What is the Role of Ice in Summer Rain-Showers?[1,2]

ROSCOE R. BRAHAM, JR.

Cloud Physics Laboratory, The University of Chicago

(Manuscript received 24 January 1964, in revised form 22 June 1964)

ABSTRACT

Recent observations indicate that ice pellets and snow pellets are present in most convective clouds in the Central United States by the time these clouds reach top temperatures of −10C. The attendant circumstances raise the question of whether the ice plays an active role in rain development in these clouds or whether its presence is purely incidental. The ice pellets are usually preceded by the development of liquid precipitation particles large enough to produce rain by coalescence with cloud droplets. The pellet concentrations are not related to ground-level ice nuclei concentrations. Apparently the pellets form as a result of freezing of the drops, contrary to most laboratory studies of droplet freezing. Observations can be brought into harmony by invoking the droplet splintering measurements of Mason and Maybank. The presence of numerous small ice particles in these clouds at temperatures warmer than −10C casts doubt upon the value of seeding with ice nuclei for rain inducement.

1. Introduction

Almost thirty years ago, on 19 September 1933, before the Fifth General Assembly of the U.G.G.I. in Lisbon, T. Bergeron presented a scientific paper which was destined to become one of the most important papers of that assembly. His paper marked the beginning of a new branch of meteorology which has come to be known as Cloud Physics.

In his original paper Bergeron noted that rain from clouds which did not reach the freezing level was commonplace in the tropical and semi-tropical regions. The truth of this observation is well known by those who have studied clouds in the low latitudes. However, it is also recognized that the heaviest rains come from clouds which in fact do reach above the freezing level and which, at least in principle, could contain solid hydrometeors. It is mainly those clouds whose tops extend above the zero degree isotherm with which this paper is concerned. We will focus our attention upon the solid hydrometeors, i.e., ice crystals, ice pellets and snow pellets, and the role they may play in the development of rain from summertime convective clouds of low and middle latitudes.

This paper is based primarily upon observational results of a recent series of cloud studies carried out in South-Central Missouri in "Project Whitetop." Our studies have been aimed at learning more about the convective precipitation processes and testing whether those processes can be altered detectably by silver-iodide seeding. We have completed four summers of these operations, and some of our findings, have already been published, at least in preliminary form. During the flights of 1960 and 1961 we noted that summer cumulus clouds of this area frequently developed large numbers of drizzle-sized drops through the warm-rain mechanism (Brown and Braham, 1963). The presence of snow pellets at the surprisingly warm temperature of −6C in these clouds was reported by Hoffer and Braham (1962), who came to the conclusion that these pellets could not have originated from heterogeneous freezing upon mineral nuclei. From a study of the hydrometeor collections made during the 1960 and 1961 seasons, Koenig (1963) reached the conclusion that the snow pellets must have come from freezing of the drizzle drops produced by the warm-rain mechanism. A study of the physical character of the pellets was carried out by Braham (1963). Further studies of the nature, origin and mode of action of these pellets were carried out during the summers of 1962 and 1963 with the result that it is now possible to bring together the results from these several kinds of studies to form a single, logical picture of the physics of precipitation in the summer convective clouds of Missouri. Such a picture then will serve as a basis for inference about the suitability of these clouds for rain inducement by seeding. Conclusions of this paper relate specifically to the summer clouds of Missouri—how they relate to clouds of other seasons and locations is yet to be determined.

2. Project Whitetop measurements

The basic measurements of Project Whitetop are obtained in a variety of ways; however for this discus-

---

[1] Presented before Thirteenth General Assembly of UGGI, Berkeley, Calif., 27 August 1963.

[2] The research in this report was supported by the Atmospheric Sciences Program, National Science Foundation, NSF grant G22419.

sion we will be concerned largely with data obtained with a ground-based radar and from an instrumented airplane. The plane is used to obtain measurements inside the upper parts of convective clouds being studied by the radar.

The ground radar is an AN/TPS-10, a 3-cm height-finder, which gives a three-dimensional picture of regions of precipitation. It has a vertical scan rate of one sweep per second and a horizontal scan rate of 360 degrees per three minutes. The RHI scope is photographed every vertical sweep, i.e., once per second. This radar has provided two important kinds of information about precipitating regions in clouds of this area. Since the radar was operated routinely (and the scope photographed continuously) during hours of convection on all operational days, we have what is virtually a 100 per cent time-space coverage of all precipitating clouds in the research area. The film records are being analyzed for the time and location of initial echo developments (so-called first echoes) and for the complete life history of individual echoes. The size of this task has caused analysis to lay behind field operations, nevertheless the work has progressed far enough to make clear several important aspects of the rain processes in these clouds.

1) The cumulus clouds of summer in Missouri initially develop precipitation at remarkably low heights. Based upon analysis of three summer's data we find that about 50 per cent of all "first echoes" were entirely warmer than freezing, about 40 per cent straddled the freezing level and the remaining 10 per cent were entirely colder than freezing. The frequency of warm first echoes (top temperatures more than 0C) varied markedly from day to day and to a lesser extent from year to year. Other than for a slight tendency for the first echoes to be higher and colder on days with cyclonic curvature of the isobars at the 850-mb and 700-mb levels and/or convergence in the lower level wind fields, these day to day variations were not associated in any obvious way with regional meteorological parameters.
2) A detailed study of the complete life histories of 928 simple, not-seeded, convective echoes of 1960 provides further insight into the precipitation process. About 40 per cent of the initial echoes showed top height growth after first detection; daily averages ranged from 20 to 60 per cent. About one-half of all those echoes which exhibited top growth reached their maximum height during the first three minutes after initial detection. Thus only 20 per cent of all echoes showed growth for more than one sweep of the radar after initial formation. The total amount of growth was, in general, very limited. Only about 20 per cent grew as much as 5000 ft and less than 4 per cent by as much as 10,000 ft. After reaching its maximum height the typical echo declined steadily until it disappeared. The average final echo top height was about 7000 ft.
3) Approximately 80 per cent of all convective echoes studied had bases which reached ground level during their life-times. This corresponds to measurable rain at the surface since our radar wavelength is 3-cm and of rather low power. The fraction of echoes that rained to ground was remarkedly constant from day to day (70 to 90 per cent), if we again restrict ourselves to convective weather situations. These figures are substantially larger than was found to characterize the summer clouds of Arizona, undoubtedly because of lower cloud bases and the moister subcloud air which would reduce evaporation losses under Missouri clouds.
4) The total duration of individual echoes of this study ranged from less than three minutes to over an hour. Echoes of short duration usually did not rain to ground. On the average about four minutes elapsed between initial detection of an echo and the time the echo based reached ground level. The average duration of rain from a single echo (echo at ground level) was nine minutes; the average total duration of these simple convective echoes was about 17 minutes.

The radar findings are interpreted as indicating that the time required for natural precipitation processes to produce echo-sized hydrometeors (*ca.* 400 microns dia.) is substantially the same as the total active growth period of the average cumulus cloud in this area. Most of these clouds are to be regarded as consisting of a single updraft impulse which comes to equilibrium and begins to descend again just about the time the precipitation processes achieve echo producing particles. Thus it appears that it is the regional dynamics of the atmosphere, not the microphysical processes, which control rain from these clouds, since it is the former that shape the spectrum of sizes and durations of the cloud producing updrafts. The same conclusion has earlier been reached in regard to clouds in Arizona (Braham, 1958; Battan, 1963).

Now let us turn to the nature of the particles which produced these radar echoes. The location of the initial echoes prove that in at least 90 per cent of the cases the echo-producing particles were liquid, not solid. However from the radar data alone we cannot rule out the possibility that the echo-producing particles began as ice crystals, growing by diffusion and riming, which fell through the melting level prior to becoming large enough to give an echo.

There are three devices on our plane which provide data directly applicable to this problem. These are: a) a continuous, metal-foil belt sampler which detects the sizes and numbers of precipitation particles (Brown, 1961; see also Garrod, 1957, and Murgatroyd and

Garrod, 1960); b) a continuous formvar replicating device essentially similar to that recently reported by MacCready (1964) and c) a four-inch diameter collection tube mounted on the belly of the plane in such a way as to lead precipitation particles from the undisturbed air stream directly into the cabin where they can be collected and studied by a variety of techniques.

Collections of cloud and precipitation particles by these three means can be used to amplify and interpret the data from the radar. Measurements by the foil sampler show that water drops in excess of 250 microns diameter occur in concentrations of more than 100 per m^3 in roughly one-third of all the cumulus congestus clouds of this area. The measurements further suggest that in the majority of these clouds the initial radar echo coincides with the development of large *liquid* hydrometeors (500–1000 microns diameter), even in cases where the top of the initial echo is at a temperature of -5 to -10C. On the basis of the measurements made thus far we must conclude that the initial precipitation in the vast majority of these summer cumulus clouds develops through the condensation-coalescence process without the involvement of ice. But this is only half of the story.

We also find that solid hydrometeors, in the form of ice pellets and snow pellets (sometimes called graupels) develop in about one-third of the clouds whose tops reach the -10C isotherm. We occasionally find very large concentrations of pellets in clouds with tops which have never been above the -5C isotherm.[3]

3. Physical properties of the ice particles

Typically the smaller ice particles are quasi-spherical grains of ice. They may be either completely transparent and colorless or they may be opaque and milky. The clear pellets are less frequent than the opaque ones, usually are less than 500 microns diameter and tend to have a fairly smooth surface. The opaque particles range in size up to more than 1 cm diameter and are roughly spheroidal, although some of them may be quite irregular in shape. We frequently find pellet concentrations as high as 10,000 per m^3 in clouds with top temperatures of -10C and warmer, (Brown and Braham, 1963; Koenig, 1963).

Under a hand-lens the clear pellets appear to be nothing more than frozen water drops whereas the opaque ones appear to have grown through riming of cloud droplets and other precipitation particles. Photographs of some of these pellets are given in Figs. 1 and 2. A microphotograph of a formvar replica of the surface of one of the opaque pellets is shown in Fig. 3. Note the numerous small droplets that make up the pellet surface.

The specific gravity of the snow pellets has been measured to be between 0.87 and 0.91 (Braham, 1963). During this past summer we measured the terminal falling speeds of some of these pellets and found it to be about 0.7 that of a water drop of equivalent mass. This result stands in marked contrast with the results or Nakaya and Terada (1935), but is in keeping with the observations of a high bulk-density.

4. Nature and origin of the ice particles

Because of their obvious importance we have devoted considerable effort to determining the origin of these particles and to determining the conditions under which they occur. Here we find some interesting puzzles. In his 1963 paper, Koenig concluded that these particles originated in the freezing of large water drops which had developed through the warm-rain mechanism. Later

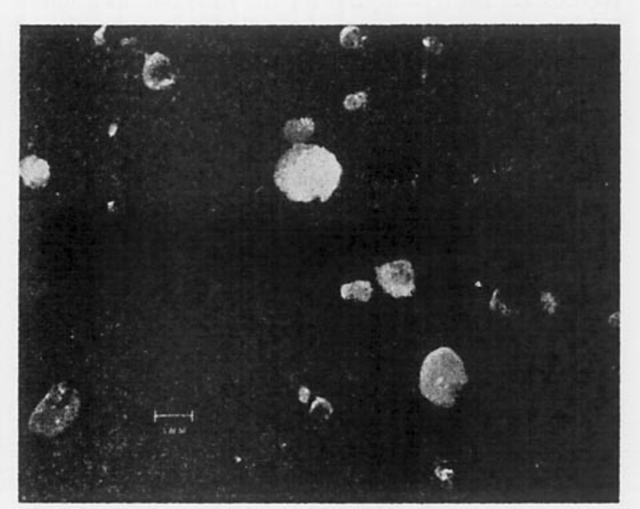

FIG. 1. Photograph of snow pellets and ice pellets from top of cumulonimbus cloud.

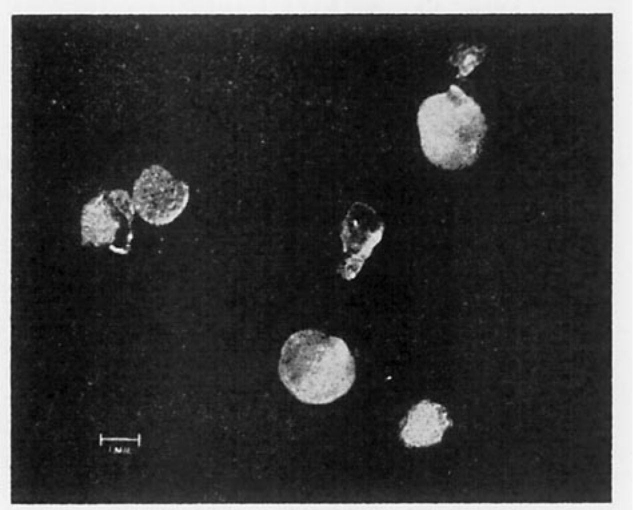

FIG. 2. Photograph of snow pellets and ice pellets. Note clear portions of pellet in center and on left center.

---

[3] Observations of ice particles at fairly warm temperatures in cumulus clouds have previously been reported (Coons *et al.*, 1949; Murgatroyd and Garrod, 1960). However it appears that the Project Whitetop studies are the first to study them in detail and to discover their role in the formation of precipitation.

measurements point to the correctness of this conclusion, at least for the majority of the pellet occurrences.

Observations of ice particle concentrations as high as 10,000 per m^3 at temperatures of -10C are completely contrary to the hypothesis of diffusive growth if we accept the ice nuclei concentrations measured by the conventional ice nuclei detectors. The Bigg-Warner detector, which uses a cold sugar solution to detect ice nuclei which have been activated in an expansion chamber, is usually regarded as one of the best devices available for monitoring the concentrations of natural ice nuclei; we operate such a device on our project. Recent papers by Kline (1963) and Bourquard (1963) give summaries of the measurements taken with this device. They show that at a temperature of -10C it is unusual to find more than 10 ice nuclei per m^3. Measurements using other types of nuclei detectors have given roughly similar results. In no instance does one find the number of ice nuclei required to account for the number of ice particles we observe at these comparatively warm temperatures. Koenig also noted that the pellets seemed to occur after the cloud had developed large water drops and that the water drops disappeared as the pellets appeared. These observations, plus the fact that ice particles of regular crystal symmetry were seldom if ever observed with the pellets, all pointed toward the origin of the ice through the freezing of drops.

Koenig's conclusion was further strengthened by the fact that electron microscope studies of formvar casts of several snow pellets showed an absence of large mineral grains of the sizes and kinds found by Kumai at the crystallographic center of natural ice crystals in winter snows (Kumai, 1961).

On the other hand, a conclusion that the pellets originated through freezing of liquid drops also runs into problems. Laboratory experiments have repeatedly shown that 500 micron diameter droplets seldom freeze at temperatures as warm as -5 to -10C.

Also consider another bit of evidence. With the help of T. Hoffer, on several days of 1962 I collected pellets from the uppermost 2000 ft of several cumulus congestus clouds. The pellets were collected into silicone-oil filled sample cups which were kept chilled to reduce any diffusive loss of water from the pellets. After the airplane landed the cups with the melted pellets were placed in a droplet freezing device and slowly cooled until the melted pellets were refrozen. The temperature at which the melt froze was determined by a calibrated thermocouple immersed into the silicone oil. The results are shown in Table 1 (Hoffer and Braham, 1962). We found that in every instance the pellet melt froze at temperatures 5 to 10 degrees warmer than the minimum temperature at which the pellets first formed. The frozen drops were remelted and refrozen only to find

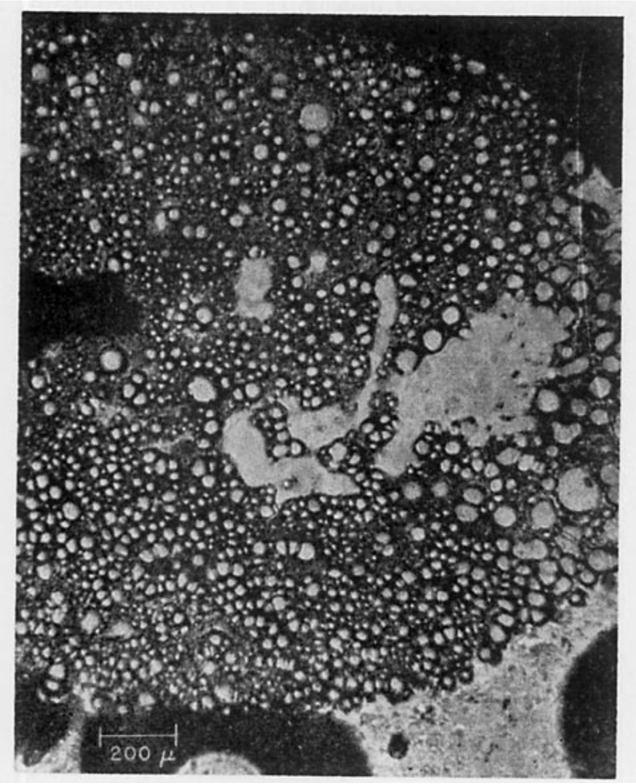

Fig. 3. Photomicrograph of replica of snow pellet surface.

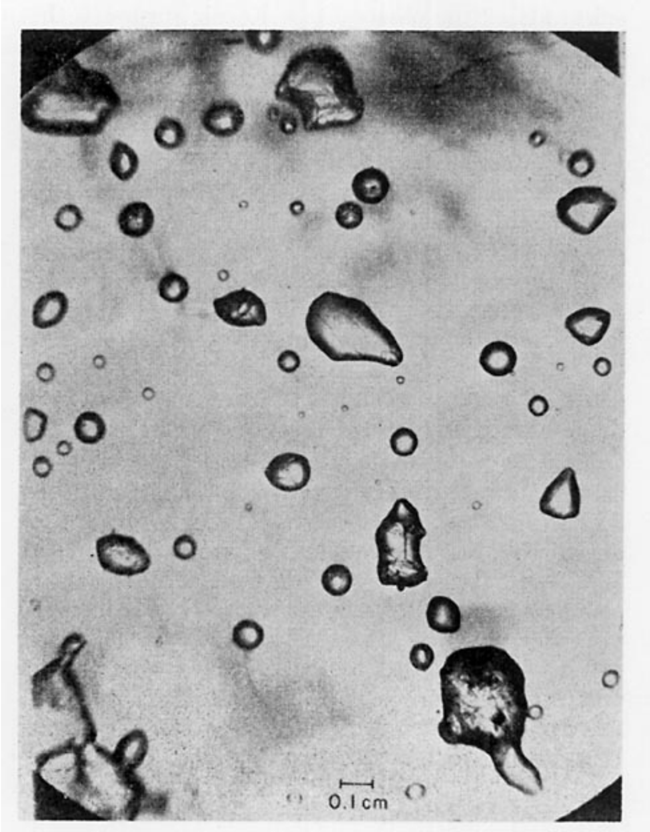

Fig. 4. Photograph of droplets and frozen drops collected in top of small cumulus congestus cloud.

TABLE 1. Freezing temperatures of droplets obtained from melted snow pellets contrasted with temperatures at which the original pellets formed. (Hoffer and Braham, 1962.)

Date	Type	Cloud description Top height	Top temp.	Number pellets	Freezing temperatures Warmest	Median
20 June	two Cu	21, & 25,000	−15 & −22C	22	−23C	−25C
1 July	Cu	19,000	−10	26	−20	−23
2 July	As	15,500	− 7	63	−19	−24
7 July	Cu	19,000	− 9	13	−24	−26
14 July	Cu	unknown	unknown	8	−23	−24
1 Aug	Cu	19,500	− 9	110	−16	−24
9 Aug	Cu	20,000	−11	53	−16	−26
22 Aug	As–Ac	unknown (collection temp. −8)	unknown	5	−23	−25
30 Aug	Cu shelf	22,000	−15	1	−21	−21

that the individual pellets repeated their freezing temperatures within one or two degrees centigrade. We have collected rainwater drops and cloud droplets and find that they typically freeze at temperatures of −25 and −35C, in keeping with the results from freezing of the melted pellets and with heterogeneous freezing experiments from other laboratories.

It is quite apparent that accepting the conclusion that these pellets were initiated by freezing also demands that we conclude that the circumstances of their freezing in nature have not yet been correctly modeled in the laboratory.

Thus we come to realize that neither the sublimation mechanism nor the simple heterogeneous freezing mechanism fits all the observations. Koenig suggested that theory and observations could be brought into accord by invoking the observations reported by Mason and Maybank (1960) concerning the splintering of freezing water drops. The splintering mechanism is associated with the fact that water drops in a cloud must freeze inwardly from the outside since the coldest temperature must be at the outer surface. The buildup of internal pressures frequently causes the drops to develop spikes and other surface irregularities and/or to spall off numerous small ice fragments. Mason and Maybank found that 20 or more ice splinters can result from freezing a single supercooled drizzle-sized drop. Only drops larger than ordinary cloud drops show this effect.

We have already noted that large water drops precede the formation of ice pellets. We also find, in droplet collections made about the same time that pellets appear, many examples of frozen droplets which have developed spikes and other surface irregularities (Fig. 4). While we have watched the development of spikes on countless freezing drops in the laboratory, we have not been able to verify, however, the development of large numbers of splinters. Neither have we observed the presence within the clouds of many small ice fragments following the first appearance of pellets. We believe that to date our observational techniques have not been adequate for detecting these very small pieces of ice and we are continuing our research in that direction. However as a working hypothesis we must assume that splintering is an essential part of the precipitation mechanism as outlined in the next section.

5. Precipitation mechanism in summer cumuli—the role of ice

The summer cumulus clouds of southern Missouri have been found to develop considerable numbers of liquid drops of drizzle sizes through the warm-rain mechanism. Between one-third and one-half of these clouds develop warm-rain particles sufficient to cause a radar echo on the ground-based TPS-10 before they have passed through the congestus stage (tops *ca* 15,000 to 20,000 ft). The observation that relatively few of the radar echoes grow in height after first detection is interpreted to mean that the time required for precipitation development is roughly the same as (or perhaps longer than) the duration of the active growing period of the average cloud. Observations indicate that cumuli which did not develop warm rain were usually those of very short life—of the order of ten minutes or less.

We have observed that ice pellets and snow pellets form in virtually every cloud which reaches a top temperature of −5 to −10C *providing* the cloud be one that had developed large liquid particles. As the ice particles appeared the liquid particles disappeared; however, the concentration of the ice particles frequently exceeded the original population of large liquid drops, (perhaps reflecting an inferior detection capability for liquid particles).

We believe that the ice particles were initiated by freezing of the large water drops and that they subsequently grew through riming with cloud particles. The cause of the freezing is obscure because it appears not to agree with laboratory experiments; however, we postulate that laboratory and field data can be reconciled through the splintering of freezing droplets. If for some reason, a few of the large drops freeze (perhaps one in every 100 m^3), the ice splinters evolved would be intercepted by the numerous large warm-rain drops causing them in turn to freeze and splinter. The proposed mechanism would be active only in clouds in which the warm-rain mechanism has already generated large numbers of millimeter-sized drops. It derives its importance from the fact that the large drops, with large cross sections and large terminal speeds, provide an effective sieving (scavenging) action not found in clouds outside the warm-rain region.

The rate of growth of the ice hydrometeors is found to be much faster than that of comparable liquid particles. I suggest that the reasons are: a) snow pellets fall almost as fast as raindrops of equivalent mass (perhaps because of their aerodynamically rough surface) and at the same time have a larger sweep-out volume because of their spheroidal shape, and b) the contact between a supercooled cloud droplet and a snow pellet results in immediate freezing of the cloud droplet onto the surface of the pellet, whereas we know from laboratory experiments that only about 10 per cent of the collisions between cloud droplets and a falling water drop result in coalescence (in the absence of moderate electric fields). This enhanced growth rate of a snow pellet over an equivalent water drop becomes of major importance when we recall the radar and airplane observations that indicate that the period of active life of most cumuli is about equal to the time required for precipitation *initiation.*

From the assumption that the drop freezing is accompanied by splintering of ice crystallites it must follow that freezing of a large number of drops will result in still larger numbers of ice crystals in the upper parts of the clouds. These could continue to grow by the Bergeron mechanism even after the initial ice pellets have fallen from the clouds. Thus, in cases where the warm rain mechanism is inadequate, the added ice splinters might increase the precipitation efficiency of the clouds, particularly in those clouds which build above the −5C level but do not reach the temperature of effective nucleation by natural sublimation nuclei.

On the other hand, there also is the distinct possibility that the freezing drops may completely overseed the tops of cumuli through large numbers of ice splinters. This would result in the premature glaciation of the cumulus tops and could be the explanation of the unusually low anvil formations, sometimes called "false cirrus," which are frequently seen in tropical latitudes.

Based upon our observations thus far, natural overseeding of cumulus tops sometimes occurs in summertime Missouri but it does not seem to occur frequently enough to seriously impair the natural precipitation efficiency of the clouds. It is my opinion that this possible hindrance to precipitation is more than overbalanced by the fact that freezing of the warm-rain drops gives these clouds the advantage of snow pellets without the necessity of going through the slow, diffusive-growth, sublimation process. It would appear that the precipitation from these clouds is substantially greater than it would have been through either the Bergeron ice crystal mechanism or the warm-rain mechanism acting alone. At the same time, however, our observations of large numbers of natural ice particles at temperatures of −5C, and the prospect of innumerous small ice splinters at these temperatures makes these clouds much less attractive for rain inducement by silver-iodide seeding than we had previously believed.

Because of the importance of this sort of study upon the whole question of cloud seeding for rain inducement our studies of these matters are continuing. As of now it appears to us that one of the central problems in weather modification research must be to delineate the meteorological, climatological, seasonal and geographical boundaries of an active warm-rain process, and to determine whether glaciation of clouds at relatively warm temperatures follows the formation of warm-rain particles in areas other than Missouri. We are intrigued by the prospect that some of the seemingly discrepant results found by various cumulus cloud seeding projects will find explanation in such studies.

Acknowledgments. The findings upon which this paper is based represent the efforts of the entire Project Whitetop team. In addition to those specifically cited I wish to acknowledge the help of John Kidney, Milton Draginis and Paul Spyers-Duran who assist me with measurements from the airplane, Thomas Morris who is responsible for our radar operations, Miss Maureen Dungey who supervised the radar analysis and James Farrell who has piloted our Beechcraft and helped us to obtain data from difficult places for five straight summers.

REFERENCES

Battan, L. J., 1963: Relationship between cloud base and initial radar echo. *J. appl. Meteor.*, **2**, 333–336.

Bergeron, T., 1933: On the physics of clouds and precipitation. *Proc. 5th Assembly U.G.G.I.*, Lisbon, 3–19.

Bourquard, A. D., 1963: Ice nucleus concentrations at the ground. *J. atmos. Sci.*, **20**, 386–391.

Braham, R. R. Jr., 1958: Cumulus cloud precipitation as revealed by radar—Arizona 1955. *J. Meteor.*, **15**, 75–83.

——, 1963: Some measurements of snow pellet bulk-densities. *J. appl. Meteor.*, **2**, 498–500.

Brown, E. N., 1961: A continuous-recording precipitation sampler. *J. Meteor.*, **18**, 815–818.

——, and R. R. Braham, Jr., 1963: Precipitation particle measurements in cumulus congestus. *J. atmos. Sci.*, **20**, 23–28.

Coons, R. D., E. L. Jones and R. Gunn, 1949: Artificial production of precipitation. *Res. Paper 33*, U. S. Weather Bureau, Wash. D. C., 46 pp.

Garrod, M. P., 1957: Recent developments in the measurement of precipitation elements from aircraft. *Meteor. Res. Pap. No. 1050*, Air Ministry, London, 8 pp.

Hoffer, T. E., and R. R. Braham, Jr., 1962: A laboratory study of atmospheric ice particles. *J. atmos. Sci.*, **19**, 232–235.

Kline, D. B., 1963: Evidence of geographical differences in ice nuclei concentrations. *Mon. Wea. Rev.*, **91**, 681–686.

Koenig, L. R., 1963: The glaciating behavior of small cumulonimbus clouds. *J. atmos. Sci.*, **20**, 29–47.

Kumai, M., 1961: Snow crystals and the identification of the nuclei in Northern United States of America. *J. Meteor.*, **18**, 139–150.

MacCready, P., Jr., and C. Todd, 1964: Continuous particle sampler. *J. appl. Meteor.*, **3**, 450–460.

Mason, B. J., and J. Maybank, 1960: The fragmentation and electrification of freezing water drops. *Quart. J. R. Meteor. Soc.*, **86**, 176–186.

Murgatroyd, R. J., and M. P. Garrod, 1960: Observations of precipitation elements in cumulus clouds. *Quart. J. R. Meteor. Soc.*, **86**, 167–173.

Nakaya, U., and T. Terada, Jr., 1935: Simultaneous observations of the mass, falling velocity, and form of individual snow crystals. *J. Fac. Sci.*, Hokkaido, ser. II, Phy., **I**, 169–171.