RADAR OBSERVATIONS OF RAIN AT SYDNEY, NEW SOUTH WALES

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Summary

The radar echoes received from rain during systematic observations carried out from January 1950 to January 1951 at the Radiophysics Laboratory, Sydney, N.S.W., are illustrated and described. Examples of echoes from melting and upper bands, non-freezing and frontal showers, thunderstorms, and echo masses are shown by vertical cross sections of the atmosphere through the point of observation.

Correlation between the rain echo and the prevailing weather situation shows that the melting-band rain, which over this period was responsible for most of the rainfall, is usually associated with low pressure, whereas non-freezing showers are shown to be more frequently associated with high pressure.

I. Introduction

It has been well established that various forms of precipitation give rise to radar echoes. Ryde (1947) and others have given a theoretical derivation of the intensity of signal received from the scattering of radio energy by raindrops, ice crystals, and snowflakes. It is shown that the reflected radio power received at the radar set is a function of the constants of the equipment and the range to the raindrops and is proportional to the summation $\Sigma N D^6$, where N is the number of drops, of diameter D, per unit volume, the summation being taken over the whole range of the drop sizes.

The sixth-power law which determines the echo intensity has the effect that, with the wavelength and equipment used, radar echoes are only received from actual precipitation, and that no echoes are received from masses of cloud droplets even at minimum range. It is this feature which enables radar techniques to be used with advantage in the study of rain physics.

Although illustrations and explanations of the most noticeable characteristics of rain echoes have already been given by Jones (1950) and others, a number of important features seen during systematic observations in this locality do not appear to have received attention. The purpose of this paper is therefore to illustrate, classify, and describe the various rain echoes received during observations carried out from January 1950 to January 1951 at the Radiophysics Laboratory, Sydney, N.S.W., and to outline an attempt to correlate the rain echoes with the weather situation prevailing at that time.

With few exceptions, radar observations were carried out whenever precipitation appeared likely between 0900 and 1800 hours each day throughout

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the period, rain echoes being recorded on 74 separate days. The rainfall on these days appears to give a fair sampling of the types of rain experienced over the period in this locality.

II. Equipment and Weather Information

The equipment consists of a search radar, type SCR717B, operating with a wavelength of 9·1 cm. The peak power of the radar transmitter is approximately 40 kW. and the pulse duration 1·25 μsec. The antenna system, a dipole-fed paraboloid, is arranged to rotate about a horizontal axis at 30 r.p.m. in such a manner that the 10° radar beam scans a path from horizon to horizon through the zenith. This results in a representation on the cathode-ray display tube of a vertical cross section through the atmosphere about the point of observation. This type of display has an advantage over the conventional Range Height Tube (R.H.T.) presentation, since the range and height are maintained in true proportion, and a better interpretation of the rain echoes immediately above the point of observation is possible.

The sensitivity of the radar equipment is such that a precipitation rate of 0·02 in./hr., assuming the rainstorm completely fills the radar beam and has a size distribution as given by Laws and Parsons (1943), will just be detected at a range of 10,000 ft. Likewise, drops all of 1 mm. diameter would just be detected at this range if their density were 100 drops/m.^{3}. Because of the double divergence of radio energy when using radar techniques, the intensity of the received echo decreases rapidly with increase in range and causes even widespread rain to appear, on the radar display, as of limited horizontal extent centred about the point of observation.

Facilities are provided for taking 35 mm. photographs of the cathode-ray display tubes every second, fifth, or tenth antenna revolution, and such photographs are used to illustrate this paper. The bottom edge of each photograph corresponds to ground level; the radar is located at about the centre. Small echoes, shown in some photographs as rising from the ground level in the form of small arcs of circles, are from nearby buildings and should not be confused with the rain echoes. The range markers visible on some photographs indicate, as usual, distance from the point of observation, which, in this type of display, corresponds to height above site level when the beam is pointing towards the zenith.

Automatically recorded on the 35 mm. films, but not shown in the reproductions, are a vertical radar "A" scope display, chronometer, date card, and aximuth bearing of the antenna. During observations this azimuth bearing or plane of rotation of the antenna is aligned with the direction of movement of the cloud mass from which the echoes are being received, so that the build-up and decay of these echoes can be seen to advantage.

The data relating to the prevailing weather situation issued by the New South Wales Branch of the Commonwealth Meteorological Bureau consist of the surface synoptic weather map, the weather reports, and the record of the radiosonde sounding taken daily at the Royal Australian Air Force station, Rathmines, N.S.W. At the Laboratory, rainfall and rain intensity measurements

are made and recorded, with personal observations on the weather situation generally. In addition, information on cloud structure and formations and reports on turbulence have been received from aircraft flying in the area.

III. Types of Rain Echo

The radar echoes received from precipitation appear to fall naturally into three distinct groups. The first group comprises the echoes which are received from widespread steady rain ; the predominant feature of these is a band of high intensity situated just below the 0 °C. isotherm. A number of investigators (Ryde 1947 ; Austin and Bemis 1950 ; Hooper and Kippax 1950) have given explanations for this intensification, and agree that the change in phase of the precipitation from the solid to the liquid state and its change in vertical velocity are contributing factors to the phenomenon. In the literature the phenomenon has been called the " bright band " or " melting band " ; the latter term is used in this paper and is considered preferable as it distinguishes it from other bands of increased intensity which sometimes appear with this type of rain echo.

The second group of rain echoes consists of those which develop as individual column-like structures. These are without doubt from rain showers and they are therefore broadly classified as " shower echoes ". There are at least three types of shower from which radar echoes are received ; firstly, that in which the precipitation apparently consists wholly of water drops, as will be seen later, and in which the icing stage has played no part ; secondly, that accompanying cold frontal conditions ; and finally, the thunderstorms. The echoes received from these showers are called non-freezing shower echoes, cold-front echoes, and thunderstorm echoes respectively.

The third group consists of rain echoes which are devoid of both the column-like structure of the shower echoes and the intense band of the melting-band echoes. They appear in cross section as a mass or layer of echo extending from the ground to a height usually determined by either an inversion layer or the 0 °C. isotherm. These have been called echo masses, and can perhaps best be visualized by reference to appropriate illustrations. Detailed descriptions and illustrations of all three groups of rain echoes are given below.

(*a*) *Melting- and Upper-Band Echoes*

The melting-band echoes comprise all those in which a band of increased intensity appears just below the 0 °C. isotherm, as shown in Plate 1. Observations and aircraft weather reports suggest that the rain which produces this type of echo is usually widespread. The radar display confirms these observations and shows that the vertical cross section of the rain echo is free from marked column-like structures that would suggest strong local convection currents or turbulence.

Usually the first indications of a band forming are faint echoes above the 0 °C. isotherm, falling towards the ground. At about, or just below, the 0 °C. level, the echoes develop the increased intensity and band structure which is the characteristic feature of this formation, and which has been identified as the melting band. Following the development of this band, echoes appear falling

from the underside in the form of diffuse patches, which eventually reach ground level. The band persists, perhaps intermittently, for the duration of the rain period, which may be several days.

The observations throughout the year agree with those of Hooper and Kippax (1950) that the intense band is invariably situated just below the 0 °C. isotherm, confirming that this is the region of transition from the solid to the liquid state. The 0 °C. isotherm in this area varied throughout the year from 5000 to 16,000 ft.

It seems clear that in this melting-band rain, the precipitation originates as ice at some height above the 0 °C. isotherm. That is the mechanism of rain formation visualized by Bergeron (1933), who has stated that in his opinion almost every real raindrop and all snowflakes originate around an ice crystal.

Frequently in the presence of melting bands the echoes above the band extend to considerable heights. The upper echoes, as they are called, sometimes take the form of horizontal striations or upper bands, which can clearly be seen to develop and gradually fall towards the melting band. A detailed description of the formation of these upper bands has been given by Bowen (1951). Plate 2 shows the formation of an upper band at a height of 8000 ft. above the melting band.

Occasionally two or more upper bands can be seen simultaneously, or the upper echoes may take various other forms such as sloping layers, diffuse patches or simply a random distribution of echoes. Plate 3, Figures 1–3, shows typical examples of such upper echoes. Usually these echoes appear to fall gradually towards the melting band, their distinctive outlines becoming less obvious as the melting band is approached. At times, when a particularly distinct upper band develops, the path traversed by the echoes can be clearly followed from their initial development above the 0 °C. isotherm down to site level, illustrating very clearly the intensification of the transition region.

Only exceptionally does the melting band show any appreciable signs of turbulence. On one such occasion the melting band, for several hours, was repeatedly seen to burst up into a very ragged formation, and then subside again to a normal melting-band formation. A similar effect is illustrated in Plate 4, Figure 1, which shows a local thunderstorm developed at the same time as a melting-band formation. The echoes forming part of the band were clearly seen to be transported from 11,500 ft. to a height of 25,000 ft., obliterating the melting band and producing this combined effect.

On two occasions a lowering of the melting band was observed. These coincided with the passing of a cold front over the area, and in each case the drop in height was of the order of 1000 ft., and the time taken about 30 min.

(*b*) *Shower Echoes*

The thunderstorm, cold-front, and non-freezing shower echoes can be readily identified by their characteristic cellular column construction. Observations on the build-up of the shower echoes, together with reports from aircraft observations, confirm the meteorological evidence that convection is the predominant factor in the development of these showers.

The rain intensities, rain echo intensities and drop size spectra (samples of the latter are taken from time to time by the stained filter paper technique) all vary considerably during the rapid build-up and decay of individual showers and between the different types of shower. The thunderstorms give rise to intense radar echoes with clear-cut edges, to rain intensities often in excess of 2 in./hr., and to numerous drops exceeding 3 mm. in diameter. At the other extreme, the smaller non-freezing showers are more often only of moderate rain intensity (0·2 in./hr.) and have a restricted drop size spectrum with a tendency for the larger drops to reach a maximum size of about 1·5 mm. diameter.

It has been well established by Bowen (1950) and Smith (1951) that non-freezing showers are a feature of this locality, and often a number of these can be seen together on the radar display tube. Plate 4, Figure 2, shows examples of these non-freezing showers in which the echo-producing precipitation elements develop wholly below the 0 °C. isotherm, presumably due to coalescence. This type of shower is of frequent occurrence in this locality during the warmer months of the year, and situations favourable for its development may last for several successive days. A well-marked temperature inversion below the 0 °C. isotherm invariably limits the maximum height reached by non-freezing showers to the inversion layer, as shown in Plate 4, Figure 3, where the inversion layer at 8000 ft. is some 5000 ft. below the 0 °C. isotherm ($+\frac{1}{2}$ °C. at 8000 ft., +3 °C. at 9000 ft.). Aircraft observations in this area suggest that usually the atmosphere above such inversions consists of clear air free from ice crystals or cloud layers.

On occasions, shower echoes are seen to extend up to and beyond the 0 °C. isotherm, and there appear to be two distinct phenomena involved. In some cases an obvious brightening or intensification at the top of each shower is clearly visible, at about or just below the 0 °C. isotherm, as shown in Plate 5, Figure 1, and on these occasions the melting stage is obviously part of the mechanism of rain formation. However, there is, generally, no visible sign of increased intensity which could suggest a transition from the ice stage and, as these showers are frequently associated with those which develop wholly below the 0 °C. isotherm, the observations tend to confirm the suggestion by Bowen (1950) and Smith (1951) that showers in which the icing stage plays no part do extend, in this area, up to and beyond the 0 °C. isotherm.

An approaching cold front, distinguished visually by the characteristic frontal cloud formation, almost invariably gives rise to showers and shower echoes. Apart from the unmistakable column construction, these cold-front showers can be readily recognized because a number of them appear together, and the radar picture suggests a series of separate convection showers embedded in the cloud, which is usually continuous, associated with the front. Observations of the development of these cold-front shower echoes, and of the cloud formations producing them, suggest this marked convection, and, although when fully developed the echoes extend from well above the 0 °C. isotherm to the ground, no apparent melting stage is visible at any level. Typical examples of these cold-front showers are illustrated in Plate 5, Figure 2, and these particular examples clearly show the tilting effect of the lower winds on the column-like

structures. These frontal showers have a more rapid development, extend to greater heights, and are usually of greater intensity than the non-freezing showers, and, although individual showers may build up and decay rapidly, the showers as a whole may last several hours.

The difference between the cold-front showers and the thunderstorms appears to be essentially one of size; in addition, the latter can develop entirely independently of frontal conditions as isolated convection showers or heat storms. The immense cumulo-nimbus cloud formation which develops before the appearance of the radar echoes, the peculiar squally wind which immediately precedes the rainfall, and copious precipitation are some of the characteristics of the thunderstorm. Hail occasionally fails, and thunder and lightning are invariably present. Precipitation elements of any size first develop at some height above the 0 °C. isotherm, and the echoes received from them are seen to extend in all directions, developing into the column- or tower-like structures illustrated in Plate 5, Figure 3. Plate 6 comprises a series of photographs showing the development of this thunderstorm echo.

A fully developed thunderstorm echo may extend to a height corresponding to 35,000 ft., the maximum height of the echo being reached at about the time the first precipitation reaches the ground. On reaching this maximum height the echo commences to collapse or decay, the precipitation elements responsible for the echo falling out of the sky in a violent local storm covering a comparatively small area and lasting only a short time.

Radar echoes from lightning flashes have been seen, as reported by Ligda (1950), the echo from the path of the discharge appearing as a streak of high intensity situated or commencing near that part of the echo which first appeared.

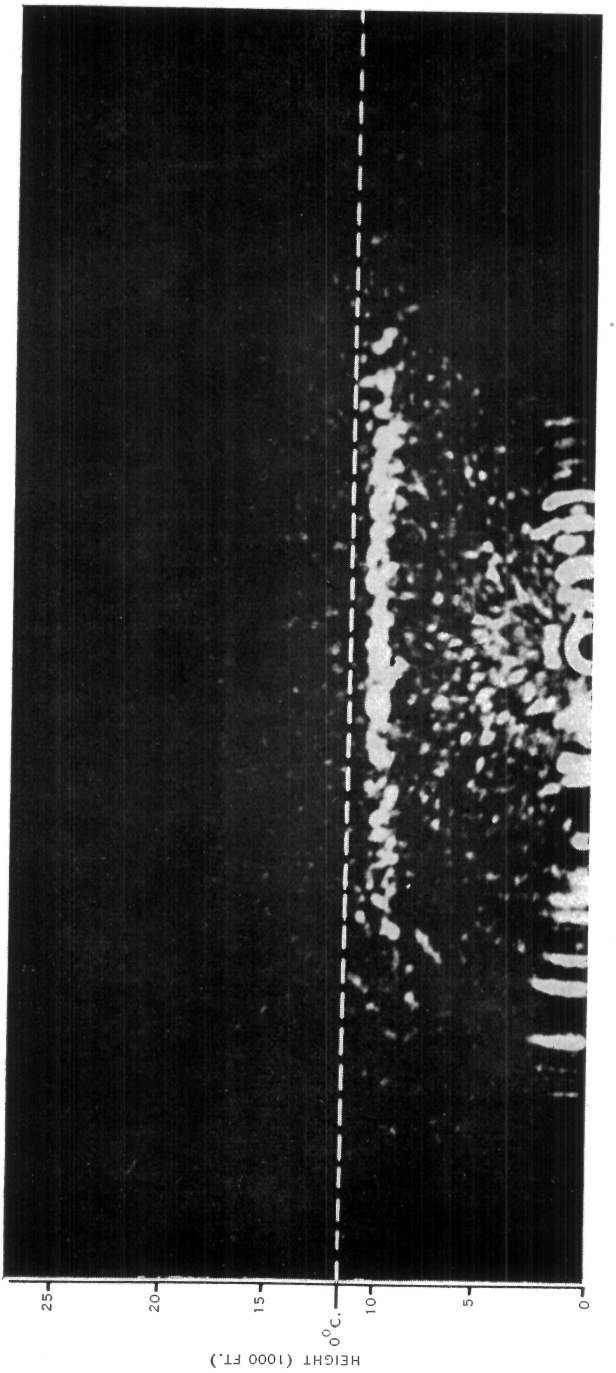
As with the cold-front showers, there is no sign of a melting or transition stage, but this does not necessarily signify complete absence of the icing stage; in fact, some observations suggest that the glaciation of the top of the cumulo-nimbus starts this phenomenon developing. It has been suggested that the extreme turbulence which is known to exist within this type of cloud formation may be responsible for the absence of any visible melting stage.

(c) *Echo Masses*

The broad layer-like formation of the echo masses can perhaps best be defined by the absence both of the column structure of the shower echo and of an intense melting band. As the name suggests, they consist of a solid mass or block of echo, limited in horizontal extent only by the sensitivity of the radar equipment. As with the non-freezing showers, there appear to be at least two distinct sets of conditions for development of echo masses, and it is by no means clear whether the two phenomena are related or brought about by entirely different mechanisms.

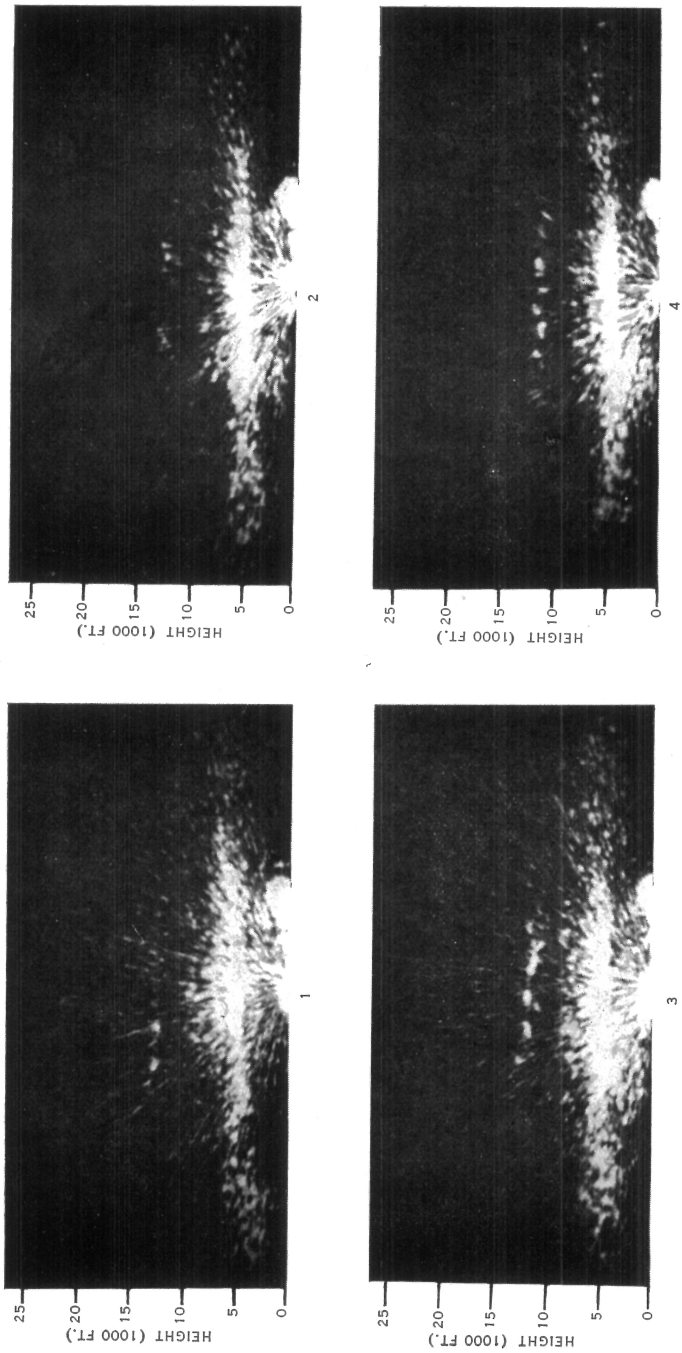
In Plate 7, Figure 1, the maximum height of the echo-producing elements of the echo mass is shown to be that of the temperature inversion derived from the radiosonde sounding taken about the time of the observation (+2 °C. at 7000 ft., +6 °C. at 8000 ft.). The 0 °C. isotherm is shown to be some 5500 ft. above this inversion layer. This set of conditions is clearly similar to that of

RADAR OBSERVATIONS OF RAIN



Melting-band echo from precipitation, August 1, 1950.

RADAR OBSERVATIONS ON RAIN



Formation of upper band, November 17, 1950, at 8000 ft. above melting band.

RADAR OBSERVATIONS OF RAIN

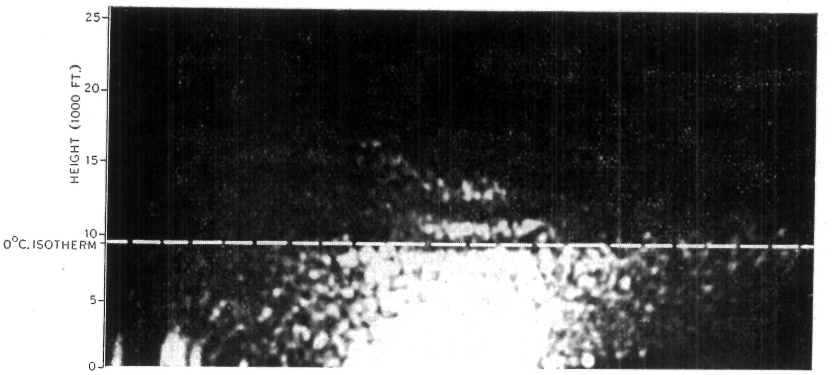


Fig. 1.—Multiple upper bands, July 10, 1950.

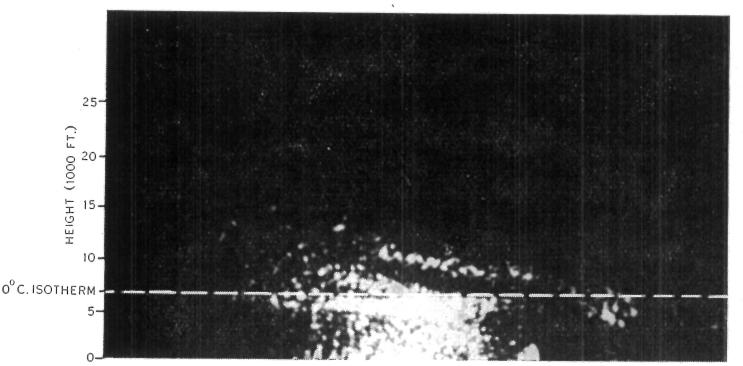


Fig. 2.—Upper echoes forming sloping layers, June 8, 1950.

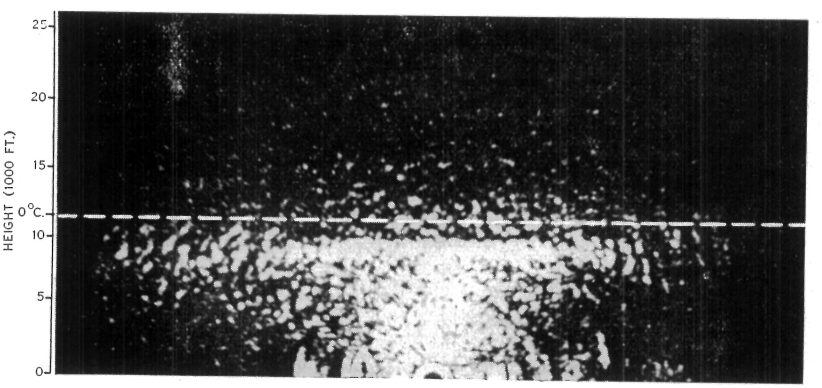


Fig. 3.—Upper echoes falling into melting band, January 18, 1950.

RADAR OBSERVATIONS OF RAIN

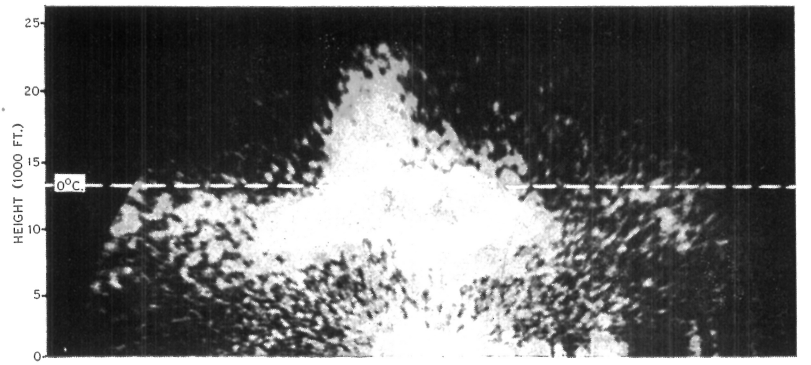


Fig. 1.—Combined melting band and thunderstorm, December 30, 1950.

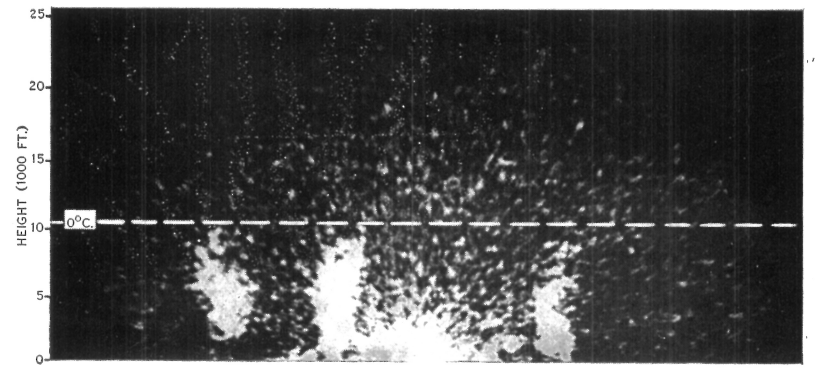


Fig. 2.—Non-freezing showers extending to 0 °C. isotherm, January 18, 1951.

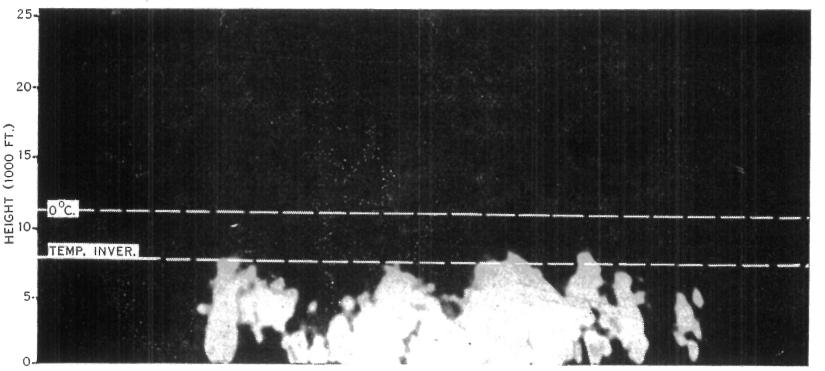


Fig. 3.—Non-freezing showers limited by temperature inversion, April 14, 1950.

RADAR OBSERVATIONS OF RAIN

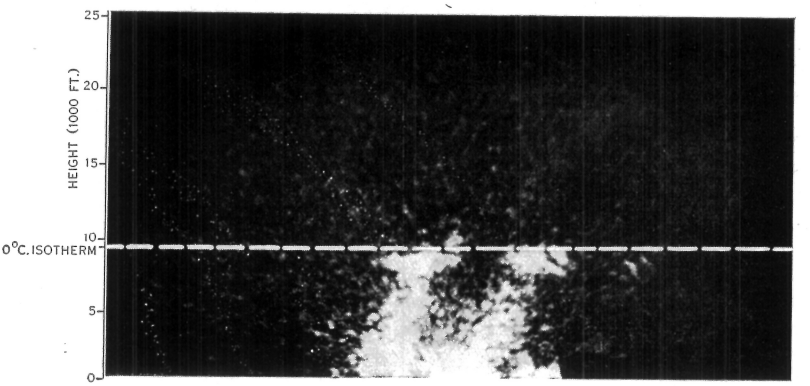


Fig. 1.—Shower echoes showing intensification at top, January 18, 1951.

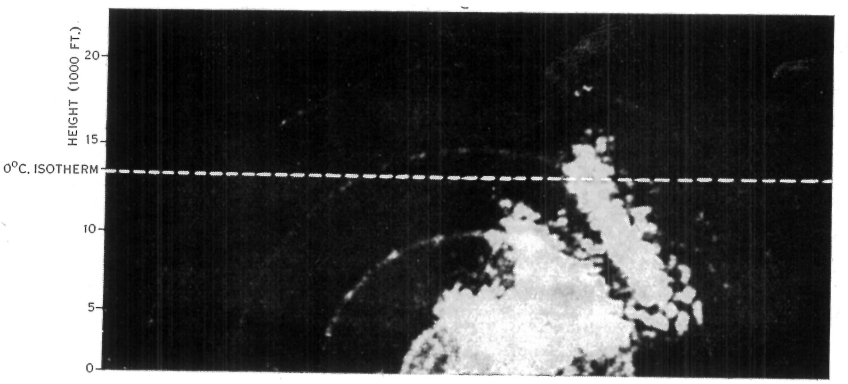


Fig. 2.—Shower echoes from cold front, March 27, 1950.

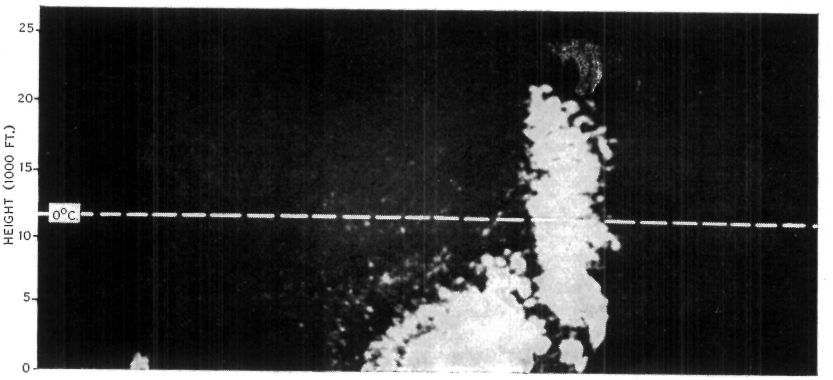
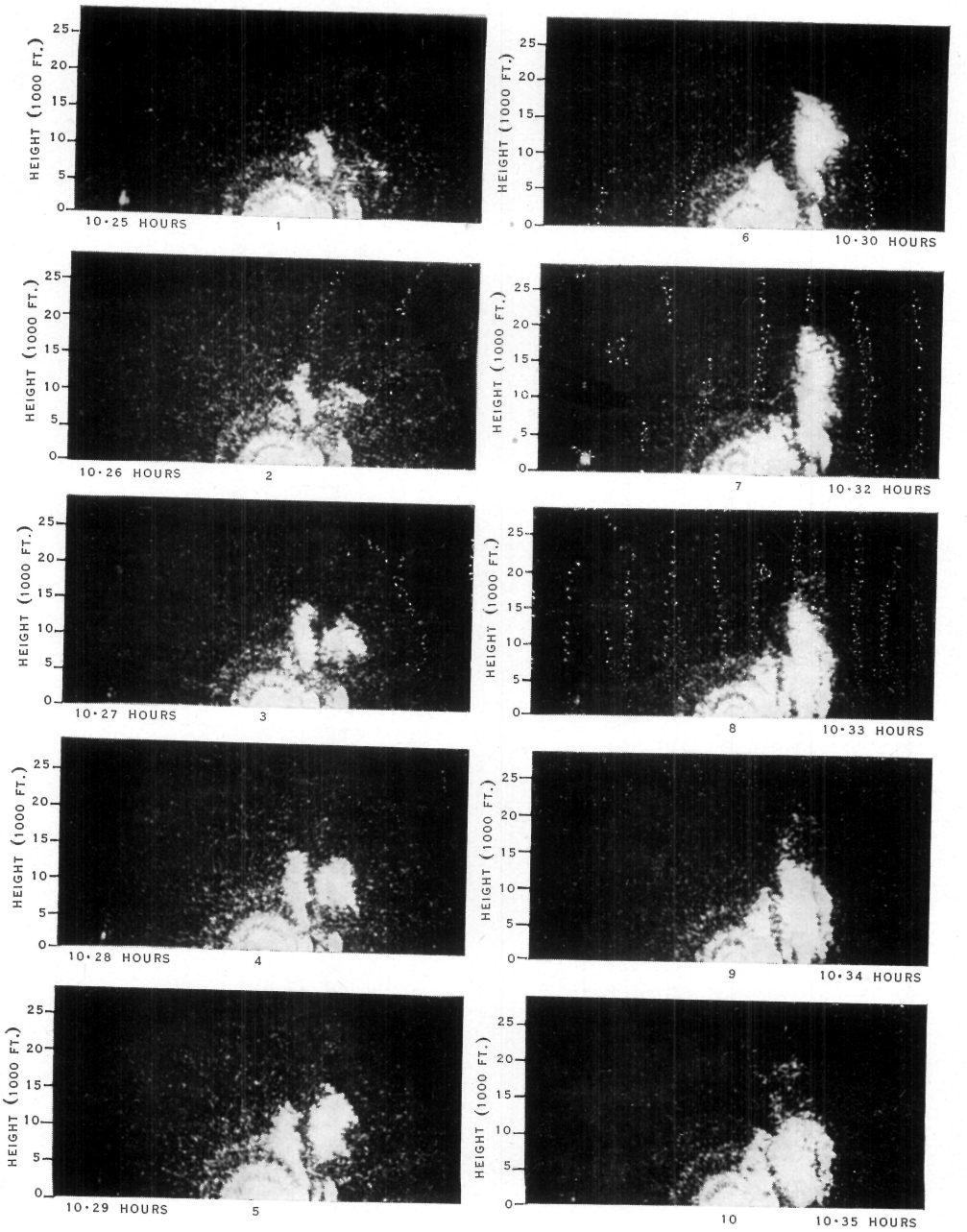


Fig. 3.—Thunderstorm echo, March 27, 1950.

RADAR OBSERVATIONS OF RAIN



Development of thunderstorm echo.

RADAR OBSERVATIONS OF RAIN

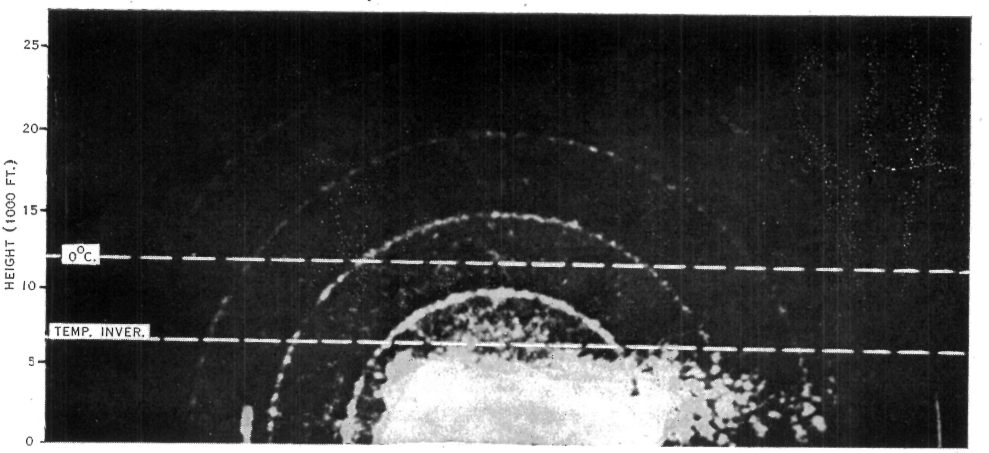


Fig. 1.—Echo mass limited by temperature inversion, April 12, 1950.

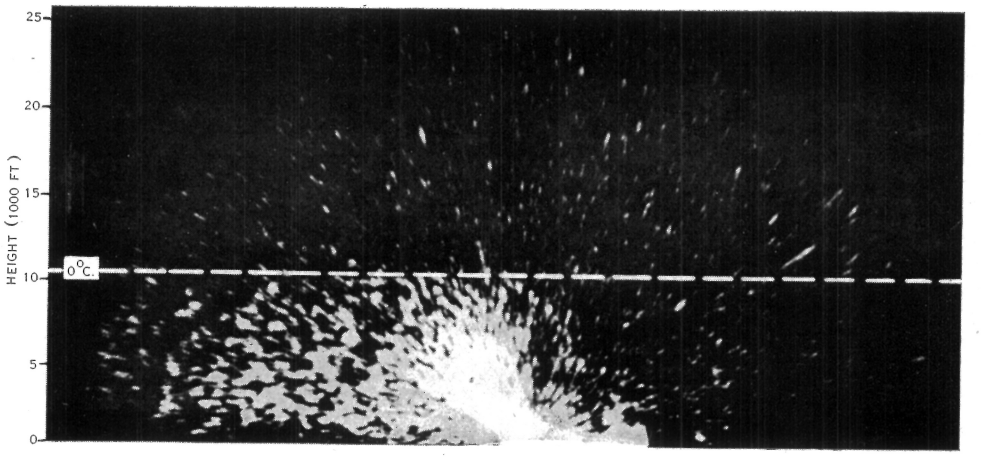


Fig. 2.—Echo mass limited by 0 °C. isotherm, February 14, 1950.

the inversion-limited non-freezing showers, and it is likely that these masses consist wholly of water drops formed from cloud droplets by a similar coalescence process. Drop size measurements taken when these inversion-limited echo masses prevail suggest a similar spectrum to the smaller non-freezing shower echoes, with no particularly large drops and a tendency for the largest of those present to be of uniform size.

The second type of echo mass, although it appears somewhat similar on the radar display tube, is not accompanied by an inversion, and the maximum height of the echo-producing precipitation approaches the 0 °C. isotherm. Although at times the top of an echo mass of this type is as clearly defined as with the inversion-limited type, more frequently there is a gradual fading of the echo intensity against height, as would be expected from its range alone. Plate 7, Figure 2, is an example of this type of echo mass. In exceptional cases patches of echoes can be seen falling into these masses from well above the 0 °C. isotherm, but without any obvious indication of a transition stage.

Although the inversion-limited echo masses may persist for many hours, this is not the case with the other type, which more frequently appears associated with melting-band formations. This suggests that a melting stage might be involved, the size or density of the precipitation elements being such that, with the sensitivity of the particular radar used, no radar echo is visible. Probably at least two distinct processes are involved, and further evidence is necessary for a complete understanding of the phenomenon.

IV. Correlation between Type of Rain Echo and Weather Situation

It seemed likely that the type of rain echo observed should depend primarily on the vertical stability of the air. Observation days were first classified into two groups according to whether the rain echoes seen indicated the presence of ice crystals or not.

(i) " Bergeron rain "—days when a melting band was present.

(ii) Purely non-freezing rain—days when the echoes (showers or masses) did not extend up to the freezing level, or where they reached close to it, but without any intensification such as would be expected if ice particles were melting just below it.

All other observation days were classified as complex. These included days when showers or thunderstorms occurred, giving echoes which reached above the freezing level, but without any band formation near it, and days on which melting bands were observed some of the time and not at others.

Some difficulty was met in finding a criterion for the vertical stability of the air. The radiosonde data from Rathmines did not seem adequate, partly because of the displacement in space (90 miles) and in time (up to 9 hr.), and partly because of the difficulty of radiosonde observations during bad weather. Aircraft reports of turbulence were found to be too sparse and inconsistent. In the absence of direct observational data, it was necessary to fall back on synoptic criteria. In the neighbourhood of Sydney the association between

TABLE 1

RADAR ECHOES, DEPARTURE OF PRESSURE FROM MONTHLY MEAN, AND RAINFALL DATA

Date	Type of Echo*	Classification†	Departure of Daily Pressure from Mean for Month (mb.)	24-Hr. Rainfall (in.)
Jan.				
18	*B*	*B*	—4·1	4·48
Feb.				
4	*B*	*B*	+0·6	1·12
6	*B*	*B*	—3·5	1·60
7	*B, M, CFS*	*C*	—7·8	
8	*B*	*B*	—6·8	0·12
14	*M*	*NF*	+1·5	0
15	*B, S*	*C*	—3·2	
18	*B*	*B*	—3·9	0·26
Mar.				
3	*B*	*B*	—5·9	0·53
6	*B, CFS*	*C*	—3·9	
7	*B*	*B*	+2·1	0·88
14	*NFS*	*NF*	+8·8	0·12
27	*T*	*C*	+5·6	
28	*B*	*B*	+2·9	0·06
30	*B*	*B*	—1·6	0·10
31	*B*	*B*	—0·2	0·02
Apr.				
3	*B*	*B*	—6·1	0·29
4	*B*	*B*	—11·7	0·09
12	*NFS, M*	*NF*	+5·2	0·09
14	*NFS, M*	*NF*	+6·3	0·24
30	*B*	*C*	+1·1	
May				
9	*CFS, M*	*C*	—10·0	
24	*B*	*B*	—8·9	3·15
June				
7	*B*	*B*	—5·3	2·05
8	*B*	*B*	—7·1	1·91
13	*NFS*	*NF*	+7·0	0·35
14	*B & S*	*C*	+5·0	
15	*B & S*	*C*	—2·2	
16	*B & S*	*C*	—5·1	
19	*CFS*	*C*	+5·5	
20	*NFS*	*NF*	+6·7	0·17
26	*S, B*	*C*	—14·5	
July				
3	*B*	*B*	—7·7	0·01
10	*B*	*B*	+2·9	2·17
July				
13	*NFS*	*NF*	+4·0	0·36
14	*S, B*	*C*	+7·3	
17	*NFS*	*NF*	+3·6	0·17
18	*S, B*	*C*	+1·8	
24	*NFS*	*NF*	+7·9	0·29
25	*NFS*	*NF*	+7·6	0·33
26	*NFS*	*NF*	+4·7	0·23
27	*NFS*	*NF*	+1·1	0·64
28	*S, B*	*C*	+3·6	
Aug.				
1	*B*	*B*	—10·6	0·25
10	*B*	*B*	+7·8	0
16	*NFS*	*NF*	+8·8	0·14
21	*B, S*	*C*	—2·9	
23	*B, S*	*C*	+6·2	
28	*B, S*	*C*	+4·0	
Sept.				
11	*B*	*B*	+6·3	1·71
12	*NFS*	*NF*	+1·0	0
13	*NFS*	*NF*	+3·0	0·72
14	*B, NFS*	*C*	+1·7	
Oct.				
6	*B*	*B*	—0·5	0·09
18	*B*	*B*	—4·0	0·88
19	*B*	*B*	—13·2	0·39
20	*CFS*	*C*	—15·9	
25	*B*	*B*	—6·3	0·31
Nov.				
1	*B*	*B*	—5·7	0
3	*B, M, S*	*C*	—9·3	
10	*CFS*	*C*	—11·4	
14	*B, S*	*C*	—2·6	
16	*B*	*B*	+4·4	0·60
17	*NFS*	*NF*	+5·7	0·01
20	*S, B*	*C*	+2·1	
21	*B*	*B*	+2·3	0·32
24	*B*	*B*	—0·2	0·60
Dec.				
6	*NFS*	*NF*	+0·1	0
8	*CFS*	*C*	—12·0	
23	*B*	*B*	+4·2	0·12
30	*B*	*B*	—1·7	0·27

* *B*, Bergeron or band echoes ; *NFS*, showers not extending above freezing level ; *CFS*, cold-front showers ; *M*, masses not extending above freezing level ; *S*, showers extending above freezing level ; *T*, thunderstorm.

† *B*, Bergeron or band ; *NF*, non-freezing rain not extending above freezing level ; *C*, complex (not plotted on Figures 1 and 2).

rain and fronts is much weaker than in higher latitudes. Most of the rain results from convergence of apparently homogeneous air masses. An attempt to relate rain echo type to the air mass as determined from the trajectory of the

lower layers failed ; the properties of the onshore maritime streams which brought most of the rain varied only slightly from one rainy day to another, and no correlation could be found with echo type. This latter result is consistent with the fact that the stability of air masses in this region is influenced more by vertical movements associated with mass convergence and divergence than by advective effects. In view of this and of the known connection between stability and surface pressure situation, it was decided simply to classify the days of

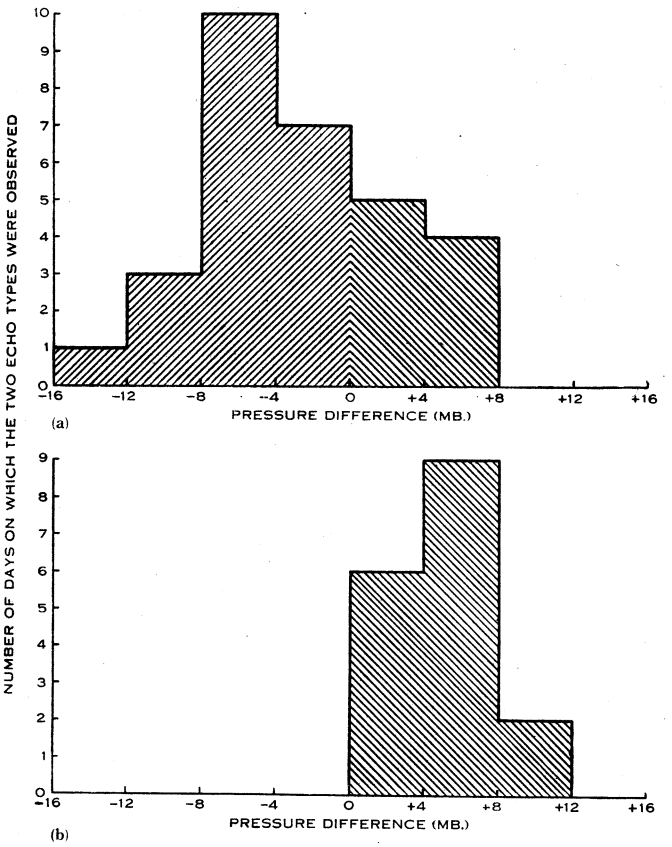


Fig. 1.—Histograms of number of days with (*a*) " Bergeron " and (*b*) non-freezing rain, grouped according to the departure of the surface pressure from the mean for the month.

observation on the basis of the pressure at Sydney. The mean of the 0900 and 1500 hours (E.S.T.) pressures being readily available, this was used as the pressure for the day. The mean value of these pressures was found for each month, and the departure of the day's pressure from this mean was found.

The relevant data are shown in Table 1. For each date is given the type of echoes observed, as described in Section III above. Then follows the classification used for the present purpose into days when the echoes showed melting bands (*B*), those when they were from non-freezing rain (*NF*) and the

undetermined or complex cases (*C*). In the fifth column is given the 24-hr. rainfall (9 a.m. to 9 a.m.) observed at Sydney Weather Bureau for days classified as *B* or *NF*. For the use made of them (see Fig. 2), these rainfall measurements may be taken as representative of the rainfall at the Radiophysics Laboratory.

The association between pressure departure and rain echo type is shown in Figure 1, which gives histograms of days of Bergeron and non-freezing rain grouped according to the departure of the pressure from the mean for the month.

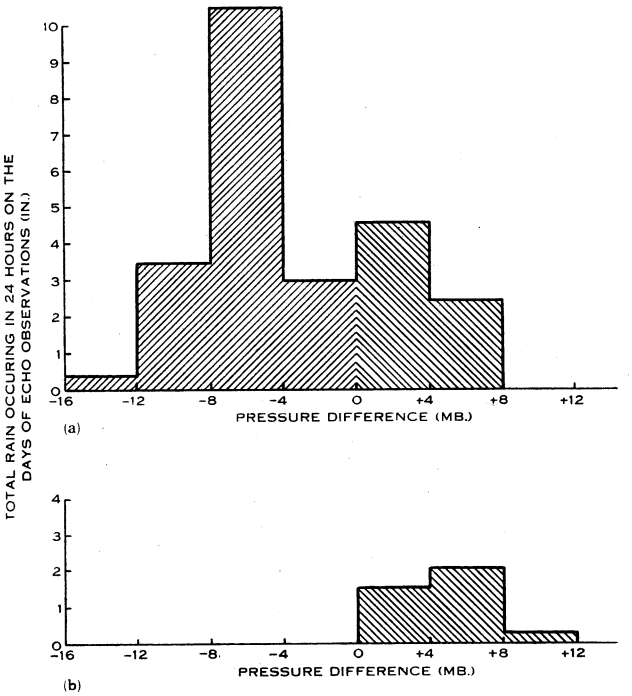


Fig. 2.—Total of 24-hr. rainfalls on days when (*a*) " Bergeron " and (*b*) non-freezing rain fell, grouped according to the departure of the surface pressure from the mean for the month.

Clearly, melting bands occurred mostly when the pressure was low ; non-freezing rain occurred in this series only when the pressure was above the norm. The same effect is shown in Figure 2, where the total amount of rain (i.e. the sum of the 24-hr. rainfalls) is used instead of the number of days. Figure 2 also shows that the days when only non-freezing rain echoes were observed accounted for only a small proportion of the total rainfall occurring on the days of observation. The latter amounted to 53 per cent. of the entire rainfall over the period of observations.

V. Conclusions

From the observations described here it appears that it is possible to classify rain echoes into several distinct types. The distinction of greatest physical interest is that between Bergeron-type rain, with the radar echo showing a

melting band just below the freezing level, and non-freezing rain where no such band occurs.

Bergeron-type rain was observed predominantly with low pressure, that is, in unstable air; non-freezing rain with high pressure, that is, in stable air. It must be noted that the presence of ice crystals in a cloud does not imply that, in their absence, no rain would have fallen. The simplest interpretation of Figures 1 and 2 seems to be that, with pressure above normal, in stable air, cloud tends to be so limited in height that ice crystals are not formed and only the non-freezing rain process—the coalescence of liquid drops—can operate giving purely non-freezing rain. This latter process no doubt operates also in deeper clouds where ice is present, but the present study gives no hint of its relative importance. Thus, although Figure 2 would indicate that the relative contribution of purely non-freezing rain to the total rainfall was small, this might be quite misleading as regards the real importance of ice crystals in the rain régime at Sydney. So far as these present observations go, it could even be that, if somehow ice were prevented from forming at all in clouds, little difference would be noticed in the total rainfall.

VI. Acknowledgments

These observations, which are part of the rain physics programme of the Radiophysics Laboratory, were initiated by Dr. E. G. Bowen. The author wishes to express his thanks to Mr. P. Squires both for his cooperation and his contribution to this paper, and to Mr. J. Warner under whose guidance the observations were carried out. Thanks are due to the New South Wales Branch of the Commonwealth Meteorological Bureau for much of the information used in the analysis, and to Mr. D. C. Dunn who constructed and maintained a number of the special radar units used.

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