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by

R.H. Douglas

Meteorological Service of Canada

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1. INTRODUCTION

Of the numerous atmospheric phenomena which the meteorologist is called upon to study and to predict, precipitation is surely one of the most important. In the mind of the man in the street, "weather" is often synonymous with "rain" or "no rain"; precipitation, or lack of it, seems to be that element in the forecast which most impresses the public mind, with the possible exception of prolonged departures of some other element (such as temperature) from its seasonal norm. Economically, the precipitation is a factor of prime importance in many walks of life, agricultural, industrial, commercial. The contribution of precipitation to the climate of a region is important, determining to a great extent the agricultural and commerical enterprises of the people; as such, it is one of our most prized natural resources. Nor can the occasionally destructive effects of precipitation be overlooked; many of the great disasters in history have been the result of unusual and unforeseen rains or snowstorms.

A great stride was made toward the understanding of the precipitation processes when the significance of adiabatic cooling in the atmosphere was understood. Now, one has an explanation of the macroscopic processes by which the extensive conversion of water-vapour to the liquid phase resulted in widespread cloud-sheets, rain and snow. With the development of the air-mass concept and the appreciation of the part played by the frontal boundaries, the large-scale lifting processes which bring about adiabatic cooling were recognized and made amenable to synoptic analysis. Studies of atmospheric thermodynamics resulted in the recognition of hydrostatic stability and instability, so that it became possible to distinguish between the processes leading to showery or convective precipitation and those leading to continuous precipitation. However, until fairly recently, not too much was known about the microphysics of the atmospheric condensation and precipitation-processes themselves.

As man took to the air, his knowledge of clouds and of their internal structure increased to some extent. Flying laboratories or observatories have made available a great deal of information about the clouds, although it has long been realized that an aircraft, moving through a cloud at high speed, is not as ideal an observation-platform as might be desired.

With radar, the meteorologist has acquired a powerful tool. By means of suitable equipment it is now possible to detect targets in the form of distant rain or snow and to follow their motion and development in space and time. In continuous precipitation, one can detect the "bright band", intimately connected with the freezing level (a fine example of which may be seen in Fig. 3); in convective situations one can see into the heart of the growing cumulus, to detect and study the developing rain-core itself. Even the paths of lightning discharges have been detected by radar. Hurricanes can be located and tracked, their "eyes" pinpointed, and their peculiarly spiralled bands studied. Recently, tornadoes have been identified on the radar screen, resulting in a renewed impetus to the study of these destructive vortices. Thus, radar is proving its worth as an important tool, which is being exploited by many research groups with most promising results.

It is the intent of this paper to describe recent and current research into the precipitation process, with particular emphasis upon certain aspects of the work of the Stormy Weather Research Group of McGill University, under the direction of Dr. Stewart Marshall. For a year now, the writer has enjoyed a close association with the Stormy Weather Group, a group which has been notably active in the field of cloud physics for almost eleven years. It is the research of this group into snow which is to be outlined in the following sections.

2. SNOW-GENERATING CELLS

The present story properly begins with a series of observations made with a radar set located at Montreal Airport during the winter of 1951-52. During snow storms, snow patterns resembling the familiar "mares' tails" patterns of cirrus cloud were observed by a radar set which scanned a vertical plane, along a fixed azimuth. During continuous snow at the ground, snow was observed to be trailing out behind a series of small cell-like sources aloft (Fig. 1). An excellent example of this phenomenon occurred in November 1951, and has been discussed in some detail by Marshall (1953a). On this particular occasion, the cells, or heads of the plumes, occurred at fifteen thousand feet, followed one another at intervals of about twenty miles, and moved at about ninety miles per hour (the speed of the wind at their own level). The cells appeared to be from two to four thousand feet thick, evidently arrayed in lines across the wind.

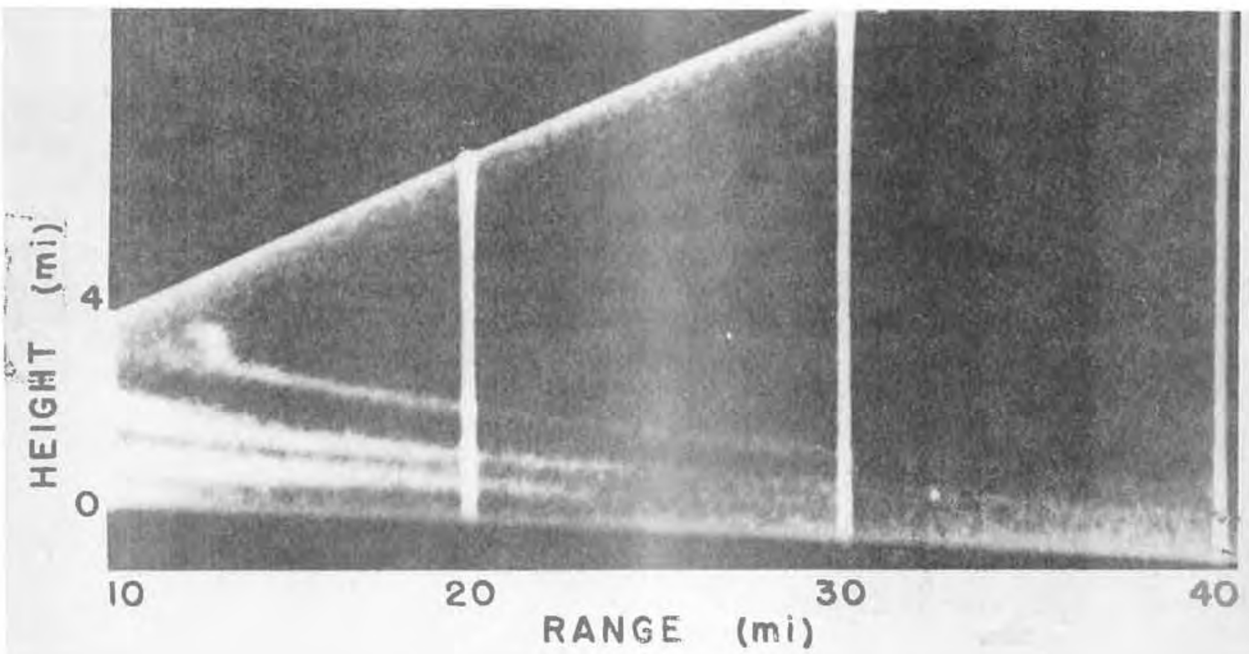

Fig. 1. Generating element, or cell, and snow trails as seen on the RHI.

Such mares' tails patterns, originating from some form of compact head or cell, have been observed frequently since this occasion, and indeed seem to be a regular feature of continuous snow or rain. The interesting and important fact is that the so-called continuous precipitation at the ground is often (if not always) the result of a procession aloft of discrete and relatively small elements or cells, each emitting a plume of snow which derives its pattern from the wind field and its velocity from that of the emitting source. For each source aloft, the wind shear below serves to sort the snowflakes both horizontally and vertically, since differently-sized flakes fall with different speeds. If a spectrum of sizes is emitted aloft, these sizes are spread out, or sorted, in the wind pattern at lower levels; patterns from adjacent cells may blend and merge at lower levels, producing the continuous snow (or rain, at warm temperatures) observed at the ground.

Similar patterns to these may often be seen in cirrus skies, where mares' tails are of fairly common occurrence. Cirrus uncinus is a familiar example of the fibrous streaks, falling from a more or less well defined parent cloud. That such cirrus forms are more properly precipitation (virga or fallstreifen) than cloud proper was suggested some years ago by Ludlam (1948).

Further importance of these generating-cells and snow-trails was indicated by Dennis (1954) who found evidence, based upon radar observation, that convective showers were stimulated where and when the cumulus heads built up into a snow trail. Two possible roles of the snow were suggested by this study. First, ice-crystals, entrained into the cloud-top, may serve to "seed" the cloud; and second, the evaporation of the crystals may so moisten the environment that the "damping" effects of entrainment into the growing cloud are at least partly overcome. Marshall (1953b) has also suggested the possibility of electrical interaction between water-cloud (cumulus) and the ice-particles of the snow-trails, leading to a lightning discharge.

3. STUDIES OF THE GENERATING LEVEL

Having noted the existence of snow trails and of the generating elements, and some evidence of their importance, it was natural that attention be paid to the reasons for their existence, and to their relationship to the various meteorological elements. The first step in this direction was made by Gunn et al (1954), the results of whose study will be summarized briefly.

The radar records of a number of of occurrences of cells and trails were examined, and sorted according to clarity and definition of pattern. Upon comparing with the available upper-air data, it was found that the well-defined cell-and-trail patterns were associated with stable air, and the poorly defined ones with unstable air. Thus, it appeared as if instability were not a cause of, but rather a deterrent to, well-defined cell development. Furthermore, it was found that the cells were located just above a frontal surface, often extending downward through the front into the so-called mixing zone. As nearly as could be determined from radiosonde data, the cell-tops extended above the top of the main frontal cloud-sheet. As noted earlier, the cells moved with the wind at their own level.

These were findings of importance, particularly the promising correlation between generating-level and frontal surface, and it was decided to pursue a similar and more detailed analysis of the radar records for the winter 1953-54. The earlier data had been acquired prior to the installation of the radiosonde station at Maniwaki, and prior to the establishment, at Dorval, of the Central Analysis Office; thus, meteorological data had necessarily been extrapolated from observations made farther south. It was hoped that the Maniwaki data, together with the availability at the CAO of the frontal contour analyses, would render the later analysis more precise.

Meanwhile, however, the type of radar equipment had changed. As indicated earlier, Gunn's observations were made with the TPS/10, a model which scanned a vertical plane along some fixed azimuth, presenting on the range-height indicator (RHI) a vertical cross-section such as is seen in Fig. 1. Such a display enables good measurement of heights and vertical extents, and some idea of the three-dimensional picture may be obtained (though not conveniently) by scanning along various azimuths. Later data was obtained on a zenith-pointing radar, which is simply a set which directs a vertical immoveable beam. One cannot scan with such a radar, and only those targets which drift across the fixed beam are detected. The cross-wind extent of a target cannot be determined. Such a radar has the advantage of viewing the target at the minimum range and through the least amount of intervening rain or snow. A continuous record is obtained photographically, on a height-time scale; since the horizontal axis is time, the horizontal velocity of a precipitation

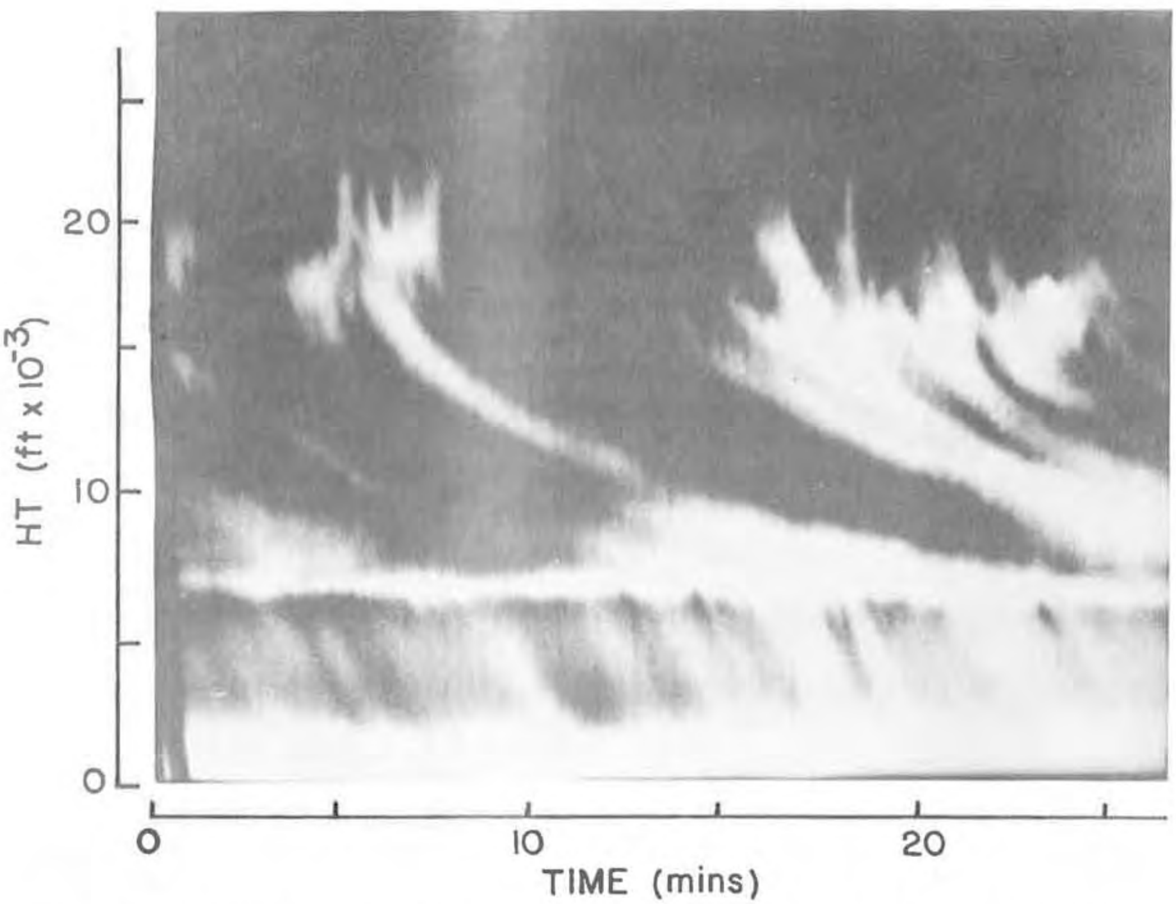

Fig. 2. Cells, snow trails, and the bright band as seen by a zenith-pointing radar.

pattern must be known before the time scale can be converted into one of distance. A portion of such a record is shown in Fig. 2. Here is seen a fine example of cells and snow-trails. The horizontal bright band is near the freezing-level. The abrupt change of slope of the trails at this level is noteworthy, and is due to the sudden increase in terminal velocity as the snowflakes become raindrops.

In studying the records of January and February 1954, time-cross-sections of the frontal structure over Montreal were prepared, making full use of the frontal contour analyses of the Central Analysis Office at Dorval. Upon these were plotted the echo-levels, measured off the records of the zenith-pointing radar. The complete radar record for a twenty-four hour period, together with the corresponding frontal time-cross-section, is shown in Fig. 3. Here are visible several examples of the snow-streamers trailing down from aloft. There is another interesting phenomenon clearly evident in this sequence, which is worth noting in passing. Prior to the arrival of snow at the ground, a number of pendulous extensions appear, resembling mammatiform cloud at the base of the echo; these lower slowly with time, as the storm moves in. This phenomenon has been observed a number of times, when the air in the lower levels is dry.

From our series of cross-sections there appeared to be no obvious relation between echo-tops and frontal surfaces, nor were the computed correlations encouraging. This was a disappointment, for it had been hoped that the more precise frontal analyses available would support Gunn's (1954) findings. The picture brightens, however, when it is recalled that the earlier and the later data were obtained by means of different radars. In the former case, an individual cell was located by radar search, and these cells proved to be some distance apart. In the latter case, one was unable to search, but was able to detect only whatever targets crossed the fixed vertically-directed beam (which, at fifteen thousand feet, has a diameter of only five hundred feet). It was considered not only possible but indeed probable that, in the latter case, many cells might pass at a distance, their snow trails being carried across the radar-beam by the wind pattern; and that while the zenith-pointing radar might detect a large number of trails at low altitude, it might see a true cell only upon a few rare occasions.

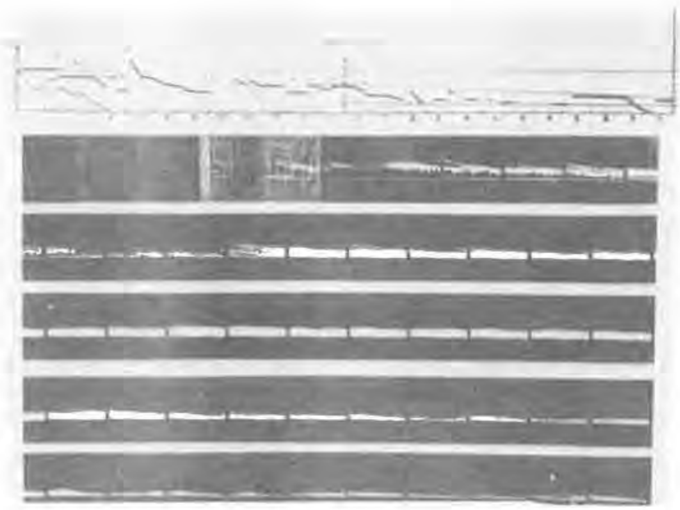

Fig. 3. Time cross-section of the frontal structure over Montreal for a 24-hour period, together with the corresponding record of the zenith-pointing radar. Echo-levels have been plotted on the cross-section; numbers along the baseline indicate hourly precipitation in hundredths of an inch (melted). Each frame of the radar record represents 26 minutes.

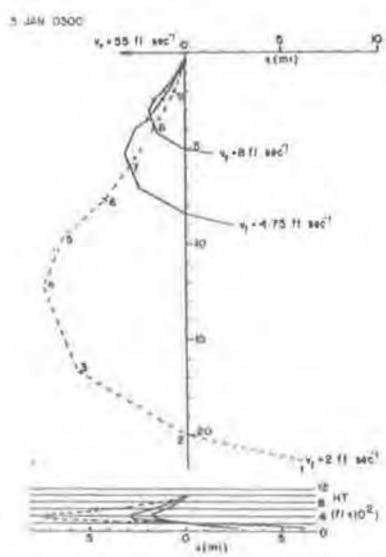

Fig. 4. Plan view of trajectories of snow particles falling from a point source at 10 thousand feet. Successive heights of points on the trajectories are indicated. Below, the corresponding cross-sectional view in a vertical plane.

This possibility has been checked, and it is clear that such indeed must be the case. The trajectories of snow particles, falling from a source at any given level, have been computed for a number of cases, and one such pattern is shown in Fig. 4. This is the plan view of a snow-trail, falling from a point source at ten thousand feet. While the wind profile determines the shape of the pattern, the terminal velocities (or sizes) of the snow particles determine the scale; paths for three terminal velocities are shown. The generating element and the accompanying pattern move with one and the same velocity - in this case 55 ft. sec^{-1}. This particular figure shows in a striking fashion how far to one side of the source the snow may be carried, as well as to what a marked extent the variously-sized snowflakes are dispersed through space. Clearly, the pattern that is seen by the zenith-pointing radar depends upon the portion of the trail which passes overhead.

Further confirmation is becoming available from later data obtained from the new CPS-9 radar, recently installed at Dorval. This is a very versatile set, and can be scanned in almost any manner desired. A technique has been devised whereby plan-patterns can be determined at any specified level. The antenna is rotated in azimuth, the vertical angle increasing by a small amount for each turn; the beam thus sweeps (or scans) a conical sheet, which intersects any specified horizontal plane aloft in a narrow ring. Photographs of successive sweeps (from zero to ten degrees in elevation) are assembled in such a way as to give a plan picture, such as would have been seen had the radar been scanning horizontally at the desired elevation. An example of such an analysis is seen in Fig. 5, on which are superimposed the echoes, seen in plan, at three levels. No echo was detected above twelve thousand feet, which was thus the generating level. Fig. 5 points up several important features. First, at the topmost level, the generating elements (black) occupy a very small fraction of the sky, and it is at once obvious that the probability of a cell passing directly over a zenith-pointing radar is rather small. Second, the echoes are displaced with height - the effect of the wind-shear. Third, echoes at lower levels occupy more and more of the sky, the spectrum of snowflakes being dispersed laterally in the wind-field. In the lower corner is shown a plot of the trajectory, computed from the known wind profile; note how the nine and five-thousand foot positions check reasonably well with the plan positions of the echoes immediately above.

We see then that the records of the zenith-pointing radar may be misleading in that the highest echo observed is not necessarily from a generating cell or source. How, then, is one to make use of these records to obtain data on these cells? The problem has been attacked in the following manner.

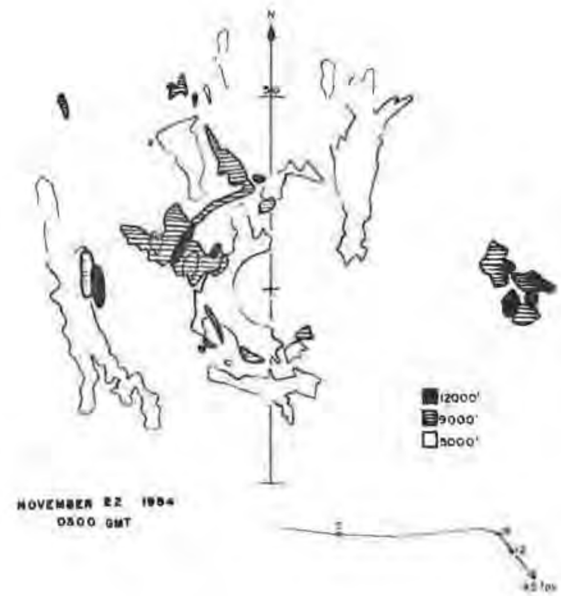

Fig. 5. Synthesized plan view of echoes at 12, 9 and 5 thousand feet. The radar is situated at the centre, and the 50-mile radius is indicated. The computed trajectory, based upon observed winds, is shown at lower right.

For any given occassion, a series of snow trajectories is worked out on the basis of the wind distribution. The winds are obtained from the Maniwaki rawinsonde, frontal shears being modified whenever the frontal surfaces are at different heights over Montreal than over Maniwaki; this requires a close study of the data and of the frontal contour charts. Several possible generating levels are selected, and corresponding trajectories computed; these are converted into patterns in vertical section. Such a vertical section is shown in the lower portion of Fig. 4. These patterns are now compared with the height-time records of the zenith-pointing radar, and the one appearing to conform most closely is fitted to the photograph by an expansion or contraction of the horizontal scale. With a fit obtained, one immediately knows the height of the generating level and the terminal velocity of the snowflakes, even though only the lower portion of the trail was detected by radar.

A number of cases have been studied in this fashion, and work is continuing. Thus far, it appears as if the earlier correlation with frontal surfaces is being confirmed, although further analysis is necessary to establish the fact conclusively.

4. STUDIES OF THE CELL MECHANISM *

Having outlined the radar observations of snow and generating cells, and having indicated some of the work in progress in the analysis of radar data, mention will now be made of some theoretical work regarding cells which has been undertaken. First let us review briefly the observational facts which require explanation.

First, the cells are relatively small discrete units, with a lifetime of at least an hour, perhaps longer. Cells have persisted while crossing the field of view of a radar having an RHI display, which may take an hour or more. Furthermore, complete trails, from cell to ground, have been frequently observed, requiring a lifetime at least equal to the time required for the snowflakes to reach the ground from the generating level. Second, the clearest and best-defined cell and trail patterns occur in stable air, as found by Gunn et al (1954). Third, Langleben (1954) has measured the terminal velocities of snowflakes, and found them to be of the order of a meter per second, a function of their size or mass; Nakaya (1954) has measured the terminal velocities of individual crystals, and found

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* The work outlined in this section has been reported in detail by Douglas and Marshall (1954).

much lower velocities (for example, about 30 cm sec^{-1} for dendrites, independent of size). The terminal velocities of the snow falling in the trail from a cell, determined from measurements made upon radar pictures, are high and correspond to snowflakes rather than single crystals, suggesting that the trail consists of the former. Fourth, it appears that the cells are imbedded in a deck of cloud, the cell-tops protruding several hundred feet above the top of this cloud. Thus we are required to consider an explanation which offers a possibility of vertical development in stable air, and in which enough turbulence is realized to afford an opportunity for aggregation.

The first step in attacking this problem has been a consideration of the thermal energy which is latent in supersaturated air. It is well known that the equilibrium water-vapour pressure over a water surface is greater than over ice, at subfreezing temperatures, so that air which is under-saturated with respect to water may be supersaturated with respect to ice. It is unlikely that any appreciable water supersaturation exists in the atmosphere, so that water-saturation may be taken as a reasonable upper limit to the atmospheric vapour content. On the other hand, ice supersaturation can and often does exist; in this regard, Dobson and Brewer (1951) writing on their observations of atmospheric humidity, state that "supersaturation with respect to ice is a relatively frequent occurrence, but supersaturation with respect to supercooled water has not been observed".

If into such moist air ice crystals are introduced, they will grow, drawing upon the excess vapour; for each gram of vapour sublimed, 670 calories of heat will be released into the air. Crystal growth, and the attendant heating, will continue until the vapour content has been reduced to ice-equilibrium. In Fig. 6 is indicated the temperature increase (T) due to such crystal growth reducing the vapour content from water to ice-equilibrium (full curves). It has been assumed that the air is clear (i.e. free of liquid cloud) and that it remains at constant pressure.

If, however, we consider air which, in addition to being at water equilibrium also contains liquid water cloud, an important difference arises. For, as the ice crystals grow, feeding upon the vapour, the relative humidity decreases and the water cloud evaporates. While the sublimation process supplies 670 calories of heat per gram sublimed, the evaporative process uses up about 600 calories; only the balance is available for heating the air. This balance (about 70 calories per gram) is only about 1/10 of the heat released in clear (liquid-free) air. Considering, then, ice crystals in water cloud, and again supposing the air to remain at constant

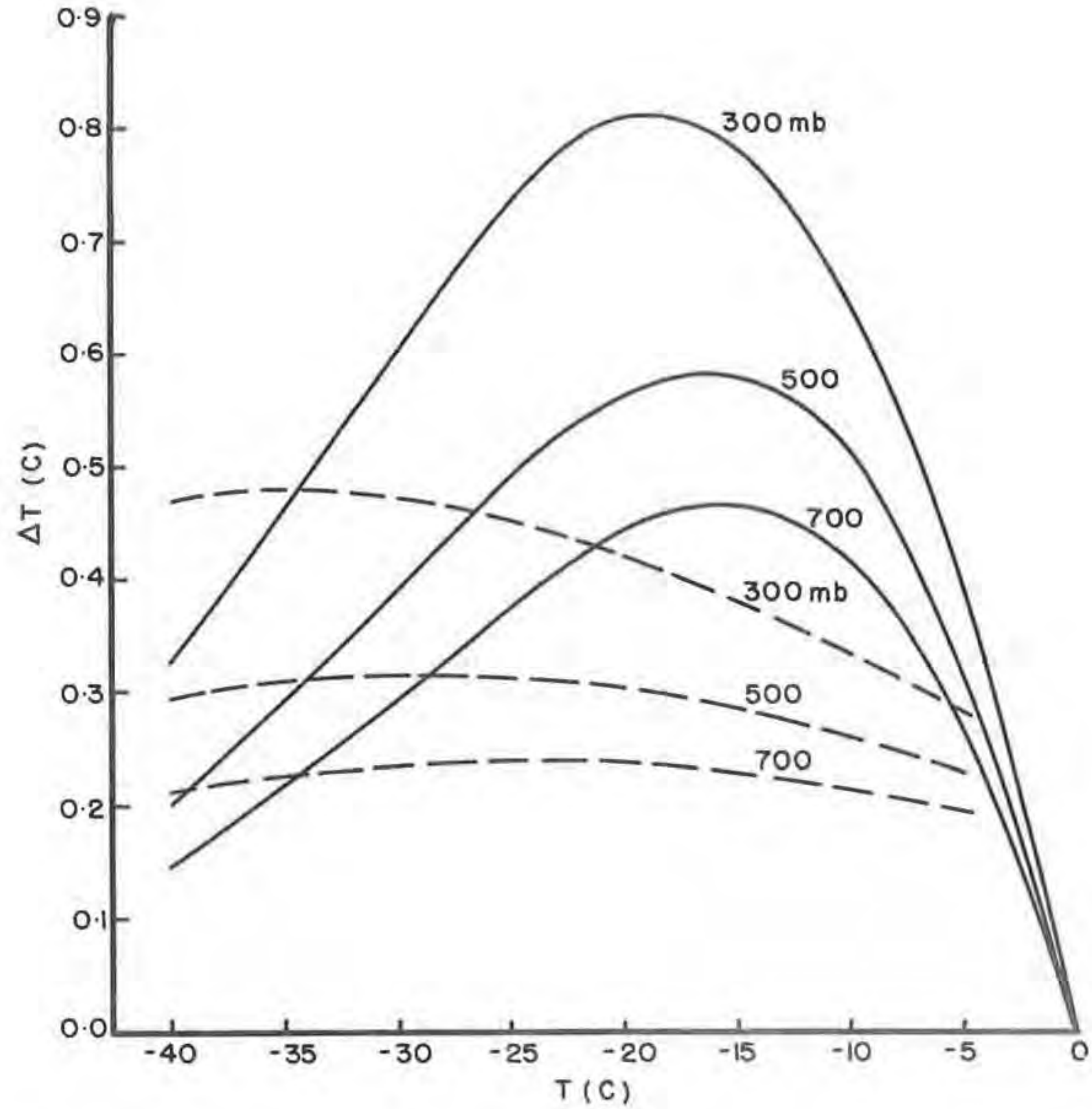

Fig. 6. Temperature increase, as a function of temperature at various pressures, due to sublimation in cloud-free air initially at water equilibrium (full curves), and in liquid water cloud of density 1 gm m^{-3} (dashed curves).

pressure, crystal growth and cloud evaporation will result in a release of heat, though only a fraction of that realized in clear air. The water cloud will ultimately be just consumed, following which the case reverts to that of clear air at water equilibrium, from which sublimation will proceed as described in the preceding paragraph. The heating of the air, up to the point of cloud-exhaustion, is indicated in Fig. 6 by the dashed lines; the heating is a function of the amount of water cloud, and the curves shown represent the case in which the cloud contains one gram of liquid water per cubic meter.

Such a cloud is a dense one, however, and much lower water contents are more realistic. Pettit (1954) has made many measurements of the liquid water content of supercooled cloud during ice-seeking flights. His data suggest a modal value, in stratiform cloud, of about 0.1 gm m^{-3}. Thus, the heating in the presence of such cloud can be expected to be only about 1/10 that shown in Fig. 6; it is clear that, in the presence of water cloud, the heating is but a small fraction of what it is in cloud-free air.

Thus it is seen that air, by virtue of a vapour excess over ice equilibrium, possesses a latent heat supply which becomes available in the presence of ice crystals; further, the presence of water cloud serves to reduce to a small fraction this available energy. The vapour excess, then, is of greater significance in this respect than the presence of liquid water cloud.

Now having considered, at constant pressure, the complete depletion of vapour excess over ice-equilibrium, and the resulting temperature increase in the air-parcel, we consider the height to which the warmed parcel will rise through the environment. While this process can be shown on a tephigram, it is indicated in Fig. 7 on a vapour density versus temperature graph. The two dashed curves are of equilibrium vapour density with respect to water and to ice. Assuming a parcel initially at 700 mb, -15C, and containing vapour at water-equilibrium (i.e. relative humidity 116% re ice), the subsequent vapour density (as ice crystals grow and the parcel rises), as a function of temperature, can be determined for any specified environmental lapse rate. The family of full curves, each corresponding to a particular lapse rate, indicates this vapour content. A further set of full lines indicates the height (in feet) through which the parcel has risen from the 700 mb level. For example, for a lapse rate of 0.7 deg C per 100 m the parcel will rise until its vapour content is at ice-equilibrium, when crystal growth ceases. This occurs where the lapse-rate line intersects the ρ_1 curve, at a temperature of -19C and a height of about 2 thousand feet.

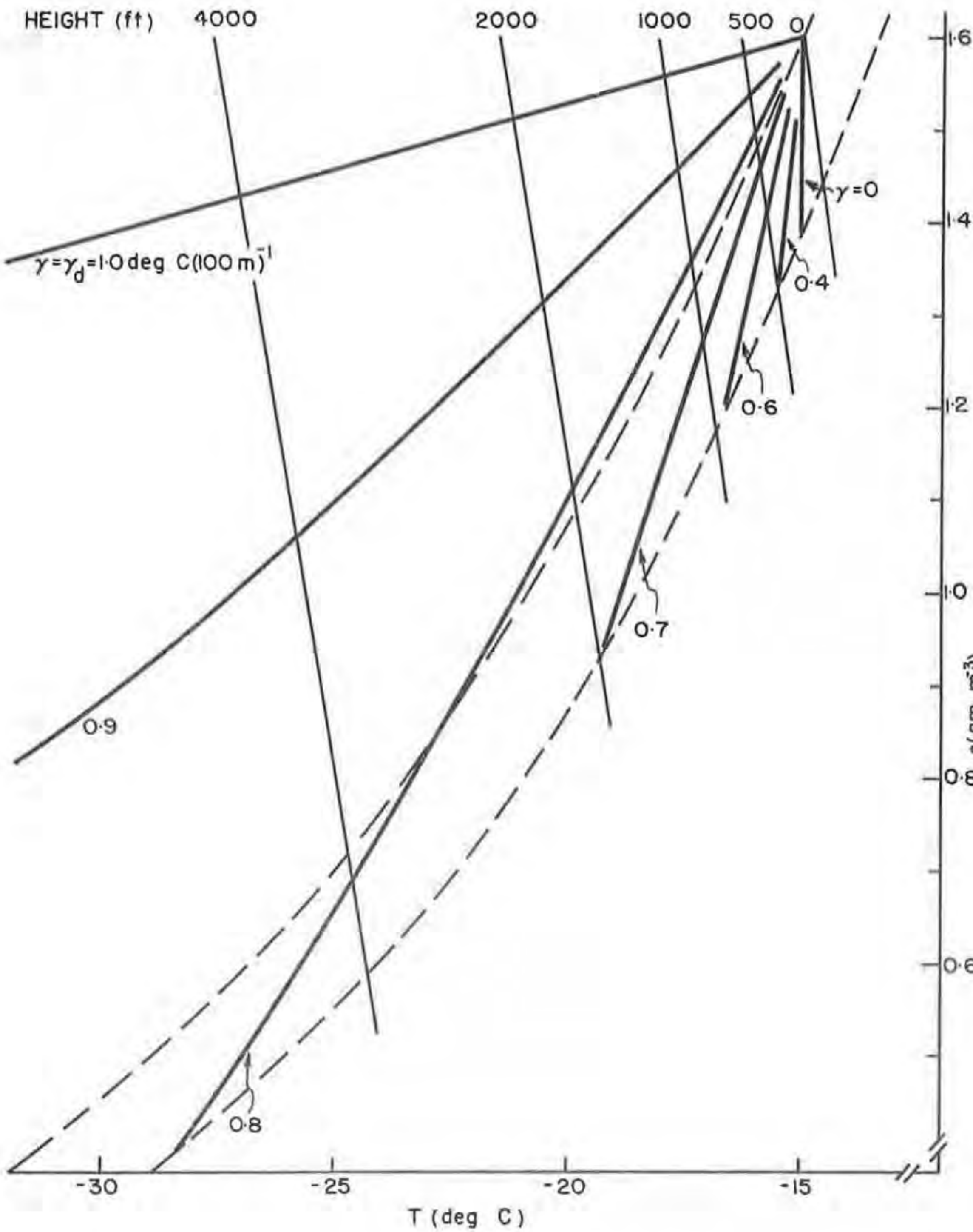

Fig. 7. Vapor density in a parcel of air (initially at 700 mb, -15C, water equilibrium) as a function of temperature for various environmental lapse rates.

It can be seen from Fig. 7 that a rise of several hundred feet may occur in an isothermal environment, and that one of several thousand feet (about the observed depth of a generating cell) may be expected where the lapse-rate is still well on the stable side of the ice or water-adiabatic.

An important point is to be noted in the figure, which was drawn to our attention by Dr. Godson. It will be seen that for certain high lapse rates (e.g. 0.9C per 100 m) the parcel achieves saturation vapour densities in excess of water equilibrium, i.e. becomes supersaturated with respect to water; the path in Fig. 7 lies above the water equilibrium curve. In such a case, water cloud may be expected to form. Here then, is an interesting idea, namely, that by removing vapour by sublimation in clear air it is possible to form water cloud. A limiting lapse-rate exists for which the parcel remains at just water equilibrium throughout its ascent. This critical lapse rate turns out to be just a little less than the saturated adiabatic lapse rate (water), and thus is representative of air which is just stable.

If supercooled water cloud is present, the same critical lapse rate separates the case in which the water cloud will be consumed from that in which it grows. From an examination of sixteen snow-generating cells, it appears that the ambient lapse rate is usually somewhat less than the critical one so that growing snow crystals would ultimately consume the cloud, leaving clear air (apart from the presence of the crystals themselves). The possible significance of this will be mentioned later.

Having considered the amount of energy released in the foregoing manner due to sublimational growth, we next examine the rate at which this release is effected. If N crystals grow, each at a rate dm/dt, then heat becomes available at the rate $NL_s dm/dt$ (in the absence of water cloud). Houghton (1950) has computed the rate of growth for a number of crystal types, and his results for plane dendritic crystals growing at water equilibrium at -15C were used. By assuming a number N of crystals per cubic meter, and their individual masses, rates of heat release were computed; these are summarized in Table I for a single crystal ($n = 1$). Over the range of masses and concentrations considered, thermal outputs ranging from 0.1 to 10 cal m^{-3} sec^{-1} may be achieved.

m	0.1	0.5	1	5	10	50	100	500
$L_s \frac{dm}{dt}$	2.83	6.56	9.35	21.3	30.4	69.0	98.0	224.

TABLE 1: No. of calories ($x10^6$) released per second ($L_s \frac{dm}{dt}$) by growth of a single plane-dendritic ice crystal of mass m, gms (-15C, water equilibrium)

The next consideration is of the vertical velocities that may arise as a consequence of this heating; for as heating occurs and the air parcel becomes buoyant, vertical motions will occur. The problem has been approached as follows. An increment of crystal growth releases an increment of heat, from which results a small buoyant rise of the air until hydrostatic equilibrium is attained; the parcel warms at constant pressure, then ascends adiabatically to a new equilibrium level. Further growth and heat release results in further rise; in the limit, the parcel may be considered to "climb" the environment curve. It is of interest to note that Hewson (1948) used a similar concept in considering the descent and dissipation of cumulus cloud as it cooled due to radiational heat loss.

If we consider the vertical motion of the parcel to proceed in this fashion, we can compute the vertical velocity as a function of the rate of sublimational heat release and of the ambient lapse rate. Vertical velocities (V_a) thus computed are shown in Fig. 8, as a function of crystal mass (m) and concentration (N); for these calculations, the air was assumed at water-equilibrium at 700 mb and -15C, the ambient lapse rate being zero. For other lapse rates, the ordinate values may be multiplied by an appropriate factor; suffice it to say that the velocities increase as the lapse rate increases. It should be emphasized that the vertical velocities of Fig. 8 pertain to the parcel only at the 700 mb level. As the parcel rises and the vapour density approaches ice-equilibrium (following a "path" on Fig. 7) the crystal growth rate and hence the vertical velocity will decrease, tending toward zero as ice-equilibrium is approached.

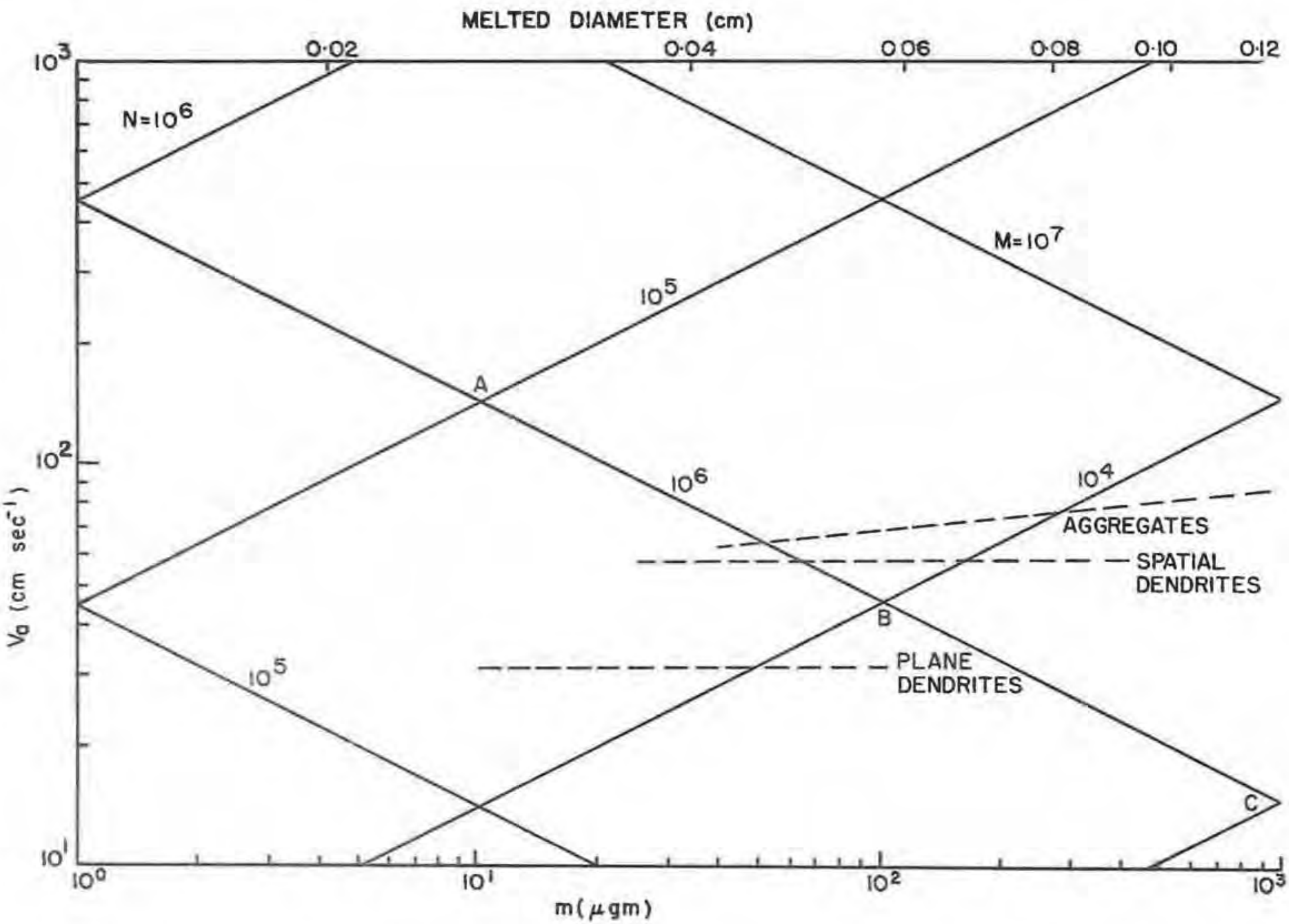

Fig. 8. Vertical velocity due to crystal growth in air at 700 mb, -15C, water equilibrium, lapse rate zero.

We note immediately that significant vertical velocities, of the order of a meter per second, may be achieved under favourable circumstances, even in an isothermal environment. Furthermore, these velocities may exceed the terminal velocities of the ice crystals themselves, which will then rise relative to the earth. Superimposed upon Fig. 8 are dashed lines indicating the terminal velocities of several types of crystals and of aggregates. These have been plotted from data of Nakaya (1954) and of Langleben (1954). Clearly, it is possible for an updraft to develop which will support a crystal but not an aggregate. Also, one may consider the effects of aggregation in the following way. Let us begin with (say) 10^5 crystals each of mass 1 μgm. These will fall (under the conditions of Fig. 8, i.e. at 700 mb, -15C, lapse rate zero), since the resulting updraft is somewhat less than the terminal velocity of the crystals. But as the crystals grow to (say) 10 μgm (along $N = 10^5$, since their number remains unchanged) the updraft increases until it finally exceeds the terminal velocity of the crystals, which are then carried aloft in the updraft (point A, Fig. 8). Suppose now that aggregation occurs in such a fashion that every ten crystals combine; there are now 10^4 aggregates (or groups), each with a mass of 100 gm, (point B). Since now the terminal velocity of the aggregates exceeds the updraft velocity, the aggregates fall out, or precipitate. Note that at point B aggregates will fall out, whereas individual crystals will rise in the updraft. Further aggregation by tens to point C results in still higher fallout velocities of the aggregates. The foregoing is a qualitative analysis only; it is unlikely that the growth rate of ten aggregated crystals is the same as that of a single crystal of the same mass; indeed it is likely to be somewhat less, thus reducing the updraft and increasing the speed of descent. Furthermore, more realistic lapse rates (greater than isothermal) serves to increase the updraft and so to reduce the fallout until aggregation is well advanced.

Fig. 8 has been derived on the basis of clear air, with no super-cooled cloud present. Where water cloud is present, as we have seen before, evaporation counteracts to a great extent the sublimational heat release, reducing the heating to a fraction of its clear-air value. So also with the updraft velocity, which is a function of the rate of heat release. The updraft will be considerably greater in cloud-free air than in cloudy air when the lapse-rate is low. With increasing lapse-rates the updrafts, while increasing in both cases, tend to become equal. Once a certain critical lapse rate (in the vicinity of the saturated adiabatic) is exceeded, the shear reverses and the "cloudy" updraft exceeds that in the clear-air. This offers an interesting possibility at the edge of a cloud sheet in stable air. Suppose that ice crystals or snow is somehow introduced into such a border region. Presumably a region exists around the edge of the cloud itself in which the air, while containing no water cloud, contains a high vapour content (as high as water saturation). In this clear moist air a higher updraft may develop than in the adjacent cloud, and there will be a narrow shear-zone across which the updraft velocity may increase as much as tenfold. Presumably such turbulence as will result from this shear will favour the clumping of crystals into aggregates, which will finally fall out.

While the updrafts and shears at the edge of a cloud sheet have been mentioned, there is a possible mechanism by means of which such an edge might make its appearance in an extensive cloud-sheet. Considering a continuous sheet of supercooled cloud, let small ice crystals be introduced thereto; sublimational growth in the cloud-free (but moist) air just below the cloud base will produce strong updrafts in channels or chimneys, assuming inhomogeneities in the cloud density and crystal sizes. If the air is stable, the cloud in the chimney will be consumed, leaving a moist column of cloud free air, and a shear (in the updrafts) will appear across the boundary of the channel. The process will probably propagate into the cloud-mass along the shear vector of the horizontal wind.

5. CONCLUSION

It will be evident to the reader that research into the mechanism of generating cells has only just begun. The foregoing discussion has dealt primarily with the observational data on cells and their environment. Only in Section 4 has brief consideration been given to some of the physical processes which might conceivably be involved, and it is clear that a great deal of research remains to be done.

Further data are being examined in order to clarify the cell-to-front relationship. As the mapping of "elevated PPI's" (using the CPS-9 radar at Dorval) proceeds, more will be learned regarding the occurrence, distribution and horizontal extent of cells through a storm. If cells show a tendency to exist in lines, it will be of interest to seek a relation between their orientation and that of the wind-shear vector; it may be that the cells align themselves after the fashion of billow-clouds (e.g. Brunt, 1951; Clem, 1955). Observations from a reconnaissance aircraft at and near the generating level would be useful in relating the radar-picture to the physical cloud- and precipitation-structure aloft. Photographic studies of the cirrus family may be helpful, for the forms of high cloud are strikingly similar at times to those of the snow-pattern.

The "stalactites" which appear occasionally on the lower edges of the snow trails are interesting, and will be studied in their turn; it is already known that they appear where the lower air is relatively dry, and that significant down-drafts may result from the cooling due to evaporating snow. A radar technique has been devised for studying the turbulence in cells, snow-trails and stalactites. The data which is presently being collected will supply evidence for or against the presence of significant turbulence aloft during snowfall.

Regarding the primary particles themselves - the ice crystals - more must be known about their growth and their forms; in particular, the vapour contents necessary for their growth in their various habits require study, and a project of this sort is being started.

There are enough problems in snow cells and trails to occupy the meteorologist and the physicist for some time to come. With their solution an important step will have been gained in our understanding of the precipitation process.

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