyclone was decaying. Compared to the other systems to be discussed in this study, the 14 November cyclone had the lowest surface pressure and was the oldest prior to frontal passage in the CYCLES network.

The analyzed 700 mb synoptic map (Fig. 1a) indicates that approximately 1 h prior to frontal passage at the CP-3 radar site, warm advection, associated
Fig. 1. Analyzed 700 mb synoptic maps for three of the cyclones discussed in this paper. (a) 14 November 1976 at 1600 PST (0000 GMT 15 November), (b) 21 November 1976 at 0400 PST (1200 GMT), and (c) 17 December 1976 at 0400 PST (1200 GMT). The height contours for the 700 mb pressure surface (labeled in dm) are drawn every 60 m and the isotherms (labeled in °C) are drawn every 4°C. Dotted lines indicate troughs. The station model is included in the lower right-hand corner of (a).
with a weak warm-frontal zone aloft, was present over the CYCLES network. The horizontal wind pattern derived from the CP-3 Doppler radar also revealed the presence of weak warm advection, at a height of \( \sim 2 \) km, as close as 15 km ahead of the surface occluded front. The CP-3 radar reflectivity pattern revealed rainbands over the CYCLES network, with orientations nearly parallel to the warm-frontal zone. These observations confirm that the occluded portion of the system was within the CYCLES network. The cold airmass behind the cold-frontal zone aloft is also evident in Fig. 1a. Associated with the cold air aloft were prefrontal cold-surge rainbands and wide cold-frontal rainbands. The leading edge of the cold airmass at the surface was marked by a narrow cold-frontal rainband.

b. 17 November 1976

Various aspects of this cyclone have been discussed by Matejka et al. (1980), Hobbs et al. (1980) and Parsons and Hobbs (1983). The system originated approximately two days earlier over the eastern Pacific Ocean. It subsequently deepened as the low center moved to the north of the CYCLES network and the trailing cold-frontal zone passed through the network.

The radar reflectivity pattern indicated warm-sector rainbands, a narrow cold-frontal rainband associated with the surface cold front, wide cold-frontal rainbands associated with the cold-frontal zone aloft, and wavelike rainbands.

c. 21 November 1976

The cyclonic system that passed through the CYCLES data network on 21 November 1976 formed on 19 November when a vortex in the polar airmass approached a trailing cold front over the central Pacific Ocean. The cyclone occluded and deepened rapidly in the next 24 h, with the central low pressure falling over 30 mb to 978 mb. As the system approached the Washington coast on 21 November, the central low pressure was slowly rising and the system had begun to decay.

The 700 mb synoptic analysis for this system (Fig. 1b) is typical of the thermal advection pattern associated with an older occluded system. At 700 mb the warm advection was located to the north of the CYCLES network, but at 850 mb it was within the network. A cold-frontal zone aloft is also evident at 700 mb. The winds aloft at both 850 and 700 mb were generally weaker in this system than in the other systems discussed in this paper; this accounts, in part, for the slower movement of its frontal surfaces.

The radar reflectivity data revealed the following
types of rainbands in this cyclone: warm-frontal, pre-frontal cold surge, narrow cold-frontal (with oriented precipitation cores), wavelike and wide cold-frontal.

d. 8 December 1976

Compared to the three cyclones described above, the cyclone that passed through the CYCLES network on 8 December 1976 was a much “younger” storm. It formed late on 6 December 1976, as a vortex in the polar air approached a trailing cloud band. The system subsequently became organized and developed slowly as the 988 mb low-pressure center moved north of the CYCLES network into central British Columbia. The trailing cold-frontal zone passed through the CYCLES network. The CP-3 radar reflectivity pattern revealed warm-sector, narrow cold-frontal, wide cold-frontal, wavelike and postfrontal rainbands.

Additional synoptic information on this system is given by Parsons and Hobbs (1983).

e. 16–17 December 1976

The cyclone that passed through the CYCLES network on 16–17 December 1976 originated over the eastern Pacific Ocean on 15 December. It formed as the result of the interaction between a trailing frontal system and a vortex in the polar airstream. The cyclone slowly deepened, until a 994 mb low-pressure center formed, and it began to fill as it reached the Washington Coast.

By the time this cyclone had reached the Washington Coast, the satellite data indicated that a wave was developing along the trailing edge of the frontal system and a second weak system was approaching the trailing front. The troughs of both systems are seen in the 700 mb analysis (they are shown in Fig. 1c as dotted lines). Weak cold advection over western Washington, with a warm-frontal zone located to the north of the network, is evident in the 700 mb analysis (Fig. 1c).

The surface cold front moved into the range of the CP-3 radar at about 0000 PST on 17 December. The cold front was associated with a sharp windshift, a pressure rise, and a slight drop in temperature and dewpoint. As the cold front moved through the CYCLES network, its speed and intensity decreased noticeably. A narrow cold-frontal rainband, with distinct oriented precipitation cores of the type discussed by Hobbs and Persson (1982), was observed as the front approached the coast, but these cores decreased in intensity as the cold front slowed.

Warm-sector, wide cold-frontal, wavelike and post-frontal rainbands were also observed in the CP-3 radar reflectivity data. An oriented core structure was observed in a rainband located within the postfrontal airmass. Also, embedded within the postfrontal airmass, was a line marking a windshift, pressure rise, and drop in temperature and dewpoint.

4. Origin and initial behavior of warm-sector rainbands

Warm-sector rainbands are located in the warm sectors of cyclones ahead of and parallel to the cold front (Hobbs, 1978). They are associated with the release of potential instability in the lower layers of the warm sector. These rainbands can be quite intense; their most vigorous form is the midlatitude squall line. In this section, we present observational data relevant to the formation and initial behavior of warm-sector rainbands, using data from 17 November 1976, 8 December 1976 and 16–17 December 1976.

a. 16–17 November 1976

A single warm-sector rainband, that extended to a height of >7 km, was observed in this cyclone. As can be seen in Fig. 2, this rainband contained several sub-bands.3 The warm-sector rainband formed near

3 In the figures, distances north and east of the CP-3 radar, which was located at Pt. Brown on the Washington coast, are indicated by positive numbers and distances south and west by negative numbers.
the leading edge of the surface cold front, and moved with a similar speed to the cold front. As the first sub-band (labeled 1 in Fig. 2) intensified it began to move faster than the cold front and a second sub-band formed $\sim 15$ km ahead of the first. As the second sub-band intensified, a third sub-band formed $\sim 15$ km ahead of the second. The time interval between the formation of each sub-band was $\sim 30$ min.

b. 8 December 1976

A series of warm-sector rainbands, with radar echo tops extending to a height of $\sim 5$ km, was observed on this day. One of the rainbands moved from the leading edge of the surface cold front into the warm sector (Fig. 3). Later, a second rainband began to form in a similar position. It is likely that the warm-sector rainbands originated at the surface cold front. Fig. 3 provides observational support for this view, since correspondences can be seen between the horizontal extent, intensity and orientation of the precipitation cores on the narrow cold-frontal rainband and the sub-structure of the warm-sector rainbands.

In contrast with the 17 November case, where new bands formed ahead of existing features, both of the warm-sector rainbands on 8 December appeared to be in a rather steady-state condition during the periods that they were within range of the CP-3 radar. Also, the positions of the updrafts on 8 December and 17 November were quite different. In the former case, the updraft was associated with convergence above 1 km (Fig. 4), whereas on 17 November the updraft originated in convergence within the boundary layer (Hobbs et al., 1980). The precipitation intensity was greater in the 17 November warm-sector rainbands, as evidenced by radar reflectivities that were 5 dB(Z) greater than in the warm-sector rainbands on 8 December. Perhaps the position of the updraft, or the intensity of a precipitation-induced downdraft, is important in the formation of new sub-bands ahead of existing rainbands.

The other warm-sector rainbands observed on 8 December did not originate within range of the CP-3 radar. However, they appeared to be rather steady state as they moved through the area of radar coverage.
c. 16–17 December 1976

A single weak warm-sector rainband was observed in this case. Again, some correspondence between the horizontal extent, intensity and orientation of the cores on the narrow-cold-frontal rainband and the structure of the warm-sector rainband is evident (Fig. 5). This correspondence suggests that frontal processes may initiate warm-sector rainbands. Examination of a precipitation core in the warm sector (A in Fig. 6a) reveals that it formed within a horizontal distance of 5 km from a precipitation core along the cold front. Subsequently, an arch-shaped precipitation area (A’ in Fig. 6b) formed and enlarged as the warm-sector precipitation core intensified. This arch-shaped precipitation area, and another precipitation core in the warm sector (B in Figs. 6a and 6b) that had also formed near a cold-frontal precipitation core, combined to form a sub-band of the warm-sector rainband (Fig. 6c). Finally, an additional precipitation area (C in Fig. 6c), which may have been associated with orography since it formed along the coastline, appeared ahead of this sub-band.

d. Discussion

In the three cases described above, the warm-sector rainbands formed at the leading edge of the cold front. A correspondence between the regions of heavy precipitation on the front and the initial distribution of precipitation in the warm sector is seen in two of the cases. In one case, the formation of banded warm-sector precipitation was due to the merger of two precipitation cores that originated just ahead of precipitation cores on the narrow cold-frontal rainband.

These results suggest that frontal processes, perhaps latent heat release or momentum imbalances associated with the cold-frontal precipitation cores, play a role in the initiation of warm-sector rainbands.
5. Formation and initial behavior of the prefrontal cold-surge rainbands

Detailed mesoscale analyses of occluded frontal systems (Kreitzberg and Brown, 1970; Browning et al., 1973; Matejka et al., 1980) have shown that the frontal zone at the leading edge of the cold airmass can contain several successive pulses of cold air. The strongest pulse is typically identified as the cold front, while the weaker pulses, located over the warm front, are called prefrontal cold surges. These cold surges are associated with mesoscale rainbands, aligned approximately parallel to the synoptic-scale cold front. In this section we present observational data on the formation and behavior of prefrontal cold-surge rainbands observed in the cold-type occlusions that passed over the CYCLES network on 14 and 21 November 1976.

a. 14 November 1976

During the initial radar coverage of this case, a wide cold-frontal rainband straddled the surface occluded front (Fig. 7a). This rainband extended to a height of ~5 km and moved with the winds aloft, at a speed of ~8 m s⁻¹ faster than the surface front. At the time it passed over the CP-3 radar site (Fig. 7b), the rainband was associated with a slight rise in pressure, perhaps indicative of a pulse of cold air aloft. The horizontal wind pattern, derived from the CP-3 Doppler radar color display, included a nearly 25° backing of the wind with height in the vertical layer between 2.5 and 4.0 km. As the rainband moved toward the eastern edge of the range of the CP-3 radar coverage, it was located over 50 km ahead of the surface front and above the warm-frontal zone aloft (Fig. 7c). At this stage, since the rainband was oriented approximately parallel to the cold front and was over the warm-frontal zone, it was classified as a prefrontal cold-surge rainband.

A second wide cold-frontal rainband was observed to form behind the surface occluded front at this time (Fig. 7c). This rainband also moved faster than the surface front and was later observed to straddle the front. The position of this second rainband with respect to the front was then similar to the location of the first rainband shown in Fig. 7a.

b. 21 November 1976

The prefrontal cold-surge rainbands observed in this cyclone were similar to those described above, but they were better defined.

A series of four rainbands was observed on 21 November 1976. They were oriented approximately parallel to the cold front, and their radar echo tops extended above 5 km. In view of their orientation and positions within the occluded system, we classify these as prefrontal cold-surge rainbands. Other observations support this classification. For example, the CP-3 Doppler radar data revealed marked backing of the winds with height, particularly in the case.

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Fig. 6. A series of CP-3 radar reflectivity PPI displays for 16–17 December 1976 taken at an elevation angle of 0°. The scan is contoured at the 24 dBZ level, and the shading is as noted in Fig. 3. The position of the mesoscale cold front at the surface (as located by the narrow cold-frontal rainband) is indicated. (a) 2331 PST 16 December, showing the location of warm-sector precipitation cores A and B. (b) 2337 PST 16 December, showing core A now as an arch-shaped area (labeled A') extending northward. Also shown is core B. (c) 0016 PST 17 December, showing the merger of the arch-shaped area (A') and core B into a sub-band (on either side of the dashed line). Also shown is an additional core region (C) that formed ahead of the band-shaped area along the Pacific coastline.
Fig. 7. A series of CP-3 radar reflectivity PPI displays taken at an elevation angle of 0° on 14 November 1976. The scans are contoured and stippled at the 24 dBZ level. (a) 1609 PST. The wide cold-frontal rainband (labeled 1) straddles the occluded front. (b) 1732 PST. The wide cold-frontal rainband is located ahead of the occluded front. (c) 1838 PST. The wide cold-frontal rainband is ~50 km ahead of the occluded front, and is now classified as a prefrontal cold-surge rainband. The formation of a second wide cold-frontal rainband (labeled 2) is also shown. The cores of the narrow cold-frontal rainband are shown in black where they were evident on the radar display.

of the first and last rainbands where the winds backed, respectively, from 260° to 230° in the layer between 3.5 and 6.0 km and from 270° to 230° in the layer between 1.5 and 4.5 km. Also, at times, these rainbands were associated with slight rises in surface pressure and a decrease aloft in the temperature and wet-bulb potential temperature (Fig. 8).

The rainbands behaved as follows. At the time of initial radar coverage, two surge rainbands were observed ahead of and parallel to the surface occluded front (Fig. 9). The second of these rainbands was shallow and less intense than the other features. Both of these rainbands moved faster than the surface front. A third rainband formed behind the surface front. It also moved faster than the front and eventually overtook it (Fig. 9b). At this time a fourth rainband was observed behind the surface front (Fig. 9c); it also rapidly overtook the surface front. The fourth rainband was particularly well defined, even when it was located behind the surface front. As it moved over the surface front, the precipitation and wind structure previously associated with the front dissipated. Prior
to the dissipation of the precipitation on the surface front, the precipitation cores associated with the front exhibited reflectivities in excess of 34 dB(Z) and they were associated with a distinct windshift. No rainbands were observed behind the fourth rainband. Although cold advection continued after its passage, the sharp frontal characteristics at the surface did not reappear.

c. Discussion

The above observations show that prefrontal cold-surge rainbands originate behind surface occluded fronts. This finding is consistent with the suggestions of Kreitzberg and Brown (1970) and Matejka et al. (1980) that the prefrontal pulses of cold air originate in the cold airmass. The observation that the prefrontal cold-surge rainbands originate in locations similar to those of wide cold-frontal rainbands is interesting, since Matejka et al. (1980) and Hobbs et al. (1980) found that wide cold-frontal rainbands are themselves associated with regions of enhanced baroclinity. The enhanced baroclinity accompanying wide cold-frontal rainbands are typically weaker than those associated with prefrontal surges; the former are often associated with irregularities in the cold-frontal surfaces aloft (Matejka et al., 1980). A possible reason for the enhanced baroclinity of the surge rainband may be the relatively long times for which differential advection aloft and/or evaporative cooling takes place compared to wide cold-frontal rainbands.

In both of the cases described in this section, the rainbands associated with the pulses of cold air aloft moved more rapidly than the core structure on the cold front. Thus, relative to the leading edge of the cold air at the surface, the cold air aloft advances in an occluded system.

6. Origin and initial behavior of narrow cold-frontal rainbands

In all cases the narrow cold-frontal rainbands were associated with a windshift across the surface front and they remained coincident with the front. Also, in all cases, the narrow cold-frontal rainbands contained precipitation cores oriented at a distinct angle to the surface front, as first noted by Hobbs (1978), James and Browning (1979) and Hobbs and Biswas (1979).

The radar echo patterns associated with the precipitation cores for each of the five cases to be discussed here are shown in Fig. 10. Considerable similarity is evident in the various cases. For example, the mean angle between the long axes of the precipitation cores and the front ranged from 34 to 38°, while the mean horizontal area of the precipitation cores for the five cases varied from ~48 to 100 km². These similarities occurred despite significant differences in the boundary layer flow ahead of the cores; the stability in the boundary layer ranged from potentially unstable in three cases to an extremely stable lapse rate on 21 November 1976 (Fig. 11). The characteristics of the narrow cold-frontal rainbands and the cores varied with time, as they were affected by interactions with other rainbands. We will consider these interactions in Section 10.

7. Formation and initial behavior of wide cold-frontal rainbands

Wide cold-frontal rainbands are associated with enhanced frontal-scale lifting above the cold front; at times this lifting appears to be associated with irregularities in the frontal topography (Hobbs et al., 1980; Matejka et al., 1980). These rainbands are oriented
approximately parallel to the surface cold front. While the narrow cold-frontal rainbands are typically several kilometers in width, the wide cold-frontal rainbands are a few tens of kilometers wide. In this section, we present information on the formation and initial behaviors of wide cold-frontal rainbands from each of the five cyclonic systems included in this study, each of which contained at least two wide cold-frontal rainbands.

a. 14 November 1976

As described in Section 3a, the two wide cold-frontal rainbands in this case moved ahead of the surface cold front, overtook the warm front, and eventually became prefrontal cold-surge rainbands. The second wide cold-frontal rainband was observed with the CP-3 radar to originate as cellular precipitation areas, about 40 km behind the surface.
Fig. 10. A series of CP-3 radar reflectivity PPI displays taken at an elevation angle of 0° for five cold fronts. In each case the precipitation cores of the narrow cold-frontal rainbands are shaded, with other areas left unshaded. (a) 1733 PST 14 November 1976, contoured at 23 dB(Z) level. (b) 0530 PST 17 November 1976, contoured at the 39 dB(Z) level. (c) 0544 PST 21 November, contoured at 29 dB(Z) level. (d) 0531 PST 8 December 1976, contoured at the 34 dB(Z) level. (e) 1206 PST 17 December 1976, contoured at the 34 dB(Z) level.

Fig. 11. Vertical profiles of thermodynamic variables in the lower layers from a sounding launched at 0450 PST 21 November 1976. (a) Wet-bulb potential temperature. (b) Temperature (solid line) and dew point (dotted line). Shown for comparison are the dry (dashed line) and saturated (dot-dashed line) adiabatic lapse rates. Note the overall tendency for a stable lapse rate in the boundary layer.
front, after the first wide cold-frontal rainband had moved ahead of the front (Fig. 12). The cellular regions covered areas up to 120 km$^2$ and extended to a height of 3.5 km. The cores slowly evolved into a band-shaped feature $\sim$20 km in width. This band-shaped feature is the second wide cold-frontal rainband shown in Fig. 7c.

b. 17 November 1976

Four wide cold-frontal rainbands were observed on 17 November 1976. They extended to heights of $\sim$5–6 km and were associated with weak generating cells near their radar echo tops (Hobbs et al., 1980). Since the wide cold-frontal rainbands were already in existence as they moved into the range of the CP-3 radar, their origins are unclear. However, from their movement and presence at least 100 km behind the surface front (Fig. 13), it is evident that the rainbands formed somewhere near the back edge of the cold-frontal cloud shield. Examination of the trailing portion of the cloud shield revealed the presence of banded areas of enhanced reflectivities aloft. These banded areas may have been the forerunners of the wide cold-frontal rainbands. The rainbands moved with the velocity of the wind at altitudes of between 3 and 6 km. Since they moved at speeds of up to 8 m s$^{-1}$ faster than that of the surface cold front, they eventually overtook the cold front and moved into the warm sector.

Fig. 12. A CP-3 radar reflectivity PPI display taken at an elevation angle of 0$^\circ$ at 1748 PST 14 November 1976. The scan is contoured and stippled at the 19 dB(Z) level. The position of the mesoscale cold front at the surface (as located by the narrow cold-frontal rainband) is indicated. The main feature shown is the first wide cold-frontal rainband as it straddled the front. The irregularly-shaped cores behind the surface cold front were the origins of the second wide cold-frontal rainband.

Fig. 13. A CP-3 radar reflectivity PPI display at an elevation angle of 0.8$^\circ$ at 0802 PST 17 November 1976. The scan is contoured and stippled at the 29 dB(Z) level and contoured at the 24 dB(Z) level (dashed line). The portion of the mesoscale cold front at the surface (as located by the narrow cold-frontal rainband) is indicated. Three of the wide cold-frontal rainbands are shown (labeled 1–3).
c. 21 November 1976

Two wide cold-frontal rainbands were observed on this day. The rainbands extended to a height of nearly 6 km and were associated with generating cells aloft. The wide cold-frontal rainbands moved with the winds above the cold front at a speed of a few meters per second faster than the surface front. They overtook the surface front, and became associated with the third and fourth pulses of cold air above the warm front aloft.

The development of the first wide cold-frontal rainband can be seen in Fig. 9b. It was associated with the third pulse of cold air (see Fig. 8) and began to form behind the cold front in the form of weak, scattered precipitation cores. In its mature form the rainband was ~30 km wide and had radar reflectivities 10–15 dB(Z) greater than in its formative stage.

The second wide cold-frontal rainband was first observed over 60 km behind the first wide cold-frontal rainband. In contrast to the first wide cold-frontal rainband, which developed rather close to the surface front (see Fig. 9b), the second rainband was already identifiable as a band when it moved into the range of the CP-3 radar. Behind this rainband were narrow bands of enhanced reflectivity aloft (Fig. 14).

d. 8 December 1976

Three rather ill-defined wide cold-frontal rainbands were observed on this day. They extended to a height of nearly 5.6 km and were associated with generating cells aloft. They moved with the winds above the cold front at a speed a few meters per second faster than the surface cold front. However, the rainbands did not move ahead of the surface cold front but instead dissipated over the front.

The first wide cold-frontal rainband was evident in the radar reflectivity pattern as it moved into the range of the CP-3 (Fig. 15a). As the first rainband moved toward the surface cold front, a second wide cold-frontal rainband began to form ~35 km behind the first (Fig. 15b). The process was repeated with the formation of a third wide cold-frontal rainband that formed ~30 km behind the second (Fig. 15c).

e. 16–17 December 1976

Although two wide cold-frontal rainbands existed in this case, one of them (~30 km wide) was the predominant precipitation feature associated with the cold front aloft (Fig. 16a). This wide cold-frontal rainband moved at a speed of 4 m s\(^{-1}\) faster than the surface front, and a portion of this rainband overtook the surface cold front and moved into the warm sector. This behavior is similar to that of the cases previously described.

The first rainband already existed as it moved into the range of the CP-3 radar. However, a second weaker wide cold-frontal rainband formed within the range of the CP-3 radar. The initial formation of this rainband began with scattered precipitation cores (Fig. 16b) located ~30 km ahead of the center of the first wide cold-frontal rainband. This core structure intensified and merged to form the second rainband (Fig. 16c) at the same time as the wavelike rainbands were intensifying within this area. The radar reflectivity structure behind the first wide cold-frontal rainband did not reveal other wide cold-frontal rainbands, but there were narrow lines of precipitation aloft.

f. Discussion

The wide cold-frontal rainbands described in this section exhibited a surprising degree of similarity. In each case, the rainband moved faster than the surface front, with velocities relative to the front ranging from a few meters per second up to 8 m s\(^{-1}\). As the rainbands reached the surface front they often overtook it, moved into the warm sector, and then above the warm front.

The motion of the wide cold-frontal rainbands relative to the cold front suggests a degree of independence between the surface front and the enhanced mesoscale baroclinic zones associated with wide cold-frontal rainbands. Recent theoretical studies (e.g., Hoskins and Heckley, 1981), and an early observational study by Sanders (1955), show that extreme
Fig. 15. A series of CP-3 radar reflectivity PPI displays taken at an elevation angle of 0° and contoured at the 24 dB(Z) level on 8 December 1976. The shading indicates the type of rainband, as noted in Fig. 3. The position of the mesoscale cold front at the surface (as located by the narrow cold-frontal rainband) is indicated. (a) 0551 PST. The first wide cold-frontal rainband (labeled 1 and denoted by a dashed line) is shown. (b) 0657 PST. The first and second wide cold-frontal rainbands (labeled 1 and 2) are shown. (c) 0723 PST. The initial formation of the third wide cold-frontal rainband (labeled 3) is shown. Note that the rainbands did not move into the warm sector.
Fig. 16. A series of CP-3 radar reflectivity PPI displays taken at an elevation angle of 0° and contoured at the 24 dB(Z) level on 17 December 1976. The shading indicates the various type of rainband, as noted in Fig. 3. The position of the mesoscale surface cold front at the surface (as located by the narrow cold-frontal rainband) is indicated. (a) 0122 PST. The location of the first and predominant wide cold-frontal rainband is shown. (b) 0206 PST. The formation of scattered cellular areas of precipitation ahead of the wide cold-frontal rainband is shown. (c) 0337 PST. The cellular areas have enlarged to form the second wide cold-frontal rainband.

Gradients of temperature and velocity in a cold front are quite shallow. Hence, it is not surprising that frontal zones in the mid-troposphere can be influenced by mesoscale features.

The formation of the wide cold-frontal rainbands took place between the back edge of the cold-frontal cloud shield and the surface cold front. In most cases the rainbands formed behind existing wide cold-frontal rainbands, although in some cases they formed ahead of existing features. The formation of the wide cold-frontal rainbands was often preceded by narrow lines of precipitation aloft and/or scattered irregularly-shaped precipitation cores. The existence of potential instability above the cold front, and the presence of the scattered precipitation cores and narrow lines of precipitation, suggest that imbedded convection aloft may precede wide cold-frontal rainbands.

8. Origins and initial behavior of wavelike rainbands

Of the five cyclonic systems described in this paper, all but one (14 November 1976) contained pronounced wavelike rainbands. In the other four cases, wavelike rainbands were located within or near the wide cold-frontal rainbands. However, the wavelike rainbands were distinct from the wide cold-frontal rainbands; wide cold-frontal bands existed without wavelike rainbands, and wavelike rainbands were located both within and outside of the wide cold-frontal rainbands. The preferred location of the wavelike rainbands appeared to be toward the rear of the upper-level precipitation deck associated with the cold front aloft.

The wavelike rainbands that were observed are shown in Fig. 17. They exhibited many similarities. For example, their mean spacing varied only from 11 to 16 km and their average area was typically between 50 and 200 km². Also, in each case, the orientation of the long axes of the rainbands was approximately perpendicular to the alignment of the synoptic-scale, surface cold front. Despite the similarities between the wavelike rainbands, they exhibited significant differences from the wavelike rainbands discussed by Matejka et al. (1980). In the latter case, the wavelike rainbands were linked to shallow but intense convection in the cold airmass behind prefrontal surges in occlusions. The wavelike rainbands being discussed here were most clearly evident in the vertical, from near the top of the frontal zone to the top of the radar echoes (typically from 1.5 to 5.5 km). In most cases only a small amount of potential instability existed near the top of the rainbands.

Since the wavelike rainbands were usually observed when the CP-3 radar was scanning at elevation angles ≥ 2°, it was difficult to follow the life cycle of individual rainbands. However, they were long-lived; in one case the wavelike rainbands were present for 3
Fig. 17. CP-3 radar reflectivity PPI displays showing wavelike rainbands (long axes along dashed lines). (a) 1102 PST 17 November 1976. The scan was at an elevation angle of 2.9° and it is contoured and stippled at 24 dBZ. (b) 0832 PST 21 November 1976. The scan was at an elevation angle of 2.9° and is contoured and stippled at 24 dBZ. (c) 0628 PST 8 December 1976. The scan was at an elevation angle of 2.9° and is contoured and stippled at 24 dBZ. The black regions are additional areas of reflectivity evident at other elevation angles. (d) 0403 PST 17 December 1976. The scan was at an elevation angle of 1.9° and is contoured and stippled at 29 dBZ. Behind the wavelike rainbands is a larger wide cold-frontal rainband.

h, and in another they were evident in data from both the CP-3 and UW search radars, which were separated by 162 km. The longevity of the wavelike rainbands is somewhat surprising since their horizontal dimensions are typical of small mesoscale areas.

9. Origin and initial behavior of postfrontal rainbands

Postfrontal rainbands are located behind the precipitation shield of the cold front but within the postfrontal airmass. Some aspects of this type of rainband have been discussed by Houze et al. (1976), Hobbs (1978) and Matejka et al. (1980). They are convective in nature and associated with potential and/or conditional instability in the lower layers of the postfrontal airmass. They are aligned approximately parallel to the surface cold front. In this section we are concerned with the origin and initial behavior of postfrontal rainbands based on data collected in the cyclones of 14 November, 8 December, and 16–17 December 1976.

a. 14 November 1976

Two postfrontal rainbands were observed on this day. They were located in the northern portion of the region of CP-3 radar coverage. During the periods of their maximum intensities, each covered an area of ~600 km². The rainbands moved with the velocity of the lower-level winds and extended to a height of nearly 3.5 km. The locations, heights and movements of the rainbands suggest that they were associated with potential instability, typically present in the lower layers of postfrontal airmasses.

The first postfrontal rainband was clearly observed in the CP-3 radar data for over 1.5 h, after which it moved into the Olympic Mountains (Fig. 18). With the exception of a slight tendency for the rainband to strengthen as it approached the coast, it appeared fairly steady-state during the period of observations. The second postfrontal rainband (Figs. 18b and 18c) formed ~20 km behind the first postfrontal rainband. Although the tendency for convective elements to form ahead of existing elements is well known, the formation of newer elements or lines behind an existing line of convection seems to be less common. In the present case it is possible that the second rainband could have existed, but was not observed prior to observation by the radar, since this rainband was shallow and weak.

b. 8 December 1976

Two postfrontal rainbands were observed on 8 December 1976 (Fig. 19). Both were convective and
launched within 40 km of these rainbands indicated that the postfrontal airmass was both potentially and conditionally unstable.

The origins of the rainbands could not be determined from the radar data. They appeared to be steady-state during the ∼1.5 h of observation, and both were narrow (∼10 km in width). The rainbands and their cores remained similar in intensity and continued to be spaced nearly 30 km apart during their movement through the region of CP-3 radar coverage.

c. 16–17 December 1976

In this case, a series of postfrontal rainbands were evident for over 9 h after the passage of the surface cold front at Pt. Brown. These rainbands moved with the velocity of the winds above the boundary layer. Their radar echo tops extended to nearly 3.5 km. Their horizontal dimensions and structures varied, although in most cases the rainbands were <10 km in width.

The first postfrontal rainband was observed for nearly 1.5 h, after which it approached the cold-frontal precipitation shield and was difficult to locate. A striking feature of this rainband was the presence of oriented precipitation cores (Fig. 20), similar to those.
observed in narrow cold-frontal rainbands by Hobbs and Biswas (1979). We believe this to be the first reported observation of core structure in a postfrontal rainband. Other postfrontal rainbands, observed behind the first, also showed a tendency toward oriented core structures. No interactions were observed between the postfrontal rainbands.

The occurrence of an oriented core structure in the postfrontal rainbands in this case is not entirely surprising. After the cold front passed the CP-3 radar site, its velocity and intensity noticeably decreased as a wave developed along the trailing edge of the frontal zone to the southwest of the CYCLES network. During this period the surface winds behind the cold front began to gradually return to a southerly direction. These conditions persisted for over 9 h, until a sharp windshift associated with a rainband moved through the network and the winds in the boundary layer became westerly. During the period that the first postfrontal rainband was observed, the boundary layer flow, which is believed to be important to the formation of an oriented core structure (Hobbs and Persson, 1982), was similar to a prefrontal condition.

10. Interactions between narrow and wide cold-frontal rainbands

Narrow and wide cold-frontal rainbands exhibited the most obvious interactions. The observed interactions can be divided into three categories (Fig. 21). In the first type of interaction, the wide cold-frontal rainband moved over and ahead of the narrow cold-frontal rainband, but the former continued to exist (Fig. 21a). The narrow cold-frontal rainband began to undergo modification when the wide cold-frontal rainband was located over the surface cold front. At this stage, it was difficult to locate the narrow cold-frontal rainband. There were indications, from Doppler radar data, that the passage of the wide cold-frontal rainband may have caused some decrease in the frontal convergence in the boundary layer which is necessary for the maintenance of the narrow cold-frontal rainband (Hobbs and Persson, 1982). As the wide cold-frontal rainband moved ahead of the surface front, the narrow cold-frontal rainband began to reform as a rather irregular line containing precipitation cores but without a distinct alignment. Later the cores aligned at an angle of 30–35° to the synoptic-scale cold front. The time period for the reformation of the precipitation cores on the front was ~10–75 min.

In the second category of interaction, the movement of the wide cold-frontal rainband over and then ahead of the narrow cold-frontal rainband permanently dissipated the latter (at least while it was within range of the radar), and the frontal windshift was greatly weakened (Fig. 21b). This pattern occurred on 21 November 1976, when the fourth surge of cold air moved over the surface front. At this time the low-pressure center was filling and the NWS analysis indicated that the front was dissipating. The wide cold-frontal rainband was later associated with the predominant cold pulse aloft.

The third category of interaction occurred when the narrow cold-frontal rainband and its core structure were particularly well defined, while the wide cold-frontal rainband aloft was rather weak. In this case, the wide cold-frontal rainband moved over the surface front and the wide cold-frontal rainband then dissipated.

11. Dissipation of rainbands

Rainbands can dissipate during interactions with other rainbands. Two examples (Figs. 21b and 21c) have been described above. Orography can also disrupt rainbands, as discussed by Parsons and Hobbs (1983). Browning et al. (1973) found that rainbands may dissipate when environmental conditions (such as the location or presence of potentially unstable layers) change.

12. Summary and conclusions

In this paper we have examined some aspects of the formation, development, interactions and dissipation of warm-sector, prefrontal cold-surge, narrow cold-frontal, wide cold-frontal, wavelike and postfrontal rainbands in five cyclones in the Pacific Northwest.
FIG. 21. Schematic showing three modes of interaction between wide cold-frontal rainbands and the narrow cold-frontal rainband. (a) The wide cold-frontal rainband overtakes the narrow cold-frontal rainband (based on the 14 cases of 17 and 21 November 1976). The narrow cold-frontal rainband is disturbed, but its core structure reforms. (b) The wide cold-frontal rainband overtakes the narrow cold-frontal rainband and the narrow cold-frontal rainband dissipates (based on the 21 November 1976 case). (c) The wide cold-frontal rainband reaches but does not move ahead of the narrow cold-frontal rainband (based on the 8 December 1976 case).

Warm-sector rainbands seem to form just ahead of the leading edge of the cold front, and the scale of their sub-structure is similar to that of the precipitation cores that comprise the narrow cold-frontal rainband. Wide cold-frontal rainbands form somewhere between the back edge of the cold-frontal cloud shield and the surface cold front, sometimes over 150 km behind the surface front. Prefrontal cold-surge rainbands form in similar locations to the wide cold-frontal rainbands, but, in the open wave portion of the cyclone, they have a tendency to form closer to the surface cold front. Wavelike rainbands show a
distinct tendency to be located behind the surface cold front, with radar echo tops near or above the cold-frontal zone aloft.

There is a tendency for weak disorganized convection, or embedded convection, to be present during the initial formation of some of the rainbands. Previous studies of squall lines, both in the tropics (e.g., Houze, 1977) and in midlatitudes (e.g., Kreitzberg and Perkey, 1977), have revealed tendencies for convective-scale systems to develop mesoscale updrafts.

We have also presented in this paper some aspects of the behavior of rainbands after their formation. The warm-sector rainbands moved away from the surface cold front in two of the three cases studied, new banded warm-sector precipitation formed upwind of existing warm-sector rainbands. All of the wide cold-frontal rainbands moved faster than the surface cold front and eventually caught up with the surface front; thereafter their behavior varied. The two wide cold-frontal rainbands in the occluded systems moved ahead of the cold front and became associated with prefrontal cold-surge rainbands above the warm front. In one of the cyclones the wide cold-frontal rainbands dissipated over the surface cold front. In two other cyclones, the wide cold-frontal rainbands moved ahead of the cold front and into the warm sector.

Matejka et al. (1980) suggested that wide cold-frontal rainbands that move into the warm sector may have dynamical and microphysical characteristics that differ from those of warm-sector rainbands that originate ahead of the cold front. However, in the wide cold-frontal rainband referred to by Matejka et al., the convergence was most intense in the lower layers; this differs from the usual pattern for wide cold-frontal rainbands above the cold front, which generally have their maximum convergence aloft. Modifications to wide cold-frontal rainbands as they move into the warm sector may be important in the initiation of warm-sector convective systems. For example, Newton (1950) found that warm-sector squall lines often originate behind surface cold fronts.

The wavelike rainbands described in this paper had a component of their movement toward the surface cold front, yet they seemed to remain behind the surface front. The most striking aspect of these rainbands was their similarity. For example, in the four cyclones that contained wavelike rainbands, the mean wavelength of the rainbands varied from only 11 to 16 km.

The postfrontal rainbands moved with the wind behind the cold front, and therefore remained within the postfrontal airmass. In one case, a postfrontal rainband was observed to form behind an existing postfrontal feature. Houze et al. (1976) described a postfrontal rainband that formed ahead of an existing rainband, in a manner that is more typical of convective systems. One postfrontal rainband observed in the present study maintained convective-like characteristics, including wind and temperature changes. Matejka et al. (1980) described a postfrontal rainband that intensified and was eventually analyzed as a secondary cold front. It appears that postfrontal rainbands can exhibit a variety of life-cycles after their initial formation.

The intensities of the narrow cold-frontal rainbands were modulated by interactions with wide cold-frontal rainbands. When a wide cold-frontal rainband overtakes a surface cold front, the narrow cold-frontal rainband and its core structure may be difficult to locate. However, subsequently, the narrow cold-frontal rainband may reform as a "wavy" precipitation line, which subsequently breaks down into the oriented precipitation cores described by Hobbs (1978), James and Browning (1979) and Hobbs and Biswas (1979). However, in one case described in this paper, the narrow cold-frontal rainband dissipated and did not reform after it was overtaken by a particularly intense wide cold-frontal rainband. On another occasion a weak wide cold-frontal rainband dissipated as it moved over a strong narrow cold-frontal rainband.

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