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RANDOMIZED SEEDING OF OROGRAPHIC CUMULI, 1957: PART II

Louis J. Battan, A. Richard Kassander, and Lee L. Sims

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ABSTRACT

During July and August 1957, orographic cumuli over the Santa Catalina Mountains of southeastern Arizona were seeded from an airplane with silver iodide. The experimental design of the program involved the randomized seeding by pairs of days; one of two days with suitable clouds was seeded on a random basis. On seven pairs of days, observations were made of the cumuli with a pair of K-17 cameras on a 1.3 mi baseleg. At the same time, radar observations were made with a 3-cm vertically-scanning radar set.

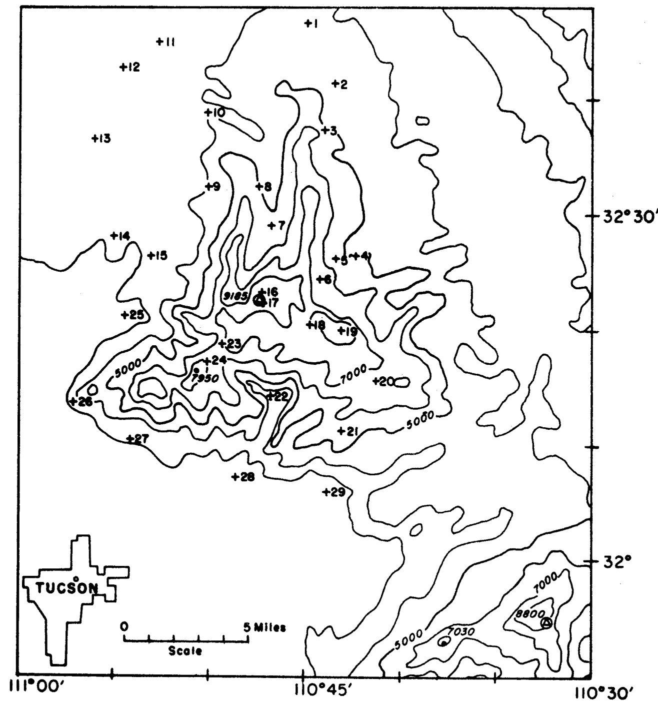
On the basis of the analysis of the camera and radar observations an investigation has been made of the occurrence of precipitation as a function of cloud size and temperature. It was found that there is a large variability in cloud behavior from year to year. Natural clouds in the arid southwest do not produce precipitation until their vertical thicknesses are of the order of at least 8 to 10,000 feet. From a comparison of seeded and non-seeded clouds it appears that the silver iodide particles may have produced changes in the precipitation formation mechanisms in orographic cumuli.

I. INTRODUCTION.

During the summer of 1957, the University of Chicago and the University of Arizona engaged in a cooperative program of research to study the effects of artificial nucleation of orographic cumuli. A detailed description of the design of the experiments has already been presented in reference 2. For the sake of this report, only a brief summary of the essential features of the design will be given.

The observational program involved the study of the behavior of convective clouds which formed over the Santa Catalina Mountains northeast of Tucson, Arizona, fig. 1. During the months of July and August these mountains are covered with clouds on about 40 days. It was decided to consider an afternoon as a unit of time and to randomize the seeding experiments in terms of pairs of days, *i.e.*, a decision, based on a suitable randomization procedure, would decide actions on a pair of days. If the first day were seeded, the second would not be seeded and *vice versa*.

In order for this system to operate effectively it was necessary to devise an objective scheme for accurately predicting when clouds capable of being seeded would form. This was accomplished by a statistical study of the relation between the formation of showers and large cumuli as a function of the precipitable water and the Showalter Stability Index. These factors were calculated from the 0500 MST radiosonde observations and a prediction as to whether or not clouds suitable for seeding would form was made by about 0800 MST.


TUCSON
0
5 Miles
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7030

Fig. 1

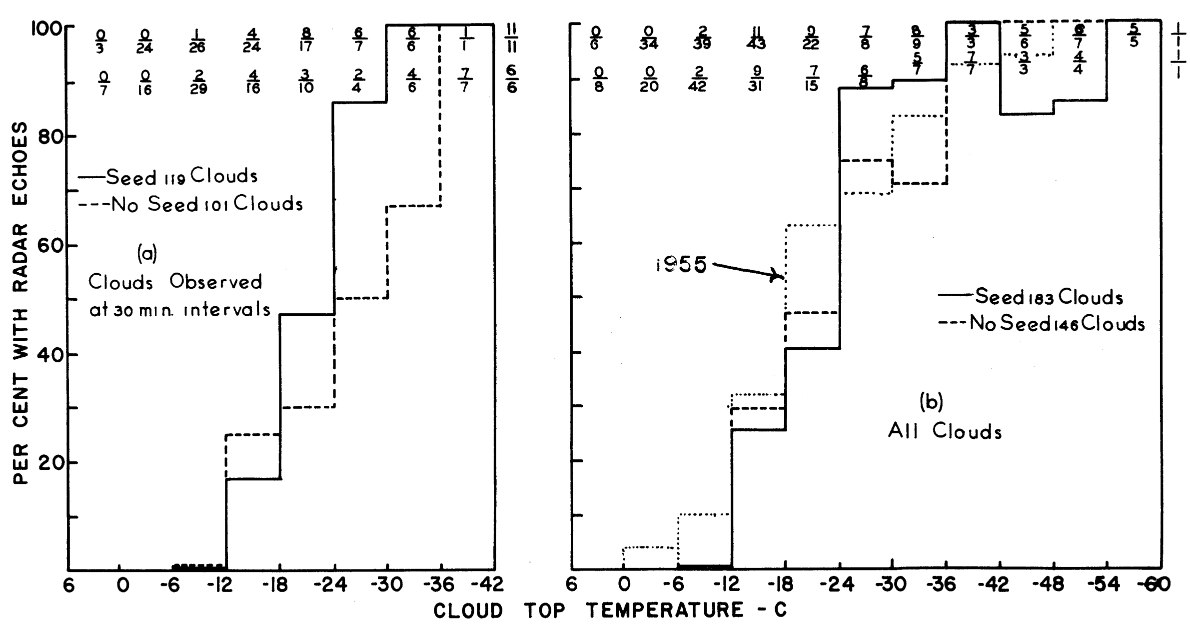
PER CENT WITH RADAR ECHOES
CLOUD TOP TEMPERATURE - C
—Seed 119 Clouds
---No Seed 101 Clouds
(a)
Clouds Observed at 30 min. intervals
1955
—Seed 183 Clouds
---No Seed 146 Clouds
(b)
All Clouds

Fig. 2

On days when conditions were suitable for seeding, an envelope was opened which contained seeding instructions for that day and the next suitable day. If the instructions stated that the clouds should be seeded, s Supercub airplane flown by the Hudgins Air Service of Tucson carried out silver iodide seeding from about 1230 to about 1530 or 1600. The nuclei were produced by a silver iodide generator[1] whose output was 2 to 2-1/2 gals per hour of a solution of AgI in acetone (about 20 per cent by weight). During the seeding period, the aircraft was flown along a track upwind from the mountain and at an altitude where the temperature was about -7C.

The effects of the seeding were studied by measuring the rainfall over the Santa Catalina Mountains. This aspect of the analysis is discussed in reference 2. It is shown that the average rainfall was about 12 per cent higher on the 16 seeded days. Also when each of the 32 days was ranked according to the maximum rainfall in any gage during the period 1300 to 1800, eight of the nine highest rainfalls occurred on seeding days. Statistical tests could not establish that the observed differences were significant at the 5 per cent level. Nevertheless, these data suggested that seeding may have affected the rainfall characteristics of the orographic cumuli under study.

The difference of mean rainfall on seeded and non-seeded days was caused largely by a few large storms rather than by an increase in the number of showers. It is suggested that perhaps the seeding was only effective in particular clouds whose dimensions and growth rates were such that the numbers of ice nuclei introduced by the seeding, were optimum for producing fairly large effects.

The differences between cloud behavior on seeded and non-seeded days were examined with cloud cameras and a vertically-scanning 3-cm radar set. The analysis of the radar data is discussed in reference 3. It was found that on the seeded days the

[1]The generator used for this work was constructed by the Commonwealth Scientific and Industrial Research Organization of Australia and loaned to the U. S. Weather Bureau and was, in turn, loaned to the University of Chicago.

distribution of the heights (or temperatures) of the tops of the initial precipitation echoes were more narrowly distributed and averaged about 1,000 ft higher (2°C colder). Furthermore, the frequency of large echo ascent rates (greater than 1500 ft/min.) was higher on the seeded than on the non-seeded days. On seeded days, 16 clouds exhibited such strong rates of echo growth while on non-seeded days only 7 such clouds were observed. These data again suggest that perhaps a small number of clouds were caused to grow rapidly by the seeding. It has been contended by a number of investigators that the conversion of supercooled cloud water into ice crystals will cause an increase in cloud bouyancy and increased upward acceleration.

The third source of observations for studying the effects of seeding were a pair of K-17 aerial cameras mounted on the ground at the ends of a baseline about 1.3 mile long. These cameras were carefully calibrated to permit calculations of the cloud base and cloud top height (7). This report deals with the analysis of the cloud observations and is particularly concerned with the relationship between the cloud dimensions and temperatures and the formation of precipitation.

II. PRESENTATION OF DATA

During the months of July and August 1957, 16 pairs of days were studied. Malfunction of the camera equipment or the radar set or poor photographic conditions reduced the number of usable pairs to seven. It should be noted that if radar or cloud camera data were missing for either the seeded or non-seeded day of a pair, the entire pair was discarded.

The basic analysis procedure involved, making a so-called "cloud census". At stated intervals of times the region over the Catalina Mountains was examined on the K-17 photographs and measurements were made of the bearing and elevation angles to all cumulus clouds which could be identified on the film from both cameras. Calculations were made of the cloud base and cloud top heights. By employing the appropriate radiosonde information, the height measurements could be converted into temperature information. Knowing the bearing and range to a particular cloud, one could use the radar data to ascertain whether or not the cloud contained precipitation. By examining many clouds it was possible to draw histograms of the fraction of clouds having a particular height, temperatures, etc., which contained precipitation echoes. When a large number of clouds are involved a comparison of histograms on seeded and non-seeded days should reveal the effects of seeding if any exist.

At the start of the seeding experiments it had been decided that an interval of 30 minutes between cloud photographs would be an appropriate one. Since the lifetimes of convection cloud towers are of the order of 20 minutes or less, an interval of 30 minutes virtually assures that the same cloud will not be listed more than once. If a cumulus cloud top was identifiable at a particular time, one would expect that 30 minutes later, if the cloud existed at all, it would have formed a large diffuse mass, easily identified as an old cloud tower.

After analyzing the cloud-camera observations at 30-minute intervals, it was found that radar data was missing for many of the periods. A tabulation was made of the times of the radar films and the K-17 films were reexamined and clouds during the intermediate times were tabulated. This was considered worthwhile because the 30-minute data showed some interesting results, and it was desirable to check these results with more observations. It should be noted however, that the design of the seeding experiment called for the 30-minute interval so that the additional data can not be considered to have the validity of the 30-minute data. On a few occasions the radar cameras were not started until echoes were observed; secondly with intervals smaller than 30 minutes the possibility existed that the same cloud was observed more than once. Both of these factors tended to slightly increase the probability of echoes. Indeed, the procedure does not bias the data in favor of or against seeding, but it does make interpretation of the data more difficult. When a cloud is examined only once, one can speak of the "probability of a precipitation echo in a cloud which is a random selection of all clouds extending to a particular altitude". If a cloud is examined more than once, it is then necessary to consider not only the altitude but also the cloud duration. It has been shown that the longer the cloud duration, the greater the likelihood of precipitation[1]. One must proceed with caution in relating the two sets of observations.

A. Observations. It has been found that in general, with cloud top heights below a certain altitude the probability of precipitation is zero, and that it increases to unity at large cloud heights. Fairly large geographical differences have been found in the shape of the curve. It also appears that there are fairly large variations from year to year, day to day, etc. Similar distributions are found when cloud top height is replaced by cloud thicknesses or cloud top temperatures. In the cloud seeding experiment described here, all the seeded and non-seeded data have been grouped together. The resulting data are presented in figures 2, 3, and 4. Note that in each figure, part (a) represents the data at 30-minute intervals. Part (b) presents all available data regardless of the interval of time between the observations.

B. Discussion. On the basis of the data presented in figures 2, 3, and 4, one can draw various inferences regarding the precipitation processes in orographic cumulus. If seeding affects natural precipitation processes by an appreciable amount, the effects should be found from a comparison of seeded and non-seeded clouds.

1. Relation between cloud top height and temperature and precipitation. The relationships between cloud top temperatures and the fractions of clouds with precipitation are shown in fig. 2. In general the data pertaining to natural clouds are in agreement with observations made in New Mexico by Braham et al., (4) and with flight observation made in Arizona by Morris (10). None of the clouds with tops warmer than about -6C contained precipitation echoes. There was a fairly regular increase of the likelihood of precipitation with decreasing cloud top temperature.

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[1] "Cloud Duration as an Important Parameter in Cloud Seeding", a paper read by R. R. Braham, Jr. at the 165th National Meeting of the American Meteorological Society, Washington, D.C., May 7, 1958.

When the cloud tops attain altitudes of about 32,000 ft (-36C) virtually all of them contained precipitation. These data show that between the cloud top temperature range -6 to -36C there were many clouds which failed to produce precipitation. The reasons for this failure can be many and varied. It has been shown that the likelihood of precipitation in a cloud depends on the horizontal "diameter" of the cloud (1). Some of the clouds which failed to produce rain may have been tall and thin. If the vertical velocity in a cloud is high, a tall cloud may form before large water droplets or ice crystals have had time to form. Another reason for the absence of precipitation may have been that there were insufficient large cloud droplets to permit growth by coalescence or there may have been insufficient ice nuclei to allow the growth of large frozen particles by the deposition of water vapor on the ice crystals.

There is increasing evidence that in many convective clouds in Arizona, even those at subfreezing temperatures, precipitation growth takes place by the coalescence of water drops. However, it appears evident that the ice-crystal process is also important in the production of precipitation. It seems reasonable to hypothesize that many of the subfreezing cumulus clouds could be caused to precipitate by the introduction of the optimum concentration of ice-forming nuclei such as silver-iodide particles. By introducing them into clouds at temperatures of -5 to -10C, they could produce ice crystals which could grow to large sizes much earlier in the life of the cloud than the ice crystals produced naturally. Observations of ice nuclei in Arizona have indicated that very few are active at temperatures warmer than -15 to -20C. (8).

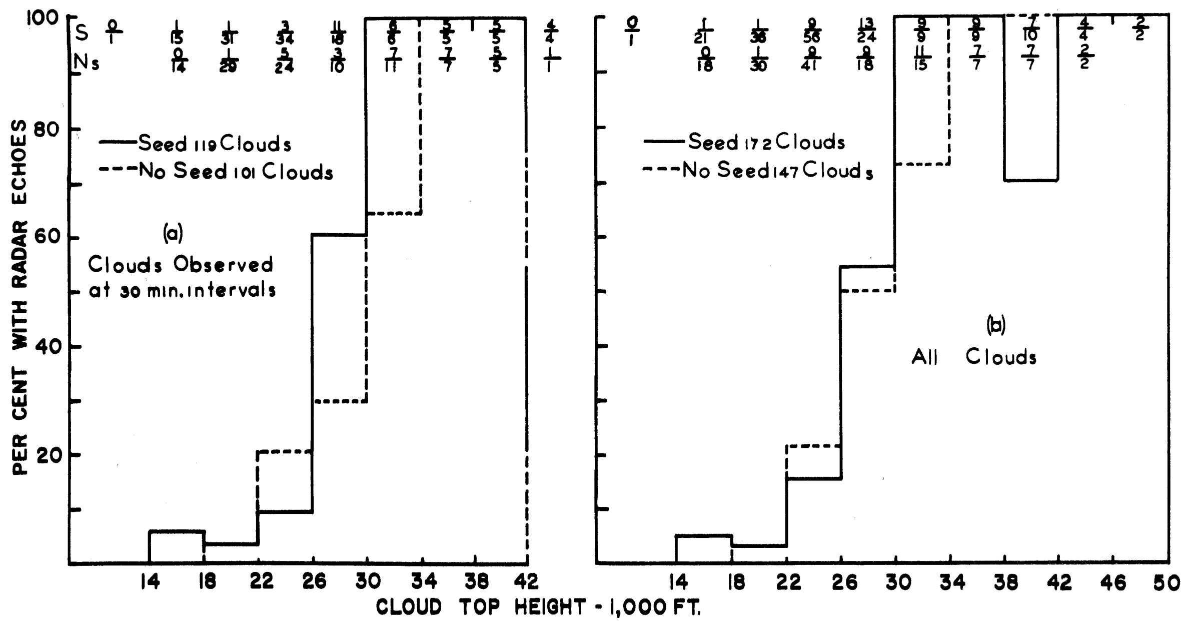
An important feature of fig. 2 is the differences between the histograms for the 1955 clouds and the 1957 non-seeded clouds. It is evident that the latter histogram has been shifted towards colder temperatures. These data show that there may be large variations in the behavior of clouds from one year to the next and they illustrate that a comparison of clouds seeded one year with non-seeded clouds of earlier years may lead to erroneous conclusions. The design of the experiments carried out in 1957 involving the use of pairs of days, tends to eliminate the effects of year to year changes in the ability of clouds to produce precipitation. It also reduces the effects of day to day correlations.

A comparison of the distribution of cloud top temperatures on the seeded and non-seeded days can be made from the rows of numbers given on figure 2. It is evident that the differences are small. On the seeded days there were relatively more larger clouds (e.g. on seeded days 35.3 per cent were colder than -18 while on the non-seeded days the corresponding figure was 32.6 per cent), but the difference is too small to be considered as anything but suggestive.

A comparison of the data collected on the seeded days (solid line) with that taken on the non-seeded days (dashed line) shows some interesting results (fig. 2a). It can be seen that in the temperature range -6 to -18C the fraction of precipitating clouds was smaller on the seeded days while at lower temperatures a higher fraction of the clouds on the seeded days contained precipitation echoes. When all the available data are considered (fig. 2b), the temperature at which the shift occurs is found to be at -24C rather than -18C. As one would certainly expect, the data pertaining to cloud heights show similar distributions (fig. 3), but since the ice crystal processes are temperature dependent this discussion will be restricted to figure 2.

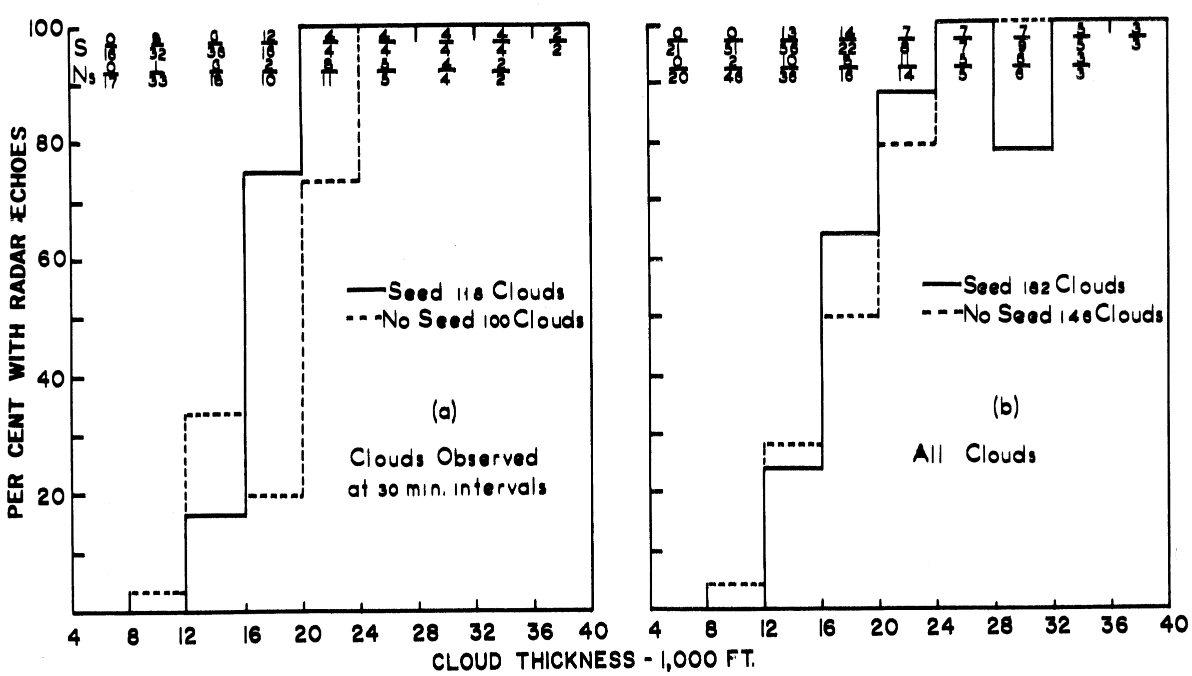
For reasons given in an earlier section of this report, the authors have more confidence in the data presented in fig. 2a, and will assume for the present that these distributions are more nearly representative of the conditions which prevailed during the summer of 1957. Additional data to be collected during 1958 will be compared with that already available to ascertain the validity of the inferences to be drawn from fig. 2a.

One must examine the question, "Could one reasonably expect the differences between seeded and non-seeded clouds shown in figure 2a to have been caused by the seeding?" Offhand the reduction of the fraction clouds with echoes at temperatures warmer than -18C could be attributed to "overseeding" which is defined as "the dispersal of such a high concentration of nuclei that so many ice crystals are formed that none can grow to precipitation sizes."



PER CENT WITH RADAR ECHOES
S
Ns
Seed 119 Clouds
No Seed 101 Clouds
(a)
Clouds Observed at 30 min. intervals
Seed 172 Clouds
No Seed 147 Clouds
(b)
All Clouds
CLOUD TOP HEIGHT - 1,000 FT.

Fig. 3



PER CENT WITH RADAR ECHOES
S
Ns
Seed 118 Clouds
No Seed 100 Clouds
(a)
Clouds Observed at 30 min. intervals
Seed 182 Clouds
No Seed 146 Clouds
(b)
All Clouds
CLOUD THICKNESS - 1,000 FT.

Fig. 4

On the basis of the operation of the silver-iodide burner used in these experiments and reasonable assumptions of the diffusion rates between the aircraft and the mountain range it has been estimated that nuclei concentrations of perhaps 400 to 4000 nuclei per liter could have been present over the mountain range. A limited number of observations made over the mountain range showed that the AgI nuclei concentration was highly variable but in two samples the concentrations were about 10^4 per liter. With ice crystal concentrations in the clouds of the order of 10^3 per liter and reasonable values of the liquid water content, it can be shown that only small crystals would form. Thus, the assumption that seeding may have caused overseeding of cumulus clouds whose tops were just above the seeding level does not appear to be inconsistent with reasonable estimates of the relevant physical variables.

The second feature of the distributions of figure 2a which needs elucidation is the increase of the precipitation likelihood at temperatures below -18C. If one starts with a parcel of air in the temperature range -6 to -18C and an ice nuclei concentration of about 10^3 per liter and assume the parcel rises at about 1000 ft/min, one can calculate the rate of growth of the ice crystals. It should be noted that as colder temperatures are reached more nuclei are activated by a factor of perhaps 10 per 5C of temperature decrease. The amount of vapor release during ascent is insufficient to cause the crystals to reach precipitation sizes by vapor deposition during the time required for the cloud tops to ascend from the -15C interval to the -21C interval. It is possible that the clumping of ice crystals may cause the production of precipitation-size ice particles. Almost nothing is known about the rates of ice crystal clumping. However, flight observations in Arizona cumuli have shown that the formation of snow pellets, apparently caused by clumping of frozen particles, may form in times of the order of 5 to 10 minutes.

It should be noted that information on the number of nuclei mixed into the cloud by the entrainment process is completely lacking. Therefore the analysis given in the preceding paragraph is subject to some question. It is possible that the number of ice nuclei in the large cumuli may be of the right order to permit precipitation development by the formation of large ice crystals by vapor deposition.

Quite obviously, at this stage of the investigation it is not possible to offer a satisfactory explanation for the observed differences between the clouds on seeded and non-seeded days. The authors recognize that they may not even be real differences, but rather, may have been caused by chance.

2. Vertical cloud thickness. As one would expect, the greater the cloud thickness, the greater the probability of precipitation, fig. 4. It is noted that no clouds with thicknesses smaller than about 8,000 ft contained precipitation echoes. Byers and Hall (5) have shown that tropical cumuli over the ocean may produce precipitation echoes when they have vertical thicknesses of about 4,000 ft. The differences certainly must be partly a consequence of the fact that tropical cumuli have higher cloud base temperatures (20°C as compared to about 10°C) and smaller updraft speeds (6,9). In addition, over the tropical oceans, in the vicinity of Puerto Rico there should always be a large supply of giant condensation nuclei which can cause the coalescence process to become active early in the life of the clouds.

Since the bases of the orographic cumuli over the Santa Catalina Mountains usually are between 10 and 13,000 ft MSL, it is reasonable to find that the histograms in figures 3 and 4 are quite similar insofar as differences between seeded and non-seeded days. The data suggest that in the shallower clouds seeding reduced the fraction of clouds with precipitation while in the thicker cloud seeding increased the fraction with precipitation.

III. CONCLUSIONS.

Analysis of the observations of clouds and simultaneous radar observations taken on seeded and non-seeded days have permitted a number of conclusions.

In general, the observations have substantiated earlier observations taken in the arid Southwest, that convective clouds do not produce precipitation until they have attained vertical thicknesses exceeding about 8,000 ft and have penetrated into subfreezing regions of the atmosphere.

As the cloud thickness and vertical extent increase and the cloud top temperature decreases, the probability of natural precipitation increases, but many clouds with cloud tops colder than -6C fail to produce echoes. Of the order of 50 per cent of the clouds with tops in the temperature range -18 to -24C fail to produce precipitation. These data suggest that if ice nuclei in optimum concentrations could be introduced, it might be possible to initiate precipitation.

The data suggest that some clouds whose tops extended to just above the seeding altitude may have been prevented from producing precipitation because of the introduction of excessive nuclei. The cloud observations and the estimates of AgI nuclei concentration are consistent with a conclusion that overseeding took place.

The observations also suggest that the AgI seeding increased the fraction of large clouds (temperatures below -18C) which contained precipitation.

None of the differences between the seeded and non-seeded clouds could be shown to be statistically significant. A continuation of the experiments is in progress and should serve to establish whether the differences were result of chance or were real differences caused by the AgI seeding.

ACKNOWLEDGEMENTS.

The authors of this report gratefully acknowledge the contributions made by Dr. James E. McDonald to this work. The estimates of nuclei concentrations and the evaluations of the effects of these concentrations on the precipitation processes are largely a result of his efforts.

Our thanks are also extended to the U. S. Weather Bureau office at Tucson, Arizona for their cooperation in this research.

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