A Model of Hygroscopic Seeding in Cumulus Clouds

GERARD E. KLAZURA AND CLEMENT J. TODD

Bureau of Reclamation, Denver, CO 80225

(Manuscript received 15 August 1977, in final form 31 July 1978)

ABSTRACT

A systematic modeling exploration has been conducted to map the growth and trajectory of hygroscopically initiated precipitation particles. The model used is a one-dimensional, steady-state, condensation-coalescence model with adiabatic cloud water content. Drop breakup and freezing were simulated but competition among precipitation particles was not considered. Sizes of initial hygroscopic seeds varied from 5 to 400 μm in diameter, updraft speed ranged from 1 to 25 m s^{-1}, and cloud base temperature varied from 0 to 20°C. The 23 July 1970 salt seeding case reported by Biswas and Dennis was also analyzed using the model.

The numerical simulations reveal several complex interactions: 1) For slow updrafts, the larger hygroscopic seeds travel through a lower trajectory and sweep out less water than small, hygroscopic seeds which are also more apt to grow large enough to break up and create additional large precipitation particles. 2) For fast updrafts, the larger hygroscopic seeds grow into precipitation and stand a better chance of breaking up and initiating a Langmuir chain reaction, while the small hygroscopic particles are carried up to the cirrus level and are lost before they reach precipitation size. 3) For very strong updrafts only large hygroscopic seeds will have a chance to convert to precipitation, and in this situation hail is produced. 4) Hygroscopic seeding produces a greater water yield from warmer based clouds.

1. Introduction

Because there are many interacting factors which determine the characteristics of a cloud and how it produces precipitation, generalizations must be made carefully. The purpose of this study has been to produce a generalization which necessarily is based upon a simplified set of assumptions. Any less restrictive set of assumptions would have caused the computational requirements to increase dramatically and increase the complexity of the interpretation. The factors chosen for this study are well suited for computer rather than intuitive exploration in that they require a large number of integration steps. However, the interpretation of the output was designed to be adjusted by conceptual reasoning for making judgments about precipitation processes and management of precipitation in real clouds.

Observation of the growth of a single hydrometeor under the influence of different cloud characteristics can lead to a good first estimate from which some general conclusions can be drawn. This observation has been simulated through the use of a simple cloud precipitation model which has in turn been used to explore the opportunity for producing artificially initiated precipitation (using hygroscopic seeding material) when the natural mechanisms are too slow to be effective.

Similar modeling investigations have been carried out by Takeuchi (1975) and Rokicki and Young (1978) using one-dimensional, steady-state, parcel microphysical models. Results of the present investigation will be compared with findings of these two works.

2. Single hydrometeor condensation-coalescence model

This study uses a one-dimensional condensation-coalescence model that follows the growth of a single precipitation particle in a specified cloud environment. It is a steady-state version of the feeder cloud model described by Musil (1970). Both the dry and wet hail growth equations were utilized as applicable [see Eqs. (A6) and (A10), Musil (1970)]. A condensation subroutine was added to the model [see Eq. (1), Chien and Mack (1966)]. The details of the model including derivations of growth equations and references and equations used for such items as terminal velocities of precipitation particles, collection efficiencies, ventilation coefficients, air viscosity, diffusivity and conductivity are discussed by Musil (1970).

The processes simulated are as follows: non-competing hygroscopic particles are released in the updraft region beneath the cloud and grow by condensation until they penetrate the cloud base. Then both condensation and coalescence occur until the particle has grown to a 100 μm diameter,[1] at which point growth

[1] Unless otherwise noted, all sizes refer to diameter.

proceeds by coalescence alone. A drop-freezing temperature of $-15°C$ was selected. When a drop warmer than $-15°C$ grows to 5 mm, it breaks up into a 2.5 mm drop and many other fragments. Growth then continues on the 2.5 mm drop but not on the fragments. Computations for a given trajectory are terminated under the following circumstances: 1) when the particle travels to within 0.2 km of the top of the cloud (assumed to be 16 km), 2) when the particle falls below cloud base (if liquid particle), 3) when the particle falls below melting level (if ice particle) or 4) if the particle remains in-cloud for 40 min.

Inputs to the model are cloud-base height, relative humidity, liquid water content and updraft profiles; sounding (height, pressure, mixing ratio and temperature); and initial sizes and physical characteristics (molecular weight, density and van't Hoff factor) of the particles.

The model output produces both trajectories and growth patterns for particles of various initial sizes. An example of the output of the model is illustrated in Fig. 1. The cloud conditions in this example range from what would be expected in a warm, moist air mass (Figs. 1a–1f) to a much colder, drier air mass (Figs. 1i and 1j). These graphs show the growth pattern and trajectory (height vs time) of particles with different initial sizes. In addition to the height and time axis, one other ordinate is illustrated. It is used in conjunction with the height axis to show the liquid water content profile. The trajectory curves are constructed of dotted, dashed or solid lines depending on what size category the particle is in. The curve labeled UP represents the trajectory of a parcel that would ascend exactly at the speed of the updraft.

3. Design of modeling experiment

Multiple computer runs were made for cloud conditions characteristic of temperate and warm regions. Moist adiabatic conditions were assumed in-cloud and adiabatic values of liquid water content were used. The relative humidity was 100% at cloud base with a supersaturation of 0.1% existing at 100 m above cloud base all the way to cloud top. Relative humidities below cloud base were computed using a dry adiabatic temperature lapse rate with a constant mixing ratio. For simplicity, constant updrafts ranging from 1 to 25 m s^{-1} were used. Initial hygroscopic particle sizes ranging from 5 to 400 μm were introduced at 0.5 km for cloud bases of 1, 2 and 3 km and in-cloud saturation adiabats (θ_m) of 16 and 23.2°C.

Some of the input data may not reflect accurate cloud conditions. The assumptions of steady updraft, adiabatic values of total liquid water content and non-competing precipitation particles can be validly questioned. Their use is justified by the nature of the twofold objective of the investigation. The first goal was to paint a broad picture of the effects of hygroscopic seeding under different cloud conditions and to form some general conclusions from it. Second, it was desired to illustrate how such a simple model can be used to gain a better understanding of complex precipitation processes, and how it might also be used on a real-time basis as a tool in decision making.

In addition there is no universal agreement on some of these matters. For instance, some investigations have shown that liquid water contents in cumulus clouds are generally less than moist adiabatic (e.g., Warner, 1955; Draginis, 1958; Hirsch and Schock, 1968), whereas others have found moist adiabatic cores to exist in cumulus congestus clouds (e.g., Heymsfield *et al.*, 1978; Ackerman, 1974). Twomey (1976) and Rokicki and Young (1978) conclude that it is the rare pockets (1% of total cloud volume or less) of adiabatic or near-adiabatic liquid water content which dominate the formation of large drops. Based on his model runs, Nelson (1971) has found that high local liquid water contents, even if maintained for only 1–2 min, completely dominate the coalescence history of the rest of the cloud.

Competition between hygroscopic seeding particles and natural condensation nuclei should be minimal due to the relatively low density of seeding particulates which are anticipated to be required (on the order of 1 ℓ^{-1}). Biswas and Dennis (1972) theorize that the raindrop size distribution below a seeded cloud does not differ greatly from that in rain below an unseeded cloud. The drop distribution evolves during fall, with some drop collisions leading to coalescence and others leading to drop breakup (e.g., Spengler, 1972). These drop impactions reveal a self-regulating mechanism in nature that enables collisions to influence both the initial growth and the determination of final size for large drops. This mechanism may preclude any significant competition between hygroscopically induced drops. Rokicki and Young (1978) conclude that unlike silver iodide seeding, there is no danger of overseeding using hygroscopic seeds.

4. Results

a. Case studies

Referring back to Fig. 1, it can be seen that initially the hygroscopically initiated hydrometeors rise at almost the same velocity as the updraft, but fall rapidly as they grow to larger sizes. The particles in Fig. 1a (1 m s^{-1} updraft) rise only 0.5–1.0 km into the cloud and fall out the base 21–28 min later as 0.6 to 1.5 mm diameter drops. It is interesting to note that the smallest particles (5 μm initially), which rose highest and spent the most time in cloud, appeared at cloud base as the largest drops.

The same pattern is apparent in Fig. 1b (2 m s^{-1} updraft), except here the in-cloud time of the particles is decreased by about 4 min and the drops are larger (2–4 mm diameter). In this case, the hydrometeors

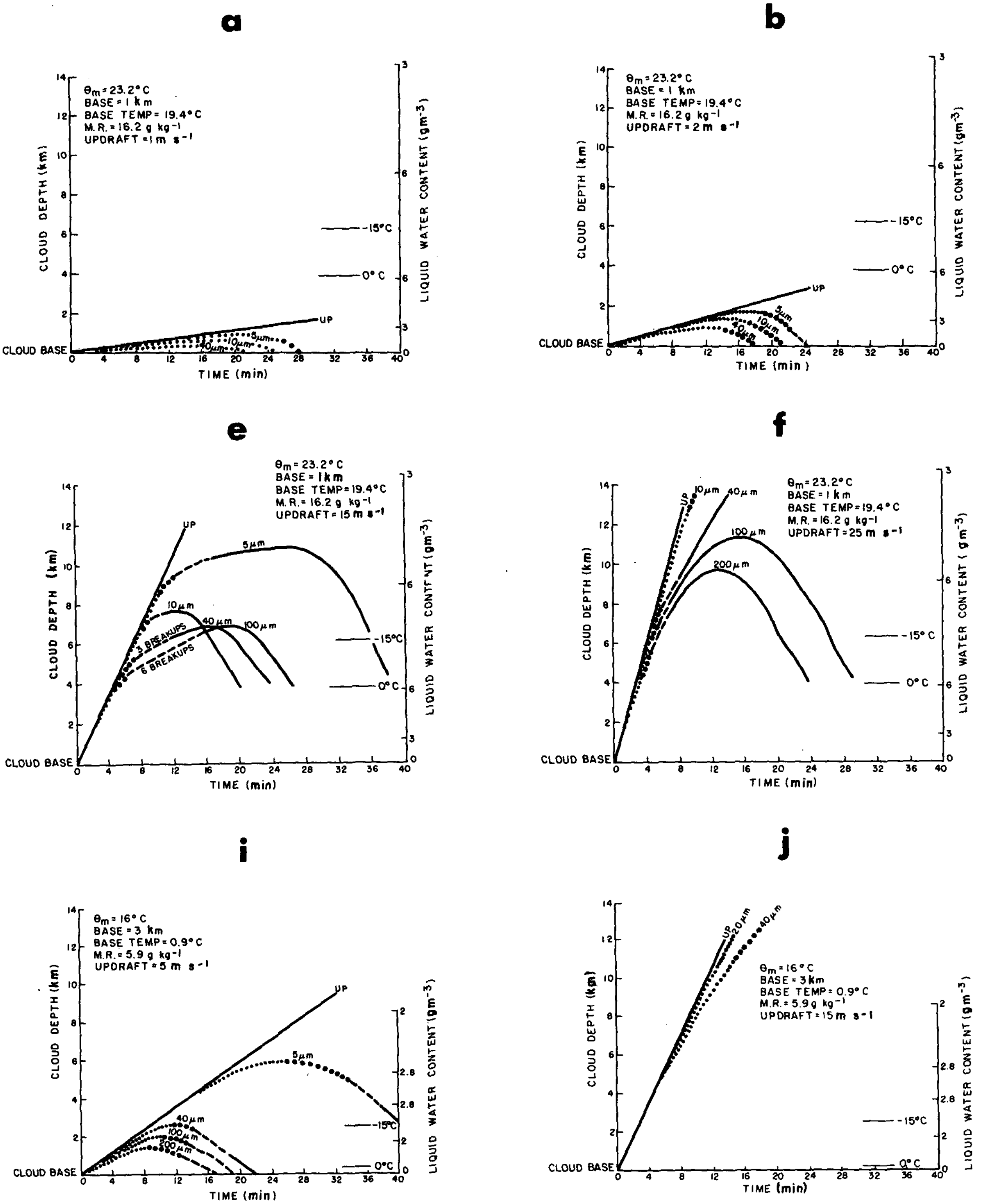

Fig. 1. Condensation-coalescence model computations of the growth pattern and trajectory of various sized hygroscopic particles released beneath the base of clouds having different physical characteristics (updraft speeds, liquid water content profiles, etc.). See text for discussion.

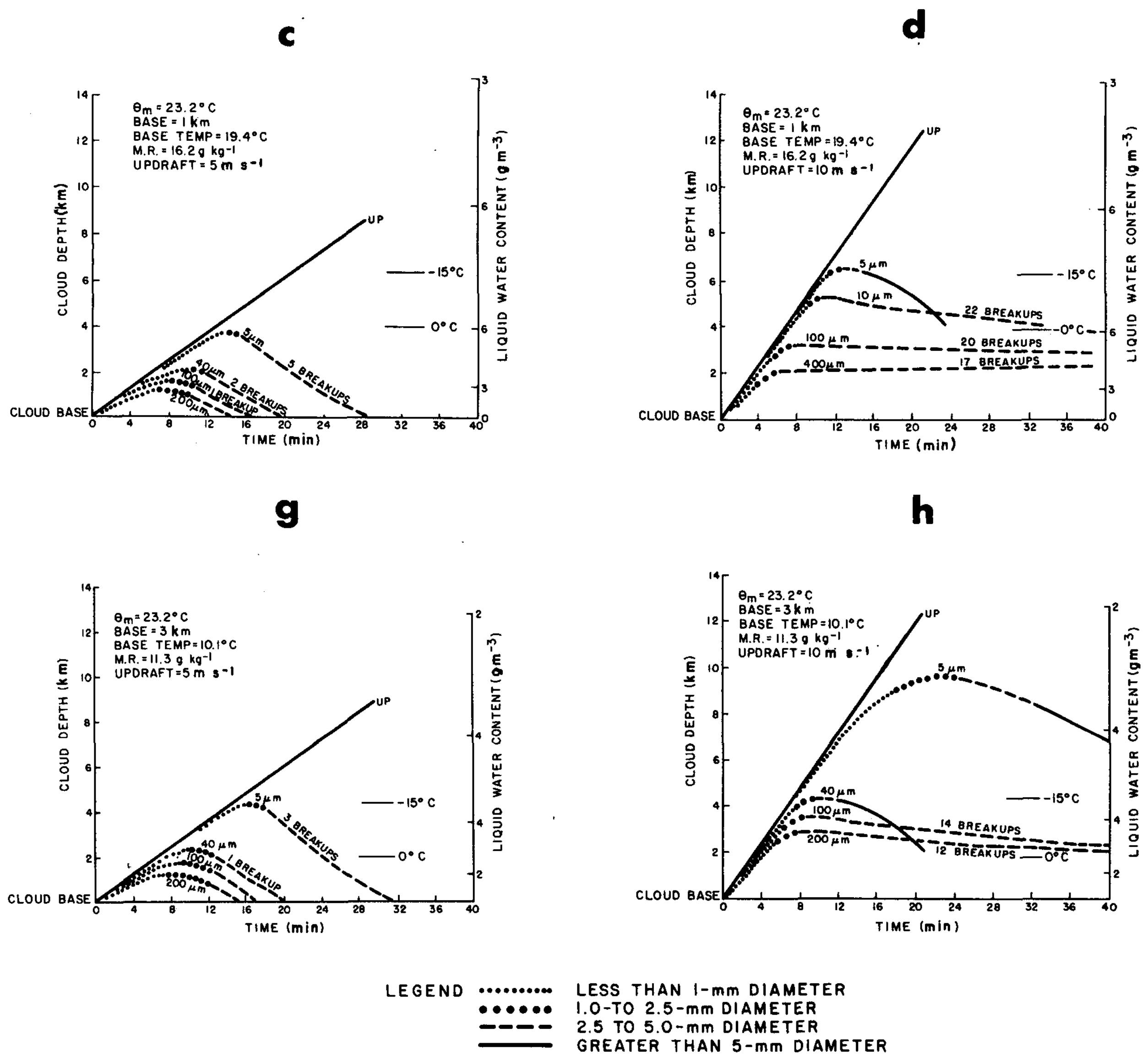

FIG. 1. *Continued*

are carried about 500 m higher into the cloud and thus coalesce faster due to the higher liquid water contents encountered.

Figs. 1c and 1d illustrate a phenomenon that is believed to contribute to the success of warm cloud seeding. Here the updrafts (5 and 10 m s^{-1}) are sufficiently strong to support raindrops big enough to undergo breakup and set off a Langmuir (1948) chain reaction. When the drop attains the size of a raindrop of approximately 5 mm, it breaks up into numerous smaller drops. Many of these smaller drops would then be carried by vertical air motions higher up into the cloud, where they again would grow large enough to break up, etc. In Fig. 1c the 5–40 μm seeds are able to fall through the updraft as they break up, finally reaching the cloud base 19–28 min later as 2.5–5 mm drops. However, for hygroscopic seeds larger than 100 μm the breakup mechanism does not occur since the drops reach cloud base prior to growing to 5 mm. In the 10 m s^{-1} updraft case (Fig. 1d), a large-drop accumulation zone is observed to form 2–5 km above cloud base for 10–400 μm hygroscopic seeds. However, the 5 μm particle would rise high enough in the cloud to freeze prior to reaching 5 mm size, and therefore no breakup would occur from it. The large drops in this accumulation zone would be expected to fall through to the cloud base as they migrate outward toward the periphery of the updraft core (List and Lozowski, 1968), and/or when the updrafts become less vigorous in the later stages of cloud life.

All the particles in Fig. 1e (15 m s^{-1}) are carried

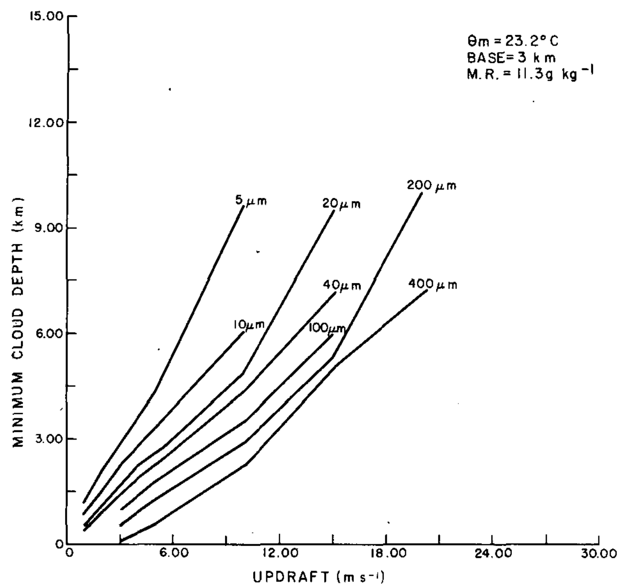

FIG. 2. Variation of the minimum cloud depth required for a particle to grow large enough to begin to fall through the cloud as a function of updraft speed for initial hygroscopic drop diameters of 5–400 μm (model computations).

high enough to freeze and subsequently grow large enough to fall through the updraft and emerge at the melting level as 1–3 cm hailstones. However, many more precipitation particles would be produced by the 40 and 100 μm seeds, which would undergo drop breakup three and six times, respectively, prior to freezing.

Fig. 1f illustrates the very strong updraft case (25 m s^{-1}). As would be expected, the smaller seeds are all ejected out the top of the cloud, whereas the 100 and 200 μm seeds grow large enough to fall back through the updraft as hail.

The same general pattern is apparent for higher based clouds such as are found in the Great Plains regions. However, since these clouds have lower liquid water contents, the particles take a higher trajectory above cloud base to grow large enough to fall out, and therefore require a greater cloud depth. Fig. 1g illustrates this point well. The same in-cloud moist adiabatic temperature was used as in the preceding example, but a higher cloud base (3 km) was assumed. Comparing this graph with Fig. 1c (both are for 5 m s^{-1} updrafts), it can be seen that the particles travel 200–700 m higher above cloud base in the high-base situation.

Quite a dramatic change is apparent in the high-base situation compared to the low when updraft speeds are 10 m s^{-1} and greater. Since the hydrometeors travel into colder regions sooner in the high-base clouds, they become ice particles earlier in the growth stage. A large-drop accumulation zone was shown to occur in Fig. 1d for all but the 5 μm hygroscopic seed. However, in the high cloud-base situation (as illustrated in Fig. 1h), all seeds of initial size of 40 μm or smaller freeze prior to reaching water breakup size. In this case all seeds larger than 100 μm initial size would grow large enough to break up and float near a balance level. These characteristics are further accentuated in the colder cloud cases. Figs. 1i and 1j illustrate computer runs for an in-cloud moist adiabatic temperature of 16°C, a 3 km cloud base, and updraft speeds of 5 and 15 m s^{-1}, respectively. Notice the much lower liquid water content values and lower temperatures, which account for the absence of a drop breakup zone in Fig. 1i. It also accounts for all the seeds 5–40 μm being blown out the top of the cloud with a 15 m s^{-1} updraft (see Fig. 1j). For the same updraft speed but more moist cloud conditions these same size particles grew large enough to fall back to cloudbase (see Fig. 1e).

b. Syntheses of case studies

A large number of graphs were generated by the computer model for various initial conditions. Certain patterns are apparent from which specific conclusions can be drawn:

1) For a given updraft speed, the smaller initial-size hygroscopic particles require a greater cloud depth to grow large enough to start falling through the cloud. Fig. 2 illustrates this fact well. For instance, about 2 km more cloud depth is required at 5 m s^{-1} updraft for a 5 μm seed compared with a 40 μm one. Notice also that the smaller seeds pass through the top of the cloud much more readily. At 15 m s^{-1} updraft speed, a 5 μm seed passes through the top (16 km summit), whereas a 40 μm seed would start falling through the cloud at 7 km above cloud base.

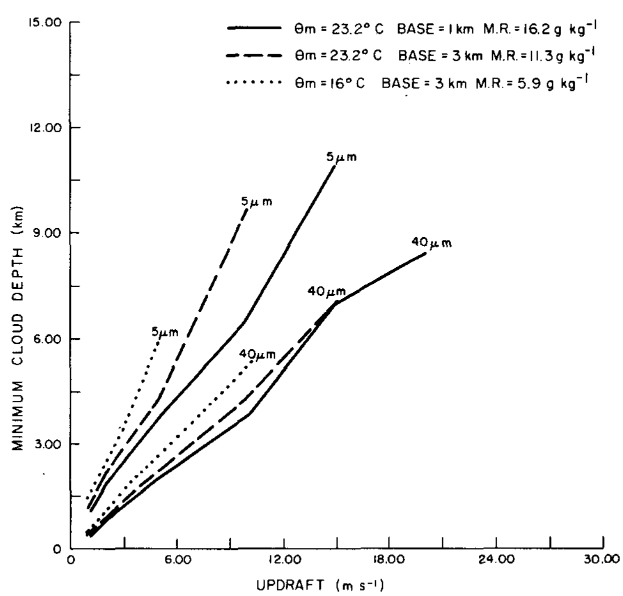

FIG. 3. As in Fig. 2 except for drop diameters of 5 and 40 μm and for cloud conditions ranging from cold and relatively dry to warm and moist (model computations).

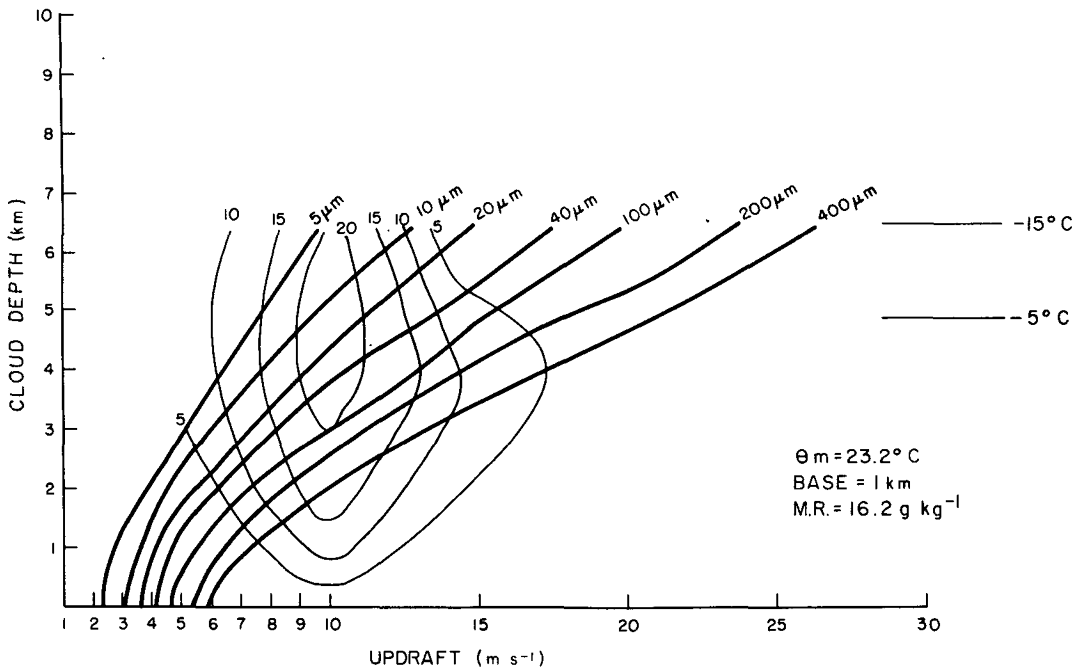

FIG. 4. Variation of the cloud depth at which hygroscopic drops (5–400 μm initial size) would first break up as a function of updraft speed for a warm, moist cloud. Total number of breakups (40 min limit) are overlaid on these curves (model computations).

2) For higher and colder cloud bases a greater cloud depth is also required for particles to grow large enough to begin to fall. Higher and colder based clouds contain less liquid water for a given volume of cloud air. Consequently, the production of large drops by the coalescence process takes longer. A 5 μm hygroscopic seed injected into a 3 km cloud base (moist adiabat of 23.2°C) for a 10 m s^{-1} updraft would require 3 km more cloud depth to grow large enough to begin to fall through the cloud than a similar size seed injected into a 1 km cloud base at the same moist adiabatic temperature (see Fig. 3). And a 5 μm seed injected into a 3 km cloud base (moist adiabat of 16°C) at the same updraft speed never would grow large enough to fall through the cloud.

3) For a given updraft speed, larger hygroscopic seeds will result in drop breakup lower in the cloud.

4) Stronger updraft clouds require larger hygroscopic seeds to produce drop breakup. Figs. 4 and 5 show the height at which the first drop breakup would occur with respect to updraft speed for the various initial-size seeds and for two different cloud base temperatures. The number of breakups that occur (40 min limit) are overlaid on these curves. Breakup occurs before the particle reaches its peak height in the cloud for updraft speeds greater than 10 m s^{-1} and after for updraft speeds less than 10 m s^{-1}. In the warmer cloud base situation (Fig. 4), for an updraft speed of 10 m s^{-1}, a 100 μm seed will grow large enough to break up about 2.2 km lower in the cloud than where a 10 μm seed would break up. At 20 m s^{-1} only hygroscopic seeds larger than 100 μm would have a chance to break up before they reached the level where they glaciated.

5) For weaker updrafts, drop breakup occurs only on the smaller seeds. Since the smaller seed travels higher up into the cloud it can grow large enough to break up before it falls out the base of the cloud.

6) The vertical depth of the drop breakup region decreases as the cloud-base temperature decreases. Smaller cloud-water contents and decreased vertical distance to drop freezing occur as the cloud-base temperatures become lower. The slower coalescence growth and earlier particle freezing combine to shrink the drop breakup zone. This also tends to shift upward the smallest size seed that can initiate breakup. Fig. 5 illustrates this shrinking effect for higher (and thus colder) based clouds.

7) Hygroscopic seeding produces the greatest water yield from clouds with the warmest bases. Fig. 6 shows the maximum sizes attained by a 5 μm hygroscopic seed in a warm (base = 1 km, θ_m = 23.2°C) and cold (base = 2 km, θ_m = 16°C) cloud. Not only do the precipitation particles grow larger in the warmer clouds at higher updraft speeds, but also a broad drop breakup region is present (note flattening of curve at 5 mm) indicating the production of many more drops. This trend is shown more clearly in Figs. 4 and 5. Drop breakups are far more numerous and occur over a much broader span of updraft speeds in the warmer cloud situation.

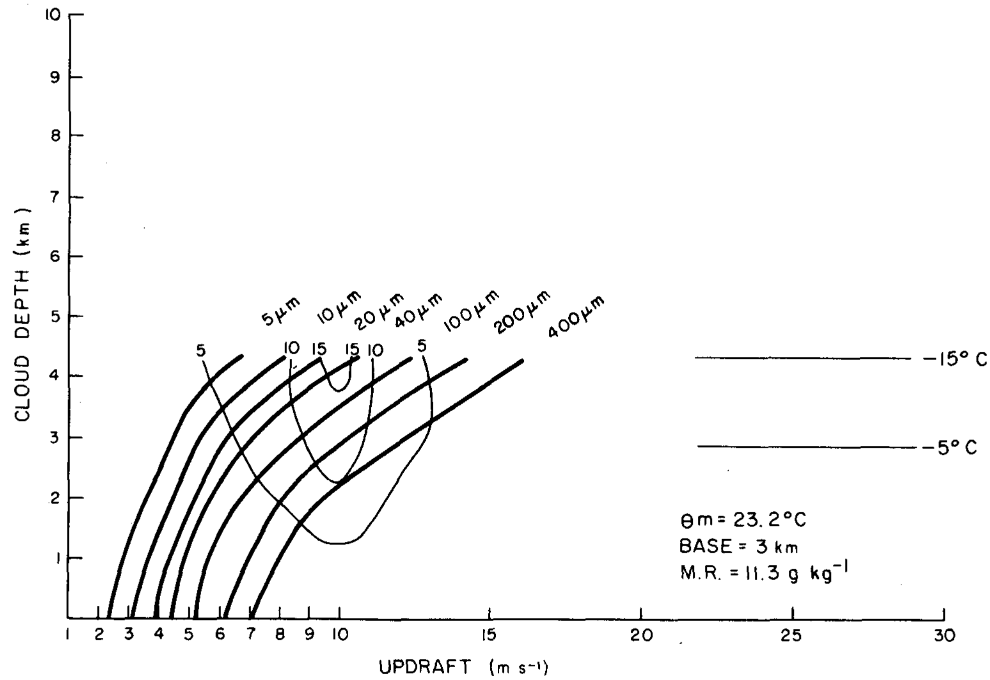

FIG. 5. As in Fig. 4 except for cooler, drier cloud.

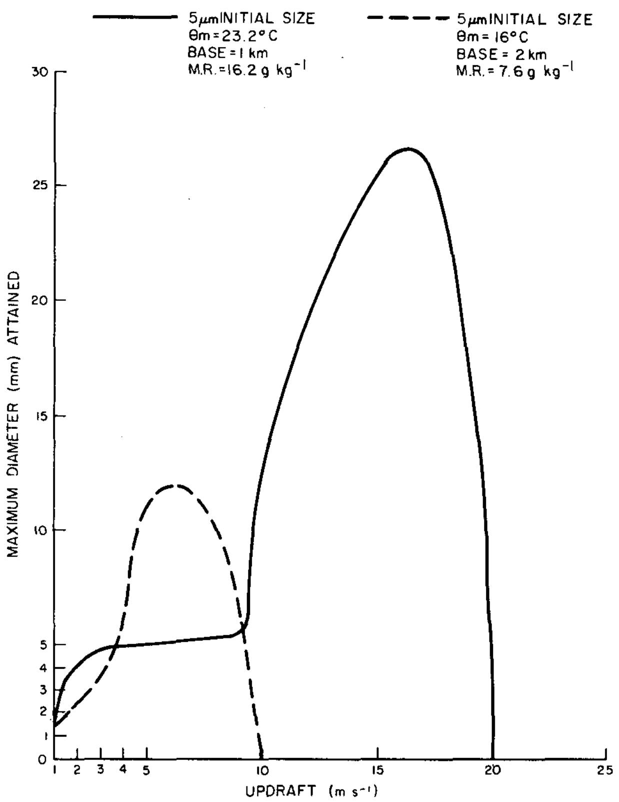

FIG. 6. Variation of the maximum drop size attained as a function of updraft speed for initial hygroscopic drop diameter of 5 μm for moist and relatively dry cloud conditions (model computation).

5. Comparative analyses

a. Comparison with natural embryos and AgI nuclei

Prior to seeding, a determination has to be made of the suitability of a particular day for hygroscopic seeding. Even if a given day is considered suitable, it may well be that only clouds that have specific physical characteristics are deemed seedable. Such parameters as cloud-base height and temperature, cloud thickness and diameter, updraft and cloud-water profiles, and cloud droplet spectra all play a very important role in determining the efficiency with which hygroscopic seeds will act to stimulate additional precipitation from a cloud.

It is a very difficult task to determine just how much help a particular seeding effort may have contributed to the total precipitation from a cloud system. There are still many uncertainties to be resolved before this problem is solved. For instance the stochastic theory for the production of large droplets (>100 μm) does not always adequately explain the formation of these droplets in the times observed. In-cloud measurements have shown particles of this general size to already exist at cloud base in concentrations of 0.5 to 1.0 ℓ^{-1} in Texas, Arizona and South Dakota (Takeuchi, 1972). Others have also found evidence of the existence of large cloud droplets (40–100 μm) near the bases of cumulus clouds (e.g., Ludlam, 1959; MacCready and Takeuchi, 1968; Kopcewicz, 1965; Rosinski and Kerrigan, 1969). Accordingly, it might be more appropriate in the present

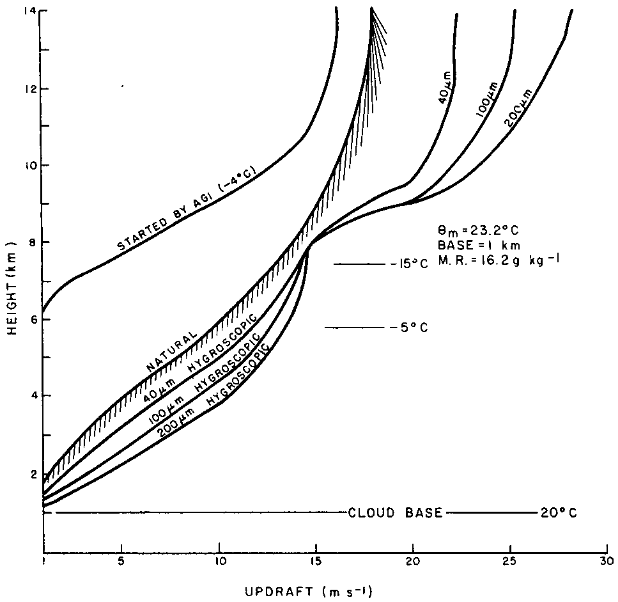

FIG. 7. Variation of the minimum cloud depth required for a particle to grow large enough to begin to fall through the cloud as a function of updraft speed for initial hygroscopic drop diameters of 40 to 200 μm, naturally formed hydrometeors, and ice particles formed through the nucleation of AgI nuclei in a warm, moist cloud (model computations).

discussion to consider the onset of natural precipitation to evolve from particles that can be approximated by 10–20 μm hygroscopic seeds released beneath cloud base (they grow to about 50–70 μm by the time they reach cloud-base region).

With this concept in mind we can investigate the height at which precipitation particles become large enough so they are just balanced by the updraft for various hygroscopic seeds, for large drops evolved from continental clouds, and for ice particles grown following the nucleation of AgI nuclei.

Calculations used for growth of ice particles from nucleation of AgI are described by Smith *et al.* (1974). Time and height at which precipitation particles form may be critical factors to the efficiency with which a cloud precipitates. The smaller the cloud depth required for the precipitation particle to begin to fall through the updraft, the less time it takes for rain to begin and the better the chances for the Langmuir chain reaction mechanism to occur.

We consider a warm, humid air mass with clouds containing (naturally) 50–100 μm size particles in the base. One might expect hygroscopic seeding to be more effective in producing colloidal instability earlier and lower in the cloud than either natural cloud processes or through ice-phase (AgI) seeding. Fig. 7 verifies this conceptual "feeling."

The height at which a precipitation particle becomes large enough so it is just balanced by the updraft is given for hygroscopic seeds (40, 100 and 200 μm initially), for large drops evolved naturally from a continental cloud, and for ice particles grown from AgI nuclei. Notice how much lower in the cloud the large drop is formed in the hygroscopically seeded case. A similar graph is illustrated in Fig. 8, except the cloud conditions here are much drier and colder. Nucleated AgI particles require less cloud depth than the natural process for updraft speeds greater than 2 m s^{-1}, and only slightly greater depth than 40 μm hygroscopic seeds for updrafts between 3 and 12 m s^{-1}. Thus, as would be expected, as the cloud base gets colder, the ice-phase mechanism for initiating colloidal instability becomes more efficient.

The variations in growth rate for the three categories just discussed have been observed to occur in real clouds. Dennis and Koscielski (1972) have analyzed first radar echoes in salt seeded, AgI seeded and unseeded clouds in South Dakota, and found quite a variance in the height above cloud base of the first echo between the three categories. The median height above cloud base was 3353 m for unseeded clouds, 2103 m for AgI seeded clouds and 1615 m for salt seeded clouds.

b. *A cloud seeding case study*

A case of rain apparently being produced as a result of hygroscopic seeding occurred on 23 July 1970, near Rapid City, South Dakota (Biswas and Dennis, 1971). The cloud system that produced the spectacular results was observed visually, photographed and scanned by radar (with signals digitally recorded) before, during and after the rainshower. A best estimate of the internal cloud profiles was predicted by

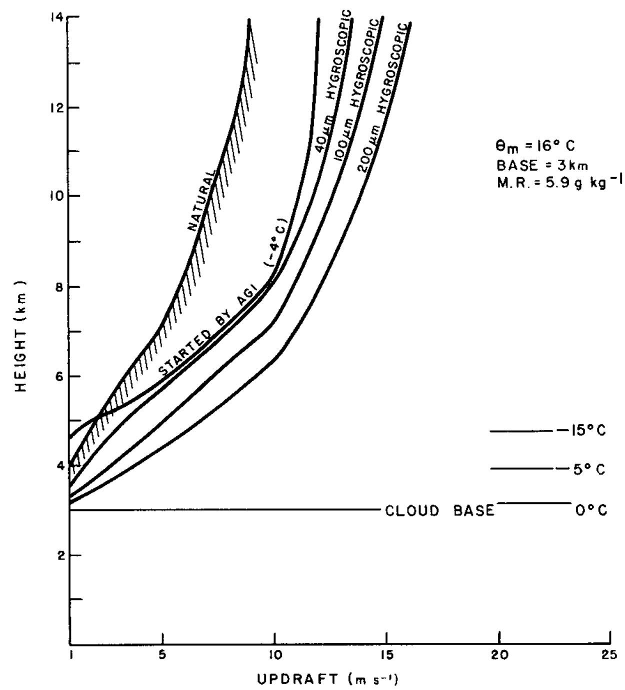

FIG. 8. As in Fig. 7 except for colder, drier cloud.

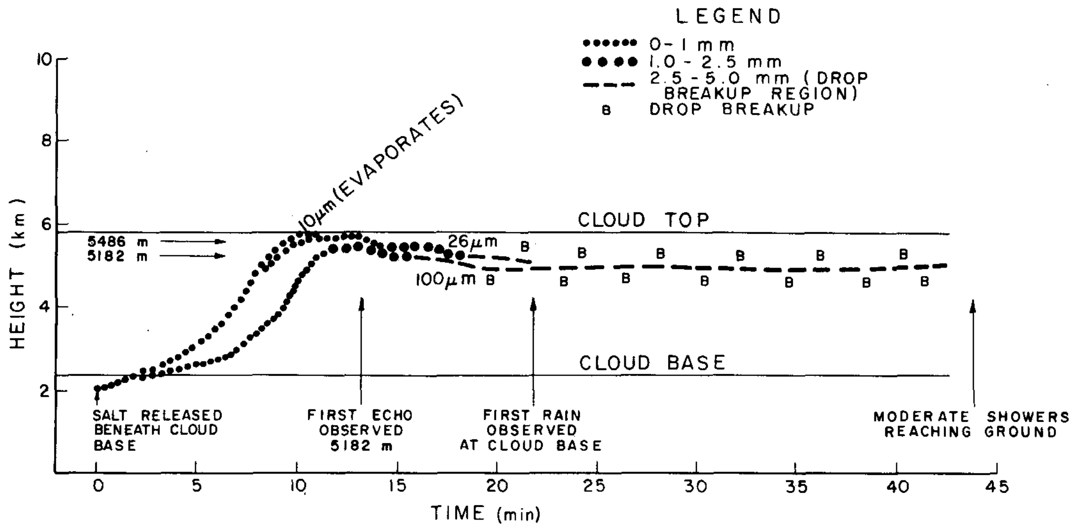

FIG. 9. Condensation-coalescence model computations of the growth pattern and trajectory of three different sized salt particles released beneath the base of a cloud whose physical characteristics are believed to be similar to a real cloud system that was stimulated to rain through salt seeding. See text for discussion.

the Hirsch (1971) convective cloud model (Biswas and Dennis, 1972). These internal profiles (liquid water content, updraft, etc.) were then used as input data to the condensation-coalescence, single particle model. Salt seeding was simulated on this predicted steady-state cloud. Rather than assume the particle to be ejected when it reached within a certain distance from cloud top, condensation or evaporation was allowed to act throughout the process. The results are shown in Fig. 9.

Following the reasoning set forth in the last section, it is assumed that the 10 μm hygroscopic seed represents the natural state of existence of large cloud droplets (i.e., ~50 μm) near cloud base. Notice that this size particle travels right to the top of the cloud where it evaporates. This is consistent with the fact that none of the unseeded portion of the cloud system ever precipitated. The larger hygroscopic seeds (26 and 100 μm shown) were predicted to grow to 1 mm size around 5334 m about 11–15 min after release beneath the cloud. The first radar echo was observed at 5182 m 13 min after seeding began. The larger particles continued to grow and reached a balance level around the 5 km level (4953 m). Drop breakup began about 19–21 min after seeding began, and due to the steady-state nature of the simulated cloud, continued on indefinitely. The first rain was observed at cloud base by the seeding aircraft's observer 22 min following the start of seeding.

Up to the point where the first echo was observed there is good agreement between the model results and actual cloud observations. However, since no drop competition or negative buoyancy and divergence effects due to waterloading are accounted for, the interpretation of results gets more qualitative concerning a drop breakup situation. The formation of a drop breakup or waterloading zone as predicted by the model seems to indicate that a rainshower would be expected from the real cloud. The model does not predict the amount of precipitation to occur from seeding, but it can give a good indication of whether or not initiation or enhancement of precipitation would be expected.

6. Comparison with similar studies

In the Introduction it was mentioned that Takeuchi (1975) and Rokicki and Young (1978) carried out similar modeling investigations using one-dimensional, steady-state, parcel microphysical models. Takeuchi's model computes the growth of an array of particles in an ascending parcel. It computes the growth of 26 categories of precipitation particles (13 liquid and 13 crystal) using continuous coalescence equations as were used in the present study. Particles are removed by sedimentation, but are not considered in subsequent parcels which may be rising in the cloud. Collection processes in the model used by Rokicki and Young are treated quasi-stochastically and sedimentation is not computed. As would be expected some of the results of the present investigation can be compared with related ones from these two studies.

All three studies agree that seeding with large drops (or hygroscopic seeds which grow to large drops at cloud base) produces precipitation more efficiently than AgI in all cases with cloud base temperatures >10°C. Furthermore, the present study and that of Rokicki and Young found this to be true for cloud-base temperatures >0°C. The reason why Takeuchi found AgI seeding to be effective at the warmer cloud-base temperatures may be due to his assumption that the effect AgI seeding had was to freeze the large particles (40–80 μm) that occurred naturally at cloud base when they reached the $-5°C$ level. In the present study the nucleation of AgI particles was assumed, which would lead to a longer growth period to precipitation sizes. The reason why Rokicki and Young found hygroscopic seeding to be more effective at the lower cloud-base temperatures (0–10°C) may be due to their stochastic growth assumption which allows for the interaction with other large drops, whereas in the AgI seeded situation many of the interactions would be between crystals. Rokicki and Young also point out that the exclusion of sedimentation in a parcel model results in overestimates of the response to large drop seeding.

It was found that for faster updrafts the larger hygroscopic seeds grow into precipitation and stand a better chance of breaking up, while the small seeds are carried to cirrus level and are lost before they reach precipitation size. The requirement for larger seeds becomes more critical as cloud bases become higher and colder. Takeuchi found that the effectiveness of hygroscopic treatments can be improved with higher concentrations of larger hygroscopic particles for stronger updrafts. Rokicki and Young found that increasing the seed drop size hastens precipitation formation significantly.

Hygroscopic seeding produces the greatest water yield from clouds with warmest base temperatures (and consequently highest liquid water concentrations). Related to this is the fact that the vertical depth of the Langmuir drop breakup region increases as the cloud-base temperature increases. Takeuchi found that initiation occurs earlier in clouds with a given top temperature and increasing base temperature. He also concluded that in warmer base cloud cases with updrafts of 10–15 m s^{-1} the chain reaction of drop breakup occurs which results in complete conversion of available moisture. Rokicki and Young also found that hygroscopic seeding produced its largest effect in warm based clouds.

Updraft speeds of 5–15 m s^{-1} are the optimum for the Langmuir chain reaction to occur which then should lead to the most rapid conversion of cloud water to precipitation. Takeuchi found the optimum updraft speed range for hygroscopic seeding to be 10–15 m s^{-1}.

For clouds with strong updrafts ($\gtrsim$15 m s^{-1}) only large hygroscopic seeds will have a chance to convert to precipitation, and in this situation hail is produced. Takeuchi's model computed appreciable fallout due to hygroscopic seeding for deeper and warmer clouds for updrafts 15–20 m s^{-1}. In these cases the particles falling were hail. He concluded that hygroscopic seeding would work well in deeper clouds with moderate liquid water concentrations and strong updrafts but that hail would result.

7. Remarks

The results of this study and those of Takeuchi (1975) and Rokicki and Young (1978) suggest that the potential for hygroscopic seeding as an effective technique of enhancing precipitation from convective clouds is very high. Hygroscopic seeds can be very effective in producing precipitation by an all-water process, but they can also be effective through the ice mechanism as well since large water drops freeze at warmer temperatures than small ones. Rokicki and Young (1978), in fact, come out strongly in favor of hygroscopic over AgI seeding. They conclude that its effect is generally greater than that of AgI, the physical processes involved are fairly well understood, and more reliable systems for dispensing hygroscopic material are now becoming available.

There are many processes that have not been simulated in this model but will have to be considered before a complete understanding of precipitation physics is possible. Such factors as the interaction between large drops and the dynamic effects due to large drop accumulation zones have to be studied and understood before an accurate model will evolve. In the meantime, simple models such as those discussed here can serve as one of the tools with which to reduce some of the major uncertainties connected with precipitation formation. One should, however, be cautious in the use of such models and not extract information that they were not designed to provide.

Acknowledgments. The authors are grateful to Mr. Dennis Musil, South Dakota School of Mines and Technology, and Dr. C. W. Chien, Meteorology Research, Inc., for providing us with their accretion and condensation computer programs, respectively.

REFERENCES

Ackerman, B., 1974: Illinois precipitation enhancement program phase I. Interim Report, Bureau of Reclamation Contract 14-06-D-7197, Illinois State Water Survey, Urbana, 14 pp.

Biswas, K. R., and A. S. Dennis, 1971: Formation of a rain shower by salt seeding. *J. Appl. Meteor.*, **10**, 780–784.

——, and ——, 1972: Calculations related to formation of a rain shower by salt seeding. *J. Appl. Meteor.*, **11**, 755–760.

Chien, C. W., and D. P. Mack, 1966: Computation of droplet growth from giant salt particles in ascending air below cloud base. *J. Atmos. Sci.*, **23**, 810–812.

Dennis, A. S., and A. Koscielski, 1972: Height and temperature of first echoes in unseeded and seeded convective clouds in South Dakota. *J. Appl. Meteor.*, **6**, 994–1000.

Draginis, M., 1958: Liquid water content within the convective clouds. *J. Meteor.*, **15**, 481–485.

Heymsfield, A. J., P. N. Johnson and J. E. Dye, 1978: Observations of moist adiabatic ascent in northeast Colorado cumulus congestus clouds. *J. Atmos. Sci.*, **35**, 1689–1703.

Hirsch, J. H., 1971: Computer modeling of cumulus clouds during project cloud catcher. Rep. 71-7, Inst. Atmos. Sci., South Dakota School of Mines and Technology, 61 pp.

——, and C. L. Schock, 1968: Cumulus cloud characteristics over western South Dakota. *J. Appl. Meteor.*, **7**, 882–885.

Kopcewicz, T., 1965: Selected problems in hail physics and hail suppression. *Przegl. Geofiz.*, *Warsaw Univ.*, **10**, 84 pp.

Langmuir, I., 1948: The production of rain by a chain reaction in cumulus clouds at temperatures above freezing. *J. Meteor.*, **5**, 175–192.

List, R., and E. P. Lozowski, 1968: Some effects of high concentrations on the growth of precipitation and the dynamics of cloud models. *Proc. Intern. Conf. Cloud Physics*, Toronto, 504–509.

Ludlam, F. H., 1959: Hailstorm studies, 1958. *Nubila*, **2**, No. 1, 7–27.

MacCready, P. B., Jr., and D. M. Takeuchi, 1968: Precipitation initiation mechanisms and droplet characteristics of some convective cloud cores. *J. Appl. Meteor.*, **7**, 591–602.

Musil, D. J., 1970: Computer modeling of hailstone growth in feeder clouds. *J. Atmos. Sci.*, **27**, 474–482.

Nelson, L. D., 1971: A numerical study on the initiation of warm rain. *J. Atmos. Sci.*, **28**, 751–762.

Rokicki, M. L., and K. C. Young, 1978: The initiation of precipitation in updrafts. *J. Appl. Meteor.*, **17**, 745–754.

Rosinski, J., and T. R. Kerrigan, 1969: The role of aerosol particles in the formation of rain drops and hailstones in severe thunderstorms. *J. Atmos. Sci.*, **26**, 695–715.

Smith, T. B., D. M. Takeuchi and C. W. Chien, 1974: San Angelo cumulus project. Final Report, Bureau of Reclamation Contract 14-06-D-7132, Meteorology Research, Inc., 139 pp.

Spengler, J. D., 1972: Drop impaction and raindrop size. *Bull. Amer. Meteor. Soc.*, **53**, 25–26.

Takeuchi, D. M., 1972: Considerations of microphysical variations upon the potential for cumulus modification by the warm rain process. *Preprints Third Nat. Conf. Weather Modification*, Rapid City, Amer. Meteor. Soc., 166–170.

——, 1975: Variational study of the effects of seeding on microphysical processes in cumulus clouds. Final Report, Bureau of Reclamation Contract 501 ER 02218, Meteorology Research, Inc., 50 pp.

Twomey, S., 1976: The effects of fluctuations in liquid water content on the evolution of large drops by coalescence. *J. Atmos. Sci.*, **33**, 720–723.

Warner, J., 1955: The water content of cumuliform cloud. *Tellus*, **7**, 449–457.