

A SYSTEM OF HYPOTHESES FOR PRECIPITATION MANAGEMENT TODAY

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I. INTRODUCTION

Evidence suggests that a given cloud-seeding treatment sometimes increases precipitation and sometimes decreases it. Despite many hints and suggestions, there is as yet no generally accepted theory to explain why this should be so or guide cloud seeders toward a more efficient practice. Until this situation is improved, the credibility of cloud seeding will remain low. In the study reported here, we seek to improve this situation by developing a system of physical expectations sufficiently generalized and simplified to explain tendencies toward increase or decrease in a wide variety of weather situations and to help guide the cloud seeder in the field.

Each potential precipitation event affords a certain *time available* within the cloud for precipitation to form and fall. Under the particular set of conditions for that event, there is a certain *time required* for precipitation to form and fall. Treatment is expected to shorten, or in some cases lengthen, the *time required* by some modest amount. If the *time available* is much longer than the *time required*, as with prolonged gradual lifting of moist air, no treatment is likely to close the time gap, and precipitation efficiency approaches its upper limit. If the *time available* is much shorter than the *time required*, even with treatment, as with small puffy cumulus clouds, no precipitation can be expected.

Attention is focused, then, on those events when the *time available* and the *time required* are nearly the same, when precipitation efficiency is neither very high nor very low, when the effect of seeding on *time required* is most likely to find expression in a change of precipitation efficiency. We have sought, by combining physical reasoning with the hints derived from widely reported cloud-seeding experiences, to identify the general types of situations likely to be affected by treatments, and within them to derive expectations of precipitation increases and decreases, respectively.

In the back of our minds is the notion that nature does not separate weather situations into neatly compartmented boxes. Instead, the most important situation variables are continuously distributed. Perhaps the effects of some of the important variables can be depicted in ways that show how they affect expectations over a wide range of their variation, one connected and physically reasonable curve instead of a series of boxes.

In most work on cloud seeding, primary attention has been given to the concentration of par-

ticles that become able to grow by collecting cloud particles. Expectation of a seeding effect has been mostly based on increasing the number of particles capable of acting as collectors, a mechanism that would operate effectively only if the collectors naturally present were insufficient to sweep out the available cloud particles. There is an implied assumption that the treatment does not greatly affect the collection efficiency of an average collector. Our work has led us to question that assumption.

In Section II, we develop a conceptual model depicting growth of precipitation embryos carried along in a rising cloud parcel up to the time when a 20-dBZ radar echo first appears. It shows some expected effects of ice nuclei (IN) and giant cloud condensation nuclei (CCN), natural or artificial, on typical maritime and continental clouds. In Section III, we extend this model to follow the growth of liquid precipitation from liquid embryos and examine the effects of hygroscopic seeding in greater detail.

In Section IV, we go on to depict the effects of freezing on the growth of the embryos and on the transformations of precipitating water and ice. In this section, the effects of IN seeding, both by itself and in combination with hygroscopic seeding, are treated in detail. In particular, we examine the proposition that the effect of IN seeding on the collectability of small particles may be important.

In Section V, we draw the inferences of the three preceding sections together into a more comprehensive depiction in which the expected effects of IN and hygroscopic treatments are shown over a range of cloud-base temperatures, cloud depths, and updraft speeds. Its purpose is to make the expectations more accessible for application to weather conditions prevailing in many different places where cloud seeding is under consideration.

In Section VI, we single out the situations and treatments particularly to be sought after for increasing precipitation, and those particularly to be guarded against if the treatment is to avoid decreasing the precipitation. The idea of influencing the collectability of cloud particles is explored in its practical context. In Section VII, the implications for hail suppression are touched upon briefly. Section VIII puts forth general conclusions and outlines further work we hope to accomplish.

This is a work in progress. We present it at this time in tentative form because it has led us to some unforeseen expectations as well as to the apparent reconciliation of some experimental results that previously seemed anomalous. We need the encouragement of constructive criticism.

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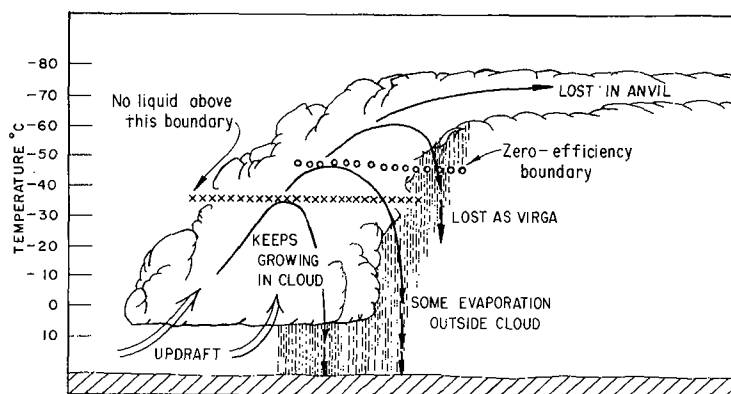


Fig. 1. Precipitation paths in a sheared cumulus

II. CONCEPTUAL MODEL

Our exploration begins with a model imitating a cumulus cloud that grows actively until it reaches a certain height, then loses its top either through mixture with dry air aloft or through wind shear. Figure 1 shows one of the larger members of a family of such clouds. The smallest members of this family will be too shallow to develop precipitation.

We propose to model the most important domains in this cloud. There is an upper domain from which precipitation does not reach the ground; we call it the loss domain. All the moisture that enters it eventually evaporates, either from falling precipitation or from the cirrus plume of ice particles carried away. We have divided this moisture between the virga component (precipitation that falls outside the cloud and evaporates before reaching the ground) and the cirrus component. We make this distinction because the virga would reach the ground if it had a cloud to fall through and hence might be called potential yield. However, the cirrus has no ordinary way of reaching the ground and hence is always a loss. Beneath the loss domain is a yield domain where some fraction of the condensed water substance is converted to precipitation that reaches the ground.

In every cloud there is a boundary between these two domains. Anything that increases the moisture flow upward through this boundary decreases the yield and increases the loss. Anything that decreases the upward moisture flow through this boundary, perhaps by converting more of it to precipitation particles or by enabling the precipitation particles to turn earthward sooner, increases the yield and decreases the loss (increase of precipitation efficiency). Marwitz (1972) and Leichter and Dennis (1974) estimate the efficiency of convective clouds.

Another pair of domains is notable. Above a certain level (below a certain temperature), all condensed moisture is in the form of ice particles that stay separate when they collide, and growth by diffusion is negligible. With no riming and no aggregation, these particles cease to grow. When this boundary is passed, microphysical processes contribute nothing more to the precipitation yield.

This section develops the first stage of our model, the formation of precipitation embryos, corresponding generally to the first appearance of a radar echo at about 10 dBZ. We consider an undiluted constant updraft rising from cloud base

to a specified height. This is a first approximation to what takes place inside a large updraft, away from the diluting effects of entrainment through the top and sides of the cloud. The model could also apply to a cloud surrounded by moist air as in a stratocumulus deck. We hope it will correspond to the first formation of a radar echo in a population of growing cumulus clouds or in one of a train of bubbles rising through an atmosphere premoistened by the passage of earlier bubbles. The model shows how we expect the most favored parcel to behave, not the average parcel.

Rokicki and Young's (1978) calculations of this situation began with the quantity of moisture contained in water vapor at a specified cloud-base temperature and the quantity of water condensed as the air rose. Figure 2 shows the condensate assumed to be carried along with the rising air. The initial droplet concentration was determined according to the CCN spectrum; two cases were studied, corresponding to the continental and maritime CCN spectra of Spyer-Duran (1972). At

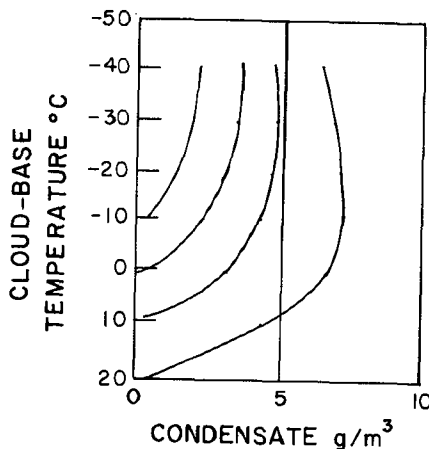


Fig. 2. Condensate that results by adiabatic lift from a given cloud-base temperature

first, the model droplets grew rapidly by condensation alone, then more slowly, becoming more uniform in size with time (Houghton, 1949). Figure 3 shows how drop diameter is related to drop concentration and water content during this stage (for the time being, considering only the part of the diagram where the rain rate is essentially zero, that is, where settling of the drops is slow compared to updraft speed).

Further growth of the droplets was then calculated according to the succession of processes shown in figure 4. The calculation was halted when the calculated radar reflectivity reached 20 dBZ, corresponding roughly to a drop approximately 0.3 mm in diameter. This usually occurs a very few minutes before the particles reach true precipitation size and begin falling rapidly through the air, that is, before gravitational sorting within the model introduces serious error. Additional calculations were made to consider the growth of ice particles activated by the average background spectrum of IN and of ice particles grown on AgI nuclei under optimum IN seeding.

The main results are shown in figure 5. Each panel represents a successively colder cloud-base temperature. The ordinate is cloud-top temperature and the abscissa the time available for particle

growth within the model. The sloping straight lines are parcel trajectories at different updraft speeds.

The solid curves at the upper right depict the time required for formation of 0.3 mm drops from the number of nuclei, N , written along the line. The left one represents the sparser, more maritime CCN spectrum and an earlier echo; the right one is the more continental. The lines of stars represent first-echo formation by frozen particles resulting from optimal IN seeding with AgI. The stars to the right are the more continental.

We note first that fast updrafts carry the entire particle population to temperatures colder than -35°C (the temperature at which Rokicki and Young assumed all cloudwater was frozen and precipitation development stopped) before first echo

forms. For warm cloud bases, "fast updraft" means 15 m/s or more; for cloud bases 0°C or colder, it means about 5 m/s or less. At temperatures colder than -35°C , particle growth effectively ceases because colliding particles do not stick together (Hosler, et al., 1957) and because growth by condensation is negligible.

In clouds with warmest bases, all-liquid processes (mainly coalescence) produce first echoes sooner than even optimum IN seeding, and neither natural nor artificial IN play an important part in

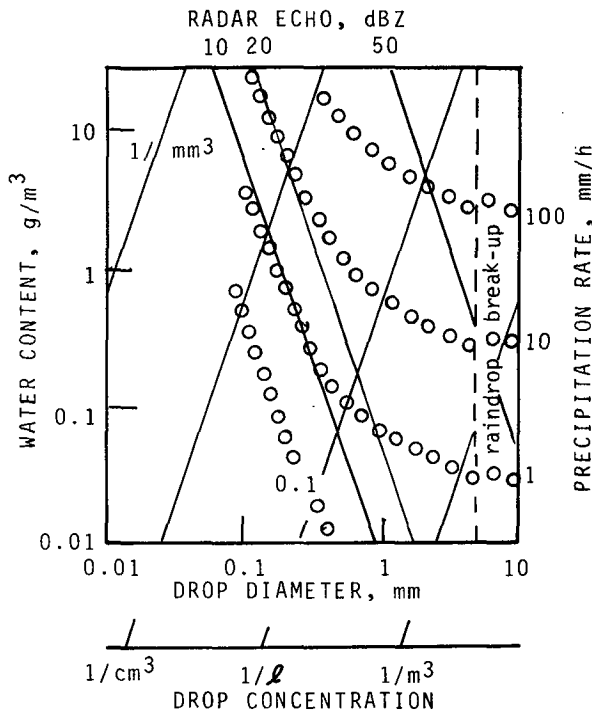


Fig. 3. Relation of drop diameter, water content, drop concentration, rain rate, and radar reflectivity, assuming monodisperse drop distribution.

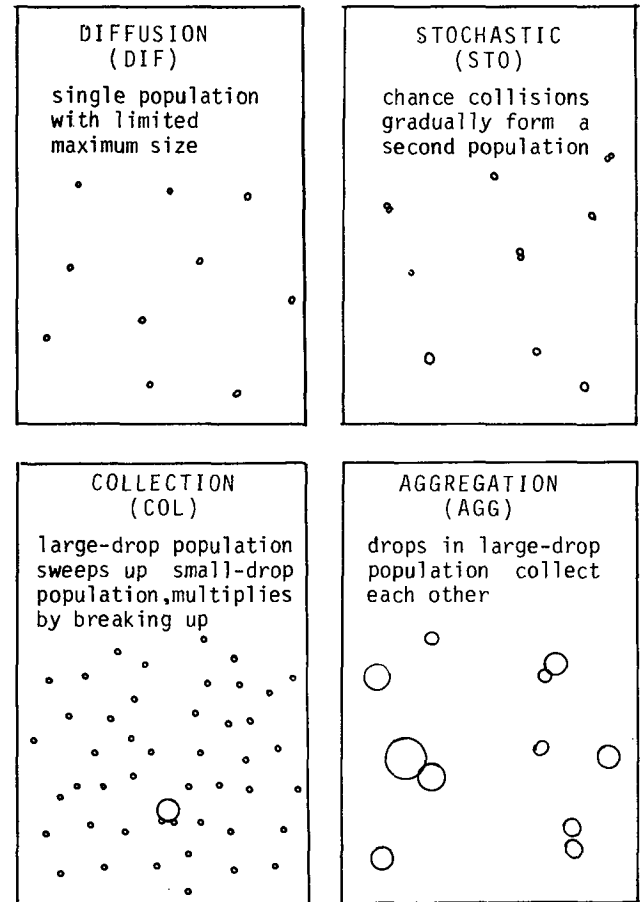


Fig. 4. Modes of drop growth.

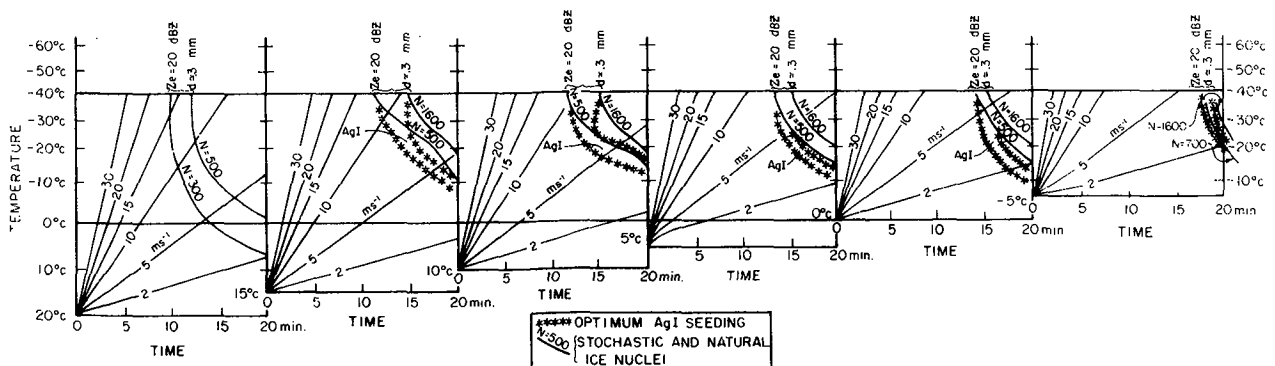


Fig. 5. The Rokicki-Young (1976) exploration of the time and depth required to produce a 300- m water drop in an undiluted parcel in a constant-speed updraft. Each panel represents a different cloud-base temperature from 20 to -5°C . See the text for further explanation.

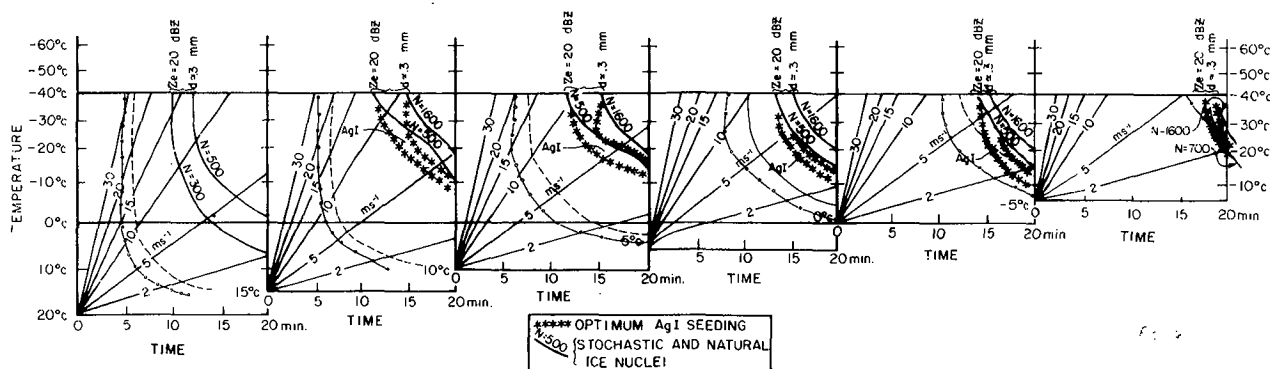


Fig. 6. From the Rokicki-Young (1976) exploration. The same as fig. 5 but to simulate the effect of large-particle or hygroscopic seeding on the time and height required to produce 300- m water drops. The broken curve on the left represents the maritime condition, the other the continental condition.

precipitation initiation. When cloud bases are coldest, natural IN form first echoes sooner than the all-liquid process, and optimum IN seeding shortens the time by a few minutes. With intermediate cloud-base temperatures, optimum IN seeding advances the time of first echo by several minutes, especially at moderate updraft speeds around 5 m/s.

For the clouds that most nearly fulfill the model conditions, which must be nearly free of giant CCN, these results translate to the following expectations in nature:

When updrafts exceed 15 m/s from cloud base to the -35°C level, expect low precipitation efficiency accompanied by a massive moisture discharge in the form of a cirrus anvil. With cold cloud bases, expect the same when updrafts exceed 5 m/s, with less massive anvils because of the lesser amount of water involved. (Compare Vonnegut and Moore's 1959 study of the precipitation efficiency of the storm that spawned the Worcester tornado.) This expectation will not be changed by any IN seeding.

At intermediate cloud-base temperatures, about 0°C and slow updrafts, expect IN seeding to advance the time, enlarge the extent, and lower the level of first echo. For critical cloud depths, corresponding to cloud-top temperatures near -20°C , expect echoes in seeded but not in unseeded clouds.

Precipitation from the cloud implies a previous first echo and may generally be substituted therefor.

Figure 6 shows the results of the Rokicki-Young model when giant aerosol particles are present at cloud base. The lines in the lower left part represent large particles equivalent to salt in quantities of $100\text{ g/km}^2 \cdot \text{min}$. The two lines correspond to cloud drop concentrations as marked. We note that this amount of large-particle material, whether present naturally or as a result of treatment, overrides the processes discussed earlier at all cloud-base temperatures and all but the most extreme updraft speeds, advancing the time of first-echo formation by 1 to 10 minutes. The underlying CCN spectrum makes little difference.

The principle of hygroscopic seeding is to shorten the time required for precipitation formation by providing a ready-made population of collector embryos without waiting for stochastic collection to do the job.

Hygroscopic particles grow by diffusion because they readily absorb water vapor at relative humidities well below 100 percent. Figure 7 shows

how hygroscopic particles grow to be embryonic collectors within the water cloud. While the larger typical CCN of about 10^{-12} moles become collectors in 10 to 100 minutes, hygroscopic particles of 10^{-10} moles become collectors in 2 to 3 minutes.

Johnson (1980), using the same physical concept of an adiabatically rising column, focused on the effects of giant natural CCN particles and hygroscopic seeding, assuming prevalence of the giant-CCN background measured by Hobbs, Bowdle, and Radke (1977) on a day with relatively clean air in the High Plains. To this he added a range of hygroscopic treatments. Figure 8 shows his results computed for 0.2-mm drops (about a 10-dBZ radar echo) in the same form as figures 5 and 6 for natural conditions. The chain of circles on the right represents untreated clouds with the Radke, et al., nuclei distribution. The one on the left represents hygroscopic treatment with seeds that grow by a factor of 10^{-5} . His results agree with those of Rokicki and Young in assigning a major effect to a relatively small number of giant CCN when these are present. When giant CCN are present naturally above some unspecified concentration, hygroscopic seeding at feasible intensities may have little effect.

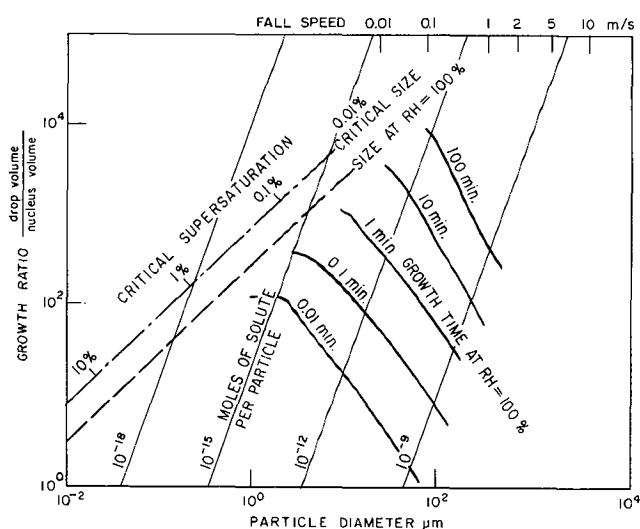


Fig. 7. Time required for hygroscopic nuclei of different molar contents to reach given diameter in saturated air.

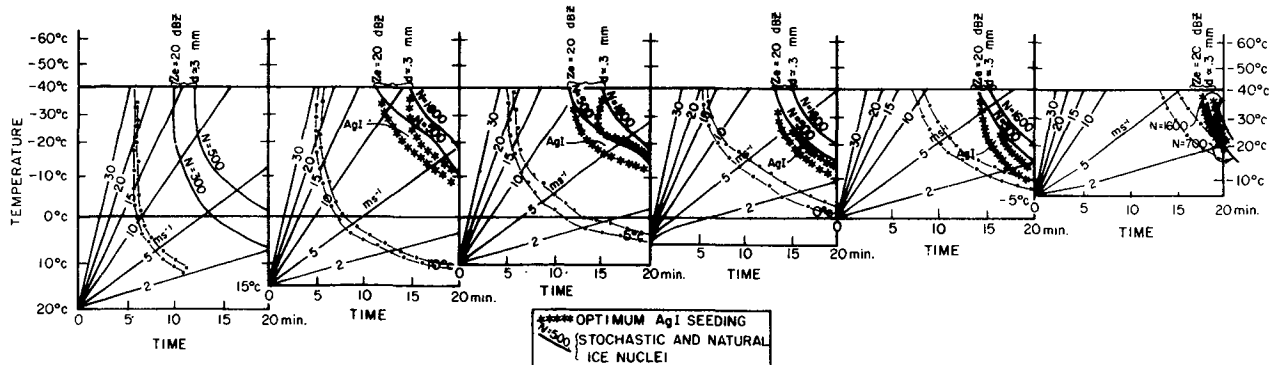


Fig. 8. The Johnson (1980) exploration to compare the time and height of the 200- μ m water drops in undiluted constant-updraft parcels for natural and hygroscopically treated clouds. See the text for explanation.

These results translate to the following expectations in nature for the clouds that most nearly fulfill the conditions of the model:

When updrafts are less than 15 m/s, expect that some clouds polluted with giant CCN will form first echoes at temperatures warmer than 0 °C if the cloud-base temperature is around 20 °C, whereas "clean" clouds will not.

When updrafts are less than 15 m/s, expect that some clouds between 3 and 4 km deep, if polluted with giant CCN, will develop radar echoes within the usual expected lifetimes of such clouds, while "clean" clouds of the same size will not.

III. DEVELOPMENT OF LIQUID PHASE PRECIPITATION

In this section, we follow the growth of the embryos by interaction with the cloud water and with each other, when ice is not involved.

In figure 9, we construct three graphs with common abscissas (drop diameter) to see what governs the rate at which collectors sweep up the collectables in their path. Figure 9A shows the falling speed of waterdrops according to Beard (1976). When the drops grow so large that their surface tension no longer holds them spherical against the drag forces, they become flattened, and increased drag checks their fall. Aerodynamic drag makes them unstable, and in time, drops larger than a critical size break up. The right side of figure 9A shows this limit according to Komabayasi, Gonda, and Isomo (1964). Liquid drops would have to be smaller than 4 mm diameter to fall many kilometers without breaking up. Frozen drops can, of course, grow larger and fall faster than liquid ones.

Figure 9B shows domains of interaction between liquid collectors and collectables. The efficiencies for the sweep out are those of Klett and Davis (1973). Along the sloping left-hand boundary, collectors and collectables are the same size, overtake speed is zero, and little collection occurs. Within the region just to the right of this boundary, the particles are nearly enough the same size to be considered members of a single population. The far left region, labeled STO, represents stochastic growth within a population of cloud droplets. Higher and to the right, the area marked AGG shows where aggregation occurs among the precipitating particles (they often have a wider size spectrum than the cloud droplets).

The third region, marked COL, is where collection of cloud droplets by precipitation particles predominates: the cloud-droplet size changes slowly, so the trajectory of growing collectors on

the graph is more or less directly to the right. Note that a given particle at a given time may be collecting cloud drops (in the COL domain) and aggregating with other collectors (in the AGG domain). Note also that the smaller collectables are inefficiently collected.

The impact of two drops colliding may overcome the stabilizing force of surface tension and produce satellite drops. The likelihood of this as observed in the laboratory by Brazier-Smith (1973) is shown in the upper right corner of figure 9B.

The sweep rate within the cloud is the product of the sweep rate of the individual particles and their concentration. Figure 9C shows how the concentration of collectors is related to their diameter and the collector water content in grams per cubic meter. From figures 9B and 9C together,

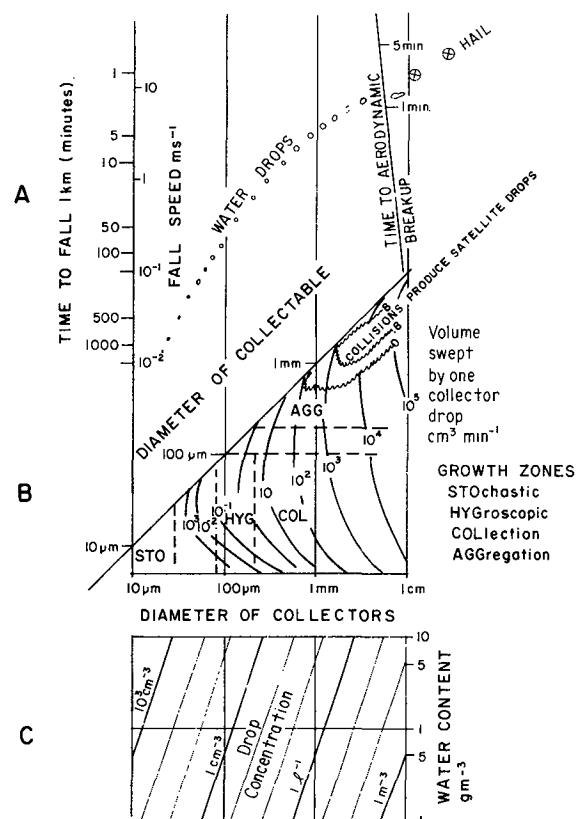


Fig. 9. Derivation of sweep volume of individual collectors in the unfrozen domain. See the text for explanation.

one can calculate approximately how rapidly the collection and aggregation processes advance. For example, 500- μm diameter collectors at a concentration of one per liter will sweep up all the 10- μm cloud drops in about 2 minutes.

Most of the time required for precipitation formation is consumed in generating the collector population that emerges gradually from the stochastic domain. Once established, this population gathers water relatively rapidly. If drops reach breakup size, sweep out accelerates and aggregation becomes a significant factor.

Between the COL and AGG zones lies the so-called spectral gap. Collectors grow through this size range quite rapidly once they become collectors, and drop size spectra tend to show a minimum in concentration compared with larger and smaller drops.

Returning to figure 9, we may define the effect of hygroscopic seeding as creation of a particles population in the HYG domain that are thereby already established in the COL domain and (because of high collection efficiency within the population region) qualified to move quickly to the AGG domain.

Figure 10 shows the minimum size that a drop must attain before it can fall to earth without evaporating. At 5 mm diameter, it would reach the ground after being sheared from the top of the tallest cloud even if the environment were dry. For a 3-mm drop to reach the ground from such a height, the environment should have 70 percent or greater relative humidity.

The next step in our modeling of the domain boundaries of figure 9B is to estimate the growth of single hygroscopic particles over a range of sizes and cloud conditions by rerunning calculations similar to those that produced figure 5. These calculations, by Klazura and Todd (1978), assumed constant speed, undiluted adiabatic updraft, and geometric sweep of cloud drops, are illustrated in figure 11. Consider first the center panel. It shows the results for a cloud-base temperature of 10 °C, and a 10- μm hygroscopic particle. The arched lines are drop trajectories. Intersections with the down-trailing lines shown their diameters as they grow. The region pecked with small circles represents particles large enough always to reach the ground but smaller than damaging hail. The irregularly shaded region at far right represents damaging hail.

After 10 to 15 minutes, depending on updraft speed, the particle becomes a drizzle drop and

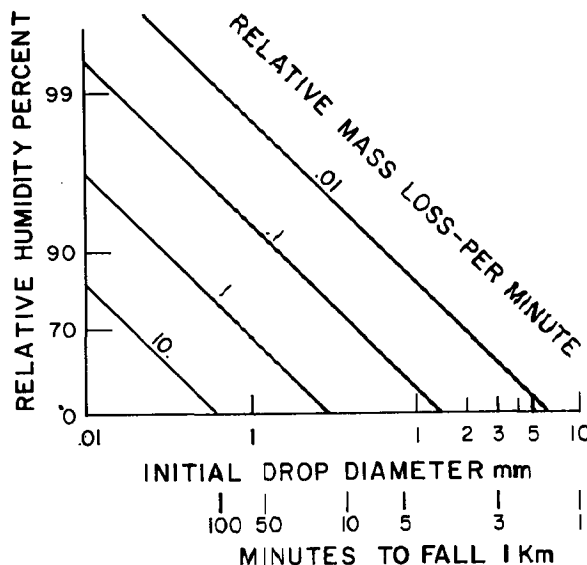


Fig. 10. Relative evaporational mass loss per minute as a function of drop diameter and relative humidity.

collects cloud droplets very efficiently. In another 6 to 8 minutes, it attains breakup size, or, if frozen, small-hail size that assures that it will reach the ground even falling through dry air.

Comparison with the panels for other cloud-base temperatures shows that the process is approximately 6 minutes faster for these same 10- μm hygroscopic seeds if the cloud base is 10 °C warmer, regardless of updraft speed. With a cloud base temperature 10 °C colder, the process is slowed 6 to 8 minutes in the fast-updraft clouds but is relatively unchanged in slow-updraft clouds (an approximate 2-m/s rise rate).

Each particle that becomes a 5-mm raindrop is assumed to break up into eight equal drops, which continue growing. However, depletion of the cloudwater content by precipitation is not modeled. The calculations therefore model the formation of the first cohort of precipitation particles to form within the cloud but not the later stages during which cloudwater becomes depleted.

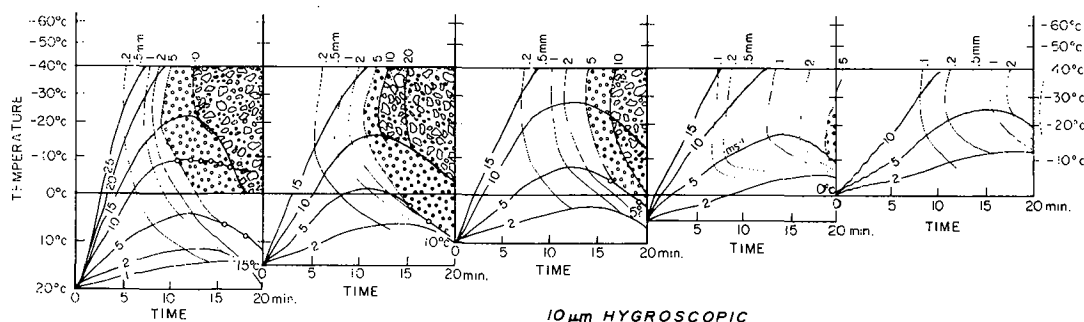


Fig. 11. The Klazura-Todd (1976) exploration of the time and cloud depth required to grow precipitation drops from 10- μm hygroscopic particles in an undiluted constant updraft from cloud base. See the text for explanation.

IV. EFFECTS OF FREEZING ON PRECIPITATION DEVELOPMENT

Before drawing expectations of nature from this system of models, some of the ways freezing changes the aggregation process within the model must be addressed further.

To this point, we have identified the parameters used to calculate the time required for precipitation formation (in addition to the three that define the time available) as: cloud-base temperature, cloud-top temperature, CCN spectrum (including large particles), and IN spectrum. The last two parameters are divided into natural and treatment categories corresponding to untreated and treated events.

Figure 12 illustrates the effects we will discuss. In part A, at temperatures between 0 and -22 °C, without seeding, a frozen particle collects liquid water. If collection is faster than

the water freezes, the excess is shed as liquid drops (List, 1963). In part B, with seeding, some of the cloud particles are frozen; but, in ascending air, there are usually enough supercooled droplets still present to keep the collector at least partly wet, so frozen particles may stick to it if the impact is not too strong.

In the colder regime of part C, from -22 to -40 °C, if there is only light seeding or none at all, there may still be enough supercooled droplets to glue the cloud-ice particles to the collector, though bounce-off is more likely as the cloud gets colder. At these temperatures, the heavy seeding illustrated in part D_S freezes all the water substance: collection does not take place, and precipitation growth stops. The same is true wherever the temperature is below -40 °C, shown in part D_N.

Finally, part E shows when to expect bounce-off from a wet frozen collector. The dashed line is where the impact energy equals the liquid surface energy and bounce-off might begin. To the right of the solid line, bounce-off is practically assured.

If some of the collectables are frozen and the right size to stick on impact, then the collector need not shed so much heat and its surface is roughened, and it can grow faster without shedding liquid droplets. If the collector surface is dry, then we expect that even the smaller frozen collectables will bounce off as depicted in figure 12D_S (IN-seeded) and figure 12D_N (natural).

The frozen collector may resume collection and begin melting as it falls to a lower, warmer level. However, even in a warm part of the cloud, the collector can appear as a frozen particle (a hailstone, perhaps). The labels A, B, C, and D in this figure will be used for later reference.

It is important to know whether growth is mostly in the COL or in the AGG domain (fig. 9B). In the COL domain, moderate AgI seeding will freeze only a few of the cloud drops and will have little effect on growth. In the AGG domain, on the other hand, it will freeze nearly all the drops and stop aggregation.

This idea describes a means whereby relatively light seeding may, under appropriate conditions, lead to rapid freezing of nearly all the supercooled water in a cloud and hence to rapid release of its latent fusion heat and the latent heat of the vapor that comes into equilibrium with the frozen state.

We are now ready for the crucial step of integrating all that we have examined thus far into a single concept to describe the location of the critical boundaries in figure 1 and the expected effect of hygroscopic seeding on the position of these boundaries and thus on the efficiency of the precipitation process in that cloud.

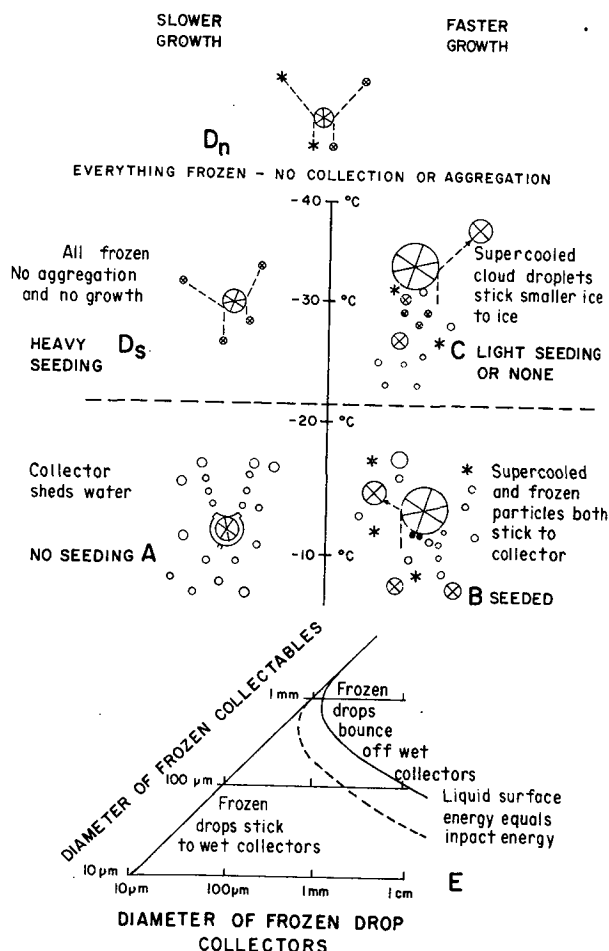


Fig. 12. Collection process of frozen collectors growing at different temperatures below 0 °C by collision with collectables in different conditions.

Look first at the boundary in the key chart of figure 13, part B (heavy outline), separating the domains of growth and completely frozen nongrowth. We established that the temperature at which the growth process completely freezes up depends on the temperature at which the collectables (not the collectors) freeze. This, in turn, depends on their size. (We shall consider the dependence on seeding presently.) With temperature as ordinate and size of collectables as abscissa, we postulate that we can draw a boundary on this graph that corresponds to the boundary in the cloud.

The heavy (-N-N-N-) line on part B represents the growth/no-growth boundary in the cloud. To explain its position, we shall calculate, roughly, what size of collectables will become frozen after a 1-minute exposure to the given temperature.

Consider part C first. It is the same as figure 3 and relates drop size to liquid water content and number density. Its abscissa is lined up with the abscissa of part B. Suppose that the liquid water content is 5 g/m³ and the number density is one per liter (the circle). This yields a diameter of 2 mm. How much volume will this drop sweep in a minute? Go to part A, which relates volume swept per minute to drop size. Its abscissa too is lined up with part B. The 2-mm drop is sweeping more than 1 liter per minute of drops or ice crystals that are larger than 15 μ m.

What is the expectation that the drop will sweep up an IN before the end of that minute?

Refer to part D (based on North Dakota, 1980); it shares the temperature ordinate with part B and shows the ordinary range of IN concentrations active at the corresponding temperatures. One per liter is found at a temperature of approximately -21 °C. Here we place the boundary. Noting that a change of 4 °C produces a tenfold change in IN activity, we think it not worthwhile to push the accuracy much further. Following the same set of paths for other collectable sizes places the rest of the boundary as shown.

Liquid collecting on ice (figure 12, part A) predominates in the lower left corner of part B because the smallest collectables freeze slowly. A transition to supercooled droplets is noted toward the upper left corner, mediating the capture of frozen collectables as frozen cloud particles appear among the liquid cloud particles at lower temperatures (part C).

The next step is to observe how the extent of the all-frozen domain is affected by seeding the imagined cloud with AgI. The curves on part E show the temperature dependence of nuclei output according to North Dakota (1980). Each of these curves can be overlaid on the key graph in the same manner as we overlaid the "natural ice nuclei" curve if we can determine how far leftward it should be placed to correspond to a given seeding intensity. For example, if seeding is done at a rate that disperses 1 g/km³ of AgI, we should then find 1 IN per liter active at about -6 °C (using the

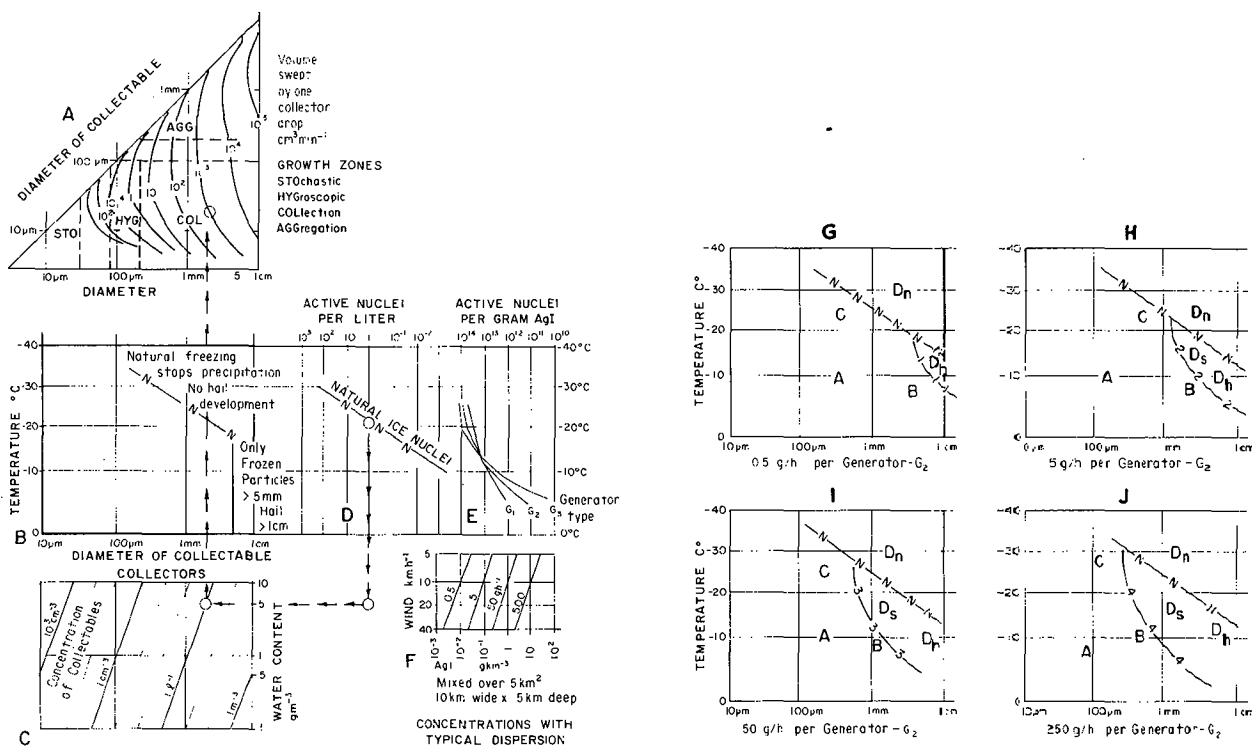


Fig. 13. Multi-factor diagram of frozen precipitation growth. See the text for explanation.

"median" generator, G2). In this case, we move the generator graph leftward until 1 IN per liter is aligned vertically with 1 droplet per liter obtained from part C. Then, each droplet at -6°C will encounter an AgI IN in approximately 1 minute. Part F beneath part C suggests how many grams per hour are needed to generate the corresponding number of IN per liter for different wind speeds, assuming a mixing layer 0.5 km deep and one generator each 10 km of crosswind distance on the ground.

Figure 13 shows in parts G, H, I, and J the results of conducting this exercise for four different seeding rates. Observe first the case of very heavy seeding, 250 g/h per generator (or per 10-km front across the wind). The D domain of no-growth (refer back to figure 12) is extended downward toward higher temperatures for all collectables except those with a very low sweep-out rate (small size). The extended part of the D domain splits into two parts. Only hail-stones exist in D_H . The transition to a D domain is the same as saying that hailstone growth by autoconversion is stopped by seeding outside the narrow temperature window from 0 to approximately -5°C . In the domain marked D_S , the seeding is expected to freeze all collectables, thereby rendering them unavailable to feed the growth of larger particles or to undergo autoconversion growth. Thus, if hygroscopic seeding succeeds in converting most of the cloud's water content into particles larger than approximately $200\text{ }\mu\text{m}$ according to the criteria of figure 11B, we expect that the combination of hygroscopic with heavy AgI seeding will lock the available water into frozen particles too small to constitute damaging hail except in the 0 to -5°C temperature window where hail growth is slow anyway.

Lower and to the left, the heavy AgI seeding pushes the A/B transition (figure 12) downward and leftward and may squeeze the B/C transition leftward also. Within the B domain, which may contain much of the collectable supercooled water in a cloud not seeded hygroscopically, the AgI seeding increases the expected growth rate of both hail and nonhail precipitation. To the right of the boundary at a 5-mm diameter for the worst conditions, but 3-mm under more favorable conditions, all particles are large enough to survive to the ground. Therefore, seeding with AgI is not expected to reduce their effectiveness as precipitators once they have been formed.

At lesser seeding rates, the D domain shrinks back toward its natural extent, which is to say that the hail-suppression effect is expected to fade, while the B domain takes over the vacated space. Since seeding may increase hail growth in the B domains, light seeding is expected to increase rain and hail efficiencies in the overall cloud budget.

V. THE COMPREHENSIVE MODEL

Figure 14 shows how freezing affects precipitation formation from seeding with $10\text{-}\mu\text{m}$ hygroscopic treatment when the cloud base is 10°C . Freezing from natural nuclei and AgI seeding depicted in figure 13 is mapped onto the graph of figure 11A to generate figure 14. The "-N-N-N-" line shows where nearly all the drops started by

the $10\text{-}\mu\text{m}$ CCN seeding would be frozen within 1 minute by natural IN. The "-2-2-2-" line shows where moderate AgI seeding of figure 13, part H, would freeze these drops, and "-4-4-4-" line is the same for very heavy seeding as of figure 13, part J.

If the $10\text{-}\mu\text{m}$ hygroscopic treatment has supplied enough particles, and if they have grown large enough to sweep up all of the cloud water, then when they are all frozen, precipitation development will stop. If they are in a sheared cloud, their fate will depend upon their size at total freezeup as shown in figure 1. The height, timing, and size of particles at freezeup will depend on the concentration and temperature activation of IN and on the size and concentration of the natural and treatment CCN.

We consider the probable upper limit of affordable CCN treatment (hygroscopic seeding) to be one that sweeps up 10^5 parts of cloudwater per part of treatment. We have shown this line as heavy "---". Each line on either side represents about a tenfold difference in ratio of water to hygroscopic material and about a minute in growth time. The model "works" most efficiently when sufficient time for growth and sweep out is available to permit the use of a lesser amount of material.

The area to the right of the heavy "---" line and above the "-N-N-N-" natural IN line we color yellow on our graphs. The additional area to the right of the 10^5 CCN line and above the very heavy IN seeding line "-4-4-4-" we color red to show what we consider near the limits of affordable CCN and IN seeding for both precipitation and hail suppression. Subsequently, we refer to these lines by their color, so we suggest that readers color them in. The blue line we discuss later in connection with hail suppression.

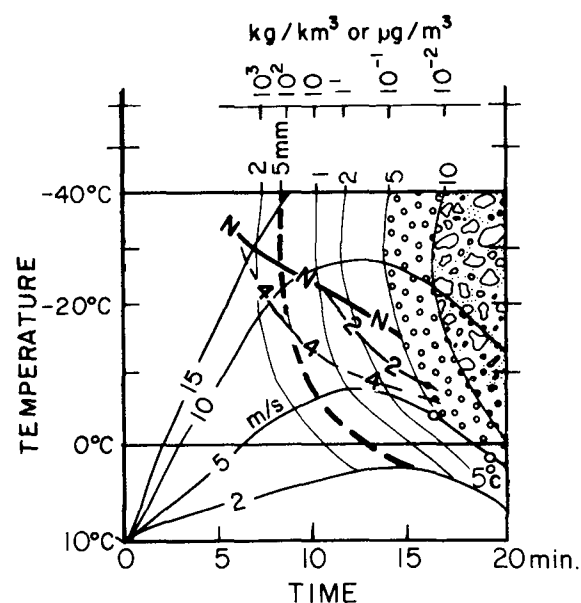


Fig. 14. Ice-phase seeding domains from fig. 13 mapped onto fig. 11, for $10\text{-}\mu\text{m}$ hygroscopic seeding particles. See the text for explanation.

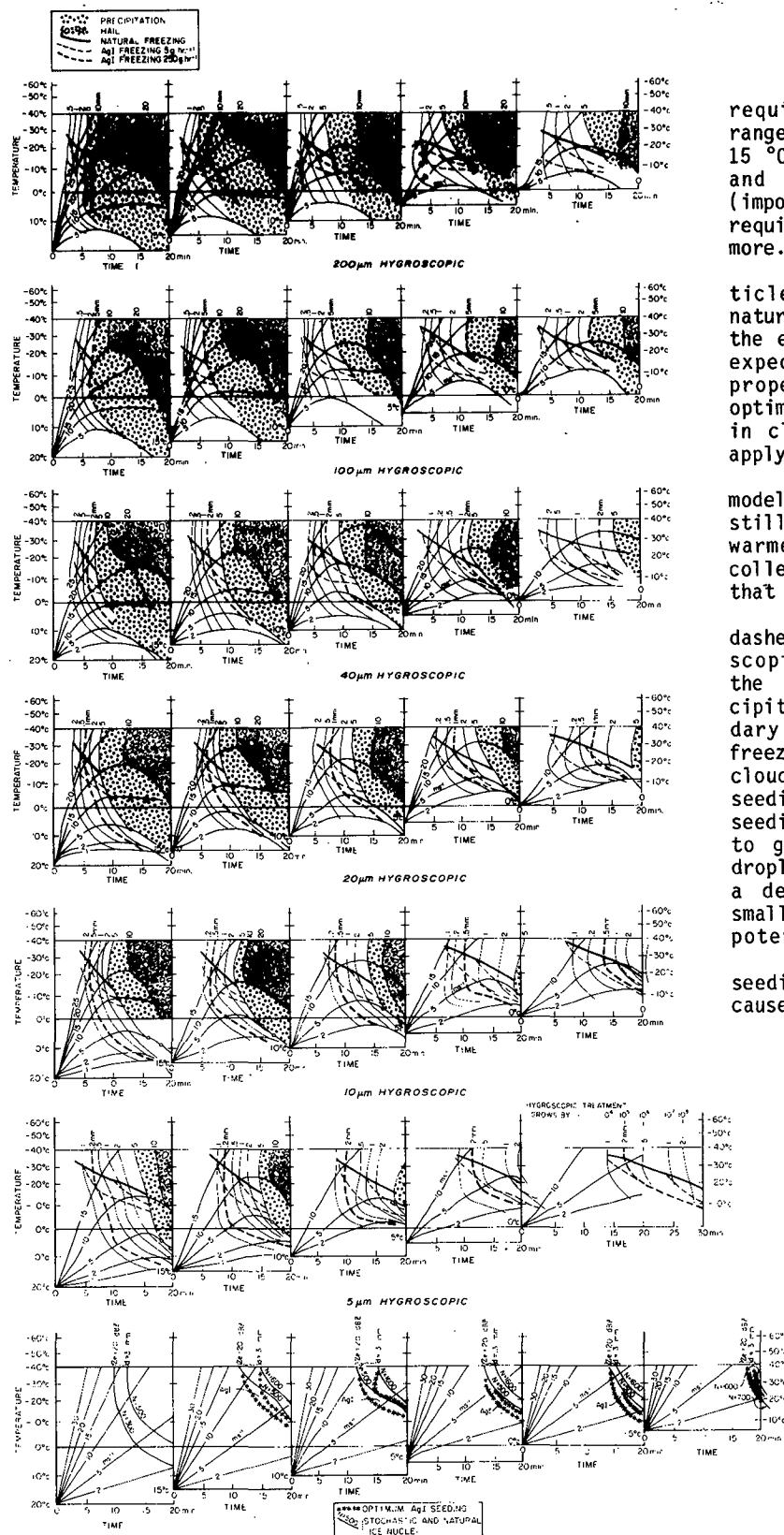


Fig. 15. Ice-phase seeding domains from fig. 13 mapped onto figs. 5 and 11, extended for a wide range of CCN sizes.

The panels of figure 15 extend these mappings to other cloud base temperatures and other hygroscopic treatment sizes. Row 7 (repeated from fig. 5) shows the time required for the model to evolve a 20-dBZ radar echo under natural conditions, and with optimum AgI seeding. (In this case, natural conditions are taken to exclude giant CCN.) AgI seeding shortens the expected time

required by at least 2 or 3 minutes for a wide range of updraft speeds and cloud-base temperature 15 °C and colder. For slow updrafts (1 to 3 m/s) and cloud-base temperatures around 5 to 0 °C (important for precipitation over mountains), the required time appears shortened by 5 minutes or more.

Row 6 models the effect of hygroscopic particles 5 µm in diameter. This case simulates naturally occurring giant CCN, or in cleaner air, the effect of one mode of hygroscopic seeding. We expect that 5-µm hygroscopic particles in the proper concentration will be as effective as optimum AgI seeding in speeding up echo formation in clouds with bases 5 °C or warmer. This will apply even more to 10-µm particles.

The remaining rows in figure 15 extend the model to larger hygroscopic particles. They are still limited to the case where liquid condensate warmer than -40 °C remains undepleted, so that collectors continue to grow after they freeze until that critical limit is reached.

In figure 15, as in figure 14, the heavy dashed line identifies the point at which hygroscopic seeds grow by a factor of 10^5 , marking the expected minimum affordable growth for precipitation management. The line marks the boundary at which these particles are expected to freeze naturally and cease growing if all of the cloudwater has been swept up by the hygroscopic seeding, precipitation. With lesser hygroscopic seeding, we expect that the embryos would continue to grow by collection of still-unfrozen cloud droplets. Hygroscopic seeding in this case models a decrease in precipitation efficiency. The smaller the hygroscopic seeds, the stronger the potential for this modeled overseeding effect.

When AgI seeding is added to the hygroscopic-seeding model discussed above, growth cessation caused by complete freezeup occurs even sooner.

The red lines show how AgI seeding would extend the zone. They also show, for the 5-µm hygroscopic seeding, row 6, where AgI seeding models complete freezeup in a cloud containing a natural population of giant CCN.

In clouds with warm bases and enough natural CCN to convert all the cloudwater to millimeter-size collectors in the supercooled region, we expect heavy AgI seeding to freeze all the water into particles too small to reach the ground and thus to stop precipitation formation. Perhaps AgI seeding acted this way to decrease precipitation from tall cumulus clouds in Project Whitetop (Braham, 1979).

IV. INCREASING PRECIPITATION WITH ICE-PHASE SEEDING

The prognosis in the situation just described is that AgI seeding will reduce precipitation. Where, then, does our model predict that AgI seeding will increase precipitation? We consider four possibilities. The first is the situation shown in row 7 of figure 15. Giant CCN are lacking, and in all but the warmest-based clouds AgI provides a *time-required* advantage over stochastic formation of precipitation embryos.

The second possibility is when ice-crystal collectables grow very rapidly and in a short time have cross-section areas many times larger than the cloud drops they

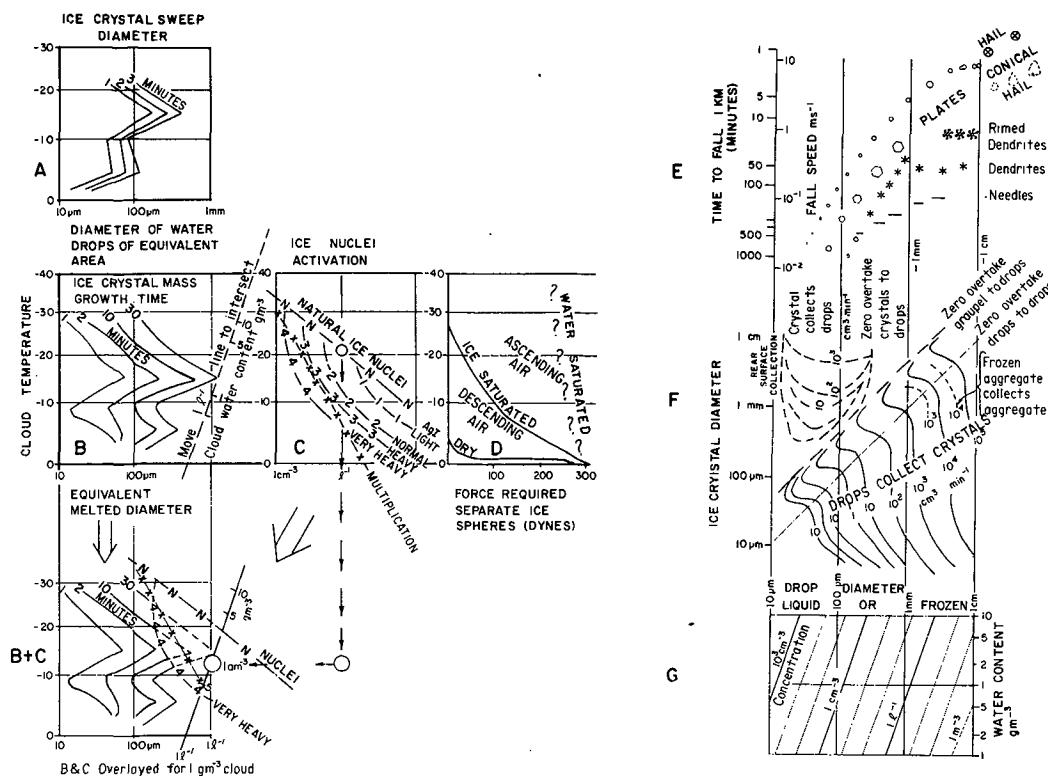


Fig. 16. Multi-factor diagram of snow-crystal growth and sweep-out. See the text for explanation.

replace. (See Appendix for derivation of this relationship.) By virtue of this, their exposure to collision with each other and with collectors is much greater than that of cloud drops. However, not all collisions result in collection. Figure 16 shows the conditions that lead to respectively more or less effective precipitation formation with the production of more ice crystals.

Following the format of figure 13, the heavy outline, 16B, is a key graph with which others are coordinated. Figure 16A shows the time to attain given crystal diameters by diffusional growth as a function of temperature (Ryan, Wishart, and Shaw, 1976). For example, 2 minutes after nucleation at -10°C , a crystal will have an equivalent sweep diameter of $80\text{ }\mu\text{m}$. Figure 16B shows the time to accumulate mass by diffusional growth as a function of temperature (shown as the diameter of the droplet that results from melting the crystal). Figure 16C shows the number of activated ice nuclei, natural and from treatment, as a function of temperature. If 16C is moved to the left to where its one-per-liter line intersects the cloud water content on the dashed diagonal of 16B, the intersections of the growth-time lines with the active-nuclei lines show how long it takes for these nuclei to turn all of the cloudwater to ice crystals at any given temperature. It also shows the equivalent crystal mass by the time the water is converted to ice. The combined figure 16 (B and C) at the bottom of the page shows this superposition for a cloud of 1 g/m^3 water content (the scale on the slant lines). At -15°C , 3 minutes would be needed for very heavy AgI seeding to convert the cloud to $300\text{-}\mu\text{m}$ equivalent mass ice crystals, and 10 minutes at -20°C . With only natural IN and no multiplication, more than 30 minutes would be needed. (With ice multiplication, the cloud might be converted to ice in 10 minutes at -15°C .)

Figure 16D shows the conditions necessary for ice crystals to stick to frozen drops, after Hosler *et al.*, (1957). In rising air, where vapor pres-

sure equals or exceeds ice saturation in an all-ice cloud, the sticking force diminishes to zero by -25°C . In a water-and-ice cloud, the ice-to-ice sticking force remains large to the coldest temperature at which water drops exist. In a descending ice cloud, where the vapor pressure is less than ice-saturated, sticking does not occur until the temperature is warmer than -3°C . Some ice crystals tangle and hence do not require a sticking force for aggregation.

Ice crystals collect and are collected much more effectively than liquid cloud drops because in 1 or 2 minutes after nucleation they grow by diffusion to approximately 100 times the cross sectional area of the cloud drops they replace. From the collection efficiencies derived by Pitter and Pruppacher (1974), we compute the volume per minute swept clear of water drops of various sizes by flat plate crystals of up to $800\text{-}\mu\text{m}$ diameter. From Sasyo (1971) we extend this to 1 cm. (Note that Sasyo finds rear surface collection of $10\text{-}\mu\text{m}$ drops on large plates.) We have shown this in the upper left of figure 16F. Plate crystals collecting water drops become more dense and fall faster and thus become more effective collectors. This changes the domains in figure 16F.

Figure 16E shows what size drops overtake ice hydrometeors of various sizes and shapes. With this in mind, we draw a chart similar to figure 9B for estimating the sweep of ice by drops. The drops, of course, freeze after their first ice contact. Thereafter, they decrease in density and fall speed, but increase in cross sectional area as they accumulate ice crystals. So the zero-overtake boundaries and sweep rates of figure 16F change as precipitation develops. The sweep rates should shift to those of aggregate-collects-aggregate as shown in the upper right of figure 16F. This is adapted from Passarelli and Srivastava (1979) and is based upon equivalent melt diameters. Figure 16G repeats figure 13C for convenient reference.

Figure 16F shows some examples used to construct table 1.

Table 1

500 μm drop sweeps	10 μm drops from 8 cm^3/min 20 μm drops from 25 cm^3/min 200 μm crystals from 10 ² cm^3/min
500 μm crystal sweeps	10 μm drop from 0 cm^3/min 30 μm drops from 1 cm^3/min
30 μm drop sweeps	20 μm from <10 ⁻³ cm^3/min

To recapitulate briefly, conversion of supercooled cloud droplets to ice crystals that grow for a few minutes before they are swept up by larger collectors makes for several times more rapid production of precipitation embryos than can be achieved with cloud-droplets collectables, provided that the crystals are captured on collision. The opposite is true if collisions do not result in capture. This reversal of effect is dependent on local temperature and direction of vertical motion.

The third situation of possible advantage for AgI seeding occurs when the breakup of 5-mm drops is a disadvantage that can be prevented by freezing them. Breakup is a disadvantage when the broken-up drops are too small to descend through the updraft and are therefore carried into the upper all-frozen domain while still too small to survive the long fall to the ground. The blue line in figures 14 and 15 indicates the point at which AgI seeding establishes a domain boundary where large drops freeze before they break up and continue growing by accretion until they are large enough to reach the ground. This, of course, is a model of hail.

A fourth domain lies outside the scope of the model as thus far explained, such as updraft speeds varying with height or with time, and mixing processes occurring at cloud top. (We must defer further discussion on this subject.)

This modeling provides a basis for expecting some cloud-seeding consequences so different from those expected on the basis of the conventional hypothesis - formation of additional collectors in the portion of the cloud where supercooled cloud droplets are present - that a re-examination of past experiences is called for. Specifically, we may look for precipitation increases when seeding (by our model) tends to make the collectables more collectable and the time available is too short for seeding to add to the collector population already present naturally. We would expect this to occur, for example, in orographic seeding when the extent of natural precipitation shows that collectors are present even without seeding, and when transport from the seeding point to the mountain crest does not allow enough time for nucleation, growth, and fallout of new embryos, provided the temperature in the lower part of the ascending cloud is in the range from -5 to -25 °C. Also, we may look for precipitation decreases under conditions that would destroy supercooled droplets that would otherwise sustain the vapor pressure necessary for sticky collisions, provided the temperature is in the vicinity of -25 °C or colder.

With this in mind, we review the results of six winter cloud-seeding projects in the Western United States that involved about 1,000 cases randomly divided between seeded and nonseeded. In

an analysis of these projects, Vardiman and Moore (1978) found discrete windows where seeding was associated with increased precipitation and others where it decreased precipitation on mountain crests. Todd and Howell (1980) reanalyzed the data to see if instances of apparent increase, no effect, and decrease could be organized into a physically meaningful multidimensional continuum. The surprising outcome was that the seeding effect, whether increase or decrease, appeared to be greatest when the time of transport from seeding generators to target was too short to produce the supposed collector particles and have them take effect. Furthermore, in most cases, precipitation was observed outside as well as inside the target and upwind as well as downwind of the generators. The model proposed here, whereby seeding makes the collectables more collectable, offers at least one possible explanation of these results.

Pflaum (1980) argues that low-density collectors make effective hail embryos in that they can develop a broad sweep cross section before they finally fall through the updraft, where they fill with supercooled water and freeze into hail.

There are many possible variations in strategy for affecting precipitation development rates by creating a few more or a lot more ice crystals. We have not studied this enough yet to have an expectation as to what would be optimum strategies.

VII. HAIL SUPPRESSION

In this section we consider the hail domain and cloud depletion within the model. Particle growth in the undepleted cloud leading to hail is depicted in the COL region of figure 9 when the collector is frozen. Hail growth continues in the AGG zone when the collector surface is wet. Growth in the COL domain stops when cloudwater is depleted, which happens in the model with hygroscopic seed. We estimate that depletion in the model will be accomplished as in table 2.

Table 2

100- μm hygroscopic seeds growing by a ratio of 10 ⁵
40- μm hygroscopic seeds growing by a ratio of 10 ⁶
20- μm hygroscopic seeds growing by a ratio of 10 ⁷
10- μm hygroscopic seeds growing by a ratio of 10 ⁸

Treatments that fail to eliminate all supercooled water but increase the ice-to-water ratio in the fast-growth domain would be expected to increase the hail growth rate and size, as shown in figures 12B and 12C.

Real clouds do not have uniform, steady updrafts. In nature, much hail forms in the -20 to -30 °C regions above the updraft maximum. Nevertheless, the model may yield insights about the nature of the collectables on which hail feeds. In the model, seeding with affordable quantities of hygroscopics keeps hail embryos to the left of the red line and reduces hail when hail embryos in the natural case cross to the right of the red line. AgI seeding also keeps hail embryos in the model to the left of the red line and stops the hail when the embryos in the natural case cross to the right of the red line. To the left of the lines, hygroscopic seeding costs more than the effort is worth. This zone of impotency is large at cloud-base temperatures near 0 to 5 °C and gets smaller for warmer cloud bases. We suspect, as did Atlas

(1977), that this is why hail from warmer clouds is rare and why it is hard to stop in the colder-based clouds.

VIII. CONCLUSIONS

We have developed the concept that each cloud-seeding situation exists as a point in a single physical continuum governed by a single set of laws. A proposed simplified set of laws comprises a single general hypothesis within which the circumstances of each trial exist as a special case, so that the evidence derived from each trial contributes to testing of the general hypothesis. We found greater complexity than we had anticipated in developing a physical rationale and constructing these hypotheses even with our simple stylized cloud model. The opportunities for slowing precipitation formation and decreasing precipitation seem nearly as likely as those for increasing precipitation. We think simple operating rules can be developed that would yield mostly increases and avoid most operational risks of decrease. However, achieving maximum increases and minimizing the decreases will require close monitoring. We believe this could best be done, at least for a sampling of cases, by observing the final stages of precipitation development from an aircraft in the cloud region. From here, the observer would call for the treatment to be delivered to the cloud inflow that would most probably produce the desired changes.

The more carefully we review the rationale that we have constructed, the more we realize that it needs extensive critiquing by the scientific community, particularly from those scientists with wide in-cloud experience. Some of the basic physical relationships, specifically those that have to do with aggregation, water-to-ice, and ice-to-water capture, require further exploration. The simple models presented in this paper should be refined to produce a more consistently constructed system of expectations.

REFERENCES

- Atlas, D., 1977, "The Paradox of Hail Suppression," *Science*, vol. 195, No. 4274, pp. 139-145, January 14, 1977
- Beard, K. V., "Terminal Velocity and Shape of Cloud and Precipitation Drops Aloft," *Journal of the Atmospheric Sciences*, vol. 33, pp. 852-864, 1976
- Blanchard, D. C., and A. T. Spencer, "Experiments on the Generation of Raindrops - Size Distributions by Drop Breakup," *Journal of the Atmospheric Sciences*, vol. 27, pp. 101-108, January 1970
- Braham, R. R., "Field Experimentation in Weather Modification," *Journal of the American Statistical Association*, vol. 74, No. 365, pp. 57-104, 1979
- Brazier-Smith, P. R., S. G. Jennings, and J. Latham, "Raindrop Interactions and Rainfall Rates Within Clouds," *Quarterly Journal of the Royal Meteorological Society*, vol. 99, pp. 260-272, April 1973
- Hallgren, R. E., and C. L. Hosler, "Preliminary Results on the Aggregation of Ice Crystals," *Physics of Precipitation*, Geophysical Monograph No. 5, Am. Geophysical Union, Washington, pp. 257-263, 1960
- Hindman, E. E., and D. B. Johnson, "Numerical Simulation of Ice Particle Growth in a Cloud of Supercooled Water Drops," *Journal of the Atmospheric Sciences*, vol. 29, pp. 1313-1321, 1972
- Hosler, C. L., Capt. D. C. Jenson, USAF, and Pvt. Leon Goldshlak, USA, "On the Aggregation of Ice Crystals to Form Snow," *Journal of Meteorology*, vol. 14, pp. 415-420, 1957
- Houghton, H. G., "Problems Connected With Condensation and Precipitation Processes in the Atmosphere," *Bulletin of the American Meteorological Society*, vol. 19, pp. 152-159, 1938
- Johnson, D. B., "Hygroscopic Seeding of Convective Clouds," Illinois Institute of Natural Resource, State Water Survey Division, Meteorology Section, University of Illinois, SWS Contract Report No. 244, 1980
- Klazura, G. E., and C. J. Todd, "A Model of Hygroscopic Seeding in Cumulus Clouds," *Journal of Applied Meteorology*, vol. 17, pp. 1,758-1,768, 1978
- Klett, J. D., and M. H. Davis, "Theoretical Collision Efficiencies of Cloud Droplets at Small Reynolds Numbers," *Journal of Atmospheric Sciences*, vol. 30, pp. 107-117, 1973
- Kombayasi, M., T. Gondo, and K. Isono, "Lifetime of Water Drops Before Breaking and Size Distribution of Fragments," *Journal, Meteorological Society of Japan*, vol. 42, pp. 330-340, 1964
- Leichter, I., and A. S. Dennis, "Moisture Flux and Precipitation Studies of Convective Storms in Western South Dakota Using Pibal and Radar Data," Reprints, Conference on Cloud Physics, Tucson, Arizona, American Meteorological Society, pp. 438-441, 1974
- List, R., "General Heat and Mass Exchange of Spherical Hailstones," *Journal of the Atmospheric Sciences*, vol. 20, p. 189, 1963
- Marwitz, J. D., "Precipitation Efficiency of Thunderstorms on the High Plains," Reprints, Third Conference, Weather Modification, Rapid City, South Dakota, American Meteorological Society, pp. 245-247, 1972
- The North Dakota CLOUD MODIFICATION PROJECT - AN OPERATIONS MANUAL, North Dakota Weather Modification Board, Box 1833, Bismarck, North Dakota 58501, vol. II, pp. 37-38, February 1980
- Passarelli, R. E., and Ramesh C. Srivastava, "A New Aspect of Snowflake Aggregation Theory," *Journal of the Atmospheric Sciences*, vol. 36, pp. 484-493, 1979
- Passarelli, R. E., Jr., "An Approximate Analytical Model of the Vapor Deposition and Aggregation Growth of Snowflakes," *Journal of the Atmospheric Sciences*, vol. 35, pp. 118-124, 1978
- Pflaum, J. C., "Hail Formation via Microphysical Recycling," *Journal of the Atmospheric Sciences*, vol. 37, pp. 160-173, 1980
- Pitter, R. L., and H. R. Pruppacher, "A Numerical Investigation of Collision Efficiencies of Simple Ice Plates Colliding With Supercooled Water Drops," *Journal of the Atmospheric Sciences*, vol. 31, pp. 551-559, 1974
- Rokicki, M. L., and K. C. Young, "The Initiation of Precipitation in Updrafts," *Journal of Applied Meteorology*, vol. 17, pp. 745-754, 1978
- Ryan, B. F., E. R. Wishart, and D. E. Shaw, "The Growth Rates and Densities of Ice Crystals Between -3 °C and -21 °C," *Journal of the Atmospheric Sciences*, vol. 33, pp. 841-850, 1976

APPENDIX

Sasyo, Y., "Study of the Formation of Precipitation by the Aggregation of Snow Particles and the Accretion of Cloud Droplets on Snowflakes," Papers in Meteorology and Geophysics, American Geophysical Union, vol. 22, No. 2, pp. 69-142, July 1971

Spyers-Duran, P., "Observations of the Cloud Nucleus Concentration Around the St. Louis Urban Complex," University of Chicago Contribution, Project METROMEX-1, Technical Note 45, pp. 35-52, 1972

Todd, C. J., and W. E. Howell, "General and Special Hypotheses for Winter Orographic Cloud Seeding," Journal of Weather Modification, vol. 12, No. 1, 1980

Vardiman, L., and J. A. Moore, "Generalized Criteria for Seeding Winter Orographic Clouds," Journal Appl. Meteorology, vol. 17, pp. 1, 769-1, 777, 1978

Vonnegut, B., and C. B. Moore, "Giant Electrical Storms," Recent Advances in Atmospheric Electricity, Pergamon Press, London, New York, Paris, Los Angeles, 1959

Because the relative collectability by falling collectors of ice crystals and the droplets that these replace assumes great importance in our model, the grounds for this relationship are presented in this appendix.

The principal reference is to Ryan, et al. (1976). Their figure 6 shows that a crystal growing at -15°C for 150 s attains a mass of 230 ng, and figures 2 and 3 show this crystal to be approximately a hexagon of $160\text{ }\mu\text{m}$ arm length and an effective area of about 0.07 mm^2 . If we assume that, in growing, this crystal replaces a like mass of 13- m cloud droplets each having a cross-sectional area of $3.3 \times 10^{-5}\text{ mm}^2$, we find that it consumes 200 droplets having a combined area of $6.6 \times 10^{-3}\text{ mm}^2$. In other words, the geometrical projected area of the crystal, presuming it is falling in its normal habit with its surface horizontal, presents a geometric cross section roughly 10 times greater than that of the droplets it replaced. Since we have assumed a 10 cloud droplet on the small side of what one would expect in a cloud progressing toward the precipitation stage, this 10x estimate is on the conservative side.

Also to be reckoned with is the difference in collection efficiencies involved. The collector may be an ice crystal, a rimed snow pellet, or a spherical particle of ice. (The case of a water droplet is trivial because, in the supercooled regime, it would freeze after the first encounter with an ice particle.) If the collector is an ice crystal, then according to Pitter and Pruppacher (1974), the collection efficiency for any cloud droplet up to more than $100\text{ }\mu\text{m}$ is zero. For collection of crystals by crystals, Passarelli (1978)* gives a collection efficiency of 1.4 ± 0.6 . A lower collection efficiency, of the order of 0.1, is given by Hallgren and Hosler (1960)**.

* Passarelli, R. E., Jr., "An Approximate Analytical Model of the Vapor Deposition and Aggregation Growth of Snowflakes," Journal of Atmospheric Physics, vol. 35, pp. 118-124, 1978

** Hallgren, R. E., and C. L. Hosler, "Preliminary Results on the Aggregation of Ice Crystals," Physics of Precipitation, Geophysical Monograph No. 5, Am. Geophys. Union, Washington, pp. 257-263, 1960