

MICROPHYSICAL AND DYNAMICAL STRUCTURE OF MESOSCALE CLOUD FEATURES

IN EXTRATROPICAL CYCLONES

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1. INTRODUCTION

When Bjerknes (1919) and Bjerknes and Solberg (1922) introduced their classical model of fronts, they explained, with remarkable success, the differences in clouds, precipitation, and weather which had been observed to occur regularly from one region of extratropical cyclones to another. They recognized that the gradual thickening of stratiform clouds and relatively steady, widespread precipitation ahead of the warm front, the fair or sometimes showery weather in the warm sector of the cyclone, and the brief, heavy rain and clearing accompanying the passage of the cold front were all results of distinct dynamical processes occurring in the various regions of the cyclone where different atmospheric conditions prevailed.

Although the classical model is still invaluable in depicting in a general way the dynamical processes which lead to the formation of clouds and precipitation in extratropical cyclones, it has been recognized more recently that the precipitation is often produced on scales much smaller than those of the broad frontal circulations (Browning, 1974; Harrold and Austin, 1974; Houze *et al.*, 1976a). In order to understand in detail how precipitation develops in extratropical cyclones, it is necessary, therefore, to focus attention on those dynamical and microphysical processes which are mesoscale in their extent.

The CYCLES (*Cyclonic Extratropical Storms*) PROJECT at the University of Washington has afforded an opportunity to observe and analyze the mesoscale structure of frontal systems, clouds, and precipitation in a large number of extratropical cyclones and to deduce the dynamical and microphysical processes acting within the various types of mesoscale cloud and precipitation features which occur in different regions of the cyclone.

These mesoscale features, which are often elongated in shape and, hence, can be referred to as "rainbands", have previously been classified according to their locations and orientations with respect to the fronts in an extratropical cyclone (Houze *et al.*, 1976a). A refined version of this classification is shown in this volume in Fig. 2 of Hobbs (1978), which is hereafter referred to as Fig. H2. The purpose of the present paper is to ascribe to each type of mesoscale rainband a

physical interpretation, including both dynamical and microphysical processes. We present herein short descriptions and schematic vertical cross-sections illustrating these physical interpretations.

2. WARM-FRONTAL RAINBANDS

Warm-frontal rainbands are mesoscale bands of precipitation oriented parallel to the surface warm front. They may occur in advance of the surface warm-frontal zone (type 1a in Fig. H2) or coincident with it (type 1b in Fig. H2).

Synoptic-scale ascent of air above and within the sloping warm-frontal zone in a cyclone produces a widespread layer of stratiform cloud (Fig. 1). Marshall (1953) and Plank *et al.* (1955), however, found that significant warm-frontal precipitation falls from the stratiform cloud primarily when it is seeded with ice crystals which grow in and fall from convective cells (termed "generating cells") near the top of the otherwise stable cloud layer, above the warm front. The source of potential instability necessary for this convection may be attributed to the subtropical origin of the air ascending over the warm front, since potential instability is characteristic of the middle troposphere of tropical and subtropical air masses.

The potential instability released in generating cells above the warm front tends to be concentrated in large mesoscale bands parallel to the warm front. Kreitzberg (1964) and Kreitzberg and Brown (1970) have shown that the thermal pattern above the warm front, in the large mesoscale regions where the convection occurs, imparts a multiple or "leafed" structure to the warm front. This picture is supported by our analyses of high-frequency rawinsonde data and is depicted in Fig. 1.

The precipitation in mesoscale warm-frontal bands is produced in two stages, in which convective and stratiform cloud processes are important in turn. Relatively large vertical motions in a band of generating cells aloft enable ice crystals to form in them and grow to precipitable size. The stratiform cloud through which these crystals subsequently fall provides an environment for their more rapid growth by deposition and by collection, that is, aggregation and possibly slight riming (Houze *et al.*, 1976b; Hobbs and Locatelli, 1978).

KEY	
L	SURFACE LOW PRESSURE CENTER
	SURFACE COLD FRONT
	SURFACE WARM FRONT
	SURFACE WARM OCCLUDED FRONT
	COLD FRONT ALOFT
	PREFRONTAL COLD SURGE ALOFT

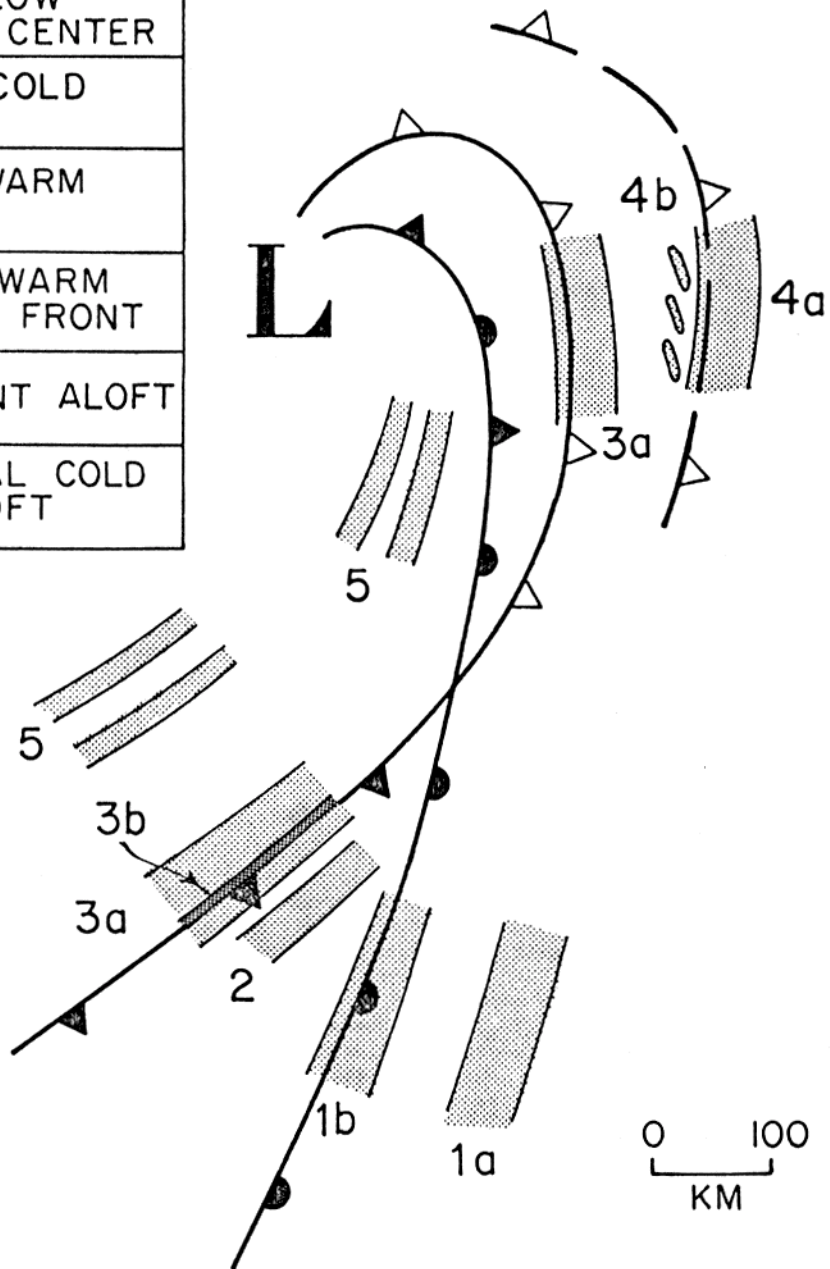


Figure H2. Types of rainbands (shaded areas) observed in cyclonic storms (see text for details).

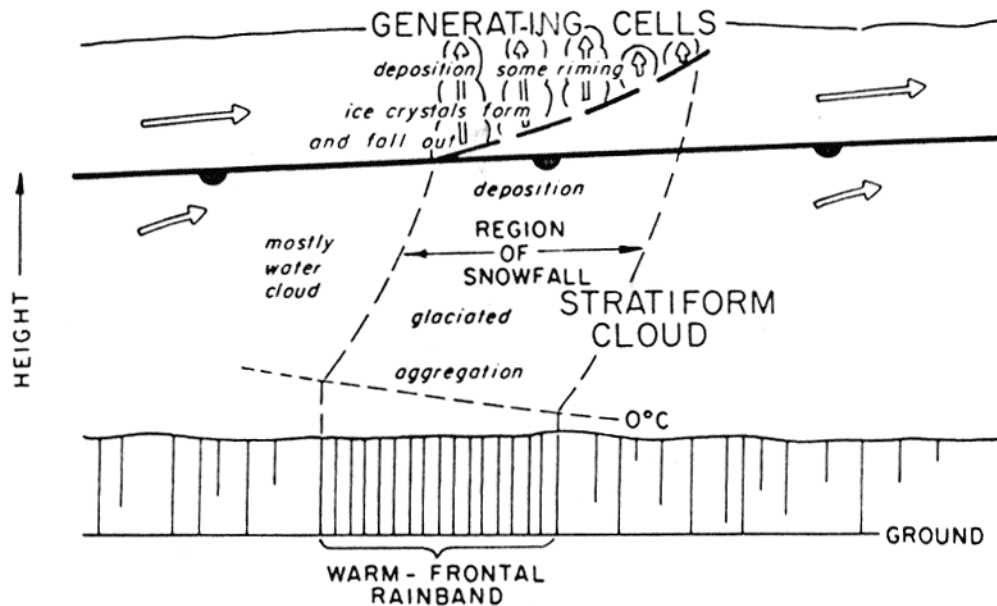


Figure 1: Schematic vertical cross-section through the clouds associated with a mesoscale warm-frontal rainband. The structure of the clouds and the predominant mechanisms for precipitation growth are indicated. Vertical hatching below the cloud base represents precipitation; the density of the hatching corresponds to the precipitation rate. The heavy, broken line indicates the top of a mesoscale stable layer and the base of a mesoscale region of potential instability in which generating cells develop. Open arrows depict airflow and contrast the stable lifting within and above the warm-frontal zone with convective ascent in the generating cells. The motion of the rainband in the figure is from left to right.

In the warm-frontal band of precipitation described by Matejka and Houze (1976), it was observed with aircraft that, outside the zone of precipitation, the stratiform cloud consisted of supercooled cloud droplets and no ice, while, inside the zone of precipitation, the cloud was glaciated with ice particle concentrations of $2-30 \text{ l}^{-1}$. This not only indicates the importance of the generating cells in providing ice crystals to initiate the precipitation within the stratiform cloud, but also shows that ice crystals may be generated in sufficient numbers in this process to consume effectively the supercooled water in the "seeded" regions of the stratiform cloud.

The warm-frontal bands in which generating cells occur aloft may be several tens to over 100 km in width. The convective generating cells, however, may themselves develop in small mesoscale patterns, producing a substructure in the precipitation of the large bands. The cells, for example, may form irregularly-shaped, small-mesoscale clusters (see Tables 2 and 3 of Houze *et al.*, 1976a), or they may develop in regularly-spaced, wavelike lines, approximately 15-20 km wide and 20-30 km in wavelength (Hobbs and Locatelli, 1978).

When the warm-frontal zone under the warm front extends into the boundary layer, as happens immediately ahead of the surface warm front, a particularly intense warm-frontal band may develop (type 1b in Fig. H2). This band is characterized by strong ascent in the stable cloud in the warm frontal zone, as predicted in the model of Gidel (1978) and shown in case

studies by Browning and Harrold (1969) and Herzegh and Hobbs (1978a).

3. WARM-SECTOR RAINBANDS

Warm-sector rainbands (type 2 in Fig. H2) occur within the warm sector of an extratropical cyclone and are oriented parallel to the approaching cold front. The severe mid-latitude squall line (Newton, 1963) is the most vigorous form of this type of mesoscale band. Warm-sector bands, however, also occur frequently in less energetic forms (Nozumi and Arakawa, 1968). These less intense warm-sector bands exhibit many qualitative similarities to squall lines.

As in squall lines, the convection in less intense warm-sector bands is fed by convergence of warm, moist air in the boundary layer of the warm sector and extends through the potentially unstable lower and middle troposphere of the subtropical air in the warm sector. The arrival of precipitation from a warm-sector band may be accompanied at the ground by a temporary windshift and a drop in the wet-bulb potential temperature, events which are usually attributed to downdrafts in squall lines.

The orientation of warm-sector bands parallel to the cold front and their frequent close proximity to the band of precipitation associated with the cold front itself suggests that their existence may be related to the presence of the approaching cold front. Possibly, gravity waves excited by the cold front trigger a line of cumulonimbus which is

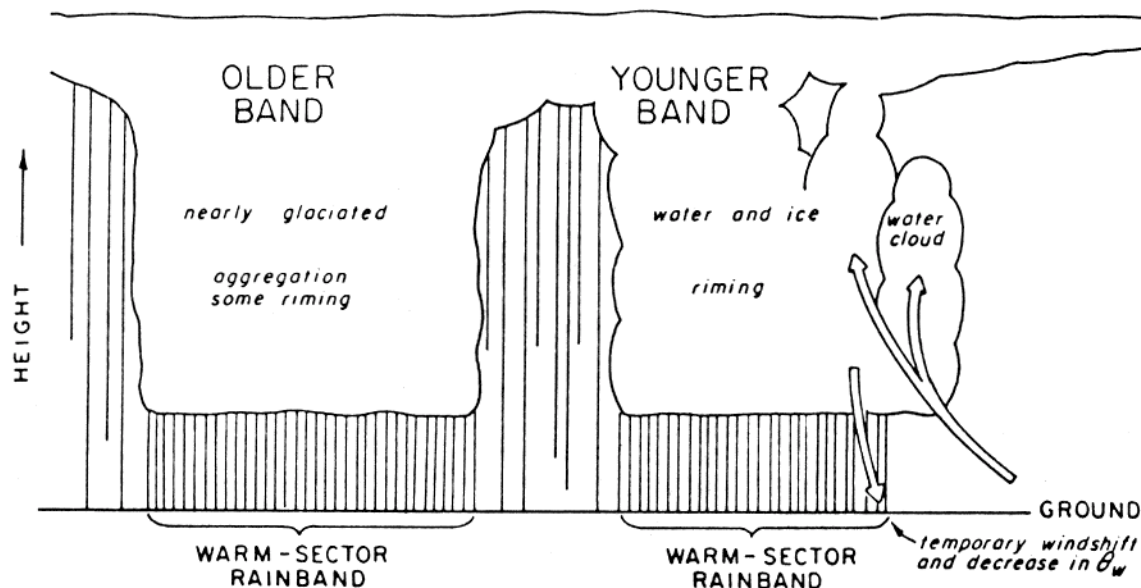


Figure 2: Schematic vertical cross-section through the clouds associated with two well-developed warm-sector rainbands. The structure of the clouds and the predominant mechanisms for precipitation growth are indicated. Vertical hatching below cloud bases represents precipitation; the density of the hatching corresponds to the precipitation rate. Open arrows depict the updraft, in which air from the boundary layer feeds into the convection, and the downdraft accompanying the onset of precipitation from the bands. θ_w is the wet-bulb potential temperature. The motion of the rainbands in the figure is from left to right.

then maintained through cooperation of the wave and convective dynamics (Lindzen, 1974; Raymond, 1975; Ley and Peltier, 1978).

Warm-sector bands may occur in a series, each band being 10 to 40 km in width. Two such bands are depicted in Fig. 2. In squall lines and other organized convective systems, new convective elements may develop at the leading edge or ahead of older elements (Houze, 1977). This pattern can be observed in less intense warm-sector bands as well. In the case illustrated in Fig. 2, the leading band appeared to be the younger feature. It was dynamically more active than the band to the rear; it contained more cloud liquid water and was associated with greater convergence in the boundary layer, indicating the presence of stronger updrafts. The second, apparently older band was nearly glaciated.

Ice particles collected from aircraft show that both riming and aggregation contribute to the growth of precipitation particles in warm-sector bands. In the case illustrated in Fig. 2, riming was predominant in the younger band, and aggregation was predominant in the older one. Occasionally, middle-level convection may be important in introducing ice crystals into warm-sector bands and enhancing or initiating the development of precipitation within them (Browning *et al.*, 1974; Herzegh and Hobbs, 1978b). This process is probably important in cases where the convective updrafts from the boundary layer are relatively weak.

4. COLD-FRONTAL RAINBANDS

Mesoscale cold-frontal rainbands occur within the zone of lifting associated with the cold front. The mesoscale structure of the precipitation in this part of the cyclone may be quite complex (see, for example, the case study, Hobbs *et al.*, 1978, in this volume); however, two general types of mesoscale cold-frontal bands may be distinguished.

The first and narrower type of mesoscale cold-frontal band (type 3b in Fig. H2) is associated with the cold-frontal windshift at the surface. Strong horizontal convergence occurs in the boundary layer at the windshift line, as moist air in the warm sector flows, in a relative sense, toward the cold front (Fig. 3). This convergence produces an updraft a few kilometers in width and a few meters per second in magnitude above the surface windshift line. The resulting band of precipitation, also a few kilometers in width, typically produces a short, intense burst of precipitation; the highest precipitation rate in the cyclone (sometimes around 100 mm h^{-1}) is often associated with this band.

Although the narrow cold-frontal band is, to a first approximation, a thin, linear feature (Kessler and Wexler, 1960; Browning and Pardoe, 1973; Houze *et al.*, 1976a), high resolution radar data show that it is sometimes, if not always, broken into individual cells (for example, see Fig. 5 of Hobbs *et al.*, 1978, and Fig. 2c of Herzegh and Hobbs, 1978b, both in this volume). The

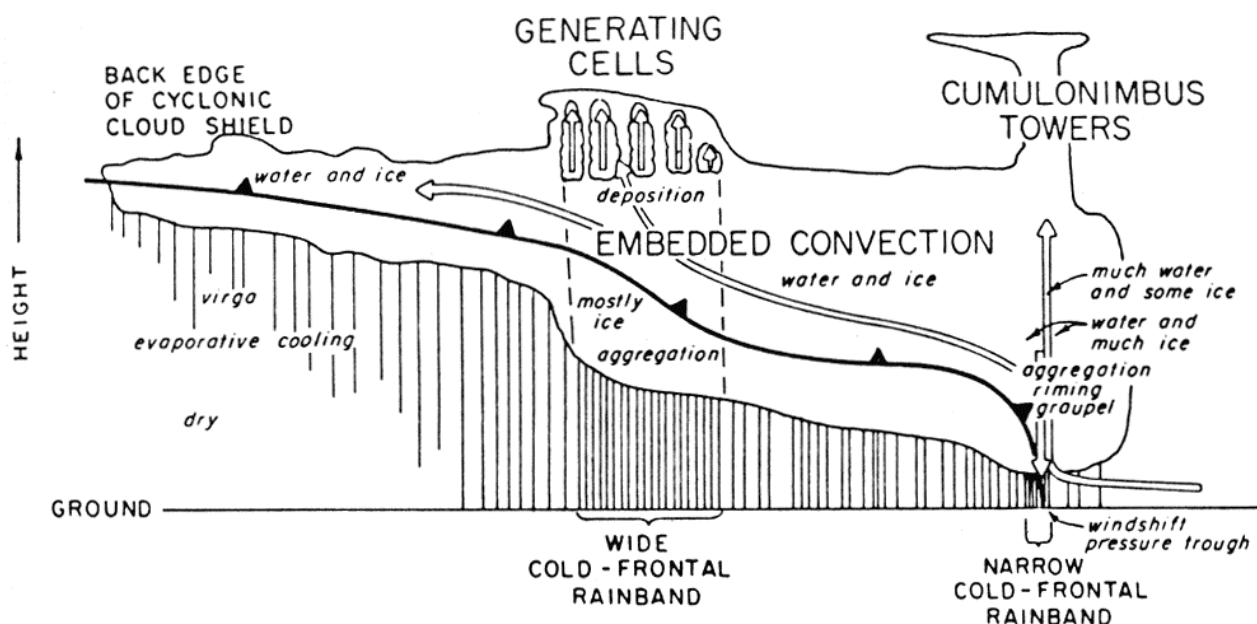


Figure 3: Schematic vertical cross-section through the clouds associated with a cold front, showing embedded narrow and wide mesoscale cold-frontal rainbands. The structure of the clouds and the predominant mechanisms for precipitation growth are indicated. Vertical hatching below cloud bases represents precipitation; the density of the hatching corresponds to the precipitation rate. Open arrows depict airflow relative to the front: a strong convective updraft and downdraft above the surface windshift line, broader ascent over the cold front aloft, and convective ascent in generating cells aloft. The motion of the cold front and the rainbands in the figure is from left to right.

cellular structure of the narrow line can be, on occasion, remarkable in its definition and regularity. Doppler radar data in narrow cold-frontal bands (Browning and Harrold, 1970; Hobbs *et al.*, 1978) show that their air motions consist of an updraft-downdraft pair, similar to that which occurs in cumulonimbus clouds. The broken cellular structure of the narrow band may be a consequence of the updraft and downdraft circulations arranging themselves in the horizontal.

Microphysical measurements within the narrow cold-frontal band show that relatively large cloud liquid water contents (sometimes exceeding 1 g m^{-3}) are present in the updraft. Concentrations of ice particles, generally high throughout the entire zone of cold-frontal precipitation, are particularly high (usually exceeding 100 l^{-1}) on the periphery of the updraft region in the narrow cold-frontal band; ice particle concentrations, however, are lower in the center of the updraft. These results point to the newness of the cloud formed in the core of the updraft. Ice particles sampled in the narrow cold-frontal band show high degrees of riming and aggregation, indicating the importance of collectional growth processes in producing the high precipitation rates associated with these bands.

The second type of mesoscale band which is associated with the cold front is approximately 20-50 km in width. These wide cold-frontal bands (type 3a in Fig. H2) are the product of more widespread, less vigorous lifting than that pro-

ducing the narrow band at the surface windshift line. Such ascent occurs aloft, above the cold front, as depicted in Fig. 3. The wide cold-frontal bands seem to occur where the uplift over the cold front is enhanced, possibly as a result of irregularities in the topography of the frontal surface; the vertical velocities in this region are a few tens of centimeters per second (Matejka and Houze, 1978).

Within the concentrated region of uplift in the wide cold-frontal bands, convective instability is released resulting in the formation of generating cells aloft (Houze *et al.*, 1976b; Hobbs *et al.*, 1978). In this respect, the wide cold-frontal bands are rather similar to the bands which occur aloft above warm fronts, in that convective instability is released as air from the warm sector ascends over colder air, the resulting convective cells providing a source of ice crystals to lower layers of cloud (Herzogh and Hobbs, 1978b, in this volume). As in the warm-frontal bands described in Section 2 above, ice crystals formed aloft in the generating cells of the wide cold-frontal band grow by deposition and collection as they fall through the lower regions of the rainbands. Collectional growth processes are not as pronounced in the wide cold-frontal bands as in the narrow cold frontal bands. This appears to be particularly true in the case of riming. Ice particle concentrations in the wide cold-frontal bands are typically $4-30 \text{ l}^{-1}$.

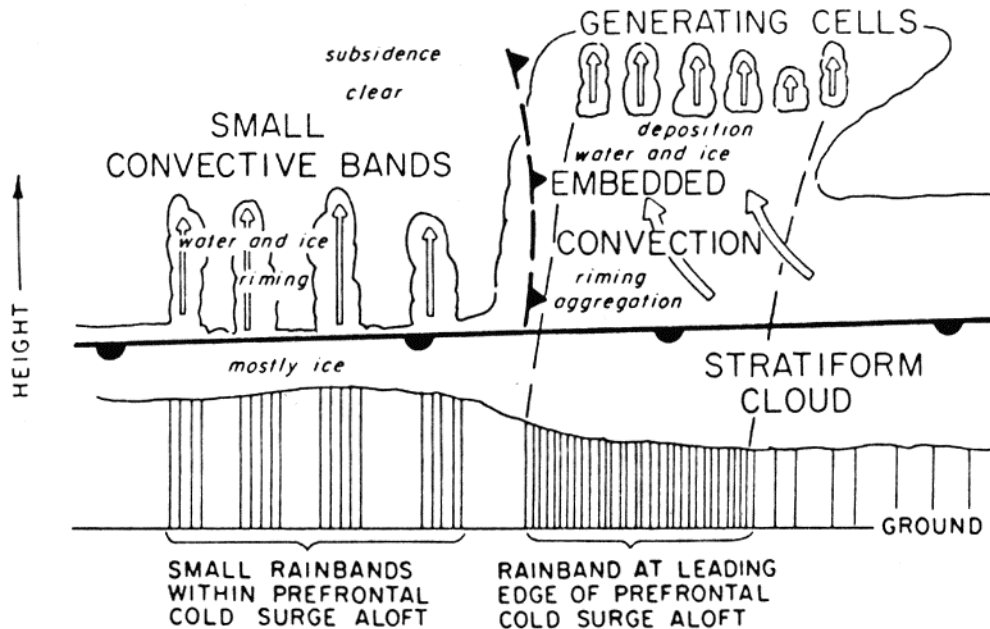


Figure 4: Schematic vertical cross-section through the clouds associated with a surge of cold air aloft, ahead of an occluded front. A broken cold-frontal symbol indicates the leading edge of the mesoscale cold surge aloft. The structure of the clouds and the predominant mechanisms for precipitation growth are indicated. Vertical hatching below cloud bases represents precipitation; the density of the hatching corresponds to the precipitation rate. Open arrows depict airflow in convective generating cells aloft and airflow ahead of and relative to the cold surge. The motion of the cold surge and the rainbands in the figure is from left to right.

5. RAINBANDS ASSOCIATED WITH PREFRONTAL SURGES OF COLD AIR ALOFT, AHEAD OF OCCLUSIONS

Kreitzberg (1964) pointed out that the cold air mass advancing over the warm front in the occluded portion of an extratropical cyclone appears to arrive in a series of pulses, with the strongest pulse associated with the cold front (see Fig. H2). Weaker pulses ahead of the cold front are referred to as "prefrontal cold surges". The effects of this fragmented, mesoscale frontal structure on the precipitation ahead of the cold front in an occlusion is significant.

Two types of mesoscale rainbands may be associated with the passage aloft of a prefrontal cold surge. The first of these (type 4a in Fig. H2), a deep mesoscale band of cloud and precipitation, precedes or straddles the leading edge of the prefrontal cold surge, whose passage overhead is marked at the surface by a temporary, slight rise in pressure (or a lessening in its general fall). This band (shown in cross-section on the right half of Fig. 4) is similar to a wide cold-frontal rainband, although it usually appears less organized on radar than bands associated with the primary cold front discussed in Section 4. This difference is undoubtedly due in part to the relative weakness of the baroclinic zone at the leading edge of the prefrontal cold surge as compared to the cold front, but it may also result from a lower moisture content in the warm-sector air aloft, ahead of the prefrontal cold surge, as compared to the large moisture content

of the boundary layer air in the warm sector ahead of a cold front.

As in the case of the cold front, warm-sector air ascends ahead of the advancing prefrontal cold surge, and the potential instability inherent in the warm-sector air is released to produce convection and generating cells embedded within the cloud structure. The embedded convection is evidenced in the precipitation pattern, which may show a pronounced convective substructure on radar, with many relatively intense bands and cores (Houze *et al.*, 1976b; Hobbs and Locatelli, 1978). Research aircraft flights through the cloud band at the leading edge of the prefrontal cold surge aloft have encountered large amounts of turbulence, further supporting the presence of convection in this band. Some of this convection may form generating cells which then "seed" lower-level clouds with ice crystals (Hobbs and Locatelli, 1978). Unlike in the warm-frontal rainbands discussed in Section 2, however, convection in the rainband at the leading edge of a prefrontal cold surge is not confined to the upper levels of the cloud.

The cloud associated with the mesoscale rainband at the leading edge of the cold surge is composed of both ice particles (in concentrations of several tens per liter) and liquid water ($0.1\text{--}0.4\text{ g m}^{-3}$). Both riming and aggregation occur in these rainbands.

Behind the leading edge of the prefrontal cold surge (the left half of Fig. 4) is a mesoscale

region of marked subsidence (Kreitzberg and Brown, 1970) which may suppress upper cloud layers. However, a field of convection develops in this region just above the warm front as potential instability is generated by the cold air of the prefrontal cold surge overrunning the warm front. This convection, which penetrates into the air of the prefrontal cold surge aloft, sometimes occurs in sharply defined, small-mesoscale rainbands (type 4b in Fig. H2); an example of the organization of this convection into lines has been described by Houze *et al.* (1976a), who refer to them as "wavelike bands". In their case, the bands were 20 km in width with wavelengths of approximately 20-30 km. The convective towers growing in the air of the prefrontal cold surge consist of both ice particles and water; liquid water contents may reach 0.8 g m^{-3} . Rimed ice particles have been detected during aircraft flights through these towers.

As the rainband associated with the leading edge of the prefrontal cold surge passes overhead and is followed by the field of relatively shallow convection, a sudden, significant decrease in the cloud tops occurs. This change can sometimes be observed in infrared satellite imagery; the line of discontinuity in the cloud tops provides a way of identifying and tracking prefrontal cold surges with satellite data.

6. POSTFRONTAL RAINBANDS

Postfrontal rainbands (type 5 in Fig. H2) are lines of convection which form in the cold air mass to the rear of the zone of strong subsidence which immediately follows the cold-frontal zone. These bands can often be observed both visually and from satellite imagery, since postfrontal bands are not usually obscured by a cirrus shield nor embedded in widespread layer clouds associated with the frontal system.

Convection in the potentially unstable polar air mass appears to develop in response to the heating of the surface layer as it moves over a warm ocean surface. The occasional arrangement of this convection in postfrontal bands indicates the presence of some mesoscale organizing feature. The orientation of the postfrontal bands parallel to the cold front and measurements of surface pressure, temperature, and winds during the passage of postfrontal bands suggests that these bands may sometimes be associated with secondary frontal zones within the polar air mass, similar to those described in the early work of Bjerknes and Solberg (1922).

Aircraft data show high concentrations of ice particles in precipitating towers of postfrontal bands. However, these bands must also contain significant quantities of supercooled water since they commonly produce heavy showers of graupel.

7. SUMMARY AND CONCLUSIONS

The patterns of clouds and precipitation in extratropical cyclones are characterized by several clearly distinguishable types of mesoscale rainbands. In this paper, we have described the types of rainbands which occur in various regions of a cyclone and have related them to the frontal

structure and air mass characteristics. We have shown that each type of rainband appears to involve distinct dynamical and microphysical processes which act to produce the precipitation associated with it.

The differences which exist among the various types of mesoscale rainbands are significant and account in part for the variety in the character of the precipitation experienced during an extratropical cyclone. Several important aspects, however, are common to all of the rainbands. First is the presence of convection. In the cases of warm-sector bands, narrow cold-frontal bands, and postfrontal bands, the bases of the convection are low, and the convection is associated with convergence of air in the boundary layer. This convection may be relatively deep. There is evidence in these rainbands that both well-organized convective updrafts and downdrafts may be present. Consequently, these rainbands resemble and behave in many ways similar to organized convective systems, such as squall lines or severe thunderstorms, even though they may not themselves possess the great intensity and severity of the latter systems. On the other hand, in warm-frontal bands, wide cold-frontal bands, and the rainbands associated with prefrontal cold surges, the convection occurs aloft, above the primary fronts of the cyclone. This convection tends to be relatively shallow, and it is often important in varying degrees in introducing ice crystals into dynamically less active clouds below, thereby initiating or facilitating the growth of precipitation within the lower clouds. In warm-frontal bands, as well as occasionally in those warm-sector bands in which convective updrafts from the boundary layer alone are inadequate to produce precipitation, the "seeding" from convective generating cells aloft appears to be critical to the production of a significant amount of the precipitation. In wide cold-frontal bands and in the rainbands at the leading edges of prefrontal cold surges, the cloud below the level of the generating cells may itself contain embedded convection and be capable of producing significant precipitation; the "seeding" of this cloud by upper-level generating cells may merely enhance the total amount of precipitation. Finally, in the field of convection behind the leading edge of a prefrontal cold surge, the cloud is primarily convective, and any "seeding" of the shallow stratiform cloud along the warm front below is likely of secondary importance.

A second similarity among the different types of rainbands is the critical role played by ice in the production of mesoscale precipitation. All of the rainbands which we have identified from radar and raingauge data have been associated with clouds in which ice particles are present in large numbers, always exceeding about 1 l^{-1} , and usually reaching values from 4 to over 100 l^{-1} . Clouds in which ice particle concentrations are less than 1 l^{-1} are characteristic of non-precipitating or lightly precipitating cloud between the rainbands. The occurrence and importance of large numbers of ice particles in extratropical cyclones have been discussed by Hobbs and Atkinson (1976); they conclude that "ice multiplication" processes, by which the number of ice particles is greatly increased beyond the number of available ice nuclei, are likely

occurring at times in these storms. The present study refines these previous findings by showing that high concentrations of ice particles are commonly associated with mesoscale rainbands within the cyclones.

The third similarity noted among the various types of mesoscale rainbands is the increasingly important role played by collectional growth processes as the precipitation rate increases. The highest rates of precipitation observed among the cases examined are characterized by relatively high degrees of riming of ice particles. These high precipitation rates generally occur in strong warm-sector bands, narrow cold-frontal bands, and postfrontal bands, all of which are associated with deep convection.

During the CYCLES PROJECT we have found that the characterization of the different types of mesoscale rainbands is sufficiently well-drawn and consistent that the interpretation of the mesoscale pattern of precipitation observed with Doppler radar can be a valuable, often essential, component of accurate, real-time synoptic and frontal analyses and in the short-term forecasting of precipitation. The construction of detailed physical pictures of the dynamical and microphysical processes in mesoscale cloud and precipitation features is, therefore, essential not only for the eventual modeling of precipitation growth in these features, but also to the development of skill in detailed short-term forecasting.

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