

MESOSCALE STRUCTURE OF RAINFALL IN OCCLUDED CYCLONES

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1. INTRODUCTION

As a result of numerous studies (see reviews by Harrold and Austin, 1974, and Browning, 1974), it is now recognized that the rainfall in extratropical cyclones tends to be concentrated within mesoscale areas, which have horizontal dimensions of tens to hundreds of kilometers. The largest mesoscale areas tend to be elongated, with lengths exceeding widths by a factor of two or more. In this paper such elongated features are referred to as rainbands (or bands for short).

Since 1973, the Cloud Physics Group at the University of Washington has been engaged in an intensive study of cyclonic storms in Western Washington, known as the CYCLES (Cyclonic Extratropical Storms) PROJECT. As part of the CYCLES PROJECT we have investigated the mesoscale structure of rainfall in eleven occluded cyclones. In this paper, we present examples of the rainbands which were observed in these storms and suggest a classification scheme for them. Although our observations are exclusively of occluded cyclones in the Pacific Northwest, we have found that rainbands in extratropical cyclones in various parts of the world, which have been described by other investigators, also fit neatly into the suggested classification. Consequently, it appears that our classification of rainbands may be applicable to extratropical cyclones in general.

2. LOCATIONS OF STUDIES AND FACILITIES

Two types of studies were conducted. The first type (referred to as the Pacific Ocean studies) focussed on precipitation patterns occurring over a region of the Pacific Ocean extending west of the Washington State coastline. The primary facility for these studies was a large radar installation located on the Pacific coast of Washington at Neah Bay. This radar provided coverage of rainfall patterns over the Pacific Ocean out to a distance of about 200 km from Neah Bay.

The second type of study, referred to as the Washington studies, was concerned with rainfall patterns over inland western Washington. Primary data for these studies were obtained from a network of raingauges operated by the National Weather Service and by the University of Washington (UW). The time resolution of the gauges operated by the Weather Service was 5-10 min in moderate rain while those operated

by the UW had a time resolution of 15 s in moderate rain. For the Washington studies two weather radars were operated in Seattle, one by the UW (wavelength $\lambda = 3.2$ cm, peak power 250 kW, beam width 1°) and the other (the CP-3) by the National Center for Atmospheric Research ($\lambda = 5.45$ cm, peak power 338 kW, beam width 1°).

3. EXAMPLE OF A PACIFIC OCEAN STUDY

Examples of data obtained from the Neah Bay radar on November 27-28, 1973, are shown in Fig. 1. The relationship of the small-scale features observed on the radar to the large-scale storm system can be inferred from the superimposed sea-level frontal positions. When a pattern of widespread rain was located over Neah Bay, the PPI display typically appeared as shown in Fig. 1(a), with a very bright echo surrounding the center of the display and extending out to ranges of up to 75 km. (Note: The Neah Bay radar PPI displays shown in Fig. 1 are not range corrected or quantized into various intensity levels.) Structural features embedded within the general rain area, such as band A in Fig. 1(a), are seen as they existed in the region outside of the central echo. Band A was located parallel to the warm front and moved in a direction normal to its orientation at a speed of 24 m s^{-1} . Band B in Fig. 1(b), which occurred in the warm sector, appeared to move northeastward, parallel to its orientation. When bands A and B passed over raingauges on the Washington coast the fifteen-minute average rainfall rates were 2 to 5 mm h^{-1} .

The surface cold front on 27-28 November was accompanied by a remarkably narrow (≈ 2 km in width) and continuous radar echo, band C, portions of which can be seen in Figs. 1(b) and (c). The precipitation rates which occurred as this long narrow band passed over the coastal rain gauge stations were consistently very high with 5 to 10 minute average values of 25 to 50 mm h^{-1} . Band C was about 4 km in vertical extent.

Long, thin and continuous rainbands similar to band C, coinciding with surface cold fronts, have been observed previously by Kessler and Wexler (1960) and Browning and Pardoe (1973). The radar echo lines observed by these investigators were each followed by a 100-km wide zone of lighter precipitation. Browning and Pardoe hypothesized that the narrow rainband was an intense line of convection generated by lifting at the leading edge of the surface frontal

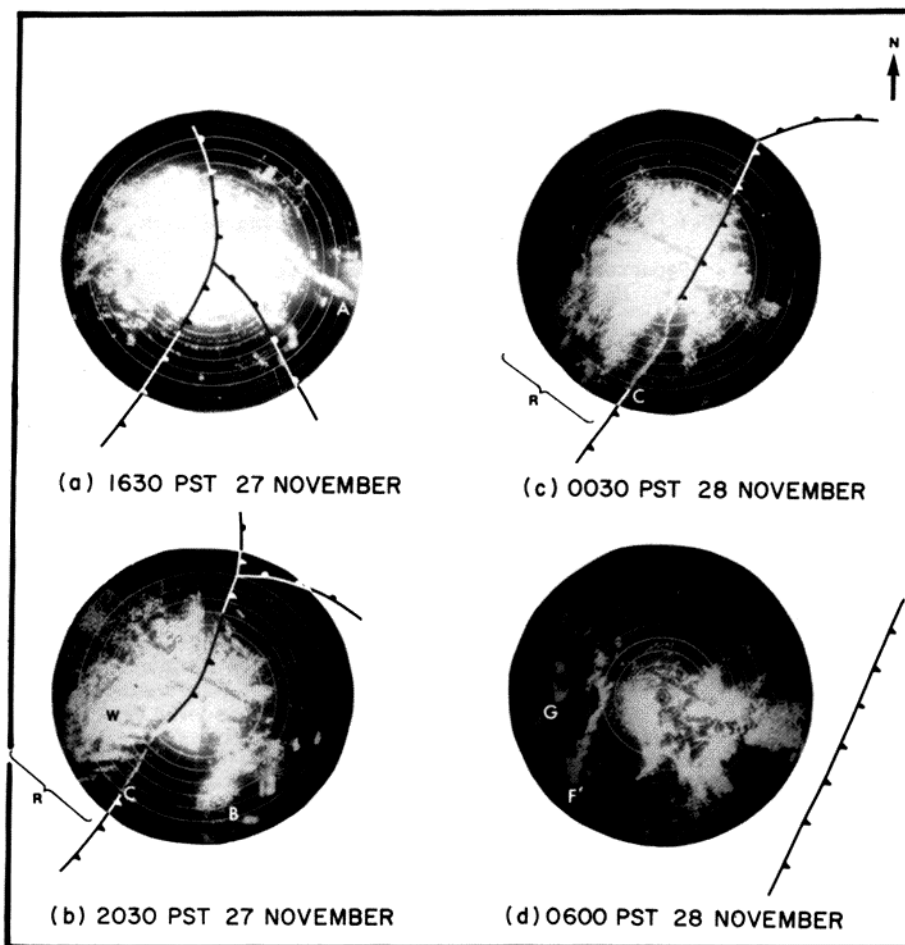


Figure 1. Photographs of PPI displays from Neah Bay, Washington, radar and sea-level frontal positions. Letters designate rainbands referred to in text. Range markers are separated by intervals of 18.5 km.

system, while the zone of lighter precipitation which followed it was due to gradual, slant-wise ascent above the sloping frontal surface. In our case, a 100-km wide zone of relatively light rain [Region R in Figs. 1(b) and 1(c)] followed the intense narrow band C, as in the cases of Kessler and Wesler and Browning and Pardoe. However, unlike the broad bands of precipitation behind their fronts, which evidently had a fairly uniform texture, the region R in our study exhibited considerable substructure, as seen, for example, in Fig. 1(b) where a series of wave-like bands (south and east of point W) were superimposed on R. These ripples were typically $15 \text{ km} \times 70 \text{ km}$ in dimension and were moving toward the northeast, parallel to the front, at a speed of 32 m s^{-1} .

After the cold front, and the accompanying rainband C and Region R, had passed over the Washington coast, post-frontal rainbands were observed on the Neah Bay radar. Band F' (which formed from a part of a previous band F) and band G are shown in Fig. 1(d). These bands were comprised of small-scale elements, ranging in size from 10 to 1500 km^2 in area. The

discrete structure of the post-frontal bands suggest that they were more convective in nature than the other bands.

4. EXAMPLE OF A WASHINGTON STUDY

In the Washington studies, precipitation patterns were deduced from rain gauge data using a procedure similar to that of Elliott and Hovind (1964). Plots of 15-minute average rainfall rates were arranged in order of their geographical situation, and similarities in the time distributions of the rainfall rates were noted and labeled, as shown in Fig. 2. The features denoted $B_1 - B_4$ in Fig. 2 were four rainbands embedded in an occluded frontal cloud system which passed over Western Washington on 20 December 1973. The times that the front and back edges of each rainband passed over each station were plotted on a horizontal map, and isochrones of the front and back edges were constructed. From the isochrone patterns, the positions of the rainbands at any given time could be determined, as shown in Fig. 3.

In comparing rain gauge traces, such

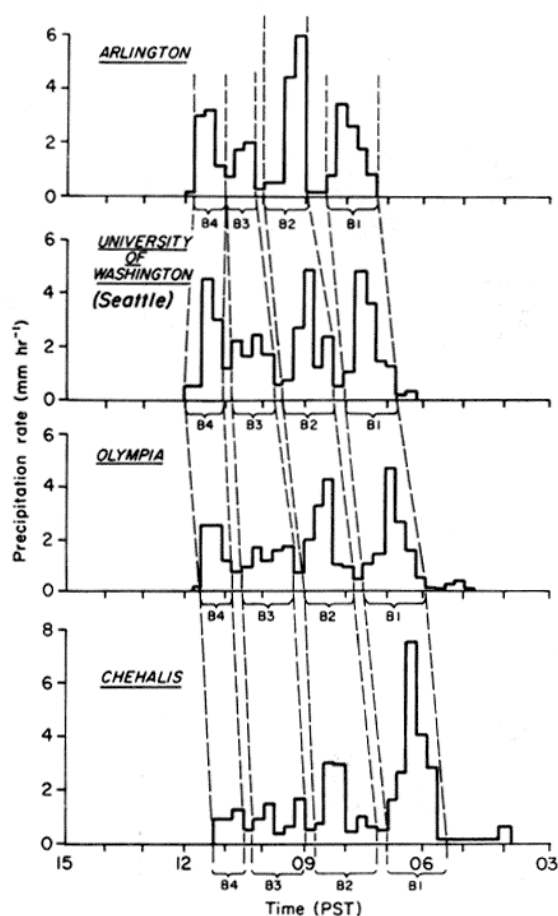


Figure 2. Precipitation rate at stations along an approximately north-south line. Lines connecting plots show front and back edges of rainbands $B_1 - B_4$.

as in Fig. 2, there is some subjectivity in deciding upon the boundaries of features such as $B_1 - B_4$. The chosen boundaries were checked in two ways. First it was assumed that the large bands moved in a more or less continuous manner over the raingauges. Hence, the boundaries were required to conform to reasonably continuous isochrone patterns for both front and back edges. Second, whenever the bands were within the area of coverage of the UW weather surveillance radar, the band structure deduced from the rain gauge data had to be consistent with the radar data (see Fig. 2).

Properties of bands $B_1 - B_4$ are summarized in Table 1. Generally, all of the bands were very similar, except in their orientation. The first two bands (B_1 and B_2) were oriented along a northwest to southeast line, while B_3 and B_4 were oriented nearly north-south. Detailed synoptic analysis, based in part on serial rawinsondes launched from the UW at intervals of 2 to 3 h, showed that the earlier bands B_1 and B_2 occurred with the passage of the warm front (of the occlusion) aloft, while the later two bands were associated with the passage of a double cold front aloft.

It is evident from the superimposed radar echoes in Figs. 3(a)-(d) that a pattern of small-scale areas of high-intensity rainfall existed within each of the large bands. The small-scale elements embedded in rainbands $B_1 - B_4$ were investigated by identifying and tracking the horizontal motion of individual radar echoes appearing in the PPI displays of the UW radar. The average areas, concentrations and motions of the echoes sampled at two receiver gain settings (maximum H and minimum L) are listed in Table 2. The sampled echoes (described in Table 2) were on the order of 10's to 100's of

Table 1. Characteristics of rainbands observed on 20 December 1973. Numbers in parentheses are extreme values.

Rainband	Period of Observation PST	Number of Stations Passed Over	Mean Rainfall Rate mm h^{-1}	Maximum Rainfall Rate mm h^{-1}	Mean Duration Over a Station min	Mean Amount of Rain at a Station mm	Width km	Orientation Relative to True North	Velocity Normal to Band m s^{-1}
B_1	0445-1000	17	2.8 (1.8-5.1)	12.4 for 1 min	69 (45-105)	3.3 (1.8-7.6)	75 (24-117)	NW-SE to NNW-SSE	18 from SW to NE
B_2	0715-1100	16	2.6 (0.8-4.1)	13.8 for 1 min	66 (30-105)	2.7 (0.8-6.1)	74 (19-145)	NW-SE	20 from SW to NE
B_3	0700-1245	13	2.2 (1.0-6.4)	21.3 for 5 min	56 (30-90)	2.1 (0.4-7.1)	48 (29-68)	N-S to NNW-SSE	16 from W to E
B_4	0830-1230	17	2.6 (0.5-6.8)	15.2 for 7 min	55 (30-90)	2.5 (0.4-10.2)	50 (15-72)	N-S	14 from W to E

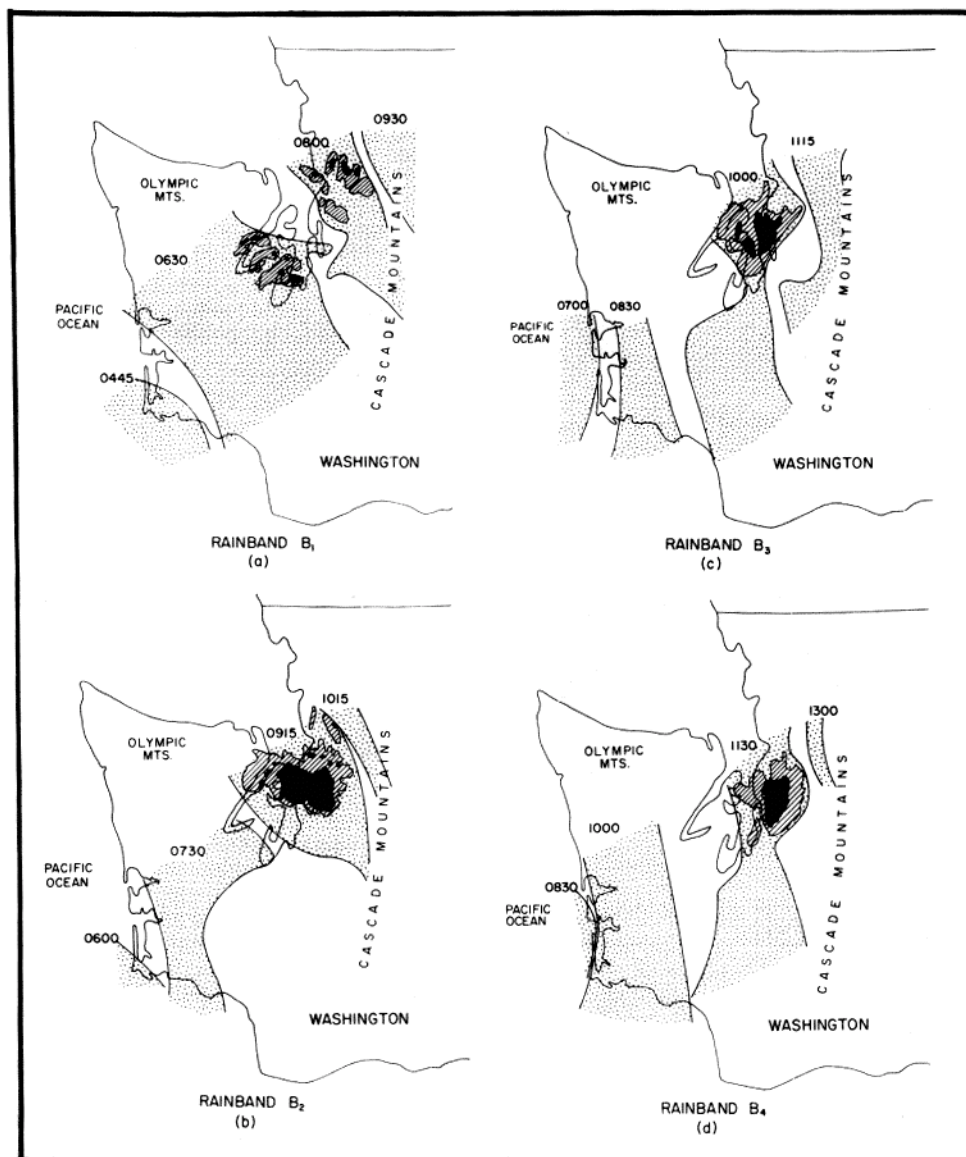


Figure 3. Rainbands B_1 - B_4 at different times (PST) during their passage over western Washington. Stippling indicates rainband positions deduced from raingauge data. Hatching shows maximum gain echoes seen on University of Washington radar. Solid areas are minimum gain echoes.

Table 2. Characteristics of the small-scale elements embedded in the rainbands observed on 20 December 1973. H and L refer to high and low gain echoes, respectively.

Rainband	Concentration of Echoes (No. per 10^3 km 2)		Echo Size (km 2)		Echo Velocity (deg/m s $^{-1}$)		Winds Aloft (deg/m s $^{-1}$)		
	H	L	H	L	H	L	850 mb	700 mb	500 mb
B_1	1.1	1.9	431	30	220/26	220/24	160/18	220/28	215/40
B_2	1.4	0.8	523	85	225/28	230/32	180/22	210/35	210/40
B_3	0.9	0.6	112	12	220/33	215/33	200/30	220/38	210/40
B_4	1.7	0.6	43	36	230/29	225/26	200/30	210/32	210/42

km² in area. Previous investigators (e.g. Browning and Harrold, 1969, and Austin and Houze, 1972) have also found that small-scale elements of this size were embedded in large mesoscale rain areas such as B₁ - B₄. The small-scale echo motions indicated in Table 2 are in close agreement with the winds between 850 and 700 mb with the best agreement at 700 mb. The precipitation in the small-scale elements was presumably generated at those levels.

5. CLASSIFICATION OF RAINBANDS

Figure 4 illustrates schematically the rainbands observed in the two case studies described above. The types of bands shown in the figure are:

Type 1: Warm frontal. Bands approximately 50 km in width oriented parallel to cold front and found toward the leading edge of a frontal cloud shield (e.g. band A on 27-28 November and bands B₁ and B₂ on 20 December).

Type 2: Warm sector. Bands typically 50 km in width, found south of the intersection of the surface warm and cold fronts and tending to be parallel to cold fronts (e.g. band B, 27-28 November).

Type 3: Cold frontal--wide. Bands approximately 50 km in width oriented parallel to cold front and found toward the trailing edge of a frontal cloud shield (e.g. band D on 27-28 November and bands B₃ and B₄ on 20 December).

Type 4: Cold frontal--narrow.

Extremely narrow band (≈ 5 km in width) coinciding with surface cold front (e.g. band C, 27-28 November).

Type 5: Wave. Bands occurring in a very regular pattern similar to waves. Generally smaller than other types of bands (typically 5 km \times 40 km, sometimes as large as 10 km \times 100 km)(e.g. bands W in Fig. 1(b)).

Type 6: Post-frontal. Rainbands located in the convective cloud field behind the frontal cloud shield (e.g. bands F' and H on 27-28 November).

6. RAINBANDS IN OTHER OCCLUDED CYCLONES

We have examined the precipitation in eleven occluded cyclones, including those described in § 3 and § 4 above, and have noted that rainbands occurred in each of these occlusions. All but one rainband could be identified as one of the six types listed in § 5, and each type of rainband was observed in more than one occlusion. Table 3 summarizes the characteristics of all of the rainbands that we have examined.

In Table 3, small areas within the rainbands are indicated as "not observed" for band Types 1-5 in the Pacific studies. Since the Neah Bay Radar display was not systematically quantized into a series of echo intensity levels, it was not possible to detect small echo cores embedded within the bands, except in Type 6 (post-frontal) bands which were composed of lines of very discrete small-scale echoes. From the Washington studies listed in Table 3, it is evident that types 1, 2, 3, and 5 bands did in

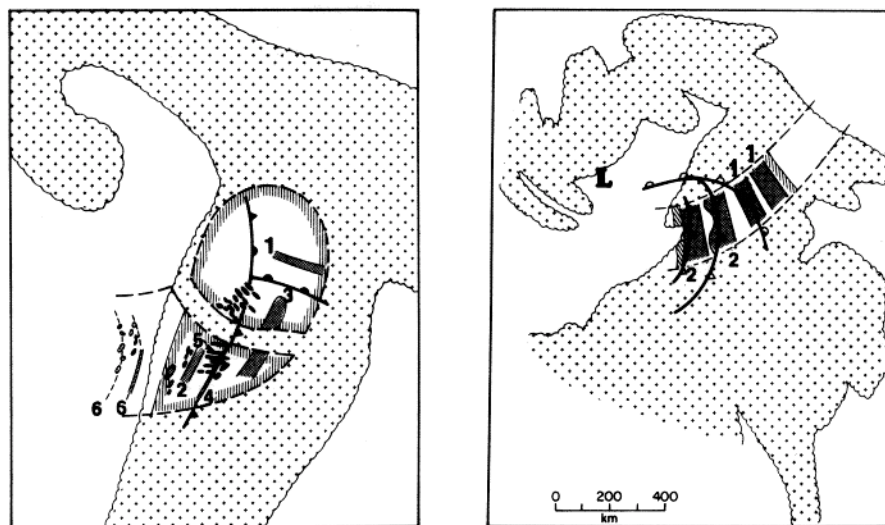


Figure 4. Schematic representation of storms observed on (a) 27-28 November 1973 and (b) 20 December 1972. Cloud pattern observed by satellite is shown by (*.*.*). Dashed lines enclose portion of cloud shield which passed over area of observations. Hatching (---) encloses light rain areas. Heavy rain areas are indicated by (■■■■). Rainbands are numbered according to types given in text. Fronts are for sea level in (a) and for the 750 mb level in (b). Surface low pressure center is indicated by L.

Table 3. Average characteristics of rainbands observed in eleven occluded frontal systems. Dash indicates not observed. H and L refer respectively to high and low radar gain echoes which were analyzed separately for the Washington cases.

Type of Band	No. of Cases	Width	Rain Rate	15-min Peak Rain Rate	Size of Small Areas	No. of Small Areas per 10 ³ km ²	Absolute Value of Difference Between Velocity of Small Area and Winds at Pressure Level Indicated							
							deg/m s ⁻¹							
							km	mm h ⁻¹	mm h ⁻¹	km ²				
(a) PACIFIC STUDIES							850 mb	700 mb	500 mb					
1 Warm Frontal	1	15	7	7	-	-	-	-	-					
2 Warm Sector	1	40	3	7	-	-	-	-	-					
3 Cold Frontal Wide	4	44	-	-	-	-	-	-	-					
4 Cold Frontal Narrow	2	6	28	*	-	-	-	-	-					
5 Wave	1	15	-	-	-	-	-	-	-					
6 Post Frontal	15	20	4	5	270	2.9	15°/4	14°/5	12°/21					
(b) WASHINGTON STUDIES														
					H	L	H	L	H	L	H	L		
1 Warm Frontal	4	60	3	7	400	60	1.8	1.8	29°/4	33°/8	9°/7	7°/3	13°/13	11°/10
2 Warm Sector	3	50	2	7	210	35	2.0	0.8	13°/3	10°/5	8°/4	8°/5	13°/6	17°/5
3 Cold Frontal Wide	8	65	3	11	200	40	2.3	1.4	28°/7	24°/6	11°/6	11°/4	18°/10	13°/16
4 Cold Frontal Narrow	0	-	-	-	-	-	-	-	-	-	-	-	-	-
5 Wave	1	21	1	5	-	-	-	-	-	-	-	-	-	-
6 Post Frontal	2	51	2	9	90	55	1.4	0.7	14°/4	17°/4	13°/1	13°/1	5°/1	10°/1

* Duration over station less than 15 min.

fact contain small mesoscale areas. These bands were observed with the quantized UW radar.

Although our results indicate a tendency for rainbands to occur in occluded cyclones, and for the bands to be of six types, it should be noted that the rainbands which we observed did not always occur in the same sequence or combination. In some cases rainbands were interspersed with large irregularly-shaped regions of light rain (100's of km in dimension), while in other cases small non-banded mesoscale rain areas (10's of km in dimension) occurred between the bands. Fig. 5 illustrates the various arrangements of rainbands in several of our case studies. Fig. 5(d) and (f) show examples of rainbands accompanied by large regions of non-banded light precipitation. In the case of 7 January 1975, (Fig. 5(f)) the first large non-banded region had a very uniform structure while the second one contained a pattern of smaller mesoscale and cumulus-scale elements, including some small wavelike bands similar to those labeled W in Fig. 1(b).

7. RAINBANDS IN OTHER GEOGRAPHICAL AREAS

The above results suggest that the six types of bands listed in § 5 occur rather generally in extratropical cyclones. This conclusion is further supported by the fact that rainbands observed in extratropical cyclones in other parts of the world fit nicely into our classification. Rainbands parallel to and ahead of warm fronts have been observed in open wave

cyclones by Browning and Harrold (1969) and Reed (1972). These bands would be Type 1 in our classification. Browning and Harrold's observations were over the British Isles, while Reed's were in New England. Similar rainbands, with warm frontal orientation, were found in the leading (eastern) portions of occluded frontal systems described by Nagle and Serebreny (1962) over the eastern Pacific Ocean and by Kreitzberg and Brown (1970) over the northeastern U.S.

In the frontal systems studied by Nagle and Serebreny (1962) and Kreitzberg and Brown (1970), the Type 1 bands in the leading portion of the cloud shield gave way to bands with cold frontal orientations (which would be Type 2 by our classification) in the trailing (western) portion. In an occluded cyclone over the northeastern Atlantic Ocean, Browning *et al.* (1973) observed a series of Type 2 bands parallel to multiple cold fronts aloft. Their Type 2 bands, however, were apparently not preceded by a series of warm frontal bands

Warm sector bands (Type 3 in our classification) were observed frequently in open wave cyclones near Japan by Nozumi and Arakawa (1968). They found that the warm sector bands tended to be parallel to the cold front, often intersecting the warm front at right

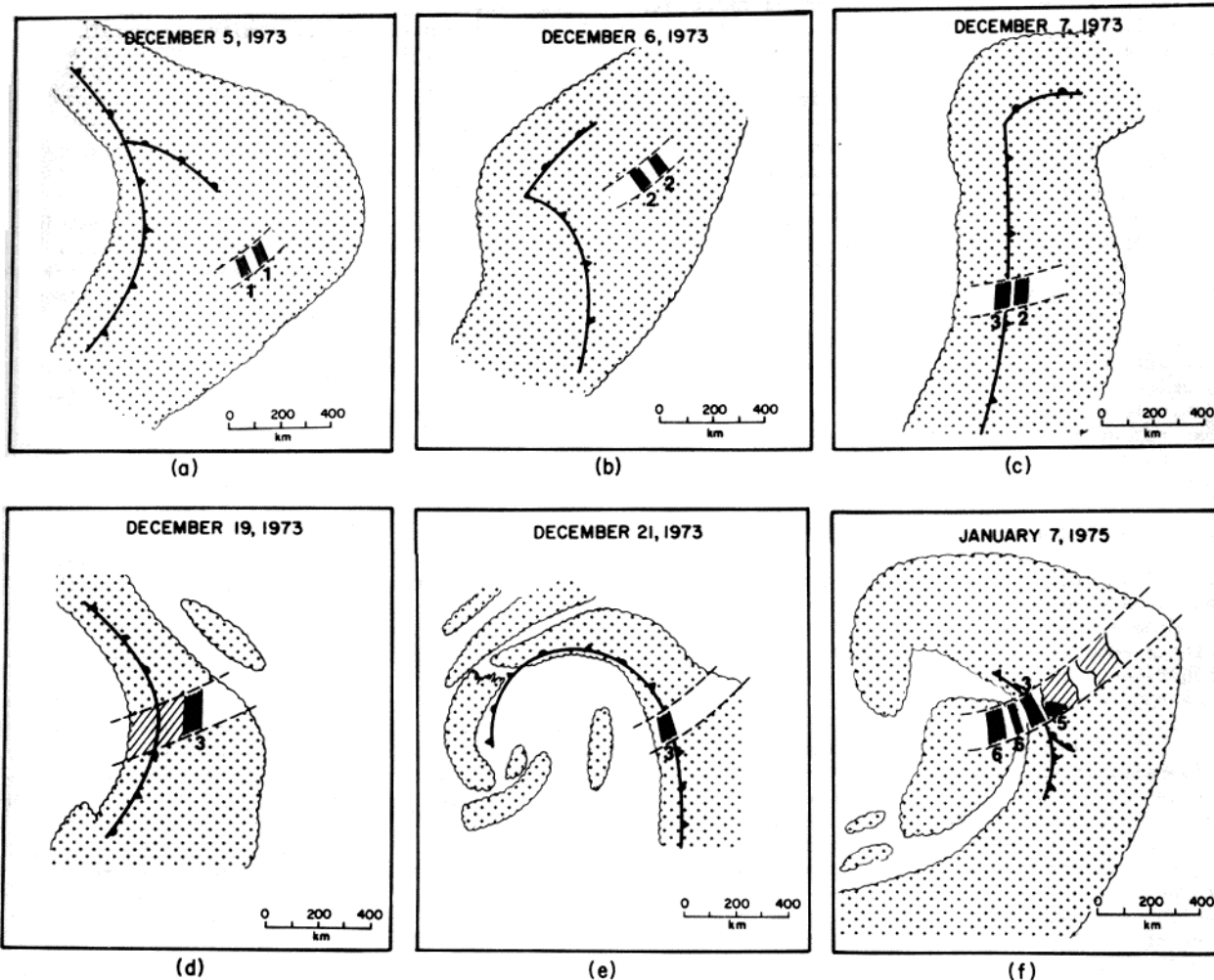


Figure 5. Schematic representation of rainbands (■) observed in six frontal cloud systems (+ + +). Numbers refer to band types discussed in text. Hatching (---) indicates areas of light non-banded rain. Surface frontal positions are shown.

angles. Harrold (1972) also reported that warm sector bands parallel to the cold front occurred frequently in cyclones near the British Isles. Browning and Harrold (1969) found warm-sector rainbands over England which were not parallel to either the cold or warm front in a wave depression. In their case, however, the orientation of the warm sector bands may have been influenced by topographical effects over the British Isles.

As noted in § 3, Type 4 rainbands have been observed previously by Kessler and Wexler (1960) in New England and by Browning and Pardoe (1973) in six cases over the British Isles.

Post-frontal convective rainbands (Type 6) were included by Nagle and Serebreny (1962) in their schematic model of radar echoes in occluded cyclones over the eastern Pacific Ocean. The occurrence of mesoscale precipitation bands in cold air masses to the west of surface cyclonic systems is a well known phenomenon during the winter over the Sea of Japan (e.g. Matsumoto *et al.*, 1967).

8. CONCLUSIONS

We have examined the rainfall patterns in eleven occluded cyclones in the Pacific Northwest. When presented against the background of previous work on mesoscale precipitation patterns, our results provide a more comprehensive picture of rainbands in extratropical cyclones than has been available previously. Six types of rainbands have been identified and each type has been observed repeatedly in cyclonic rainstorms in the Pacific Northwest. Rainbands observed in mid-latitude cyclones in other parts of the world all appear to fit into our six categories. One type of band, the very regular small wavelike band (Type 5), has only been reported in our case studies. Except for the Type 5, all of the bands show a strong tendency to be parallel to either the warm front or the cold front of the parent cyclonic storm.

The large rainbands in our study contained small mesoscale elements (~ 10 's of km in dimension) of maximum rainfall intensity. These small mesoscale areas, in concentrations of 1-3 per 1000 km², were most pronounced in the

post-frontal (Type 6) bands. The small mesoscale areas within the rainbands moved with the wind between 850 and 700 mb.

The fact that the precipitation in extratropical cyclones is concentrated in rainbands, and within still smaller mesoscale elements within the rainbands, indicates that the problem of understanding frontal precipitation processes is largely one of understanding the dynamics and cloud microphysics of the individual mesoscale areas. In future work, progress can be expected if the identification of mesoscale areas by raingauge and conventional radar observations is combined with detailed aircraft and Doppler radar measurements of the dynamical and microphysical properties of the mesoscale systems. One study of this type has been reported by Hobbs *et al.* (1975). Further studies are now underway at the University of Washington.

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