RADAR AND AIRBORNE STUDIES OF RAINBANDS ASSOCIATED WITH
FRONTS IN THE PACIFIC NORTHWEST

by

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Several case studies of mesoscale rainbands associated with cyclonic storms in the Pacific Northwest are described.

In one case study the following bands were identified: a 15 km wide band which preceded the warm front (and traveled faster than it); two warm-sector bands 40 km in width which moved parallel to the cold front; a warm-sector band which extended across the cold front; a narrow, intense band on the cold front (which produced some of the highest precipitation rates); a broad band just... (cont.)
behind the cold front; ripple-like bands (possibly associated with roll-clouds) normal to the cold front and superimposed upon the broad band; and, two bands about 350 km behind the cold front.

In another case study an occluded frontal system produced a narrow, intense rainband at the front and numerous post-frontal bands, fifteen of which are described in this report. The apparent effects of orography on dissipating a portion of a rainband are described.

Also presented are airborne measurements of particle sizes in a 70 km wide rainband associated with an occluded front. The concentrations of precipitation sized particles (>100 μm) were greatest in a 5 km region at an altitude of 2.5 km; the concentrations of particles decreased rapidly with increasing distance from this region.
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CHAPTER 1
INTRODUCTORY REMARKS

In recent years meteorological investigators have found that precipitation is organized on several different scales within extratropical cyclonic storms. The classical model of a cyclonic storm, as proposed by Bjerknes and Solberg (1922), hypothesized a broad, fairly homogeneous region of precipitation preceding the warm front, a more narrow region of precipitation behind the cold front, and practically no precipitation in the warm sector of the cyclone. Recent studies of the structure of frontal precipitation have shown, however, that the rainfall actually has a substantial amount of non-homogeneity. Austin and Houze (1972), for example, found that precipitation was organized into large mesoscale areas (between $10^3$ and $10^4$ km$^2$). Some of these areas were shaped like bands* while others had more irregular shapes. They found that the rainbands and other large mesoscale areas usually contained small mesoscale areas (on the order of 100 km$^2$) of more intense precipitation connected by regions of lighter precipitation and that the small mesoscale areas themselves contained a sub-structure of "cells" ($\approx 1$ to 10 km$^2$ in area) with still higher precipitation rates.

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*In this thesis a rainband will be defined as a precipitation area the length of which is at least twice its width.
The sizes, movements and orientations of the large and small mesoscale areas of cyclonic storms often follow a consistent pattern. Fig. 1.1 shows a composite sketch, consistent with many studies, by Harrold and Austin (1974) of rainbands ahead of the warm front and in the warm sector of a cyclone. The precipitation pattern in Fig. 1.1 modifies the classical frontal model in two principal ways:

(i) the presence of precipitation in the warm sector;

and

(ii) the organized sub-structure of more dense precipitation within regions of lighter precipitation.

Studies have shown that the lifetimes of large mesoscale rainbands are between 1 and 10 hours (Harold and Austin, 1974; Kreitzberg and Brown, 1970). The movements of rainbands have been found to follow the winds in the layers where the precipitation particles are generated, typically between 800 and 500 mb (Browning and Harold, 1969; Austin and Houze, 1972; Matsumoto, Ninomiya and Akiyama, 1966; Kreitzberg and Brown, 1970). The large mesoscale areas which are band-shaped are typically aligned parallel to fronts or along the wind shear vector in the cloud layer where the rain is produced (Kreitzberg and Brown, 1970; Reed, 1972).

The purpose of the work described in this thesis was to investigate the structure of the precipitation in several cyclonic storms in the Pacific Northwest. The sizes and shapes of various precipitation areas have been noted, as
Fig. 1.1 (a) Structure of rate of precipitation within a partially occluded cyclone. Isopleths denote precipitation rates of 0.5 mm h$^{-1}$ (outer line), 4 mm h$^{-1}$ (solid shading). The dashed portion on the forward side of the system evaporates before reaching the ground. (b) Height-distance section along AB in (a).
well as their intensities, orientations and movements. These observations were made using horizontally and vertically-pointing radars, raingages, synoptic maps and satellite photographs. In one case an aircraft, with special meteorological instrumentation, was used to examine the micro-physics of a large mesoscale area (a frontal band) and two small mesoscale areas. The aircraft measurements included cloud particle concentrations, temperature, relative humidity, vertical and horizontal wind measurements, as well as time lapse movies taken from the aircraft.
CHAPTER 2

TYPES OF DATA AND METHODS OF ANALYSIS

2.1 Types of Data

2.1.1 Radars

Three of the radars used in this study were located at the Makah Air Force Station, Neah Bay, Washington, which is on the northwest tip of the Olympic Peninsula. The exact specifications of the Neah Bay radars are classified and can only be described in very general terms. One radar was used for PPI (plan-position indicator) displays, while the other two provided RHI (range-height indicator) information at selected azimuths. The PPI displays had a maximum range of about 250 to 300 km. Usually only one of the RHI radars could be operated at one time for collection of meteorological data. The field-of-view of the radars is indicated in Fig. 2.1; Vancouver Island and the Olympic Mountains obscure some of the view but there are no obstructions in the region of main interest over the Pacific Ocean.

Military use of the radars sometimes precluded their use for this study. For example, when certain missions were being held by the Air Force, photographs of the radar screen were not allowed. However, our most frequent handicap was the use of filters on the PPI radar which suppressed all but the strongest precipitation echoes. The most troublesome filter was that producing circular polarization. The
Fig. 2.1 Map showing the areas viewed by the Neah Bay radar and the NCAR radar. ///// - precipitation regularly seen by the Neah Bay radar; \*\*\*\* - precipitation sometimes seen by the Neah Bay radar; \*\*\*\* - precipitation regularly seen by the NCAR radar.
primary purpose of circular polarization was to reduce the amount of data to be transmitted to a central military site, since periods of bad weather would often overload the data processing capabilities. The mode of operation best suited for observing precipitation was called "horizontal polarization". It was usually permissable to have the weather-suppressing filters turned off for a few minutes every half-hour in order to take photographs of the precipitation echoes. On some occasions the weather suppression circuits were deactivated for periods of several hours in order to facilitate longer periods of data collection. Military radars along the Pacific coast have overlapping coverage so that if one is inoperative, the adjacent radars cover its area. Thus, when permission was given by the central site, the Neah Bay radar could be left in the horizontal polarization mode and the transmission of the PPI data to the central site neglected until some event occurred which necessitated transmission of the Neah Bay radar data. The ways in which the above restrictions affected our study were (i) to reduce the overall quantity of data collected (particularly from the RHI) and (ii) to produce occasional gaps of several hours in the data coverage.

The PPI radar scope was photographed in the form of 16 mm time-lapse movies. In addition, 35 mm photographs were taken of the PPI and the RHI displays. The 35 mm photographs of the PPI were taken every half-hour using
three different receivers which had different gain settings, however, two were very similar so it was possible to detect two different intensities of precipitation. The timing and azimuthal directions chosen for the RHI photographs were variable and subjective.

The only calibration of the radar pictures which was possible for this study was to compare the rainfall rates at various stations when a weather-produced radar echo was observed at a certain radar gain setting. It was found that at distances around 100 km the radar could differentiate between rainfall rates greater and less than 5 mm h$^{-1}$.

The PPI scope often had an echo of about 80 km in radius at its center that obscured this area of the radar screen. This could have been caused by light rain, however, even when it was not raining in the vicinity of the radar this echo sometimes persisted. Since the PPI scanning radar has a wide vertical beam width it is possible that the central echo was due to an extensive ground clutter pattern. On occasions the central echo was nearly absent on one of the receivers or stronger weather produced echoes could be detected moving through the central echo. The variability in the central echo may have been due to some change in the sensitivity setting of the radar which was unknown to the writer or possibly due to the variability of atmospheric conditions.
From December 16, 1974, to February 7, 1975, the National Center for Atmospheric Research's (NCAR) mobile CP3 Doppler weather radar was operated at the Lake Forest Park Reservoir site which is situated 13 km north of the University of Washington in Seattle. The NCAR radar has a peak power of 1 MW, a beam-width of 1.1°, a wavelength of 5.45 cm and 120 km range (Fig. 2.1). Quantitative measurements of the mean radar reflectivity and mean precipitation particle velocity along the radar beam were made for sampling volumes bounded by range intervals of 0.27 km and azimuth intervals of approximately 1°. The radar was operated in a variety of scanning modes and data were recorded both photographically and on magnetic tape. In this study only the photographic records were used. These are 16 mm color films of the real-time color display of the CP3 radar (Gray et al., 1975). The photographs taken during a typical 30 min sequence were as follows:

(i) PPI reflectivity scan at 0.1° elevation (about 1 min duration).

(ii) A sequence of conical PPI scans showing Doppler velocities for eleven elevation angles between 0.5° and 23.0° (about 6 min duration).

(iii) Photographs of a time-height plot of the Doppler vertical velocities of precipitation particles (about 8 min duration).

(iv) PPI reflectivity scan at 0.1° elevation (about 1 min duration).
(v) PPI scan of Doppler velocities at 0.1° elevation (about 1 min duration).
(vi) Five to twenty RHI scans of Doppler velocities at selected azimuths (about 5 min duration).
(vii) Photographs of time-height plot of the Doppler vertical velocities of precipitation particles (about 8 min duration).
(viii) Repeat steps (i) - (vii) until the end of a storm period.

Thus a PPI display of precipitation was available every 15 min.

In this study data from the NCAR radar were used only for determining the presence or absence of precipitation; the PPI displays of Doppler velocities (ii) and (v) above were found to be best suited for this purpose since they were the most sensitive to light precipitation.

It was hoped that some comparisons could be made between precipitation features seen over the ocean with the Neah Bay radar and those same features seen on the NCAR radar as they moved over the Puget Sound area. Simultaneous data from the two radars obtained in one storm are compared in this thesis but the comparison was complicated by the presence of the Olympic Mountain range between the two radar sites (see Fig. 2.1).
2.1.2 Precipitation Gages

Rainage records were obtained for many stations in Western Washington and Oregon and on Vancouver Island (see Fig. 2.2).

The thirteen stations in the United States which were used are part of the National Weather Services cooperative-observers network and were obtained from the National Climatic Center*. These data were in the form of strip-chart records from weighing bucket recording raiingages. The time resolution of these data was about 7 min and the rainfall amounts, for 15 min periods, were read to 0.01 inches, although some estimation of the least significant digit was necessary. Rainfall rates for 15 min periods are probably accurate to within 20%. There was also a University of Washington weighing bucket raingage, similar to the National Weather Service's raiingages, located at the Neah Bay radar site.

The Canadian precipitation data were from tipping bucket gages which recorded the time intervals between collection of 0.01 inches of rain. The Canadian charts were obtained from the Atmospheric Environment Service**.

*Environmental Data Service, National Climatic Center, Federal Building, Asheville, N.C. 28801.

**Atmospheric Environment Service, 4905 Dufferin Street, Downsview, Ontario, Canada.
Fig. 2.2 Locations of rawinsonde (X) and recording raingage (o) stations used in this study.
2.1.3 Synoptic Data

The positions of fronts over the ocean were generally taken to be those shown on the three-hour facsimile synoptic maps prepared by the National Weather Service in Washington D. C. Hourly surface synoptic maps were prepared from the National Weather Service's teletype data. Vertical profiles of temperature, dewpoint and wind were also plotted using data from the National Weather Service's rawinsonde site at Quillayute, Washington, which is located 40 km south of the Neah Bay radar site.

Occasionally the National Weather Service's frontal positions were adjusted to bring them into better agreement with the radar data.

2.1.4 Satellite Data

Visual and infrared satellite pictures showing cloud cover over the North Pacific at 12 h intervals were obtained from the National Environmental Satellite Service*. The satellite pictures used for the 1973 storms were from the NOAA-2 satellite and those from the 1975 storms were from the NOAA-4 satellite.

2.1.5 Aircraft Measurements

A twin-jet aircraft (the NCAR Sabreliner) was used

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*National Climatic Center, Satellite Data Services Branch, Washington, D. C. 20233.
to obtain meteorological measurements through a rainband on January 30, 1975, and through isolated mesoscale areas on January 31, 1975. Characteristics of the instruments used aboard the Sabreliner are listed in Table 2.1 (for further information on the Sabreliner's capabilities see *Atmospheric Technology*, March, 1973). NCAR processed the raw data and presented the results to the Cloud Physics group at the University of Washington on magnetic tape and micro-film. The parameters which were contained on the micro-film and displayed as a function of time were:

(i) Inertial latitude
(ii) Inertial longitude
(iii) Inertial ground speed
(iv) Inertial true heading
(v) North-south velocity
(vi) East-west velocity
(vii) Static pressure
(viii) Rosemont temperature
(ix) True air speed
(x) Cryogenic hygrometer 196
(xi) Cambridge dewpoint 137
(xii) Pitch angle
(xiii) Roll angle
(xiv) C-12 magnetic heading
(xv) Boom true air speed
(xvi) Sideslip angle
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<td>A. Air temperature</td>
<td>Total temperature</td>
<td>Rosemount Engr. Co.</td>
<td>-70 to +30°C</td>
<td>± 0.5°C</td>
<td>0.1 sec</td>
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<tr>
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<td>Thermoelectric hygrometer</td>
<td>Cambridge Instruments, Inc.</td>
<td>-50 to +50°C</td>
<td>± 1°C</td>
<td>3°C/sec</td>
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<tr>
<td>C. Pressure altitude</td>
<td>Servo altitude</td>
<td>Bulova Watch Co.</td>
<td>0 to 65,000 ft</td>
<td>50 ft</td>
<td>0.5 sec       @ 40,000 ft</td>
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<td>1100 to 50 mb</td>
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<td>undetermined</td>
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Table 2.1 Instruments on the NCAR Sabreliner.
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<th>MANUFACTURER AND MODEL NUMBER</th>
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<th>ERROR</th>
<th>TIME CONSTANT</th>
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<tr>
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<tr>
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<td>Intervalometer</td>
<td>Developed in-house</td>
<td>1,2,4,8,16,30, 60 ft/min</td>
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<tr>
<td>O. Time</td>
<td></td>
<td>Developed in-house</td>
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<tr>
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<td>Air sampling</td>
<td>North American Rockwell</td>
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<td>Q. Pod-external store</td>
<td>Dropsonde application</td>
<td>Fairchild-Hiller</td>
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<tr>
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<td>FM air to ground</td>
<td>Airtron</td>
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<td>Sperry Gyroscope Co. 360°</td>
<td>± 0.75°</td>
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</tr>
<tr>
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<td>Compass</td>
<td>Sperry Gyroscope Co. 360°</td>
<td>± 0.75°</td>
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Table 2.1 Continued.
(xvii) Attack angle
(xviii) Pressure altitude
(xix) Undamped vertical airplane velocity
(xx) Vertical acceleration at the center of gravity of the aircraft
(xxi) 3rd order damped vertical airplane velocity
(xxii) 3rd order damped inertial altitude
(xxiii) Vertical component of the wind
(xxiv) Vertical component of the wind with hi pass filter
(xxv) Attack lilly
(xxvi) Wl lilly lift with low pass filter
(xxvii) Combined vertical wind velocity
(xxviii) U-component of the wind
(xxix) V-component of the wind
(***w) W-component of the wind (unfiltered lift)
(***i) Inertial ground speed
(***ii) Inertial wind speed
(***iii) Inertial wind direction
(***iv) Inertial drift angle
(***v) Wind vectors plotted along course indicated by X and Y distance from start
(***vi) Y distance from start versus X distance from start
(***vii) Potential temperature
(***viii) Event marker 1 (ARIS)
The above data were available in 1 sec averages on the microfilm and in 10 sec averages on the magnetic tape. The data used in this work were longitude latitude, inertial true heading, Rosemont temperature, true air speed, Cambridge dew point, pressure altitude, combined vertical velocity, inertial speed, inertial wind direction and potential temperature.

Cloud particle concentrations were also available on the micro-film in 10 sec averages. The Saberliner was equipped with a Knollenberg probe (see *Atmospheric Technology*, March, 1973) which recorded particle counts per liter in each of 15 size categories from 50 to 1116 μm. The first two categories registered particles with diameters between 50 - 115 μm and 115 - 180 μm. The other thirteen size categories measured particles in ranges of 72 μm: 180 - 252 μm, 252 - 324 μm, ... 1044 - 1116 μm. The Knollenberg probe does not distinguish particle type, in particular one does not know whether a detected particle is a liquid water drop or a certain type of ice particle. Pilot and observer reports of icing on the aircraft were used to indicate whether liquid water was present in the cloud. From a
black "snow stick" near a window of the Sabreliner, an aircraft observer could note what types of particles were in the clouds (although this was not done very often).

2.2 Methods of Analysis

2.2.1 Radar, Raingage, Satellite and Synoptic Data

The storms chosen for study in this thesis were those which exhibited distinct band-shaped radar echoes. Radar echoes which were continuously identifiable for at least 30 min were tracked. By tracing the half-hourly positions of the radar echo of a rainband onto a single piece of paper, the dimensions, orientations, directions of motion and speeds of motion of the rainband were established.

To compare the radar features of precipitation areas before and after they crossed the Olympic Peninsula, the tracings of the radar echoes from the NCAR radar were made in the appropriate relative position on the same chart as those from the Neah Bay radar. It was then possible to see the movement of features from the area covered by the Neah Bay radar to the area covered by the NCAR radar.

Histograms of 15 min rainfall rates were compared with the radar photographs in order to establish how much rain fell from various mesoscale features observed on the radars.

The spatial relationships of distinct cloud features on the satellite photographs were compared with the radar echoes. This made it possible to deduce the rough dimensions
and orientations of cloud systems that were too large to be encompassed by the radar.

By overlaying synoptic maps and radar tracings [see, for example, Fig. 3.5(a)] relationships between the synoptic features and the radar echoes were observed. The velocities of the fronts were compared with the velocities of motion of various radar echoes. The velocities of motion of the radar echoes were also compared with the upper-level winds.

2.2.2 Temperature, Cloud Particle Concentration and Horizontal Wind Velocity Data from NCAR Sabreliner

The aircraft measurements from January 30 and 31, 1975, were primarily represented on vertical cross-sections. 20 sec averages of potential temperature and particle concentrations in three size categories were tabulated. The east-west position of each measurement was found from the plot of longitude versus time. These values were plotted on an altitude versus distance graph along the level at which the aircraft flew and at the appropriate east-west position. Contour lines were drawn from these points by linearly interpolating between points. The horizontal wind speeds and directions measured by the Sabreliner were plotted on the cross-section that showed the lines of constant potential temperatures. From this cross-section it was possible to analyze the position of the front using the criteria discussed in § 6.3.
2.2.3 Vertical Velocity Measurements from the NCAR Sabreliner

Several problems were encountered in interpreting the vertical velocity measurements on the Sabreliner. Firstly, the magnitude of the mean values recorded for the vertical velocities seemed to contain a large systematic error. Therefore, only the relative values will be considered here. However, even the relative values seemed to vary under similar conditions from flight to flight. Fig. 2.3 shows four examples of the vertical velocities from three different flights when the aircraft was flying in non-turbulent air at altitudes of about 9 km which were well above the clouds. The following points should be noted (Fig. 2.3):

(i) High frequency oscillations (= 10 min⁻¹) were not significant in Flight 12 (Fig. 2.3(a)) although they were present, in varying degrees, in the other flights.

(ii) Lower frequency oscillations (= 1 min⁻¹) were more apparent in Flight 12 (Fig. 2.3(a)) than the other flights.

(iii) The mean measured velocities not only differed appreciably from zero (which is not to be expected at these high altitudes) but the mean values from Figs. 2.3(a), (b), (c) and (d) are -1.7, -1.0, -1.3 and -1.4 m s⁻¹, respectively. Figs. 2.3(c) and (d) were taken during the same flight and the oscillations about the mean seem
Fig. 2.3 Measurements of vertical velocity versus time for four different time periods from three flights. All four sets of measurements were made during periods of straight and level flight well above the clouds. (Note time scale differences for different flights.)
to be similar in period and magnitude. These observations indicate that the noise level in the vertical velocity measurements may have been fairly constant throughout a flight.

In view of these problems, we only considered significant changes in the magnitude of the vertical velocity during straight and level flight or significant changes in the amplitude or frequency of the oscillations. Moreover, the interpretations of the vertical velocity measurements were qualified by the recorded comments of the flight crew, the particle measurements and the synoptic situation.

The traces of the vertical velocities were displayed on vertical cross-sections (see Fig. 6.13) but the median values of the measured vertical air motions was arbitrarily set to zero (i.e. only fluctuations about the mean are shown). The time scale was converted to distance by taking the average aircraft speed for the pass. The cross-sections showing vertical velocities did not cover as much distance as those showing air temperature and particle concentrations because it was assumed that the vertical velocities were invalid for the first two minutes after a direction or altitude change of the aircraft.
CHAPTER 3

CASE STUDIES OF RAINBANDS IN OCCLUDED FRONTAL SYSTEMS:

I. NOVEMBER 27-28, 1973

3.1 Introduction

A frontal system which moved into western Washington on November 27, 1973, was given particular attention because nearly all of the precipitation was confined to large or small bands. The most interesting feature of this storm was a narrow (1 to 3-km wide) and intense radar echo seen on the Neah Bay radar. This precipitation band (to be referred to as rainband E) coincided exactly with the surface cold front and had a high rainfall rate associated with it. This storm also had a 100-km wide rainband (band F) directly behind the surface cold front and a 15-km wide rainband (band A) ahead of the surface warm front. These precipitation bands will be described in this chapter as well as three warm sector bands (B, C and D) and three other post-cold frontal bands (G, G' and H).

3.2 Synoptic Situation

At 0000 PST November 27, 1973, an occluded front moved onto the Pacific coast of Washington and moved through the state during the next seven hours while a stationary front remained 80 km south of the Washington-Oregon border [Fig. 3.1(a)]. At 0400 PST on November 27 a wave was
Fig. 3.1 Successive frontal positions for November 27-28, 1973.
developing on the stationary front 150 km west of the northern coast of Oregon, just east of the upper-level trough. Between 0400 and 1600 PST on November 27 the upper level trough became more pronounced and as it progressed eastward, overtaking the developing wave, an occluded front was formed very suddenly. This process has been referred to as "occluded frontogenesis" by Anderson et al. (1969). The warm-air sector associated with this occlusion moved NNE reaching Neah Bay at 1700 PST on November 27, one and one-half hours after meteorological radar observations were commenced at Neah Bay. Between 1700 and 2200 PST the surface cold frontal zone remained over Neah Bay as the warm air continued its movement to the northeast /Fig. 3.1(c), (d) and (e)/. The radar data indicated that the frontal boundary (as shown by its associated radar echo) actually moved 10 to 20 km to the northwest of Neah Bay between 1900 and 2200 PST before moving back over the land. After 2230 PST on November 27 the cold front moved steadily across the state at about 20 kt* /Fig. 3.1(f), (g) and (h)/.

It is apparent from the satellite picture for 2100 PST on November 27 (Fig. 3.2) that a wave was developing. The curvature of the clouds over Washington and Oregon is associated with the warm air pushing northeastward. The cold air mass, which was moving southeast, was centered

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*Abbreviation for knots.
Fig. 3.2 Infrared NOAA-2 satellite photograph for 2100 PST on November 27, 1973. At this time the surface cold front was at the leading edge of the 100-km wide cloud band between the arrows.
near 45\textdegree N and 140\textdegree W and was characterized by many small convective clouds.

3.3 Warm Frontal Rainband A

From 1530 PST (the beginning of radar coverage) until 1700 PST on November 27 a 15-km wide rainband (designated as rainband A) was observed (see Fig. 3.3). When first observed on the PPI scope, rainband A was 20 to 60 km ahead (to the northeast) of the surface warm front and oriented parallel to it. The speed of movement of rainband A normal to its length was 47 kt, while the speed of movement of the warm front normal to its length was approximately 35 kt.

The time that rainband A passed over various raingage stations is indicated in Fig. 3.4. The histograms in Fig. 3.4 indicate that rainband A was the last of the pre-warm frontal precipitation that lasted 1 to 5 h. The rainfall from rainband A lasted about 20 min at a station and averaged 7 mm h\textsuperscript{-1} in intensity.

3.4 Cold Frontal Rainbands E and F

In the middle of the broad band of clouds that lies between the arrows in Fig. 3.2, there is a band of relatively clear air roughly 100 km wide. Lying just to the northwest and parallel to this clear band is a solid, especially bright, cloud band which is also about 100 km wide. The front was located along the boundary between this cloud
Fig. 3.3 Photograph of the Neah Bay radar scope on high gain taken at 1630 PST on November 27, 1973. The warm frontal rainband A is shown. The circular range marks are 10 statute miles apart.
Fig. 3.4 Precipitation rates for November 27-28, 1973, against local time. An arrow denotes the passage of the cold front. Letters corresponding to the precipitation bands identified on the radar scope are placed above the time at which they produced rain at a station. The histograms on the left are from coastal stations. The location of all of the stations are shown in Fig. 2.2.
band and the adjacent clear band. The rainbands E and F were embedded in the bright cloud band. Since E and F appear to be closely related they will both be discussed in this section.

Fig. 3.5(a) shows the extent of the radar echo at 2100 PST on November 27 superimposed on the hourly synoptic observations and Fig. 3.5(b) shows the actual PPI photograph. By the time the rainband marked E in Fig. 3.5(a) was over the land, the cold front was analyzed as being coincident with this band. The much broader rainband F was found immediately behind rainband E.

From the raingage data shown in Fig. 3.4 it is apparent that the rainfall associated with rainband E, aligned on the cold front, was consistently high along the length of E for several hundred kilometers and remained high at four inland stations. The raingage charts indicated that the precipitation rates associated with rainband E were between 25 and 50 mm h\(^{-1}\) and lasted typically for 7 min at a station. When the rainfall rate at a station was averaged over 15 min, as shown in Fig. 3.4, the rate was typically between 15 and 20 mm h\(^{-1}\). Fig. 3.6 shows the extent of the frontal echoes on the Neah Bay radar at 2300 PST on November 27 for two different receiver gain settings. The dark regions in Fig. 3.6 are for the lower gain setting and the narrow line of dark echo corresponds to rainband E which produced the consistently high rainfall rates at all stations. The movements of precipitation bands E and F between 1700 PST on November 27
Fig. 3.5(a) Radar echoes and synoptic observations at 2100 PST on November 27, 1973. A photograph of the PPI scope is shown in Fig. 3.5(b)
Fig. 3.5 Photograph of the Neah Bay PPI radar scope on (b) low gain and (c) high gain at 2100 PST on November 27, 1973. The precipitation bands C, E and F are indicated and the ripple-like echoes within F can be seen. The circular range marks are 10 statute miles apart.
Fig. 3.6  Radar echoes at two different receiver gain settings at 2300 PST on November 27, 1973. Raingage data indicated that the stippled region (■■■■) corresponded to rainfall rates greater than 5 mm h\(^{-1}\) and the cross-hatched region (////) corresponded to rainfall rates less than 5 mm h\(^{-1}\).
and 0200 on November 28, as seen on the Neah Bay radar scope, are shown in Fig. 3.7.

The radar echo produced by rainband E is very similar to echoes observed along cold fronts by other investigators. For example, Kessler and Wexler (1960) observed a 2-km wide, intense radar echo at a surface cold front on the eastern coast of the United States. The rainfall rate associated with the band was about 25 mm h\(^{-1}\) and it was followed by a 100-km wide zone of lighter precipitation. The radar echo in the narrow bands of intense precipitation observed by Browning and Pardoe (1973) and Kessler and Wexler (1960) were about 3 km in vertical extent, whereas the top of rainband E observed in this study ranged from 3.7 to 4.6 km (see Table 3.1).

It can be seen from Fig. 3.5(a) that rainband F was much broader than rainband E and also less intense. The cases examined by Browning and Pardoe (1973) also showed this structure and in their study Doppler radar was employed to measure the vertical air motions in the rainbands. The deduced dynamical structure, based on their measurements, is shown in Fig. 3.8 and appears to explain the observed structure of the rainbands E and F. Rainband E was probably an intense line of convection triggered by lifting at the leading edge of the frontal system while F was due to gradual, slant-wise ascent above the sloping frontal surface. Whereas the broad band of precipitation behind the front described by Browning and Pardoe had a fairly uniform consistency, rainband F exhibited considerable substructure,
Fig. 3.7 Photograph of the Neah Bay PPI radar scope on low gain at (a) 1730 PST and (b) 1930 PST on November 27, 1973. The precipitation bands E and F are indicated and the ripple-like structure in F is just beginning to become apparent. The circular range marks are 10 statute miles apart.
Fig. 3.7 Photograph of the Neah Bay PPI radar scope on low gain at (c) 2030 PST on November 27 and (d) 0030 PST on November 28, 1973. The ripple-like structure in F is most pronounced in (c) but has vanished by the time of (d). The circular range marks are 10 statute miles apart.
<table>
<thead>
<tr>
<th>Designation</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G &amp; G'</th>
<th>H</th>
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<td>warm sector</td>
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<td>post-frontal</td>
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<td>2000-2300</td>
<td>2230-0100</td>
<td>1630-0200</td>
<td>1530-0730</td>
<td>0230-0730</td>
<td>0400-0730</td>
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<td>40 x 100</td>
<td>40 x 100</td>
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<td>0</td>
<td>0</td>
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<td>0 to 20</td>
<td>10</td>
<td>10</td>
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<td>3.2</td>
<td>3.2</td>
<td>4.0</td>
<td>35.0</td>
<td>4.0</td>
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<td>0.1</td>
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<td>†</td>
<td>†</td>
<td>210°/52</td>
<td>†</td>
<td>210°/52</td>
<td>225°/20</td>
<td>255°/20</td>
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<td>0</td>
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<td>30+</td>
<td>4</td>
<td>3</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>100+</td>
<td>12</td>
<td>6</td>
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<tr>
<td>Maximum Echo Height (km)</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>3.7-4.6</td>
<td>4.2-5.2</td>
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</tr>
</tbody>
</table>

*Lengths are not necessarily true lengths because at least one end of the rainbands was out of range of the radar.
†No individual elements observed.
/No data available.
Fig. 3.8 Dynamical structure and rainfall rates of a thin, intense rainband observed at a cold front by Browning and Pardoe (1973).
as seen in Fig. 3.7. The substructure of band F is described in detail in § 3.6.

3.5 Warm Sector Rainbands B, C and D

The characteristics of the three rainbands (B, C and D) in the warm sector of the storm which were observed on the radar are listed in Table 3.1. From the satellite photograph shown in Fig. 3.2, it appears that there may have been considerably more rainbands in the warm sector of the storm than were observed by radar since several warm sector cloud bands can be seen to the southeast of the arrows in Fig. 3.2. They appear to be 30 to 45 km wide, which is similar to the width of the bands observed on the radar. Their lengths are difficult to judge, but they appear to have been roughly 200 km.

Even though the Olympic Mountains complicated radar coverage in the southeast quadrant, the position of the warm sector rainband B could be discerned (Fig. 3.4 and Fig. 3.7(a)). This rainband, which was parallel to the cold front, appeared in the raingage traces at two of the coastal stations (Point Grenville and Westport) between 1800 and 2000 PST on November 27 (Fig. 3.5). The cold front had little or no motion normal to its length until around 2200 PST on November 27. The warm sector rainbands also had no motion normal to their orientation, but they did move northeastward in a direction parallel to their orientation. The rain between 2030 and 2200 PST at the two coastal stations
came from a rainband (denoted by C) that was oriented along the same line as rainband B. Rainband D appeared on the PPI display over the coast at 2230 PST on November 27 and was located about 40 km ahead of the surface cold front (see Fig. 3.9). The shape of rainband D was more complex than that of rainbands B and C. The general orientation of rainband D was parallel to the front but D had many extensions oriented nearly east-west. These smaller elements are similar to small, ripple-like echoes which were found in rainband F and which are described in § 3.7. An extension out of rainband D is shown crossing the thin, intense echo E which was located along the cold front. It is very clear from the time-lapse motion pictures of the PPI displays that the extensions of D and the frontal echo E were actually moving in different directions and crossed each other. Radar echoes which cross each other have previously been noted by Geotis (1975) and apparently produced by rain which forms at different heights with movements controlled by different factors. Apparently, the extensions of D were formed in the region of slant-wise ascent above the cold front, while E was generated at a lower level and at the leading edge of the cold front (Fig. 3.8).

The warm sector bands (B, C, and D) produced rainfall rates of between 2 and 10 mm h\(^{-1}\) and the duration of the precipitation at a ground station was about one hour.
Fig. 3.9 Photograph of the Neah Bay PPI radar scope on high gain at 2200 PST on November 27, 1973. The precipitation bands C, D, E and F are shown. The circular range marks are 10 statute miles apart.
3.6 **Post-Frontal Rainbands G, G' and H**

Behind rainband F a number of post-frontal rainbands were observed. They were found within the region of what appear to be convective clouds in the cold sector (Fig. 3.2). The convective elements seen in the satellite photograph nearer to the cold frontal zone appear to have been organized in bands that were roughly parallel to the front. A similar structure appears in the radar pictures. In particular, three rainbands (denoted by G, G' and H) were observed by the radar 350 km behind the front. Figs. 3.10(a) and (b) show the shapes of G, G' and H as they appeared on the radar screen (the rainband G' formed from part of G). The bands were typically 25 km wide and 250 km long. The raingage charts indicated that the rainfall rates associated with them were 1 to 8 mm h$^{-1}$ and the duration of the rainfall over a particular station was between 7 and 35 minutes (for 15 min averages, see Fig. 3.5). The characteristics of these two bands are included in Table 3.1.

An interesting event was seen in the time-lapse movies of the PPI display for this storm. As a segment of the post-frontal rainband (G) dissipated another rainband (G') developed about 20 km to the east. Fig. 3.11 shows this sequence. Since the two events seem coupled, it is hypothesized that the rainband G' was formed by the downdraft from the rainband G as it dissipated. The development of new convective elements from the downdrafts spreading out from old clouds and providing lift for the surrounding unstable
Fig. 3.10 Photograph of the Neah Bay PPI radar scope on low gain at (a) 0430 PST and (b) 0600 PST on November 28, 1973. The post-frontal precipitation bands $G$, $G'$ and $H$ are shown. The circular range marks are 10 statute miles apart.
Sequence of radar tracings of rainbands G and G' on November 27. One band (G) dissipated while another (G') formed 20 km ahead of it. The arc in the pictures is a circle of radius 100 km centered on the Neah Bay radar site. The cross is located at 47°N and 127°W.
environmental air is a commonly observed feature of cumulonimbus clouds (see, for example, Byers and Braham, 1949; Newton, 1963; Zipser, 1969).

The post-frontal bands G, G' and H were oriented parallel to the cold front, as seen in Fig. 3.12.

3.7 Small-Scale Structure of the Rainbands

As seen in Fig. 3.4(b), 3.7, 3.9, and 3.10, the rainbands often contain smaller elements which ranged from 1 to 1000 km² in area. The speeds and directions of movement of the individual elements which are found in and often comprise the rainbands are listed in Table 3.1. Wind data from Quillayute, Washington (located 40 km south of Neah Bay) are listed in Table 3.2. By comparing the information in Tables 3.1 and 3.2, it is seen that, to within 10 kt and 10°, the individual elements located within the rainbands B, C, D and F moved with the relatively homogeneous winds between the 940 and 700 mb levels at 1600 PST on November 27. The rainbands B, C, D and F were all found within the 1000-km wide frontal cloud mass which stretched SW to NE and was centered over Neah Bay in the satellite picture of 2100 PST on November 27 (Fig. 3.2). The post-frontal bands G, G' and H were not part of this frontal cloud mass. The speeds of movement of the individual elements in the post-frontal rainbands G, G' and H corresponded to the speeds of the winds below 950 mb measured at 0400 PST and 1600 PST on November 28. The direction of movement of the individual elements in rainbands
Fig. 3.12 Radar echoes and synoptic observations at 0600 PST on November 28, 1973.
Table 3.2 Wind directions and speeds (in knots) at various pressure levels from soundings at Quillayute, Washington, for the storm of November 27-28, 1973. Dashes indicate that no data were available.

<table>
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<tr>
<th>Surface</th>
<th>970 mb</th>
<th>940 mb</th>
<th>910 mb</th>
<th>875 mb</th>
<th>850 mb</th>
<th>775 mb</th>
<th>700 mb</th>
<th>600 mb</th>
<th>500 mb</th>
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<tr>
<td>0400 PST November 28</td>
<td>190°/6</td>
<td>210°/17</td>
<td>225°/25</td>
<td>230°/36</td>
<td>225°/41</td>
<td>220°/43</td>
<td>225°/40</td>
<td>225°/72</td>
<td>210°/61</td>
<td>205°/75</td>
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<tr>
<td>1600 PST November 28</td>
<td>200°/10</td>
<td>---</td>
<td>205°/28</td>
<td>---</td>
<td>220°/23</td>
<td>---</td>
<td>225°/28</td>
<td>225°/36</td>
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</tbody>
</table>
G and G' was similar to that of the winds between 940 and 700 mb. The individual elements in rainband H moved in a direction 30° clockwise from the 940 to 700 mb winds indicated by the soundings. However, the surface wind veered 50° between the times of the upper-air soundings so rainband H may also have followed the 940 mb winds but the wind shift was not resolved by the soundings spaced 12 h apart.

Only rarely did a distinct element found in the rainbands appear and dissipate within the field-of-view of the radar. Table 3.3 lists the times in which individual elements within the rainbands G and H were observed (along with their dimensions). A plus or minus following a time indicates that the element was believed to have existed after or before the time given, respectively. Table 3.3 shows that the small scale elements comprising the rainbands G and H lasted longer than a few hours. Thus the lifetimes of these elements, which are of the order of 100 km² in area, appear to have been longer than those of precipitation areas of similar size observed in New England by Austin and Houze (1972). Nagle and Serebreny (1962) pointed out that mesoscale areas over the ocean have longer lifetimes than those observed over the land.

The frontal echo E and the 100-km wide rainband F behind it were within radar range for a ten-hour period. This allowed the equivalent of an 800-km long portion of rainbands E and F to be observed. Rainband E had very little observable small-scale structure, however, the broader rainband F
Table 3.3 Characteristics of small-scale elements within the post-frontal rainbands of November 27-28. The designation letter of a small-scale element corresponds to the rainband in which it was observed. A minus sign following a time means the element probably existed before that time. A plus sign following a time means the element probably existed after that time. The small scale elements were assumed to be elliptical for the horizontal area computations.

<table>
<thead>
<tr>
<th>Designation of small-scale elements</th>
<th>Time first observed (PST)</th>
<th>Time last observed (PST)</th>
<th>Horizontal dimensions (km)</th>
<th>Horizontal area (km²)</th>
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<td>0320</td>
<td>0630+</td>
<td>7 x 30</td>
<td>165</td>
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<td>0605+</td>
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<td>113</td>
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<td>G5</td>
<td>0242-</td>
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<td>3 x 7</td>
<td>16</td>
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<td>0250</td>
<td>0406</td>
<td>6 x 21</td>
<td>99</td>
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<td>0535+</td>
<td>18 x 16</td>
<td>226</td>
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<td>G8</td>
<td>0240-</td>
<td>0510+</td>
<td>9 x 15</td>
<td>106</td>
</tr>
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<td>G9</td>
<td>0340-</td>
<td>0600+</td>
<td>11 x 35</td>
<td>302</td>
</tr>
<tr>
<td>G10</td>
<td>0330-</td>
<td>0510</td>
<td>9 x 10</td>
<td>71</td>
</tr>
<tr>
<td>G11</td>
<td>0412</td>
<td>0615+</td>
<td>9 x 17</td>
<td>120</td>
</tr>
<tr>
<td>G12</td>
<td>0345-</td>
<td>0945+</td>
<td>26 x 35</td>
<td>715</td>
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<td>0435-</td>
<td>0625+</td>
<td>8 x 12</td>
<td>75</td>
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<td>0505</td>
<td>5 x 11</td>
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<td>0320-</td>
<td>0740+</td>
<td>12 x 16</td>
<td>151</td>
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<td>0540</td>
<td>0730+</td>
<td>9 x 13</td>
<td>92</td>
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<td>0555</td>
<td>0630</td>
<td>7 x 11</td>
<td>60</td>
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<td>H6</td>
<td>0320-</td>
<td>0650</td>
<td>19 x 28</td>
<td>418</td>
</tr>
<tr>
<td>H7</td>
<td>0425-</td>
<td>0810+</td>
<td>13 x 37</td>
<td>378</td>
</tr>
<tr>
<td>H8</td>
<td>0530-</td>
<td>0705</td>
<td>10 x 18</td>
<td>141</td>
</tr>
<tr>
<td>H9</td>
<td>0620-</td>
<td>0807</td>
<td>5 x 15</td>
<td>59</td>
</tr>
<tr>
<td>H10</td>
<td>0600-</td>
<td>0825</td>
<td>6 x 14</td>
<td>66</td>
</tr>
</tbody>
</table>
exhibited considerable, and sometimes highly organized, sub-structure which varied along its length. From 1600 PST on November 27 to 0100 PST on November 28, ripple-like echoes, typically 15 km x 50 km, were observed in rainband F. Sometimes features of similar size, orientation and movement to the ripple-like echoes were seen lying across the thin, intense echo E at the front (as noted in § 3.5 above) and extending 30 km ahead (to the east) of the front. At 1730 PST on November 27 the ripple-like echoes were embedded within other precipitation and were not very pronounced [Fig. 3.7(a)]. They gradually became more pronounced [Fig. 3.7(b)] and rotated counter-clockwise from a 130°-320° orientation at 1700 PST to a 255°-75° orientation at 2100 PST on November 27 when the ripple-like sub-structure was most pronounced [Fig. 3.7(c)]. By 0030 PST on November 28 this pattern had disappeared and the slight organization of rainband F that was observable was an elongation of the smaller scale elements parallel to the cold front [Fig. 3.7(d)].

The post-frontal bands G, G' and H were entirely comprised of small-scale separate elements and the radar echoes were generally brighter and had sharper edges than the echoes from rainbands within the frontal cloud mass. These differences may be seen by comparing Figs. 3.10(b) and 3.4(b). The smoother appearance of the rainbands inside the broad frontal cloud mass, and the more cellular appearance of the post-frontal bands, is consistent with the latter having a more convective nature.
3.8 **Summary**

Fig. 3.13 is a composite of the features of the November 27-28 storm which were observed on the Neah Bay Radar. The dashed lines enclose the area observed by the radar and the scalloped lines outline the frontal cloud mass photographed from the satellite and shown in Fig. 3.2. The different features in this diagram are:

(i) Rainband A - a 15-km wide band which preceded the warm front and traveled faster than the warm front.

(ii) Rainbands B and C - a 40-km wide warm sector rainbands that moved along the same line parallel to the cold front.

(iii) Rainband D - a warm sector rainband which had extensions into the larger rainband F behind the cold front.

(iv) Rainband E - a narrow, intense rainband that coincided with the front and resulted in some of the highest rainfall rates measured in the storm.

(v) Rainband F - the broad area behind the cold front corresponding to precipitation formed by the gradual, slant-wise ascent of air in the classical model of a front.

(vi) Ripple-like elements - found in rainband F and extending into D, sometimes crossing the frontal boundary.
Fig. 3.13 Composite of precipitation features observed on the Neah Bay radar on November 27 and 28, 1973. The dashed lines enclose the area viewed by the radar. The scalloped lines outline the frontal cloud mass (• • •) as photographed from the satellite and shown in Fig. 3.2.
(vii) Rainbands G and H - post-frontal convective rainbands located 350 km behind the cold front and outside of the frontal cloud mass.
An occluded frontal system which moved into western Washington on November 19, 1973, exhibited a narrow, intense but broken radar echo at the front and numerous post-frontal convective bands, fifteen of which will be examined in this chapter. Radar data were obtained between 2100 PST on November 19 and 1100 PST on November 20, 1973. Raingage and satellite data which extended before and after this period were also available.

4.1 Synoptic Situation

The synoptic situation for this storm can be summarized with reference to the sequence of satellite photographs shown in Fig. 4.1. At 0830 PST* on November 19 an old, occluded, low-pressure system was northwest of Washington Its center was located at 53\degree N and 140\degree W, Fig. 4.1(a) and at 2130 PST on November 19 its center was at 51\degree N and 135\degree W

Fig. 4.1(b). The front was located in the broad area of clouds which lies between 40\degree and 50\degree N and 120\degree and 130\degree W in Fig. 4.1(b). At the time of the photograph shown in

*Times given for the satellite photographs are the approximate time of satellite passage over the coast of Washington.
Fig. 4.1 NOAA-2 infrared satellite photograph for (a) 0830 PST and (b) 2130 PST on November 19, 1973.
Fig. 4.1 (c) Infrared NOAA-2 satellite photograph for 0900 PST on November 20, 1973.
Fig. 4.1(b), the surface front was over the Neah Bay radar site and was approximately 100 km to the southeast of the trailing (northwest) edge of the broad frontal cloud mass. The successive frontal positions every three hours are shown in Fig. 4.2. The satellite photograph shown in Fig. 4.1(c) shows the system at 0900 PST on November 20 when the front was close to the eastern border of the state of Washington and moderate, irregular precipitation was moving onto the coast. The low pressure system was filling (central pressure rising) throughout the period of radar observations.

Three parts of the storm stand out when the raingage data from the coastal stations are examined (left half of Fig. 4.3):

(i) a ten-hour period of heavy and relatively steady precipitation;

(ii) an eight-hour period of very light precipitation over the land in which numerous post-frontal rainbands were observed over the Pacific Ocean; and

(iii) a ten-hour period of heavy, irregular precipitation.

The rainfall data from the inland stations (right half of Fig. 4.3) exhibit a similar, though less pronounced pattern.

4.2 Frontal Precipitation

The large frontal cloud mass that covered the area centered at 45°N and 125°W at 2130 PST on November 19
Fig. 4.2 Successive frontal positions every three hours for the storm of November 19-20, 1973. The circled "L" indicates the center of the low pressure system and the adjacent numbers represent the lowest pressure at the indicated time in millibars.
Fig. 4.3 Precipitation rates for November 19–20, 1973, against local time. An arrow denotes the passage of the occluded front. Letters corresponding to the precipitation bands identified on the radar are placed above the time at which they produced rain at a station. The locations of the stations are shown in Fig. 2.2.
resulted in precipitation that lasted an average of nine hours at the coastal stations with average rainfall rates of 2 to 5 mm h\(^{-1}\); the precipitation lasted six hours at the stations 150 km inland with typical average rainfall rates of 1 to 2 mm h\(^{-1}\).

The rainfall histograms (Fig. 4.3) for the frontal and pre-frontal rain show mesoscale variations in the rainfall rate superimposed on the general frontal trend. However, these variations could not be correlated with particular radar echo bands since radar coverage was not available for the first three-quarters of the frontal precipitation period. However, from the rainfall data it appears that frontal lifting was the primary precipitation mechanism and any mesoscale organization had only a secondary effect.

At the start of the radar coverage at 2100 PST on November 19, the most easterly precipitation feature seen on the PPI scope was a thin, intense echo (rainband A) that was broken and meandering (see Fig. 4.4), but otherwise reminiscent of the frontal band E observed in the case study of November 27-28, 1973 (Fig. 3.7). When this feature was over the land, the front was analyzed to be situated along a line in the vicinity of the various segments of the thin, intense radar echo. However, the surface synoptic coverage was not dense enough to determine whether the front was exactly coincident with rainband A along the zig-zag pattern observed on the radar. As a
Fig. 4.4 Photograph of the Neah Bay PPI radar scope on low gain at 2100 PST on November 19, 1973. The locations of precipitation bands A, B and C are shown. The circular range marks are 10 statute miles apart.
result of the rather broken nature of rainband A, only one of the raingage stations (Point Grenville) showed a peak in rainfall rate coincident with its passage (see Fig. 4.3).

In a 100-km wide zone behind the surface front, but within the region covered by the broad frontal cloud mass seen in Fig. 4.1(b), three rainbands (B, C and D), 25 to 40 km wide, were observed. Their characteristics are listed in Table 4.1. Two of these rainbands (B and C) may be seen in Fig. 4.4.

4.3 Post-Frontal Precipitation

From Fig. 4.1(b) it is seen that a relatively cloud-free area was located immediately to the northwest of the broad frontal cloud mass. This 300-km wide zone did, however, contain convective appearing clouds in the satellite imagery and on the Neah Bay radar these clouds were seen to be organized into bands. Radar observations showed similar rainbands within the more solid cloud mass which was centered at 50°N and 131°W in Fig. 4.1(b) and was passing over the Washington coast line at the time of Fig. 4.1(c). The post-frontal rainbands, as seen on the radar, were composed of small, aligned mesoscale echoes. Examples are rainbands H, I, J, K and L in Fig. 4.5(a). As in the November 27-28 storm, the radar echoes of the post-frontal rainbands were brighter, more solid, and had sharper edges than the radar echoes closer to the front. Post-frontal
Fig. 4.5 (a) Photograph of the Neah Bay PPI radar scope on low gain at 0300 PST on November 20, 1973. The locations of the post-frontal bands H, I, J, K and L are shown. The circular range marks are 10 statute miles apart.
Fig. 4.5(b) Radar echoes and synoptic observations at 0300 PST on November 20, 1973.
Rainbands were observed from 2230 PST on November 19 to 0730 PST on November 20; their characteristics are listed in Table 4.1. These rainbands comprised the precipitation regime (ii) mentioned in § 4.1 which was characterized by relatively small amounts of rainfall at coastal stations. During this regime, the rainbands were typically 15 km x 150 km, however, since one end of the rainband was usually near the edge of the area covered by the radar, the lengths are uncertain. The smaller elements composing the post-frontal rainbands were typically 15 km x 30 km. These rainbands resulted in rainfall rates of 2 to 5 mm h\(^{-1}\) which lasted for 15 min at a station. Radar echoes of rainbands H, I, J, K and L are shown superimposed on a synoptic map for 0200 PST on November 20 in Fig. 4.5(b). The small element between rainbands J and K in Fig. 4.5(b) was an isolated feature unassociated with any band.

Various properties of the post-frontal rainbands are summarized in Table 4.1. The letters denoting the various rainbands listed in Table 4.1 are placed above the appropriate feature on the precipitation histograms (Fig. 4.3). From Fig. 4.3 it is evident that the convective bands observed on the radar contributed a very small fraction of the total precipitation associated with the storm. The convective bands did not produce precipitation at all of the stations they passed over probably due to their broken, cellular nature.

The banded organization of the precipitation areas becomes less obvious with increasing distance behind the
Table 4.1 Characteristics of the rainbands as observed by the radar and the raingages on November 19-20, 1973

<table>
<thead>
<tr>
<th>Designation</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
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<td>post-frontal</td>
<td>post-frontal</td>
<td>post-frontal</td>
<td>post-frontal</td>
<td>post-frontal</td>
<td>post-frontal</td>
</tr>
<tr>
<td>Period Observed (PST)</td>
<td>2100-2200</td>
<td>2100-2130</td>
<td>2100-2315</td>
<td>2300-0100</td>
<td>2150-0100</td>
<td>2315-0130</td>
<td>2230-030</td>
</tr>
<tr>
<td>Maximum Dimensions on Radar (km)*</td>
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<td>30 x 70</td>
<td>40 x 90</td>
<td>25 x 50</td>
<td>20 x 140</td>
<td>10 x 40</td>
<td>20 x 80</td>
</tr>
<tr>
<td>Orientation (from true north)</td>
<td>5°-185°</td>
<td>10°-190°</td>
<td>25°-205°</td>
<td>350°-170°</td>
<td>350°-170°</td>
<td>350°-170°</td>
<td>0°-180°</td>
</tr>
<tr>
<td>Band Motion Normal to its Orientation (kt)</td>
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<td>30</td>
<td>30</td>
<td>30</td>
<td>24</td>
<td>28</td>
<td>23</td>
</tr>
<tr>
<td>Average Rainfall Rate (mm hr⁻¹)</td>
<td>20</td>
<td>$$</td>
<td>$$</td>
<td>$$</td>
<td>10</td>
<td>2</td>
<td>$$</td>
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<tr>
<td>Average Duration of Rain at a Station (h)</td>
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<td>$$</td>
<td>$$</td>
<td>$$</td>
<td>0.15</td>
<td>0.2</td>
<td>$$</td>
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<tr>
<td>Motion of Individual Elements (direction from/kt)</td>
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<td>$$</td>
<td>$$</td>
<td>245°/25</td>
<td>240°/30</td>
<td>240°/27</td>
</tr>
<tr>
<td>Number of Individual Elements:</td>
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<td></td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>10-150 km² in area</td>
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<td>0</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>3</td>
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<tr>
<td>Maximum Echo Height (km)</td>
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<td>$$</td>
<td>$$</td>
<td>$$</td>
<td>$$</td>
<td>$$</td>
<td>$$</td>
</tr>
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</table>

*Lengths are not necessarily true lengths because at least one end of the rainbands was out of range of the radar. $\$No data available.  
†No individual elements observed.
<table>
<thead>
<tr>
<th>Designation</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
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<td>post- frontal</td>
<td>post- frontal</td>
<td>post- frontal</td>
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</tr>
<tr>
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<td>0030-0330</td>
<td>0100-0330</td>
<td>0230-0530</td>
<td>0230-0530</td>
<td>0330-0700</td>
<td>0530-1000</td>
</tr>
<tr>
<td>Maximum Dimensions on Radar (km)*</td>
<td>20 x 130</td>
<td>15 x 160</td>
<td>20 x 200</td>
<td>15 x 140</td>
<td>20 x 190</td>
<td>20 x 140</td>
<td>20 x 150</td>
</tr>
<tr>
<td>Band Motion Normal to its Orientation (kt)</td>
<td>24</td>
<td>30</td>
<td>31</td>
<td>31</td>
<td>28</td>
<td>27</td>
<td>29</td>
</tr>
<tr>
<td>Average Rainfall Rate (mm hr⁻¹)</td>
<td>4</td>
<td>2</td>
<td>f</td>
<td>2</td>
<td>f</td>
<td>f</td>
<td>5</td>
</tr>
<tr>
<td>Average Duration of Rain at a Station (h)</td>
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<td>0.3</td>
<td>f</td>
<td>0.1</td>
<td>f</td>
<td>f</td>
<td>0.3</td>
</tr>
<tr>
<td>Motion of Individual Elements (direction from/kt)</td>
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<td>235°/30</td>
<td>230°/33</td>
<td>235°/32</td>
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<td>Number of Individual Elements:</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150-1500 km² in area</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>10-150 km² in area</td>
<td>3</td>
<td>1</td>
<td>17</td>
<td>6</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Maximum Echo Height (km)</td>
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<td>f</td>
<td>3.6-4.9</td>
<td>f</td>
<td>3.6-4.9</td>
<td>f</td>
<td>f</td>
</tr>
</tbody>
</table>

*Lengths are not necessarily true lengths because at least one end of the rainbands was out of range of radar. /No data available.
front. For example, at 0800 PST on November 19, the radar echoes were quite disorganized 500 km from the front (see Fig. 4.6). This disorganized precipitation was located very near the center of the low pressure centered at 61°N and 135°W at the time of Fig. 4.1(b). The passage of this type of pattern over a raingage station was marked by intense, sporadic rainfall corresponding to precipitation regime (iii) mentioned in § 4.1. This regime showed a higher density of radar echoes and contributed much more to the rainfall at the coastal stations than did the precipitation which was organized into bands.

4.4 Small-Scale Structure of Rainbands on November 19 and 20

Figs. 4.5 and 4.6 illustrate the small scale elements observed in this storm. The small scale elements usually persisted through the period that they were within the field-of-view of the radar. The time periods for which certain small mesoscale elements were observed are listed in Table 4.2. The data indicate that the small-scale elements comprising the post-frontal rainbands (as well as those not organized into bands) usually lasted longer than a few hours.

Table 4.3 lists the wind velocities at Quillayute, Washington, for various pressure levels before, during and after the data period. From 940 to 500 mb at 0400 PST on November 20 the winds were consistantly from directions of
Fig. 4.6 Photograph of the Nehah Bay PPI radar scope on low gain at 0800 PST on November 20, 1973. The location of the post-frontal precipitation band N is shown. The banded organization of the precipitation echoes had become less predominate by this time. The circular range marks are 10 statute miles apart.
Table 4.2 Characteristics of small-scale echo elements within the post-frontal rainbands of November 19-20. The designation letter of a small-scale element corresponds to the rainband in which it was observed. A minus sign following a time means the element probably existed before that time. A plus sign following a time means the element probably existed after that time. The small scale elements were assumed to be elliptical for the horizontal area computations.

<table>
<thead>
<tr>
<th>Designation of small-scale elements</th>
<th>Time first observed (PST)</th>
<th>Time last observed (PST)</th>
<th>Horizontal dimensions (km)</th>
<th>Horizontal area (km²)</th>
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</thead>
<tbody>
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<td>0000+</td>
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<td>766</td>
</tr>
<tr>
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<td>2207-</td>
<td>0000+</td>
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<td>377</td>
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<td>E3</td>
<td>2220-</td>
<td>2345</td>
<td>8 x 8</td>
<td>50</td>
</tr>
<tr>
<td>G1</td>
<td>2207-</td>
<td>0240+</td>
<td>13 x 15</td>
<td>153</td>
</tr>
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<td>5 x 5</td>
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<td>G3</td>
<td>2207-</td>
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<td>H1</td>
<td>2207-</td>
<td>0150+</td>
<td>15 x 25</td>
<td>295</td>
</tr>
<tr>
<td>H2</td>
<td>2207-</td>
<td>0340+</td>
<td>25 x 40</td>
<td>785</td>
</tr>
<tr>
<td>H3</td>
<td>2345-</td>
<td>0340+</td>
<td>15 x 25</td>
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</tr>
<tr>
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<td>0340+</td>
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<tr>
<td>I2</td>
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<td>Designation of small-scale elements</td>
<td>Time first observed (PST)</td>
<td>Time last observed (PST)</td>
<td>Horizontal dimensions (km)</td>
<td>Horizontal area (km²)</td>
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<td>177</td>
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<td>0830-1100</td>
<td>1100+1100+</td>
<td>3 x 25</td>
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Table 4.3 Wind directions and speeds (in knots) at various pressure levels from soundings at Quillayute, Washington, for the storm of November 19-20, 1973.

<table>
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<th>Time</th>
<th>940 mb</th>
<th>850 mb</th>
<th>780 mb</th>
<th>700 mb</th>
<th>500 mb</th>
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<td>November 19</td>
<td>140°/23</td>
<td>170°/40</td>
<td>185°/52</td>
<td>220°/53</td>
<td>225°/52</td>
<td>240°/53</td>
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<tr>
<td>1600 PST</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>November 20</td>
<td>90°/10</td>
<td>150°/22</td>
<td>160°/21</td>
<td>180°/19</td>
<td>195°/17</td>
<td>215°/9</td>
</tr>
</tbody>
</table>
220° to 235°. The direction of movement of the smaller elements comprising the radar bands are between 220° and 245°. The speeds of movement of the smaller elements are between 26 and 35 kt. Thus, the average speed is somewhat higher but within 10 kt of the wind speeds given for the 940, 850, 780 and 700 mb levels. The 500 mb wind was 77 kt, therefore, the small features comprising the rainbands moved approximately with the winds between the 700 and 500 mb levels.

4.5 Summary

The different features observed in the case study of November 19-20, 1973, were:

(i) A broad band of heavy and relatively steady precipitation which produced rain for 10 h at the coastal stations. Rainbands A, B, C and D were observed in the western portion of this region.

(ii) A 3-km wide rainband (A) of intense precipitation which produced a radar echo which was broken and meandering and was located in the vicinity of the occluded front.

(iii) Three rainbands (B, C and D) 25 to 40-km wide which were directly behind and parallel to the occluded front. These rainbands were embedded in a region of lighter precipitation which was contained in the broad frontal cloud in Fig. 4.1(a) and (b).
(iv) Ten rainbands (E, F, G, H, I, J, K, L, M and N), which were presumably convective, with typical dimensions of 20 km x 150 km, which were located behind the frontal cloud. These rainbands were composed of distinct mesoscale areas which produced rainfall rates of about 5 mm h\(^{-1}\) but contributed a relatively small amount to the total rainfall from the storm.

(v) A region of heavy, irregular precipitation near the center of the low-pressure system. The radar echoes from this precipitation were not organized into well defined bands.
CHAPTER 5
OROGRAPHIC EFFECTS ON A LARGE RAINBAND:
THE CASE OF JANUARY 16-17, 1975

On January 16, 1975, a rainband, 40 km wide and 200 km long, was observed on the Neah Bay PPI radar to be moving toward the Washington coast. Echoes from this band were later observed on the NCAR radar (location shown in Fig. 2.1) over inland western Washington. The observations from the two radars showed that the band passed over the Olympic Mountains and it appears that orographic influences caused about 30 to 40 km of the southern portion of the rainband to disappear.

5.1 Synoptic Situation

The synoptic situation that produced the rainbands viewed by the two radars was complex and the low density of observations over the Pacific Ocean made the situation difficult to resolve. An occluding frontal system, originally associated with a low pressure region situated near the southwest coast of Alaska at 2100 PST on January 16, moved over Washington during the latter part of January 16. The three-hourly frontal positions, slightly modified from the original Weather Service analysis, are shown in Fig. 5.1. The frontal system was weak and it was moving into an upper
Fig. 5.1 Successive frontal positions for the storm of January 16-17, 1975. The warm frontal position at 700 mb (○○) is shown in (a). The locations of the radar-observed rainbands A and B are shown in (a) and (b). Dashed lines outline extrapolated positions of the rainbands.
air high-pressure ridge (see Fig. 5.2) which had its center over the coast throughout the period of radar observations. The surface pressure pattern and wind shifts indicated two frontal passages over western Washington and Vancouver Island at times which coincide approximately with the warm and cold frontal passages indicated in Fig. 5.1. However, the orientation of the cold and warm fronts shown in Fig. 5.1 could be off by plus or minus 15°.

Satellite photographs taken before and during the period when radar data were obtained are shown in Figs. 5.3(a) and (b). Fig. 5.3(b) is for the same time as Fig. 5.1(c). The northward occluded extension of the front in Fig. 5.1(c) was near the cloud boundary oriented nearly north-south along 125°W between 54°N and 60°N in Fig. 5.3(b). The broad east-west cloud band between 45°N and 55°N exhibits a frontal wave pattern that never became fully developed. With the 700 and 500 mb winds from the west, this broad cloud mass moved to the east bringing rain to western Washington nearly continuously for at least 16 h as shown in Fig. 5.4.

5.2 Rainbands A and B

Two elongated areas of precipitation were observed by the Neah Bay radar during this storm. Figs. 5.5(a) and (b) are photographs of the PPI scope of the Neah Bay radar which show the rainbands A and B at 1645 and 1720 PST on January 16. Rainband A was moving toward the east at 47 kt when observed by the Neah Bay radar and produced rainfall rates of 5 to
Fig. 5.2 Contours of the 700 and 500 mb pressure surfaces in decameters (---) and isotherms in °C (-----) for 1600 PST January 16, 1975. The frontal positions are shown on the 700 mb map (▲▲▲▲▲▲). Filled in station circles indicate that the dewpoint depression was not greater than 6°C.
Fig. 5.3 NOAA-4 satellite photograph for (a) 1000 PST and (b) 2100 PST on January 16, 1975.
Fig. 5.4 Precipitation rates for January 16-17, 1975, against local time. The period in which rainband A produced rain at three stations is indicated. The locations of the stations are shown in Fig. 2.2.
Fig. 5.5 Photograph of the Neah Bay PPI radar scope for (a) 1645 PST and (b) 1720 PST on January 16, 1975. Rainbands A and B are indicated. Circular range marks are in intervals of 50 statute miles.
10 mm h\(^{-1}\) which lasted 1 to 2 h at a station (Fig. 5.4).

Fig. 5.4 shows that rainband A produced rainfall amounts at a station comparable to or greater than the rainfall amounts near the time of the cold or occluded frontal passage.

The positions of the rainbands A and B as observed by the Neah Bay radar are indicated on the map showing the frontal positions for 1600 PST on January 16 in Fig. 5.1(a). The position of the warm front is uncertain at this time, but the two rainbands are probably at least partially in the region of warm ascent over the warm front. A remarkably similar cloud pattern can be observed in the satellite picture for 1000 PST on January 16 along the 135\(^\circ\)W longitude line between 43\(^\circ\) and 48\(^\circ\)N. A sketch of this cloud pattern is shown along with the corresponding synoptic analysis in Fig. 5.6. When this cloud pattern is extrapolated six hours ahead, assuming a constant orientation to the analyzed position of the surface cold front, the resulting positions of the cloud bands A\(_0\) and B\(_0\) coincide with the radar echoes of A and B sketched on Fig 5.1(a).

If the position of the warm front was placed correctly at both times, the rainbands moved from the warm sector to the region of ascent over the warm front between 1000 and 1600 PST. Fig. 5.6 shows that rainband A was one of several rainbands ahead (southeast) and parallel to the cold front. Similar orientations of rainbands have been observed by Browning et al. (1973) over the northeast Atlantic.
Fig. 5.6 Sketch of NOAA-4 satellite photograph shown in Fig. 5.3(a) for 1000 PST on January 16, 1975, superimposed on the surface frontal analysis. Cloud patterns A_0 and B_0, which had dimensions and orientations similar to the radar observed rainbands A and B, are indicated.
Rainband B was located in the warm sector extending up over the warm frontal surface and was oriented parallel to the upper air winds (700 mb). Rainbands have previously been observed in warm-sectors by Nozumi and Arakawa (1968) and Harold (1973). Their warm-sector rainbands were parallel to the cold front in most cases. Browning and Harold (1969) reported warm sector rainbands, similar to rainband B mentioned above, parallel to the winds aloft and not parallel to any fronts. Browning and Harold believed their rainbands may have been triggered by orography but this could not be the case with rainband B since it was observed over the ocean.

5.3 Orographic Effects on Rainband A

The rainband A was observed on the Neah Bay radar from 1630 to 1745 PST on January 17. After 1745 PST rainband A was obscured from the view of the Neah Bay radar by ground clutter. Strong, solid echoes appeared in the north-west quadrant of the area viewed by the NCAR radar at 1900 PST. This is later than would be predicted by a linear extrapolation of the positions that were observed on the Neah Bay PPI radar scope which indicates that the speed of the rainband was decreasing. When a trackable feature at the southwest end of band A is extrapolated from its 1700 and 1730 PST positions to the area viewed by the NCAR radar (see Fig. 5.7), the new position would be 30 to 40 km south of the actual echo that was observed on the NCAR radar at
Successive positions of the radar-observed rainband A that was shortened by the orographic effects of the Olympic Mountains. The arrow indicates the direction of movement of the band. Dashed lines indicate extrapolated and interpolated positions of the rainband.
Therefore, unless the rainband altered its shape or direction of movement radically, it can be assumed that a modification of the vertical airflow pattern by the Olympic Mountains led to the disappearance of the southwestern portion of the rainband. The extrapolated position of this portion of rainband A falls immediately to the west of the Olympic Range (Fig. 5.7). With the westerly winds aloft (seen in Fig. 5.2) this position was downwind of the Olympic Range where orographic subsidence, and resulting suppression of cloudiness, would have been at a maximum.

5.4 Radar-Observed Cloud Structure Behind the Surface Cold Front

There was no radar echo pattern which could be identified closely with the warm front in Fig. 5.1. However, a small but noticeable change in the echo pattern occurred with the passage of the cold front. When the cold front was passing through the field-of-view of the Neah Bay PPI radar many small echoes, most of which were elongated parallel to the cold front, appeared behind the surface cold front through a 100-km wide region [See Figs. 5.8(a), (b), and (c)]. These echoes were typically 10 km x 20 km and were too close together to be resolved in the raingage data. The fact that there is not a lot of change in the extent of the radar echo between Figs. 5.8(a) and (c), even though three stations (Neah Bay, Port Angeles and Point Grenville) within the echo recorded twice as intense rainfall after
Fig. 5.8 Photograph of the Neah Bay PPI radar scope for (a) 1900 PST and (b) 2000 PST on January 16, 1975. The echo extending to the west in (b) was observed near the time of the frontal passage. The circular range marks are in intervals of 10 statute miles.
Fig. 5.8 (c) Photograph of the Neah Bay PPI radar scope for 2200 PST on January 16, 1975, showing the echo pattern that occurred after the surface cold front had passed out of the field-of-view of the radar. The circular range marks are in intervals of 10 statute miles.
the front had passed, is probably due to the attenuation of the radar beam by the heavy rainfall.

5.5 Summary

The different features observed in the case study of January 16-17, 1975, were:

(i) A 60-km wide rainband (A) which was located ahead of the cold front and parallel to it. This rainband extended at least partially into the region of warm ascending air over the warm front.

(ii) A 40-km wide rainband (B) parallel to the 700 mb winds which also extended at least partially into the region of warm ascending air over the warm front.

(iii) A 1000-km wide cloud mass with an east-west orientation. This cloud mass exhibited a frontal wave that never became fully developed but produced rain for at least 16 h in western Washington.
CHAPTER 6
AIRCRAFT MEASUREMENTS IN A FRONTAL RAINBAND
AND MESOSCALE REGIONS

Five passes were made by the NCAR Sabreliner (see § 2.1.5) through a 70 km-wide stationary rainband, the center of which was located 80 km west of the Washington coast. The rainband was associated with an occluded front which moved through the State on January 30 and 31, 1975. When the front was over central Washington the aircraft made three passes through convective cells 150 km west of the Washington coast. The purpose of the aircraft measurements was to determine the microphysical and dynamical properties of the rainband and the smaller scale elements. It was hoped that by comparing the two cases it could be determined the degree to which convection played a role in the precipitation mechanisms in the frontal rainband. The measurements from the Sabreliner that were examined included cloud particle concentrations (from the Knollenberg probe), the air temperatures, the horizontal wind speeds and directions and the vertical wind speeds (see § 2.2.2).

6.1 **Synoptic Situation**

The satellite photographs for 0930 and 2000 PST on January 30 (Figs. 6.1(a) and (b)) shows the cloud pattern
Fig. 6.1 NOAA-4 satellite photograph for (a) 0930 PST and (b) 2000 PST on January 30, 1975.
Fig. 6.1 (c) NOAA-4 satellite photograph for 0900 PST on January 31, 1975.
while an occluded frontal system was stationary, 80 km off the coast. Figs. 6.2(a), (c) and (d) show the frontal positions at the times of the photographs in Figs. 6.1(a), (b) and (c), respectively. At 0600 PST on January 31 the occluded front moved onto the coast and proceeded across the State at approximately 30 kt. The frontal rainband which was studied by us was located between an upper-level ridge to the east and a closed upper-air low to the west resulting in diffluent flow at the 500 mb level over the region of study (Fig. 6.3).

6.2 General Description of the Frontal Rainband

At 1630 PST on January 30, the Sabreliner made five passes at different altitudes through the southern end of the rainband. Fig. 6.4 shows that the high-gain radar echo from the rainband along the aircraft passes marked 3, 4 and 5 was 70 km wide and the most intense part of the rainband, as seen at the low radar gain setting, was 20 km wide.

6.2.1 Temperature Distributions in a Cross-section of the Band

Horizontal measurements of potential temperature at five different altitudes through the rainband are shown in Fig. 6.5. Aircraft passes 1 through 4 show decreasing potential temperature towards the west in the vicinity of the rainband, while pass 5 shows a slight increase in potential temperature towards the west. Variations in
Fig. 6.2 Successive frontal positions for the storm of January 30-31, 1975.
Fig. 6.3 Height contours in decameters of the 500 mb pressure surface at 1600 PST on January 30, 1975.
Fig. 6.4 High (        ) and low (        ) gain radar echoes of the frontal rainband at 1615 PST on January 30, 1975. The positions along the rainband of the 5 aircraft passes are indicated by arrows (→ ←) with the number of the pass to the left. The echo around Neah Bay (        ) was due to ground clutter.
Fig. 6.5 Potential temperature versus the distance from the center of the most intense PPI radar echo for the 5 passes through the frontal rainband on January 30, 1975. A bar (-----) indicates the region where the most intense radar echo was located along the pass.
potential temperature of a few tenths of a degree, over 2 to 3 km in the horizontal, were measured across the rainband in passes 4 and 5 (Fig. 6.6). This suggests that convective elements were embedded within the rainband.

The horizontal gradient of potential temperature (θ) behind a cold front, or ahead of a warm front, is usually characterized by θ increasing towards the frontal boundary. Gradients in frontal zones in weak Pacific occlusions, such as we are considering here, are typically of the order of 0.01°C km⁻¹, which is comparable to the mean temperature gradient along passes 1 - 4 in Fig. 6.5. A plot of potential temperature on a vertical cross-section across the rainband is shown in Fig. 6.6. The wind speeds and directions, as measured by the Sabreliner, are also shown for each flight level. The positions of a warm occluded front and a cold front aloft were determined from the potential temperature tendencies mentioned above as well as from the vertical shears of the horizontal wind. It is known from the thermal wind equation that as long as the winds are in approximately geostrophic balance, cold advection is present within a layer in which the wind direction backs (turns counter-clockwise) with height. Similarly, warm advection is present in a layer in which the wind direction veers (turns clockwise) with height (beyond the veering due to surface frictional effects). Fig. 6.6 shows that the wind veered with height between the levels traversed by the fourth and fifth aircraft passes,
Fig. 6.6 East-west cross-section through the frontal rainband taken between 1536 and 1637 PST on January 30, 1975. The horizontal axis represents the distance (km) from the center of the most intense radar echo, which is enclosed by solid vertical lines. The region of the high-gain radar echo is enclosed by dashed vertical lines. Lines of constant potential temperature (°K) are shown (——). Horizontal winds in standard Weather Service format are plotted in their appropriate position along the level of the aircraft passes. The positions of the cold front (▲▲▲) and the warm occluded front (▲▲▲) are also shown.
except for the eastern most measurements. The wind backed with height between passes 3 and 4 in the vicinity of the rainband. Although the horizontal gradient of $\theta$ was essentially flat between passes 4 and 5, the strong veering of the wind in this layer substantiates the position of the warm-occluded front. The cyclonic turning of the wind along pass 5 suggests that a pressure trough was located in this region, further supporting the frontal analysis and suggesting that low-level convergence and lifting existed in the frontal zone.

The diffluent flow in the vicinity of the rainband, evident from Fig. 6.3, can be seen at the 5.2 and 4.2 km passes in Fig. 6.6.

6.2.2 Particle Concentrations Across the Frontal Rainband

The Knollenberg probe (see § 2.1.5) recorded between 1 and 200 particles $l^{-1}$ across the 70 km radar echo width of the rainband. It appears that concentrations of 10 particles $l^{-1}$ were sufficient to produce an echo on the high-gain receiver of the Neah Bay radar at a range of 100 km. Three vertical cross-sections showing cloud particle concentrations in three size ranges are depicted in Figs. 6.7(a), (b) and (c). Fig. 6.7(a) shows the concentrations of particles with diameters between 50 and 369 $\mu$m. Two regions of high particle concentrations were found. The large concentrations of small particles all along pass 2 (6 km altitude) was
Contours of concentrations (l^-1) of cloud particles with diameters between 50 and 396 μm on an east-west cross section (east is positive) through the frontal rainband on January 30, 1975. The locations of the data points are indicated (o). The solid vertical lines enclose the region of the low gain radar echo and the dashed vertical lines enclose the region of the high gain radar echo.
Fig. 6.7(b) Contours of concentrations ($\text{cm}^{-3}$) of cloud particles with diameters between 396 and 756 $\mu$m on an east-west cross section (east is positive) through the frontal rainband on January 30, 1975. The locations of the data points are indicated ($\circ$). The solid vertical lines enclose the region of the low-gain radar echo and the dashed vertical lines enclose the region of the high-gain radar echo.
Fig. 6.7(c) Contours of concentrations (g⁻³) of cloud particles with diameters between 756 and 1116 μm on an east-west cross section (east is positive) through the frontal rainband on January 30, 1975. The locations of the data points are indicated (o). The solid vertical lines enclose the region of the low-gain radar echo and the dashed vertical lines enclose the region of the high-gain radar echo.
probably associated with cirrus clouds; as can be seen in Figs. 6.7(b) and (c), larger particles were not common in this region. The time lapse movies taken from the aircraft showed that the clouds at these levels were very sparse. This cirrus deck can be seen off the Washington-Oregon coast between 126 and 130°W in the satellite photograph for 2000 PST on January 16 (Fig. 6.1(b)). The cirrus was probably generated by gradual lifting of the flow from the south.

The maximum in small particle concentrations near an altitude of 4 km coincides with a maximum in the larger particle concentrations. This region is associated with lifting produced by warm advection in the lower layers. The low-level maximum appears to be the feature most closely associated with the radar band, although it is centered at the back edge of the low-gain echo. There appears to be no obvious explanation for this offset. It is possible that the maximum particle concentrations were parallel to the warm occluded front and extended through the most intense radar echo between aircraft passes 4 and 5, but it seems unlikely that the high particle concentrations would stop abruptly before pass 4.

The measured size distributions of the cloud particles in various regions of the storm are shown in Figs. 6.8, 6.9, 6.10, 6.11 and 6.12 in the format originally used by Marshal and Palmer (1949) for raindrop size distributions measured at the ground. Marshal and Palmer determined that the
Fig. 6.8 Cloud particle concentrations (L⁻¹) per size category averaged over 30 to 20 km west of the center of the low-gain radar echo on aircraft pass 1 (7.0 km) through the frontal rainband on January 30, 1975.
Fig. 6.9  Cloud particle concentrations (l^{-1}) per size category averaged over 30 to 20 km west of the center of the low-gain radar echo on aircraft pass 2 (6.1 km) through the frontal rainband on January 30, 1975.
Fig. 6.10 Cloud particle concentrations ($l^{-1}$) per size category for pass 3 (5.2 km) through the frontal rainband on January 30, 1975.
fig. 6.11 Cloud particle concentrations (l⁻¹) per size category for pass 4 (4.3 km) through the frontal rainband on January 30, 1975.
PARTICLE DIAMETER (µm)

(a) 23 to 16 km west of the center of the most intense radar echo.

(b) 16 to 7 km west of the center of the most intense radar echo.

(c) 7 to 0 km west of the center of the most intense radar echo.

(d) 0 to 7 km east of the center of the most intense radar echo.

Fig. 6.12 Cloud particle concentrations (l⁻¹) per size category for pass 5 (2.5 km) through the frontal rainband on January 30, 1975.
Raindrop size distributions are typically of the form

\[ N(D) = N_0 e^{-\lambda D} \]

where \( D \) is raindrop diameter, \( N(D) \) the number of drops with diameters between \( D \) and \( D + dD \), \( N_0 \) a constant, and \( \lambda \) is a constant for a given rainfall intensity. This equation, which is referred to as the " Marshal-Palmer distribution", results in a straight line on a semi-log plot of the type used in Figs. 6.8 - 6.12 with the number of drops per size interval decreasing with increasing particle size.

As noted previously, level 1 had a significant number of small particles but very few large particles. Fig. 6.8 shows the particle size distribution for pass 1 averaged between 20 and 30 km west of the center of the low gain radar echo. Fig. 6.9 shows the particle distribution for pass 2 in the same region where it can be seen that there were significant numbers of medium-sized particles. Both Figs. 6.8 and 6.9 exhibit a steady exponential decrease of in particle concentrations for increasing particle diameters, closely fitting a Marshal-Palmer distribution. The concentrations of particles measured on pass 3 (Fig. 6.10) showed considerable fluctuations in the horizontal. Fig. 6.10(a) is averaged between 23 and 32 km west of the center of the low gain radar echo. This plot shows that there the concentrations of larger particles were large compared to the concentrations of smaller particles, but that the Marshal-Palmer distribution was still followed approximately.
Fig. 6.10(b) is for the region 14 to 23 km west of the center of the low gain radar echo and shows an even greater predominance of larger particles than would be found in a Marshal-Palmer distribution. However, Fig. 6.10(c), which straddles the region in pass 3 where the maximum values occurred in the middle and large size categories, is quite similar to a Marshal-Palmer distribution. East of the cold front at pass 3, the number of particles per liter in the larger size categories is very small as seen in Fig. 6.10(d). Pass 4 exhibited the largest discrepancies from a Marshal-Palmer distribution as seen in Fig. 6.11(a), (b) and (c). Throughout pass 4 the plot of particle concentration per size category were rather flat with a sudden jump in the two smallest size categories. The plots for pass 5 are shown in Fig 6.12(a), (b), (c) and (d). The plot that most nearly fits the Marshal-Palmer distribution at level 5 was found between 7 and 16 km west of the center of the low gain radar echo which includes the region of by far the highest particle concentration.

The plots that exhibited the heaviest weighting of the larger particles are Figs. 6.11(a) and 6.12(b). The region where these measurements were obtained was on the western end of passes 4 and 5, which would be expected to be characterized by subsidence. A possible explanation of the distributions shown in Fig. 6.11(a) and 6.12(a) is that lifting had stopped in this region and coalescence and
evaporation of particles decreased the number of smaller particles. Very little turbulence was reported by the aircraft observer in this region which substantiates this hypothesis. Pass 4 was reported to have had very little turbulence and only slight turbulence was reported between 20 and 40 km west of the center of the low gain radar echo.

6.2.3 Vertical Velocity Measurements

The problems associated with the vertical velocity measurements from the Sabreliner are described in § 2.2.3. In the following discussion, only the relative values of the vertical velocities are considered and these are qualified by the subjective observations of turbulence reported by observers aboard the aircraft.

Fig. 6.13 shows the vertical velocity measurements taken during straight and level flight across the rainband. Fig. 6.13 shows that the high frequency oscillations were stronger in passes 3, 4 and 5 than they were in passes 1 and 2, which would suggest turbulence was stronger at the lower levels. The observer aboard the aircraft confirmed this difference but noted that pass 4 was not as turbulent as passes 3 and 5. The region west of the area with the low-gain radar echo along pass 4 is relatively free from high frequency, large amplitude oscillations in the vertical wind. This is consistent with the observation made in § 6.4 that subsidence was occurring in this region, and thus
Fig. 6.13 Relative vertical velocities versus distance along the 5 aircraft passes through the rain-band on January 30, 1975. The vertical velocity scale (m s$^{-1}$) is at the left side of each trace (see §2.2.3 for further information).
suppressing convection, at the time of the pass.

The aircraft observer twice reported a large increase in turbulence during the flight. These correspond to the peaks at passes 1 and 5, lying between 10 and 20 km west of the center of the low gain radar echo. The peak at level 5 occurred just to the west of the maximum concentrations of cloud particles in all size categories. This was not the case for the peak at pass 1, in fact, a minimum in the small particles was observed in this region. As was the case at pass 5, local maxima in particle concentrations in the larger size categories were found to the east of regions of sustained high, positive vertical velocity at 20 km west and 5 km east of the center of the low gain radar echo on pass 4 and at -5 km on pass 3. Similar peaks in vertical velocity at higher altitudes, where there were very few large particles, showed no such correlation.

6.3 Aircraft Measurements through Post-frontal, Small Mesoscale and Cumulus Scale Precipitation Regions (Regions A and B)

Between 1645 and 1718 PST on January 31, 1975, while the occluded front discussed in the last section was over western Washington (see Fig. 6.2), three east-west traverses were made by the Sabreliner along 49°6'N latitude (Fig. 6.14). Two small mesoscale regions, which were highly convective, were moving NNE at 20 kt during this time so when interpreting the cross-sections described below it
Fig. 6.14 Low-gain radar echoes including the precipitation regions A and B flown through at 1715 PST on January 31, 1975. The position of aircraft pass 3, which occurred at the time, is indicated.
must be remembered that each of the three passes were through different parts of a moving non-two-dimensional region. The data from this flight are presented in a manner similar to that in §6.2 and comparisons between the two flights will be made in this section.

6.3.1 Temperature and Horizontal Wind Data

Fig. 6.15 shows the potential temperatures ($\theta$) measured on the three aircraft passes. Fig. 6.15(a) shows a rapid increase in $\theta$ similar to the increase seen in Fig. 6.5(a) and (b) which were taken at upper levels through the frontal rainband. Figs. 6.15(b) and 6.5(c), which were from similar altitudes, show similar fluctuations of $\theta$ which stay very close to the average $\theta$ for the pass. Fig. 6.15(c), which was taken 1 km lower than any aircraft pass through the frontal rainband, shows larger fluctuations of $\theta$ than Figs. 6.15(b) and 6.5(e).

The cross-section showing lines of constant $\theta$ (Fig. 6.16) exhibits larger amplitude oscillations of $\theta$, on the order of 5 km, than did the cross-section through the frontal band (Fig. 6.6) but Fig. 6.16 lacks the larger scale (= 100 km) horizontal temperature gradients of the frontal situation.

The measured horizontal winds, also shown in Fig. 6.16, were unreasonably high (100 kt) through the western half of region A at aircraft pass 3 and were dismissed. The wind
Fig. 6.15 Potential temperature (°K) versus distance (km) east of 127°W for the three aircraft passes through precipitation regions A and B on January 31, 1975. A bar (—) indicates that the measurements were taken within a region that produced a low-gain radar echo.
Fig. 6.16  East-west cross-section through the precipitation regions A and B on January 31, 1975. Lines of constant potential temperature (°K) are shown. Horizontal winds are plotted in standard Weather Service format along the appropriate east-west position of each aircraft pass. The horizontal axis represents the distance (km) east of 127°W. The bars (±——±) indicate that the aircraft was flying through a region which produced a low-gain radar echo.
directions measured after the large wind speeds, between 15 km west and 45 km east of 127°W on pass 3, violated the synoptic pattern and were therefore discounted. The wind data that was considered reliable failed to show any horizontal convergence as was the case in the frontal rainband in § 6.2.

6.3.2 Cloud Particle Concentrations through Regions A and B

Figs. 6.17(a), (b) and (c) show the cloud particle concentrations in three different size categories on cross-sections similar to Figs. 6.7(a), (b) and (c). However, the cross-sections through regions A and B cannot be considered to be vertical, as was the case for the more two-dimensional, stationary rainband in § 6.2. The shift with height of region A, and the absence of cloud particles in aircraft pass 1 for region B, are due to the horizontal displacement of the precipitation regions between the times of the aircraft passes. One difference between the particle concentrations in regions A and B from those of the frontal band is the lack of a region of predominately small particles at higher altitudes. This was because there was no cirrus deck above regions A and B. The magnitudes of the particle concentrations in Fig. 6.17 are similar to those for the frontal rainband. However, there is a difference in the large particle concentrations between the two cases. In the frontal rainband the maxima in the three particle
Fig. 6.17(a) Contours of concentrations ($\ell^{-1}$) of cloud particles with diameters between 50 and 396 $\mu$m on an east-west cross-section through the precipitation regions A and B on January 30, 1975. A bar (-----) indicates the position of the radar echo at the time of the pass. The locations of the data points are indicated (•).
Fig. 6.17(b) Contours of concentrations ($x^{-1}$) of cloud particles with diameters between 396 and 756 $\mu$m on an east-west cross-section through the precipitation regions A and B on January 30, 1975. A bar (-----) indicates the position of the radar echo at the time of the pass. The locations of the data points are indicated (○).
Fig. 6.17(c) Contours of concentrations ($\varphi^{-1}$) of cloud particles with diameters between 756 and 1116 $\mu$m on an east-west cross-section through the precipitation regions A and B on January 30, 1975. A bar (----) indicates the position of the radar echo at the time of the pass. The locations of the data points are indicated (•).
speeds and size categories (Figs. 6.7(a), (b) and (c)) were all in the same region (on the western edge of the low-gain radar echo) while both regions A and B failed to show comparable concentrations of large cloud particles along aircraft pass 3 where the small and middle-sized particles were most numerous. However, region A exhibited a larger number of big and middle size particles at the upper levels, which was not the case in the frontal band.

The plots of particle concentrations per size category at various levels within the precipitation regions A and B are shown in Figs. 6.18 to 6.21. The particle concentrations for regions A and B at the lowest level (1.6 km) exhibit nearly perfect Marshal-Palmer distributions. Fig. 6.19(a), which is from data taken on the western edge of region A, 3 km east of 127°W, deviates the most from a Marshal-Palmer distribution.

6.3.3 Vertical Velocity Measurements in Regions A and B

The vertical velocities for the passes through regions A and B are shown in Fig. 6.22. Although considerable data are missing from when the aircraft was in region A, it is clear that the high-frequency oscillations of the vertical winds within regions A and B had several times the amplitudes of those within the frontal rainband (Fig. 6.13). However, as mentioned in § 2.2.3, the high-frequency noise for the flight through regions A and B (Fig. 2.3(c) and (d)) was
Fig. 6.18 Cloud particle concentrations (L^{-1}) per size category averaged over 50 to 59 km east of 127°W along aircraft pass 1 (4.6 km) through regions A and B.
Fig. 6.19  Cloud particle concentrations (l-1) per size category along aircraft pass 2 (3.1-km) through regions A and B.
Fig. 6.20 Cloud particle concentrations (l⁻¹) per size category averaged over 4.5 km west to 3 km east of 127°W along aircraft pass 3 (1.6 km) through regions A and B.
(a) 32 to 39.5 km east of 127°W.  (b) 39.5 to 44 km east of 127°W.

Fig. 6.21 Cloud particle concentrations (l-1) per size category along aircraft pass 3 (1.6 km) through regions A and B.
Fig. 6.22  Relative vertical velocities versus distance (km) along the three aircraft passes through the precipitation regions A and B on January 31, 1975. The vertical velocity scale (in m s\(^{-1}\)) is at the left side of each trace. A bar (---) indicates the position of the low-gain radar echo at the time of the aircraft pass.
more evident than for the flight through the frontal band
(Fig. 2.3(a)).

6.4 Summary and Conclusions

The stationary rainband, flown through on January 30,
was associated with an old, weak, occluded frontal system.
However, the temperature gradients and vertical and hori-
zontal wind shifts allowed the location of the fronts to
be drawn on a vertical cross-section of the rainband
(Fig. 6.6). On January 31, smaller scale precipitation
areas with observable cumulus activity were also flown
through. The role of cumulus-scale convection within the
frontal rainband was not well established because of the
inadequacies of the vertical velocity measurements on the
aircraft. However, the vertical velocity measurements taken
in the convective areas (regions A and B) showed much stronger
high frequency ($\approx 2$ km$^{-1}$) oscillations than were recorded in
the frontal rainband. Nevertheless, the variations in the
vertical velocity measurements in the frontal rainband were
probably more than noise, since the degree of high frequency
oscillations seemed to correlate well with flight crew
observations of turbulence from the aircraft. Also, the
lower frequency ($\approx 0.2$ km$^{-1}$) vertical velocity maxima
were found near regions of maximum concentrations of the
larger cloud particles. Therefore, cumulus activity
probably played a role in the precipitation mechanism
within the rainband. For the most part, the measured concentrations of precipitation-sized particles (>100μm) were highest in a 5 km region at 2.5 km altitude and decreased radially from this region. It seems that the primary precipitation mechanism in this stationary frontal rainband was from convergence at the lower levels which produced frontal lifting. The relatively low concentrations of smaller cloud particles 30 to 50 km west of the center of the low-gain radar echo from the rainband, and reports of a lack of turbulence in this region on aircraft passes 4 and 5, suggest that subsidence was occurring in this region.
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