INITIATION OF SHOWERS BY SNOW

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ABSTRACT

Examination of radar records shows that snow trails frequently occur around the tops of showers. Evidence has been sought that showers are occasionally initiated by the seeding of supercooled cumulus clouds by snow. Certain observed radar patterns suggest strongly that showers were produced in this manner. As a check, plan diagrams with height contours have been synthesized and used to organize vertical sections obtained on different bearings. The constructed plan diagrams show showers occurring in regions of snow trails more frequently than elsewhere.

1. Introduction

Radar studies show that continuous precipitation originates as snow, frequently forming in compact generating cells (Marshall, 1953a). Theoretical studies show that a continuously generating element produces a pattern, or trail, which maintains its shape and moves with the velocity of the generating element. If the generating element, or cell, moves with the wind at its own level, the slope of the snow trail at any level is inversely proportional to the difference in wind between that level and the generating level.

In some cases, shower echoes are observed in close conjunction with echoes from snow trails, suggesting possible significant interactions (fig. 1). Marshall (1953b) considered the possibility that the lightning discharges, which are sometimes observed by radar around the tops of thunderstorms, occur between the thunderclouds and surrounding trails of falling snow. He suggested also that snow might act as a seeding agent to initiate showers in cumulus clouds.

The processes by which precipitation forms in cumulus clouds are not completely understood as yet. The Bergeron process, although not the explanation for all showers, is of major importance. The temperature at which glaciation of cloud droplets first occurs, to make possible growth by the Bergeron process, depends on

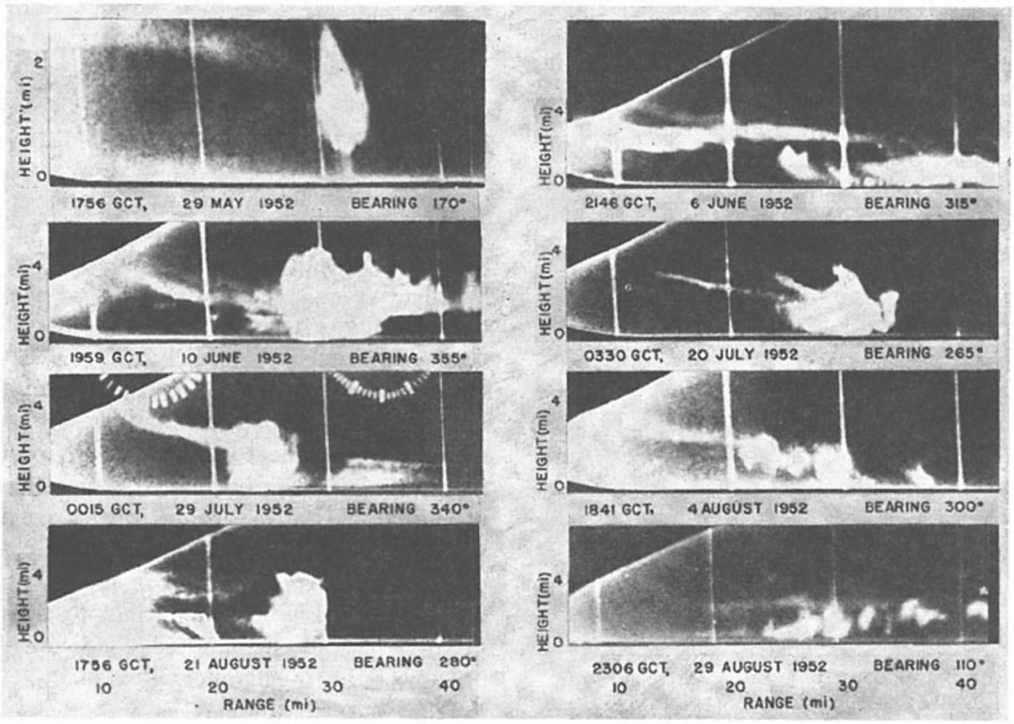

Fig. 1. Vertical-section radar photographs, showing showers associated with snow.

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the types of freezing nuclei present. It generally ranges from −12C down to −30 or −40C (Houghton, 1951).

Observations on 399 clouds in New Mexico during 1950 revealed no precipitation echoes for clouds whose tops had temperatures between 0 and −12C. Even with cloud top temperatures as low as −25C, about half of the observed clouds failed to return a radar echo (Braham *et al*, 1951). It was found further that, for the various temperature ranges colder than −12C, the percentage of clouds showing radar echoes was greater on generally cloudy days. The writers suggested that cirrus produced by one storm might seed neighboring clouds, which had not reached the height at which ordinary glaciation would occur.

2. Patterns due to interaction between snow and cumuli

The possibility that trails of continuous snow can seed cumulus clouds to produce showers will now be considered in detail. We shall consider as seeding those cases in which the introduction of precipitation particles results in the formation of a shower which is then self-sustaining. This process is not to be confused with growth in a deck of low cloud, which sometimes causes variations in precipitation intensity at the ground, such as reported by Ligda (1952). The patterns resulting from seeding could be very complex, but consideration of a simple hypothetical case shows the pattern type to be expected.

Consider a case in which wind direction is invariant with height, but wind speed increases linearly with height. A radar set pointed in the direction of the wind "sees" a snow trail as a parabolic figure, such as curve *a* in fig. 2. Assume the freezing level to be 10,000 ft, a non-precipitating cumulus cloud based at 5000 ft and topped at 15,000 ft, and moving with the 10,000-ft wind, a snow generating cell at 24,000 ft, and a wind shear of 2.5 mi/hr per 1000 ft. To simplify the diagram, the reference axes are considered as moving with the 10,000-ft wind. The cumulus thus remains fixed on the diagram, and snow-flake trajectories shown are trajectories relative to the cloud. The cumulus is subject to internal currents and to shearing effects, but these are ignored in the present case. The shape of the snow trail is a function of the snowflakes' rate of fall and the wind shear only, and so is independent of the choice of reference axes. A calculation of trajectories, with use of a fall velocity of 4 ft/sec, reveals the pattern at successive times.

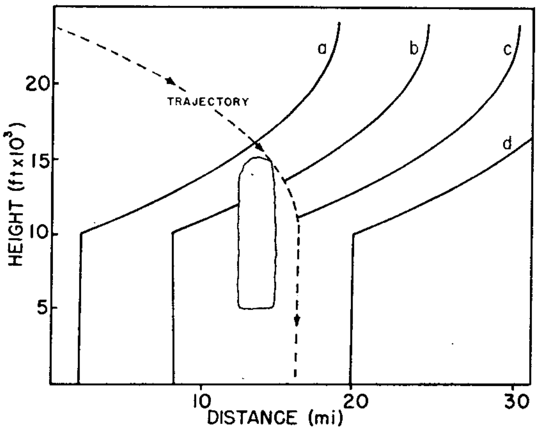

FIG. 2. Successive positions of snow trail, and trajectory of individual snowflake, with respect to cumulus cloud.

As the cumulus cloud does not return an echo until it precipitates, the first observed effect will be its "shadow" appearing as a gap in the snow trail just beyond the cumulus cloud. The snow entering the cloud will be scattered by the various vertical currents in the cloud, and may become too diffuse to return a detectable echo.

If the radar set is not pointed parallel to the wind shear (which is in the same direction as the wind for this example), the gap will not appear. Echo will be received from snow on either side of the cumulus being investigated, the "shadow" of the cumulus extending from it at an angle to the radar beam.

The region around the cloud top is one of divergence, with rising currents inside the cloud. It is therefore unlikely that any snow could enter the cloud from above. Fig. 2 (curve *b*) shows that snow comes into contact with the upwind side of the cloud, the point of contact descending as time passes. In this region, air flows into the cloud with a velocity comparable to the fall velocity of snowflakes. Therefore, snow is likely to be carried into the cloud.

In the cloud, the snowflakes may grow by condensation, accretion of cloud droplets, or by a combination of the two processes. In any event, the development of a shower is likely.

The range over which the seeding process could work is rather limited. As entrainment is not found at the very top of a cumulus cloud, a cloud-top temperature of about −3C or colder is necessary for entrainment of snow to occur. Theoretically, the snow trail could be effective as a seeding agent after melting to rain; but the higher terminal velocities of raindrops make their entrainment less likely than that of snowflakes. The greater terminal velocities of raindrops would, however, make it possible for them to enter a cumulus cloud through the top. This would require that the cumulus-cloud tops be below the freezing level, which, in middle latitudes, means rather weak convective activity. The subsequent growth by accretion and/or coalescence corresponds more closely to the process described by Ligda (1952) than to true seeding. No pictures have been found that indicate the formation of showers in this manner.

It appears that, for days with the temperature at the top of the largest cumuli between about −3 and

−12C, snow could cause showers when none would occur otherwise, except perhaps through coalescence of liquid drops. On days with cumulus tops colder than −12C, seeding by snow could increase the proportion of precipitating cumulus clouds.

3. Examination of radar records

Film records of observations made at the McGill Radar Weather Observatory, Montreal Airport, from 1949–1952 have been examined for evidence of interaction between continuous and showery precipitation. Radar pictures in vertical section, resembling stage *b* or stage *c* of fig. 2, have been found for one day in 1951 and eleven days in 1952. Sample pictures for eight of the days are shown in fig. 1. The meteorological data for each case have been collected and used to check movements of precipitation areas, slopes of snow trails, *etc.*

As an example, the situation of 29 May 1952 will now be considered. The Montreal region was covered by a weak flow of moist polar air, with a strong southwesterly flow of tropical air aloft. This tropical air was associated with an occlusion to the east.

A vertical section, on a bearing of 170 deg at 1756 GCT, shows a shower at 30 to 34 mi and a snow trail out to 28 mi. (See fig. 1.) Observations on other bearings show that the snow was forming just north and northeast of the radar set, at an altitude of 22,000 ft. The shower shown here extends up to 18,000 ft, so its velocity can be taken as that of the 10,000-ft wind without serious error. The wind shear from 10,000 to 18,000 ft was from 170 deg. Therefore, the "shadow" of the shower extended from it towards the radar in this picture. This is a possible explanation for the observed gap in the snow trail from 28 to 30.5 mi. The absence of echo beyond the shower is attributed to attenuation. On the other hand, the absence of echo from snow beyond 28 mi could be merely the result of decreased sensitivity with range.

The only sequence showing the development of a shower, from its early stages to maturity, on a snow trail was recorded on 26 July 1952. It consists of about 300 frames of motion-picture film, with each frame occupying 2 sec. When viewed with the aid of a projector, it provides striking evidence for the seeding process. A small shower echo, embedded in a snow trail, first appeared at 16,000 to 21,000 ft. The top showed only minor fluctuations, but the shower developed rapidly downwards. (See fig. 3.) The base of the echo descended at an average rate of 25 ft/sec between 1911 and 1915 GCT, and at 38 ft/sec between 1915 and 1919 GCT. By 1919 GCT, the echo top had risen at least 2000 ft, but the shower was then too close for its top to be seen. This rapid downward development, with less marked upward development, is common in showers in temperate latitudes (Battan, 1953; Rigby and Marshall, 1953). Rain at the ground, as indicated by radar, began 8.5 min after the first echo was detected. Some pictures were taken on reduced gain, but no bright band was detected at any stage.

The shower developed in a west-southwesterly flow of very warm air, associated with a high pressure area near Nantucket. The component of the thermal wind perpendicular to the radar bearing was very small. This means that the sides of the shower were nearly vertical, as shearing effects were small. The radar was pointed very nearly into the wind, and the bearing changed slightly to follow the shower as it progressed. It was concluded, therefore, that changes in the echo represented changes in the shower, and not a movement of different parts of the shower across the radar beam.

On days when pictures were recorded of mature showers only, care was taken to avoid mistaking a cumulonimbus anvil for a snow trail. Byers (1951) states that anvils and other lateral extensions of cumulonimbi usually do not return radar echoes. However, he does not rule out this possibility.

In the usual case of wind increasing with height, the only direction in which anvils extend an appreciable distance from cumulonimbus clouds is downwind. It was sometimes possible to find pictures showing an extensive trail on both sides of the shower. In other cases, plots on polar diagrams were used to confirm the existence of snow trails from generating elements at higher levels.

A comparison has been made of temperatures at the tops of the warmest showers developing on snow trails, and at the tops of the warmest isolated ones occurring on the same day. These are given in fig. 4. An attempt was made to find showers in their earliest stages, but in some cases it was necessary to make measurements on showers which already had a vertical extent of several thousand feet. It should be noted that the

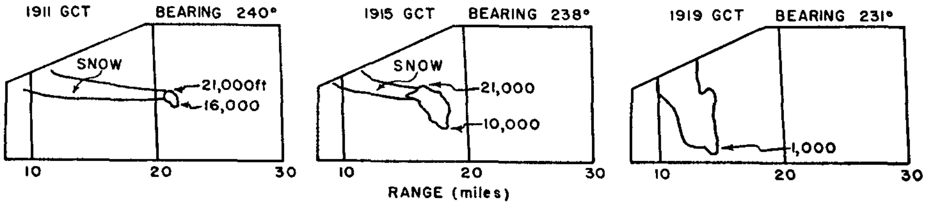

FIG. 3. Vertical sections through shower developing on snow trail, 26 July 1952.

temperatures given are for the tops of the shower echoes. The top of a cumulus cloud extends some distance above the shower developing in it, and it is therefore a few degrees colder. Quantitative observations on this point are lacking.

On two days (cases 3 and 4), showers developed in regions affected by snow trails at temperatures much higher than those of isolated showers. For the other days, however, the temperatures were nearly the same, so no general conclusions can be drawn from this figure.

In summary, one of the twelve days studied showed the complete development of a shower on a snow trail. On ten other days, showers were recorded along snow trails with temperatures at their tops between 0 and −10C. The presence of showers with tops in this temperature range suggests that the snow was responsible for their formation. However, in all but two of these cases, isolated showers developed with their tops in the same temperature range as those associated with snow. No conclusions can be drawn from the twelfth example, which showed a thunderstorm in its mature stage only.

4. Plan patterns

The clouds and precipitation occurring at any time from a three-dimensional system, and their pattern in three dimensions, are significant. So far, only vertical sections have been considered, and the patterns derived have been compared directly with the radar records used in this study. When vertical sections are obtained on different bearings in succession, a three-dimensional view of the situation can be obtained by combining the observations on plan diagrams with height contours. Theoretical plan patterns can be derived for comparison with the results obtained in this way.

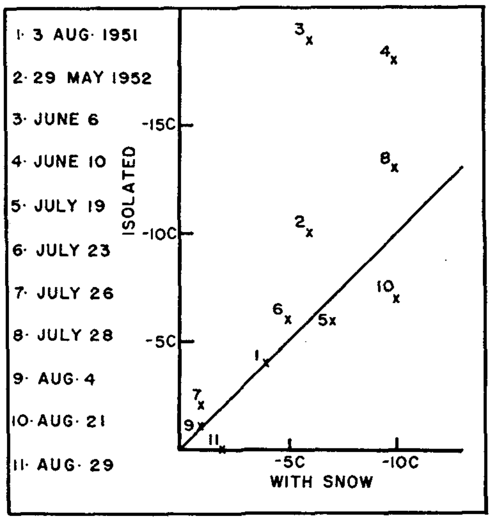

FIG. 4. Comparison of temperatures at tops of warmest showers associated with snow and at tops of warmest isolated ones occurring on same day. Number of cases above diagonal line shows tendency for showers to break out at warmer temperatures when snow is present.

If a seeded cloud develops into a shower which passes through a normal cycle and dissipates, a plan view of the patterns produced can be calculated. Various conceivable complications, such as the seeding of a second cloud by the mature shower, will not be discussed here.

Consider an air mass containing numerous cumulus clouds with tops above the freezing level, the clouds moving with a velocity $\boldsymbol{v}$. If a snow trail moves across the region and seeds a particular cloud, the shower produced will move with velocity $\boldsymbol{v}$. If the seeding occurs at point A (fig. 5), and the shower lasts for a time t, the shower will be dissipating as it passes B. In most situations, t would be of the order of 1 hr.

By time t, the point of contact between the trail and the cumulus clouds will have moved with the velocity $\boldsymbol{w}$ of the snow generating-element to C. It has already been noted that this velocity is equal, or very nearly equal, to the wind at the height of the snow generating-element. New showers will be forming at C, and the line BC will be marked by a line of showers in various stages of development.

At $2t$, the shower line will extend from D to E. Although the velocity of individual showers is $\boldsymbol{v}$, the system as a whole has a velocity $\boldsymbol{w}$.

This mechanism may be responsible for some observed cases in which air-mass thunderstorms occur in lines rather than as scattered storms, and in which no explanation has been offered for the line formation. Out of 31 days studied in Ohio during the Thunderstorm Project, with no fronts or squall lines present, the thunderstorms lined up on seven days (Byers, 1951).

Since snow trails are of the order of 10 mi wide, a band of showers should be expected rather than a sharp line. Variations in the heights of the cumulus clouds, and different rates of development for the showers, would make the boundaries of the showery region diffuse.

The photographic records made by the McGill Radar Weather Observatory during 1951 and 1952 show vertical sections. Even when a vertical section shows showers developing along a snow trail, the possibility exists that showers are occurring randomly, and that the density of showers is as great in other sectors not affected by snow. To check this, radar data, ob-

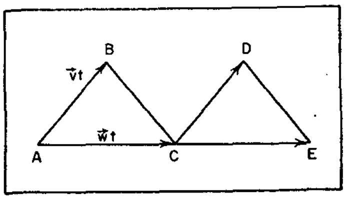

FIG. 5. Movement of shower line caused by seeding.

tained on different bearings of the set, were plotted on polar diagrams.

It was found that satisfactory diagrams could be constructed if successive observations differed in azimuth by less than 15 deg. The rotation of the beam renders the location of the boundaries of precipitation areas uncertain by an amount $r\omega T$. Here r is the distance from the radar, ω the angular velocity of rotation of the beam, and T is the exposure time used in photographing the scope. This error often completely outweighs the error in position introduced by the beam width. However, only a certain amount of detail can be plotted, so little can be gained by reducing the angular separation of successive pictures below about 5 deg. If an azimuthal sweep of 360 deg takes more than 3 or 4 min, an accurate picture of the situation is hard to obtain. Changes in the situation introduce a discontinuity in the diagram at the bearing on which the sweep begins and ends.

The actual construction of such a diagram requires 30 min to 1 hr, the time depending upon the degree of accuracy and amount of detail required. The result is more useful than a photograph of a plan-position-indicator radar scope. Echo heights are recorded, as well as their location and form. A blind spot extends from the origin to about 10 mi, its area being 1/25 of the area within range of the radar.

Fig. 6 is an example of such a diagram. (It should be noted that no attempt to correct for attenuation has been made in plotting the observed data.) A band of showers extends from 35 mi southwest of the radar set to 15 mi northwest, and from there to 40 mi northeast of the set. Snow trails, with associated bright band, occur in all but the southeast quadrant. The concentration of showers in regions affected by snow trails is apparent.

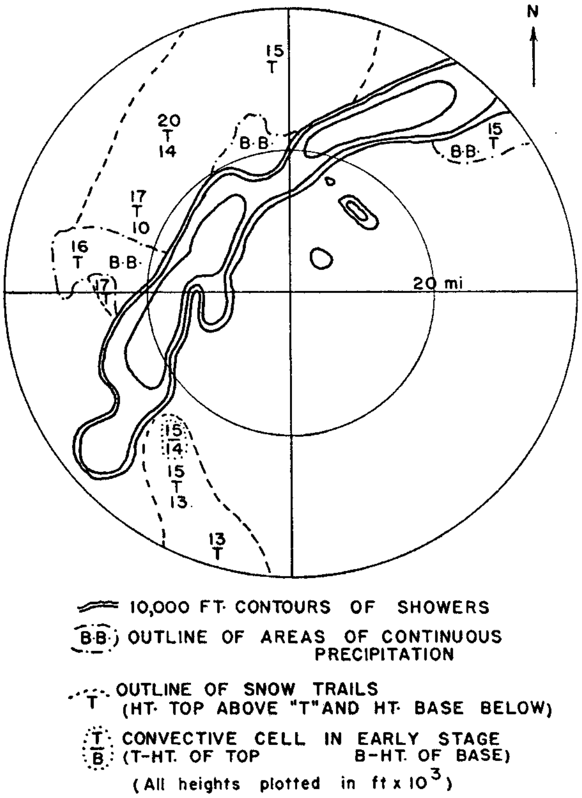

Fig. 6. Synthesized plan view of precipitation observed by radar from Montreal Airport, 2125 to 2130 GCT, 3 August 1951.

The only new-shower echo in the figure is located 25 mi from the set, on a bearing of 220 deg. It is based at 14,000 ft and topped at 15,000 ft, while the base and top of the snow trail are at 13,000 and 15,000 ft, respectively. This shows that the shower is developing in a snow-filled region.

Upper winds can be used to determine whether or not showers that were observed only in their mature stages originated in regions containing snow. If it is assumed that snow trails move with the wind at the generating level, and that showers move with the wind midway between their bases and tops, the relative motion of showers and snow trails can be found. From this, the past positions of showers with respect to snow trails can be determined approximately. The errors involved in making these assumptions are of the same order of magnitude as the possible errors in measuring upper winds.

Diagrams similar to fig. 6 have been prepared from all suitable sequences recorded on the twelve days studied. At least one has been completed for each day except 19 July 1952.

A study of the eleven cases shows six in which shower development occurred predominantly along snow trails. The synoptic situation on a given day could be responsible for the juxtaposition of showers and continuous precipitation. For example, a cold front often has both a band of continuous rain and showers associated with it. However, the existence of such patterns on over 50 per cent of the days studied, and on days with various synoptic situations, indicates some interaction between the two precipitation forms.

Precipitation from high levels could promote shower activity by moistening the air around developing cumulus clouds, as well as by seeding them. A cumulus cloud marks the ascent of a current of saturated air, which continues to rise as long as it is warmer than its environment. Entrainment of environmental air reduces the difference in temperature between the inside and outside of a cloud, and thus reduces the height to which a cumulus cloud can extend. This is particularly true if the entrained air is dry, as some cloud water evaporates into it to cause further cooling (Austin, 1951).

Where isolated snow-generating cells at high levels pass over a dry air mass, bands of increasing humidity result. Cumulus clouds forming in these areas would tend to reach a larger size than those surrounded by drier air. The probability of showers should increase accordingly in these areas.

However, the first echoes from showers due to this moistening effect could appear above the continuous precipitation. In the vertical sections studied, the first shower echoes usually appear at the same height as the associated snow trails. This makes seeding the more likely explanation for the observed patterns.

5. Conclusions

Theoretical considerations show that snowflakes could be entrained into supercooled portions of cumulus clouds to initiate showers. If the cloud top were warmer than −12C, precipitation by glaciation would be unlikely without this aid. Even at colder temperatures, snow could increase the proportion of precipitating clouds. The resulting pattern has been derived by considering the trajectories of snowflakes with respect to a cumulus cloud.

Radar pictures in vertical section resembling the predicted pattern were found for twelve days. On one day, the complete development of a shower on a snow trail was recorded. The sequence of pictures showing this is the best evidence for the seeding process obtained so far. In ten other cases, showers were found along snow trails with temperatures at their tops between 0 and −10C. However, in all but two of these cases, isolated showers developed with tops in the same temperature range. The twelfth case was that of a mature thunderstorm. No conclusions regarding its origin can be drawn.

Further evidence was obtained by organizing sets of vertical sections into plan diagrams with height contours. In over half of the situations studied in this way, shower activity occurred mainly in regions affected by snow trails.

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REFERENCES

Austin, J. M., 1951: Cumulus convection and entrainment. *Compendium meteor.*, Boston, Amer. meteor. Soc., 694–701.

Battan, L. J., 1953: Observations on the formation and spread of precipitation in convective clouds. *J. Meteor.*, **10**, 311–324.

Braham, R. R., S. E. Reynolds and J. H. Harrell, 1951: Possibilities for cloud seeding as determined by a study of cloud height versus precipitation. *J. Meteor.*, **8**, 416–418.

Byers, H. R., 1951: Thunderstorms. *Compendium meteor.*, Boston, Amer. meteor. Soc., 681–693.

Houghton, H. G., 1951: On the physics of cloud and precipitation. *Compendium meteor.*, Boston, Amer. meteor. Soc., 165–181.

Ligda, M. G. H., 1952: The horizontal motion of small precipitation areas as observed by radar. *Proc. 3rd Radar Wea. Conf.*, Montreal, McGill Univ., D41–48.

Marshall, J. S., 1953a: Precipitation trajectories and patterns. *J. Meteor.*, **10**, 25–29.

——, 1953b: Frontal precipitation and lightning observed by radar. *Canad. J. Physics*, **31**, 194–203.

Rigby, E. C., and J. S. Marshall, 1953: *The modification of rain in showers with time.* [Sci. Rep. MW-10, Contract AF 19(122)-217.] Montreal, McGill Univ., 40 pp.