THE PLAN PATTERN OF SNOW ECHOES AT THE GENERATING LEVEL

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ABSTRACT

The snow-generating elements associated with most snow storms have been observed in previous radar studies only in vertical section. Constant-altitude upper-level maps, composed from a series of plan-position-indicator photographs at progressively increasing elevation angle, reveal the plan pattern formed by these cells at the generating level.

Individual cells are rather shapeless, but with all dimensions within a factor of two of 1 mile, and persist for hours. Their velocity equals the generating-level wind, with a mean difference (including errors of measurement) of 1.6 knots. The cells occur in groups of several hundred, either randomly distributed over an area of about 10^4 mi^2 or in line arrays each about 5 mi by 75 mi over the same area. Whether or not arrays are formed, and the orientation of the arrays relative to the generating level wind when they do occur, are related to the component of wind shear along the wind at the generating level.

1. Introduction

The characteristic appearance of snow-generating cells and of the ensuing trails has been studied in vertical section by several investigators. Browne (1952), observing the A-scope of a vertically pointing radar, and both Lhermitte (1952) and Marshall (1953), using an RHI display, independently showed that the shape of a precipitation trail was related to the wind field through which the snow particles were falling. Other RHI studies (Gunn *et al*, 1954) indicated that the generating level was associated with a frontal surface. Langleben (1954) and Gunn (1955) have reported similar investigations with a zenith-pointing radar and time-height display, and have used their records to calculate the fall velocity of the snow particles.

Vertical slices through the atmosphere fail to give a complete picture of the pattern at the generating level. When viewed along the wind shear, the generating elements appear to be about 1 mi in horizontal extent. It has been suggested (Lhermitte, 1954) that the pattern consists of long continuous line elements, aligned crosswind to and moving with the wind at the generating level, the trails below streaking back in the form of sheets. The construction of constant-altitude upper-level maps has now made possible a preliminary study of the pattern at the generating level.

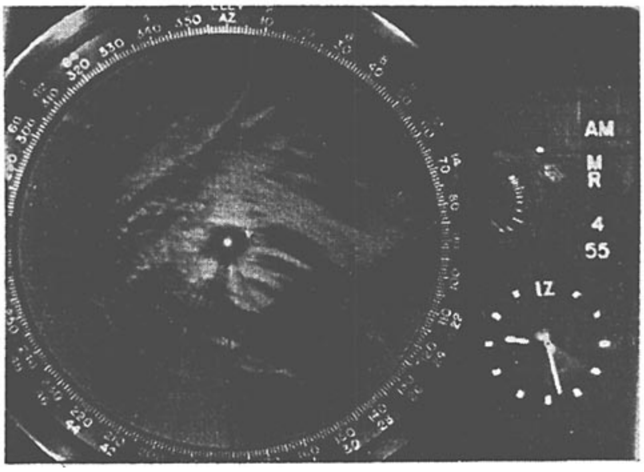

FIG. 1. CPS-9 photograph at 1.5-deg elevation and 75-mi range. Beam is cutting through pattern generated by several line arrays of elements, one long array about 35 mi to NW. Somewhat smeared-out pattern in right half of photograph is caused by geometry of situation. Precipitation streaks trail back to west and radar beam is able to intercept long portion of trail.

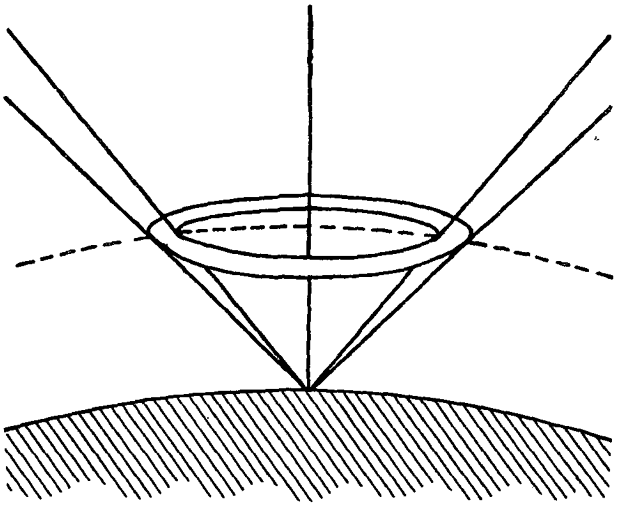

FIG. 2. Radar beam sweeps out conical slice when performing azimuth scanning at elevated angles. Beam intersects selected height in narrow annular ring, complete level being swept out if antenna elevation is changed in discrete steps each scan so one ring is fitted to next.

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2. Synthesis of constant-altitude position indicator

The method adopted as efficient for rapidly and completely sweeping out a large volume of space was to perform pseudo-PPI scanning with an AN/CPS–9 radar[2] with the antenna rotating continuously about a vertical axis. Each successive scan was made at a slightly higher angle of elevation, with $\frac{1}{2}$-deg steps from 0 to 6 deg, 1-deg steps to 10 deg. All of the 17 scans, each at 75-mi range, were photographed on 16-mm film. One such scan is shown in fig. 1.

Constant-altitude maps of the echo at any height may be constructed from the film records obtained. These maps may conveniently be referred to as CAPI (constant-altitude position indicator). The maps are made by projecting the film records and tracing from each picture the echo appearing only in the annular ring relevant to the height chosen (fig. 2). This laborious process has served to test the soundness of the general method; improved techniques are now being used.

It can be seen in the vertical section of fig. 3 that, because of the 1-deg beam of the CPS–9, the echo within a range interval of several miles on any elevated PPI can be considered to be at the same height. The height of 15,000 ft, for example, is represented fairly accurately by the range interval from 61 to 73 mi on the 2-deg PPI, 53 to 61 mi on the 2.5-deg PPI, and so on. For winter studies, a limit of 10 deg in elevation was imposed on the scanning so that a sequence could be completed in about 3.5 min. This introduced a hole of 16-mi radius at 15,000 ft which was not scanned, the radius however decreasing with decreasing altitude. The maximum elevation was increased to 20 deg for summer operation, when storms attain greater heights.

3. Form and disposition of echoes at the generating level

Radar-film records for seven days of the winter 1954–1955 have been analyzed. Maps of the pattern at the generating level were synthesized at about $\frac{1}{2}$-hr intervals. The generating level was selected by first finding the extreme tops of the echoes and then descending about 3000 ft to a level at which there was still no horizontal displacement or increase in area of the echoes.

The velocity of the echoes was the same at all levels from the generating level to near the earth's surface, becoming more difficult to measure as the ground was approached and the echo became more diffuse. Echo velocities of 30-kn average magnitude were compared to the wind at the generating level as obtained from upper-air soundings. The maximum vectorial difference was 3.5 kn with a mean deviation of ±1.6 kn. The wind vector W and the echo velocity V are shown in figs. 4, 5, 6, 8 and 9.

From studies of generating elements in vertical sections, line elements rather than points were anticipated in horizontal sections. However, the cells were found to be shapeless, their horizontal dimensions being the same within a factor of two in every direction and of the order of 1 mi. Their vertical extent was rather less. Several individual elements were followed for periods of between 1 and 2 hr (fig. 4), the analysis having to stop because of interruptions in the scanning procedure or because the cells moved to too close a range for positive identification. During this period, the cells continually changed in form, sometimes increasing and then decreasing in depth as well as changing in horizontal extent. Occasionally one was seen to split into two distinct parts which later merged; none of them showed signs of dissipating. The curved line emanating from the origin of fig. 4

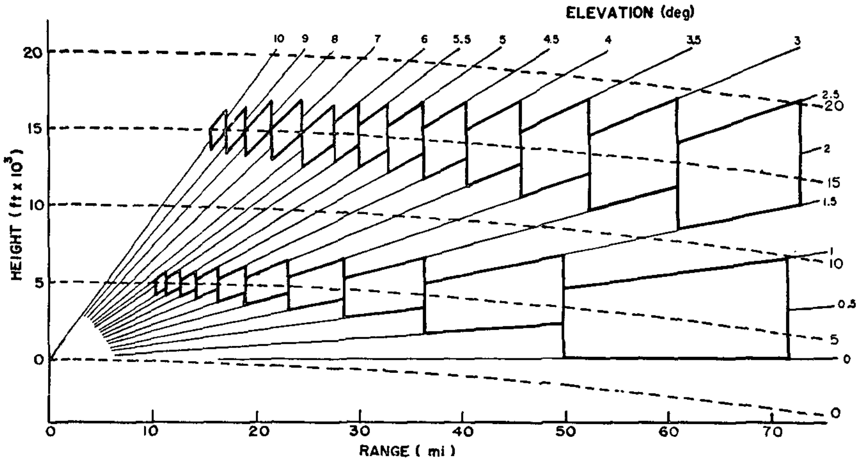

FIG. 3. Lines of constant altitude, corrected for earth's curvature and normal refraction, are plotted against range. Antenna of 1-deg beam width, scanning PPI at progressively increasing elevation angle, generates constant altitude as step function. At any step, center of beam has maximum departure of less than 2000 ft from selected altitude.

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[2] Radar characteristics: λ, 3.2 cm; peak power, 250 kw; pulse length, 0.5 μsec; p.r.f., 980 sec^{-1}; beam width, 1 deg conical.

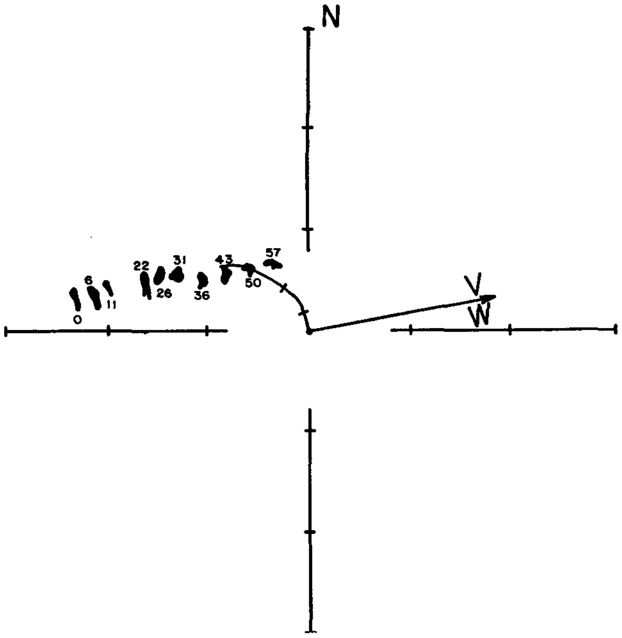


FIG. 4. Individual echo at generating level, selected from many on 15 March 1955 (see fig. 6), is plotted as it appeared on successive sequences between 1603 and 1700 EST. This particular echo, while larger than normal, reveals characteristics of random changes with time. Range marks are at 25-mi intervals. Echo velocity *V* and generating-level wind *W* are shown as vectors. Projection in plan of precipitation trail (after Gunn, 1955) has been drawn from generating level to ground, with ticks indicating heights of 10,000 and 5000 ft.

is a plan projection of the precipitation trail between the generating level and the earth's surface. It was derived from the upper-air wind data, a terminal velocity of fall of 4 ft/sec for the snow particles being assumed. Ticks have been drawn at altitudes of 10,000 and 5000 ft. Similar trails in plan are shown in many of the following figures.

FIG. 5. Line arrays observed at 0945 EST 4 March 1955. Generating level is 13,000 ft.

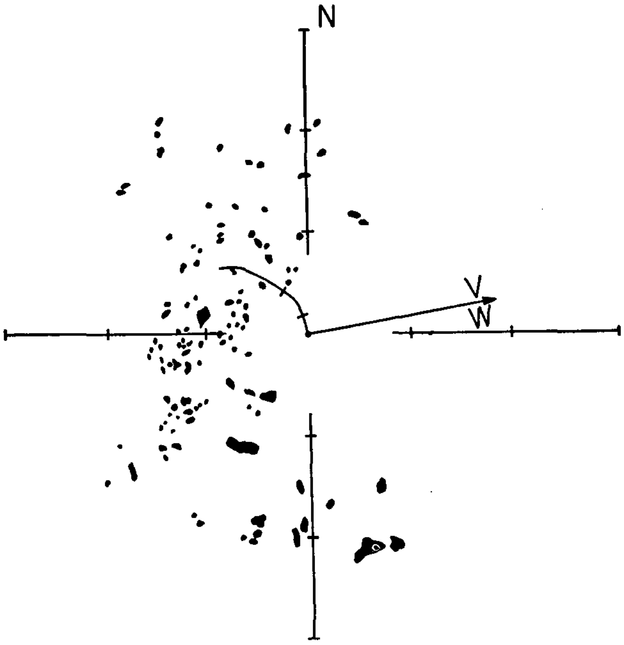


FIG. 6. Typical example of unorganized cells at generating level, 14,000 ft, at 1722 EST 15 March 1955.

The tendency on five of the seven days analyzed was for formation of many long line arrays of small generating elements. (Fig. 5 is an example.) The spacing between cells, center to center, along the line arrays, was on the average 2.5 mi with extremes of 2 and 4 mi. The distance between lines was from 6 to 20 mi and varied even during one storm. The line arrays were as short as 25 mi and as long as 100 mi, with most of them being about 75 mi long. The possibility exists that they could sometimes have been longer, their extremities being beyond the limit of radar detectability. For the other two cases, the formation into line arrays was not apparent, and the distribution of cells was termed random. The echo pattern observed for one of these cases is shown in fig. 6.

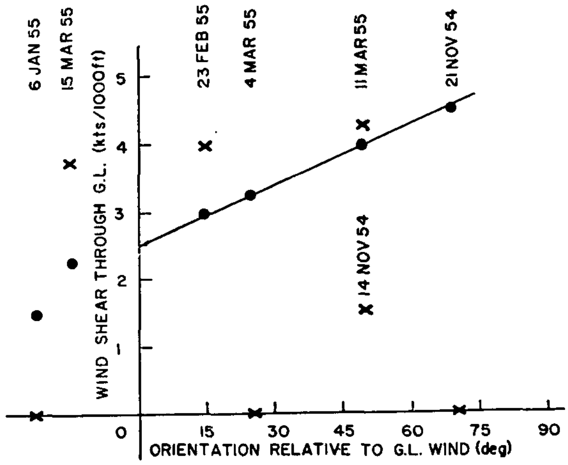


FIG. 7. Orientation angle of line arrays is plotted as function of component of wind shear through generating elements in direction of wind at generating level (·) and cross component of wind shear (x).

The "precipitation area" observed at any one time at the generating level was as large as 10^4 mi^2, whether the cells were randomly distributed or not. This observation is influenced by radar sensitivity, thus being a lower limit; but in most cases, sharp transitions from cells to no cells marked the edges of a precipitation area. The total number of cells in a precipitation area was between 100 and 200. Their concentration varied widely when the cells were randomly distributed, the fraction of the precipitation area covered by echo varying, for 200-mi^2 samples, from 0.02 to 0.1, with an average over the whole area of about 0.05. For the line arrays, the cells were found to cover from 0.1 to 0.14 of the area outlined by an array. If one considers a family of such arrays, the fraction of the overall area covered by echo would reduce to a value near that for randomly distributed cells.

There was not much evidence for a preferred orientation of the line arrays relative to the direction of motion of the echoes. The component of motion perpendicular to the line arrays varied from 25 to 94 per cent of the actual echo velocity. The orientation angle, the acute angle between the line array and echo velocity, ranged from 15 to 70 deg for the five cases considered, and so presumably any orientation is possible. This is unfortunate as far as studies by zenith-pointing radar are concerned; for interpretation of the height/time records, one would like to have a fixed value for this angle, preferably 90 deg. Soane and Miles (1955), investigating the progression of tropical showers, find a tendency for formation into line arrays. They also find that all orientations are possible.

The orientation angle of the line arrays, as defined above, showed no apparent dependence on the magnitude or direction of the wind shear through the generating elements. However, the orientation was found to be a linear function of the component of wind shear along the wind direction at the generating level (fig. 7). The two days of so-called *random* distribution, shown at the left of fig. 7, had shears less than 2.5 kn per 1000 ft in the plane of the generating-level wind; this may explain the absence of line arrays.

In the plan pattern 3000 ft below the generating level (fig. 8), the echoes were still, almost always, isolated, but exhibited some increase in horizontal area. At 5000 or 6000 ft below (fig. 9), the increase in area was as high as four-fold over that at the generating level, due to spreading by the wind shear. Line arrays tended to merge into continuous lines. Streaks from individual elements could not easily be distinguished, and the pattern became more diffuse. As

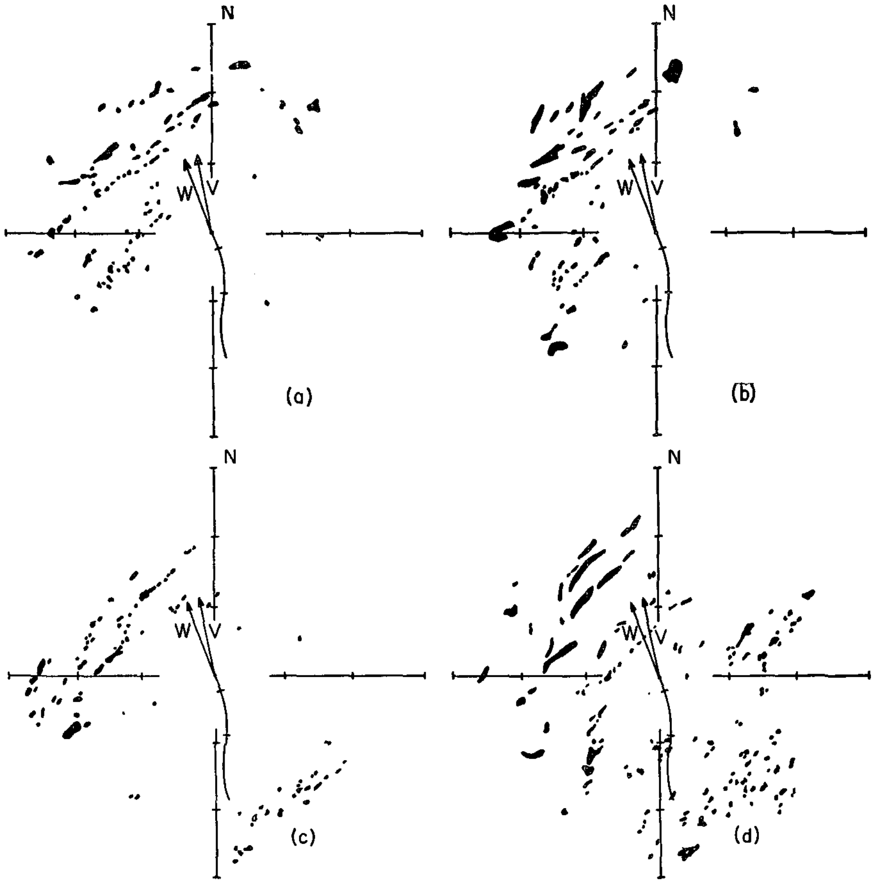


FIG. 8. Pattern on 21 November 1954. (a): 1110 EST at 15,000 ft (generating level); (b): at 12,000 ft; (c): 1154 EST at 15,000 ft; (d): at 12,000 ft.

pointed out by Gunn and Marshall (1955), the process of sorting by size of the snowflakes in falling through a wind shear continues to the surface. Snow particles of melted diameter 5 mm may slip back as much as 65 km relative to the generating source in falling from a height of 4 km through a uniform wind shear of 10^3 cm sec^{-1} km^{-1}; smaller particles, of 0.5-mm melted diameter, are displaced by 130 km. Thus, the precipitation originating from a point source aloft could be spread out over 65 km at the earth's surface. This would explain the diffuse nature of the echo observed with a PPI scanning at 0-deg elevation through snow, and the more or less continuous (except for fluctuations in intensity) nature of the precipitation associated with generating elements.

In review of figs. 8 and 9 it may be noted that, in some part of each figure, the cell patterns do spread out and tend to form rather large echoes. The writer is reasonably certain that these are not the true shapes of the generating cells. By relating the bearings of these large echoes and the sectors in which they occur to the wind pattern, this distortion can be attributed to a combination of the geometry of the radar beam and the configuration of the precipitation streaks in space. If a precipitation streak is advancing toward and trailing back from the radar site, the beam will intercept it sharply, and the pattern at any height will be well defined. After the echo has passed over and is receding from the site, a long portion of the trail is intercepted by the radar beam at any one time. This is apparent in fig. 1, where practically the full extent of the trails is visible in the right half of the picture, but only isolated portions of the upper parts of the trails and the generating elements are seen at the left. The difference in size of the echoes in opposite quadrants of figs. 8 and 9 is accounted for in the same way.

4. Photographic synthesis of CAPI's

The findings that have been presented are from a few cases only, and more data are needed. Because of the length of time and subjectivity involved in obtaining the tracings shown, new techniques are being developed to synthesize the film records photographically.

A circle of light is generated on an oscilloscope by an audio oscillator. This source of light is brought to a focus on the 16-mm radar film, illuminating a ring on the processed film. A 16-mm camera on the other side of the film then photographs the circular image which has been modulated by the pattern on the radar film. The Lissajous circle is made to shrink

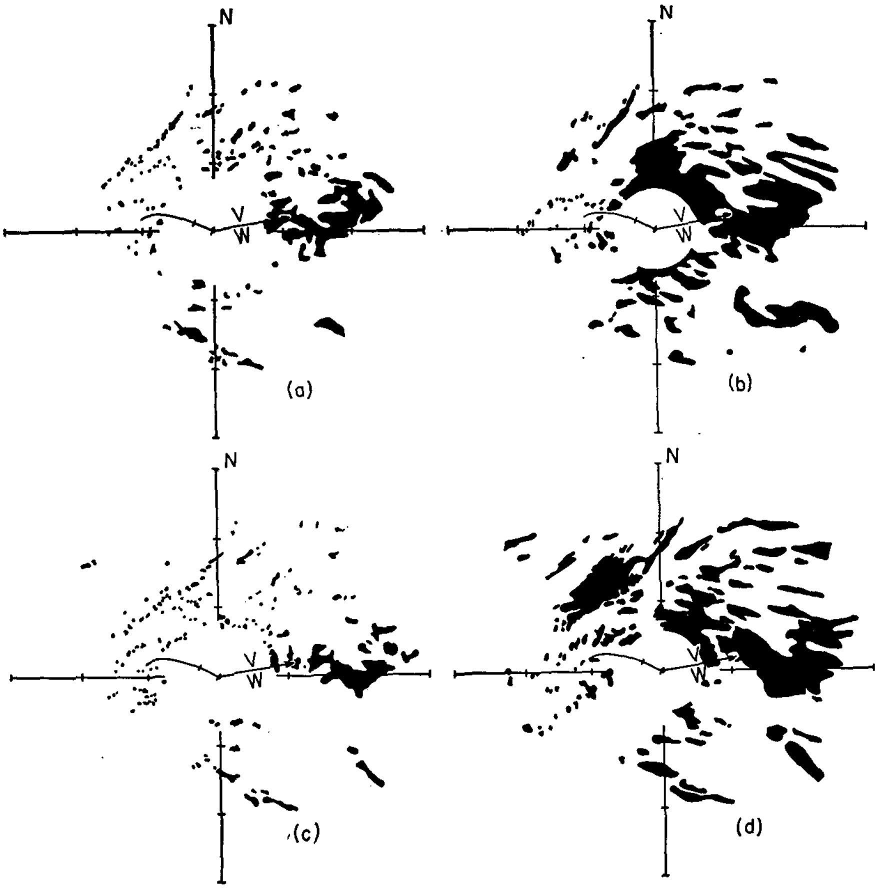
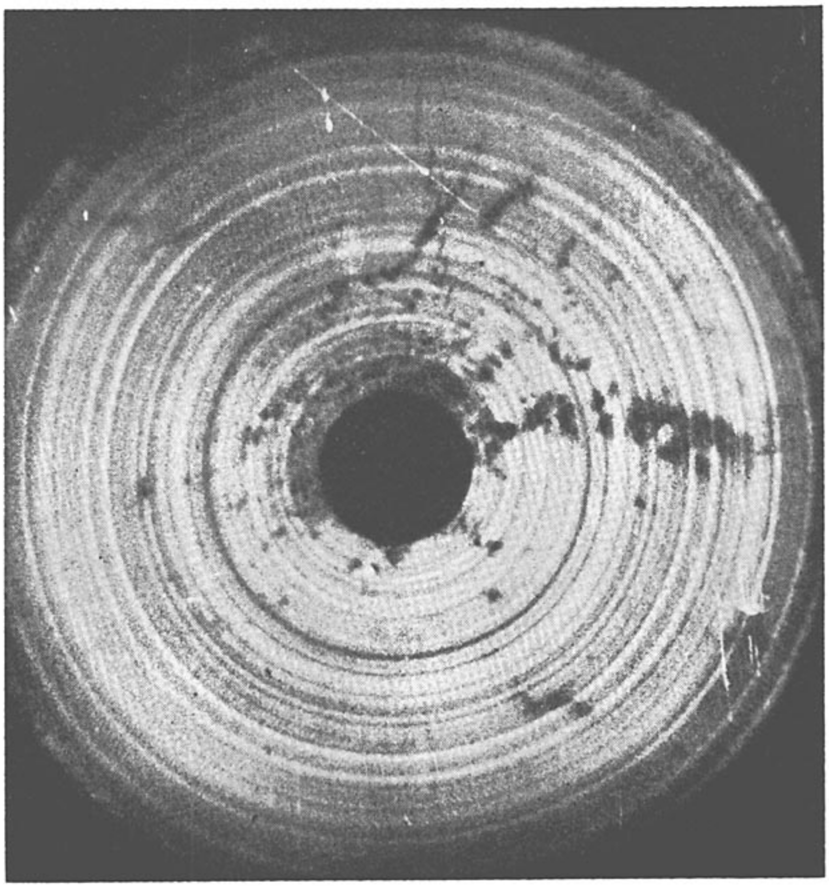


FIG. 9. Pattern on 4 March 1955. (a): 0909 EST at 13,000 ft (generating level); (b): at 8000 ft; (c): 0930 EST at 13,000 ft; (d) at 8000 ft.



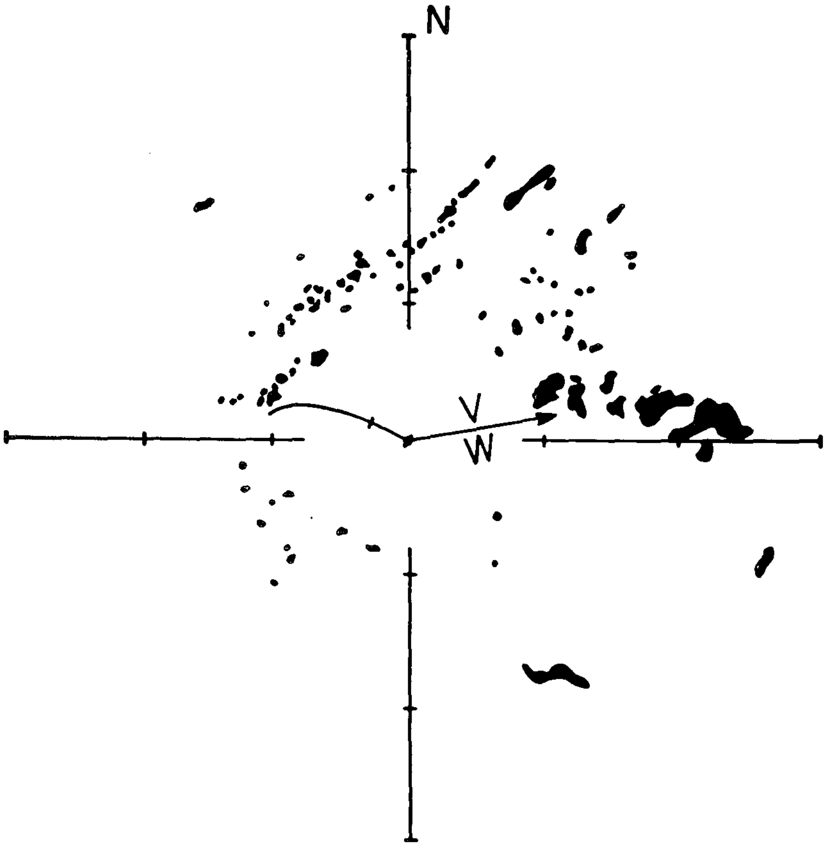


FIG. 10. Constant-altitude picture synthesized photographically for 0745 EST 4 March 1955. Height is 13,000 ft. Tracing of same situation is also shown.

slowly (in about 2 min) in radius, and the frames of film record are rapidly changed with good registration at the proper instants to satisfy the conditions outlined in section 2, above.

A photograph obtained in this way is shown in fig. 10, as is the equivalent tracing. While the product is completely useable, the lack of quality arises from imperfections in the first model of the apparatus. The system is amenable to technical improvement.

5. Conclusions

The technique of obtaining constant-altitude upper-level maps from a series of PPI photographs at increasing elevation angles has been demonstrated as useful for studying generating-level patterns.

This study has added further verification to the suggestion of Marshall (1953) that the steering level for the snow precipitation-streaks coincides with the height at which the "generating" elements are found. This height must then be a true generating level; otherwise, good agreement could not be expected between the wind at this height and the echo velocity.

The generating elements were found to be roughly about 1 mi in every horizontal dimension; in stable air, their extent in the vertical was slightly less. They tended to form into line arrays, not line elements. Consideration of the seven cases dealt with showed that the orientation of the line arrays relative to their direction of motion can be correlated to the wind shear through the generating elements resolved in the direction of the wind at the generating level. However, correlation achieved from only five cases is not reliable enough to attempt a physical explanation.

As compared to the cyclical $\frac{1}{2}$-hr life of a cumulus cell, snow generating elements have long lifetimes. Continuous observations (on several snow cells) for periods of 1 to 2 hr have not shown a decaying stage. There must be a constant supply of water vapor and/or cloud being used to grow the snow crystals. The observed continual change in form of the elements is probably related to vertical circulation in the cellular structure discussed by Douglas (1955) and to the turbulence in the cells as measured by Hitschfeld and Dennis (1955).

Within a precipitation area at the generating level, the fraction of that area covered by echoes varied from about 0.1 to 0.05. If it is assumed that there is no growth of the precipitation particles during their fall (sometimes a reasonable assumption, surely not always), the intensity of precipitation in the cells would be at least 10 to 20 times that at the earth's surface.

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