# Physical Studies of the Santa Barbara Cloud Seeding Project[1]

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## ABSTRACT

Physical storm characteristics during the operational period of the Santa Barbara Cloud Seeding Project have been studied. It is shown that the vertical storm structure, particularly the depth of the low-level convective layer, is of importance in determining (1) the area distribution of precipitation, (2) the transport of seeding material from the ground to the nucleation levels, and (3) the existence of supercooled liquid water at nucleation levels. Item (1) above influences the correlation between target and control precipitation amounts, and items (2) and (3) influence the effective seeding of the storm. The seeded and unseeded storms of the Project have been treated using these concepts in order to investigate their influence on the inconclusive statistical results of the Project.

On the basis of qualitative seedability criteria, it is estimated that approximately one-half of the precipitation in the Project period occurred under relatively poor seeding conditions. This was determined by classifying storms into convective and stable flow types. It is also shown that the convective and stable cases have differing orographic precipitation characteristics and that, as a consequence, the target-control relationship is a function of vertical storm stability.

The study suggests that the possibility of detecting seeding effects can be improved by elimination of poor seeding cases through development of better seedability critera and by stratifying target-control relationships according to storm type. Also indicated is a need for improved understanding of natural rainfall variations before substantial progress can be made in detecting detailed variations caused by seeding.

## 1. Introduction

The Santa Barbara Cloud Seeding Project was designed as a randomized statistical experiment to test the effectiveness of a commercial-type seeding operation in increasing precipitation. Seeding operations were carried out by North American Weather Consultants, statistical analyses were performed by the Statistical Laboratory of the University of California at Berkeley, and the Department of Water Resources, State of California, operated a special raingage network in Santa Barbara County for the purposes of the Project. Meteorology Research, Inc., conducted physical studies of storm structure, primarily from LaCumbre Peak.

The statistical results of the program for the first three years have been discussed in detail by Neyman, Scott and Vasilevskis (1960). In general, the results were inconclusive, due in part to the large precipitation increases required for significant effects. Additional statistical data are given in a joint report of the Santa Barbara Weather Modification Project (1960).

Limited physical measurements were made during the course of the Project to supplement the weather observations available from the standard reporting network in and near the Project area. These additional data were obtained at a single observing location and stressed PPI radar coverage of each storm. The physical data were not integrated into the statistical evaluation during the Project. Primarily this resulted from the lack of existence of an adequate model of the possible effects of seeding on winter storms.

The principal potential benefits from integration of physical measurements into a statistical program such as the Santa Barbara Project will arise from improvements in the sensitivity of the statistical tests. Analysis of the physical storm data during and after the Project period suggests that storm structure characteristics have a pronounced effect on (1) target-control relationships and (2) the relative seedability of the storm. Physical measurements can be used to stratify the storm data according to these characteristics and bring about an improvement in the ability of the statistical tests to detect seeding effects. It is tacitly assumed that storm reactions to seeding may vary considerably from one storm to another and even within one storm. Consequently much of the Meteorology Research, Inc., effort during the Santa Barbara program was devoted to studies of storm structure which might permit a rational description of the storms in terms of relative seedability.

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In view of the lack of a definitive answer in the Santa Barbara program, it is also valuable to examine the physical and meteorological environment in which the tests were conducted. Although this examination cannot be construed as an evaluation of the Project, it may suggest physical reasons which contributed to the inconclusive results and should aid in the planning of future experiments of this type.

## 2. Terrain features

Fig. 1 shows a relief map of Santa Barbara County. Among the terrain features of interest in the County are the east-west coast line and coastal plain, about 3 to 5 mi wide. North of the plain is the coastal ridge, about 4000 ft high and extending east-west for about 45 mi. About 3 mi north of the ridge is the Santa Ynez River Valley running nearly east-west with elevations ranging from around 700 to 1500 ft. North of the Santa Ynez Valley the terrain becomes rough and unorganized with numerous 5000- to 6000-ft peaks except in the northwest section of the County where the terrain is lower and more uniform.

During winter storm conditions in Santa Barbara County, winds at precipitation-producing levels are generally between south-southwest and west-southwest. For these wind directions the coastal ridge comprises an orographic barrier which markedly affects the distribution of precipitation in the County. It can be seen in the figure that the ridge is sharp, uncluttered with extensive foothills, and nearly uninterrupted for a considerable east-west distance. It thus provides an unusually simple example of orographic lifting.

Some 37 recording raingage locations were available or established for the Project in Santa Barbara County. Particular use is made later in this paper of data from six gage locations along the coastal strip and four locations on the crest of the coastal ridge (2000- to 4000-ft elevation). Locations of these gages are shown in Fig. 1 for later reference.

About 25 to 30 mi south of the Santa Barbara coast line are the Channel Islands where locations of six recording raingages are also shown (20- to 1470-ft elevation). Highest elevation in the island chain is about 2100 ft and, under some conditions, orographic effects are generated by flow over the islands before the air parcels reach the mainland. The Channel Islands, together with a group of recording raingages on the mainland to the north of Santa Barbara County, provide the unaffected control area precipitation used by Neyman *et al.* (1960) in the statistical tests. Two silver iodide generators were located on the Channel Islands and operated occasionally during the Project but under wind conditions such that any effects pro-

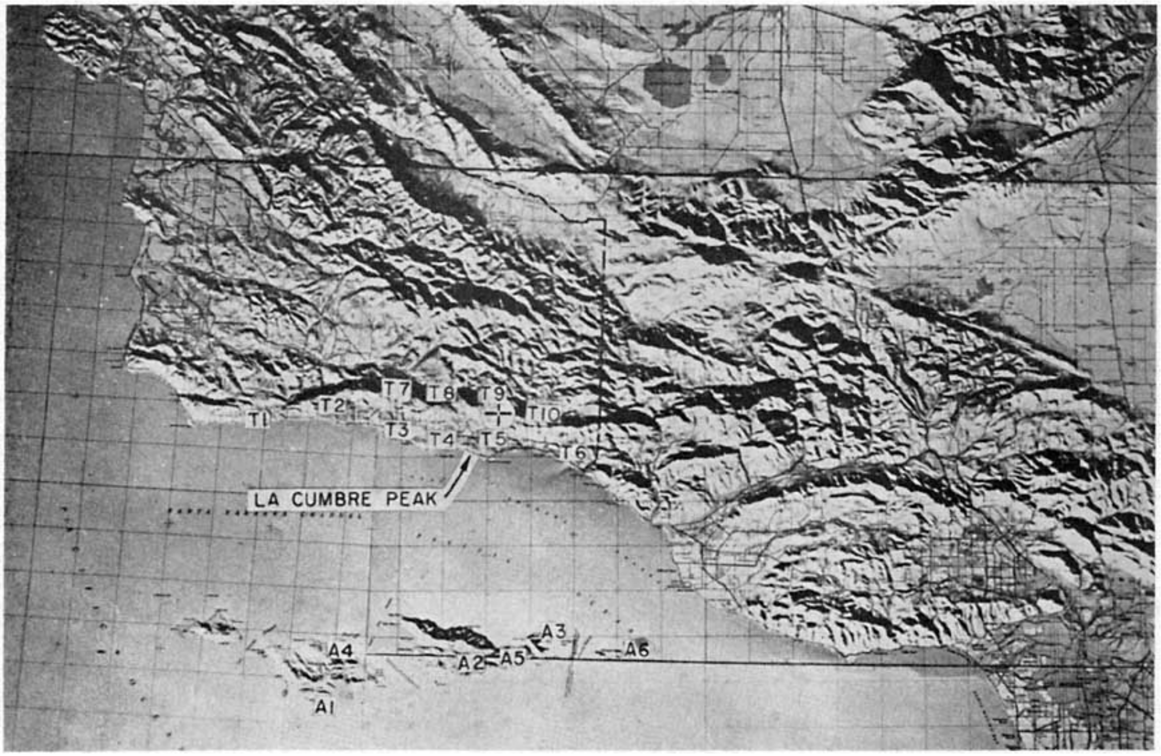

FIG. 1. Relief map of Santa Barbara County.

duced by the silver iodide would occur well downwind of the Islands.

### 3. Physical measurements

Most of the observations made by Meteorology Research, Inc., during the Project were made from a U. S. Forest Service Lookout on LaCumbre Peak at 4000 ft on the coastal ridge about 6 mi north of Santa Barbara. The 3-cm APS-15 radar was located on the roof of the Lookout and had an uninterrupted view of precipitation approaching the coast from directions between west and southeast, but considerable ground clutter appeared from high mountains to the north of the Lookout. The radar was operated in PPI fashion at a slight negative angle with respect to horizontal with frequent excursions upward in elevation to obtain information on the radar echo tops. During the 1960 rainfall season, a second 3-cm radar was operated from the Lookout in an RHI mode to obtain more detailed observations of vertical precipitation structure. Supplementary measurements at the Lookout consisted of wind, temperature and occasional measurements of raindrop size, potential gradient, and freezing nuclei concentrations. A brief analysis of a connection between raindrop size characteristics and potential gradient is given by MacCready *et al.* (1958), showing different drop size spectra for precipitation produced by the ice and water processes.

Standard meteorological observations were available from airways stations in and near the Project area and from occasional pilot reports. Particular use was made of radiosonde observations at Point Arguello (or Santa Maria) and Santa Monica, about 50 to 70 mi northwest and southeast of the area, respectively. Occasional radiosonde observations were also available from Point Mugu, a naval facility about 35 mi southeast of Santa Barbara. During the 1960 rainfall season, the frequency of radiosonde observations was increased to 3-hr intervals in storm conditions in support of a program being carried out by Aerometric Research, Inc., at Santa Barbara. Unfortunately the 1960 rainfall season was unusually dry and relatively few storm examples were obtained under this detailed observational program.

For the most part, the radar information was used in a semi-quantitative manner to determine the horizontal and vertical structure of the precipitation. Much can be learned from these studies concerning the type of air motion occurring in the precipitation process. Sheet or layer type precipitation structure is associated with slow, stable, relatively uniform upward motion. When the air becomes unstable, upward motions increase, the areas of contiguous upward motion decrease in size and the precipitation structure becomes more cellular. This information, together with vertical-time sections of temperature and moisture structure, as determined from radiosonde data, has been used to obtain a vertical-time sequence of storm structure for each storm observed during the Project period.

### 4. Storm structure

Elliott (1958) has discussed a typical storm cross-section influencing the California coast. In advance of the storm, high level cirrus and altostratus clouds generally occur. At the same time a moist marine layer, several thousand feet thick, is usually present in the lowest levels. Between these moist layers is a dry region into which early precipitation from the altostratus layer evaporates. As the storm approaches, the marine layer frequently deepens as the base of the altostratus layer lowers. When the marine layer becomes sufficiently deep, considerable convective activity can occur within the layer, and this activity increases as the marine layer becomes thicker and the front approaches. Somewhat in advance of the frontal passage the convective activity becomes the dominant feature of the vertical motion, and the precipitation pattern becomes more cellular. Subsequently the front passes and the shower activity gradually decreases.

One or more of the characteristic storm events described by Elliott is observed in all of the Santa Barbara storms. The numerous variations from the ideal model are generally in the nature of omissions of part of the sequence. Some storms, for example, do not show the deepening marine layer but remain generally non-convective throughout the storm. In other cases the stable early part of the storm is not observed and deep convective activity occurs throughout the storm. Characterization of each individual storm or each distinctive storm segment would be desirable in terms of relative seedability. Since there is not general agreement on seedability criteria, a tentative separation of storms has been made into the general categories of (a) stable flow pattern, efficient precipitation release, (b) stable flow pattern, inefficient release, and (c) convective flow pattern. These categories will be described by examples of several storm structures which exhibit these properties.

A near classic example of Elliott's storm model occurred on 25–26 January 1958. The vertical time section constructed from Santa Maria radiosonde data is shown in Fig. 2. Moisture values have been given in terms of temperature—dew-point separation, and the shaded area in Fig. 2 represents less than 10C difference. This value corresponds to about 40 to 45 per cent relative humidity compared to water saturation. With due allowance for humidity variations which may occur between radiosonde observations, it is felt that the shaded area should include all regions where ice might be expected to exist at high levels for any appreciable interval of time. The approximate vertical positions of the frontal surfaces over the area are shown in each figure. The heavy, solid line represents the approximate top of the marine layer calculated by noting the upward limit of free convection from the cloud base as determined by the vertical distribution of equivalent potential temperature.

Fig. 2 shows the advection of moisture at levels near 20,000 ft as early as 0400 on 25 January. Appreciable rain commenced on the crest of the coastal ridge about 1300, coinciding with the increase in moisture content at intermediate levels. From 1100 to 1400 the PPI radar echo distribution consisted of patches and bands of precipitation with intervening regions of no precipitation. This is the radar structure characteristic of a horizontally non-uniform precipitation release mechanism and is referred to as "inefficient release" in the subsequent remarks. The fuzzy nature of the echoes, the associated low vertical velocities and the observed vertical radar sections through such echoes are typical of the precipitation streamers described by Wexler (1955) and others. The term "inefficiency" is used in the sense that the ice crystals produced in such situations frequently occur only in patches and bands with incomplete horizontal coverage and consequent incomplete release of moisture from the lower cloud levels.

After 1400 the precipitation was general throughout the area covered by radar but the structure continued to be of the sheet or layer type typical of slow upward velocities. From Fig. 2 it is readily apparent that this precipitation was generated by the ice mechanism operating above the top of the marine inversion. Between 1900 and 2000 the vertical-time section of Fig. 2 shows the marine layer deepening rapidly, and simultaneously the precipitation structure became more cellular and continued in this manner throughout most of 26 January. According to this brief description, the storm then divides itself into (a) stable flow pattern, inefficient release 1100 to 1400, (b) stable flow, efficient release 1400 to 2000, and (c) convective flow after 2000.

Fig. 3 shows the vertical time section of the storm of 2–3 April 1958. The storm is distinctive for its lack of appreciable moisture advection aloft. The marine layer, rather deep at the start of the storm, deepened further and apparently all of the precipitation was generated within this layer. Light amounts of rain occurred on the crest of the coastal ridge prior to 2000 but in the characteristic drop-size distribution associated with coalescence-produced rain. The first ice-crystal-produced precipitation occurred about 2000 when the top of the marine layer had reached about −10C. The radar precipitation structure was cellular and contined to be so during the balance of the storm. This storm thus had no stable precipitation-producing phase but consisted entirely of convective flow patterns.

Fig. 4 shows the vertical structure of a storm (18–19 February 1958) characterized entirely by stable precipitation-producing flow patterns. The marine layer remained shallow through most of the storm until the precipitation had effectively stopped. Precipitation began shortly after 1200 on the crest of the coastal ridge as the altostratus layer thickened rapidly with the advection of moisture into the area aloft. The radar structure of the precipitation showed patchy echoes until near 2400 when it became more uniform in character. Thereafter, nearly solid stratiform-type radar echoes were observed until about 0400 after which there was a gradual trend again toward a patchy character. The radar and vertical structure information suggest that stable flow and a rather inefficient precipitation release mechanism occurred until about 2400 followed by stable flow with much more efficient precipitation release through the remainder of the storm. Essentially no precipitation of a convective nature occurred.

## 5. Effect of storm stability

It has been indicated in the previous section that stable and convective flow patterns can be distinguished, in some cases, by combined use of vertical time sections of the storm and the character of PPI radar echoes. It is useful to consider the effects of these differences in orographic flow pattern on the area distribution of precipitation in Santa Barbara County. This will be discussed in terms of the three storms described in the previous section. Particularly striking differences occur in the simplified terrain consisting of the coastal plain and the coastal ridge. To demonstrate this the six coastal plain raingage stations (Fig. 1) have been averaged and the four ridge gages averaged to provide a "coast" hourly rainfall amount and a "ridge" hourly amount for each hour of the storms.

Fig. 5 shows the cumulative coastal precipitation amounts plotted against the simultaneous cumulative ridge amount (solid line) for the storm of 25–26 January 1958. A sharp break in the cumulative curve occurs after 2000 at the time of the change from stratiform to convective flow pattern described earlier. It is of interest that the slopes of the two segments of the cumulative curve remain relatively constant before and after the abrupt change at 2000.

Fig. 6 shows the cumulative curve of coastal vs. ridge precipitation for the storm of 2–3 April 1958, which was previously described as being entirely convective in nature. The slope of the cumulative curve in Fig. 6 is relatively steep in the sense of the ridge receiving much more precipitation than the coastal plain. Fig. 7 shows a similar curve for the storm of 18–19 February 1958. In this case the slope of the cumulative curve is much less and the ridge receives only slightly larger amounts of precipitation. It will be apparent that the slope shown in Fig. 6 compares with the convective portion (after 2000) of the curve in Fig. 5 and the smaller slope of Fig. 7 compares with the stable regime of Fig. 5 (before 2000).

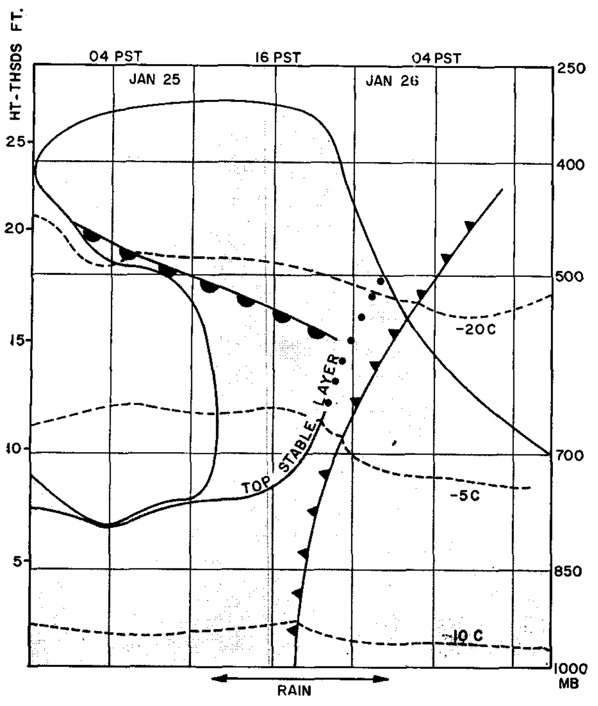

FIG. 2. Vertical time section: Santa Maria, Calif., 25–26 January 1958.

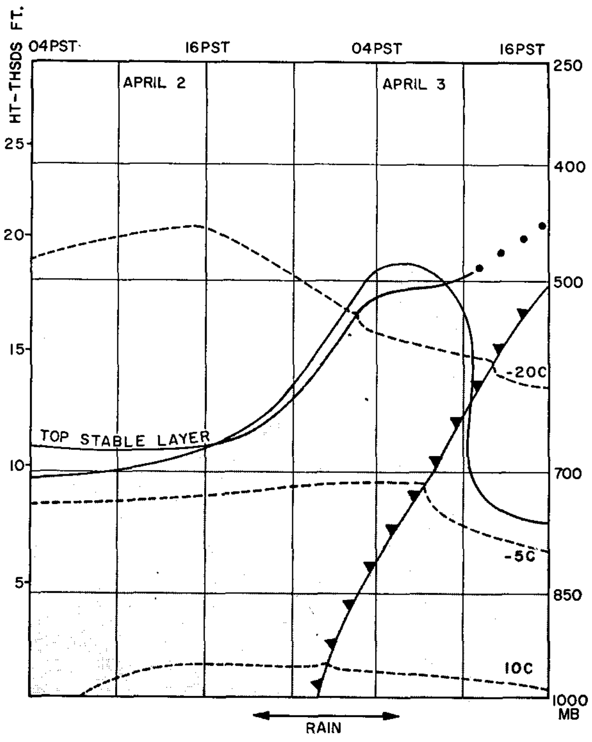

FIG. 3. Vertical time section: Santa Maria, Calif., 2–3 April 1958.

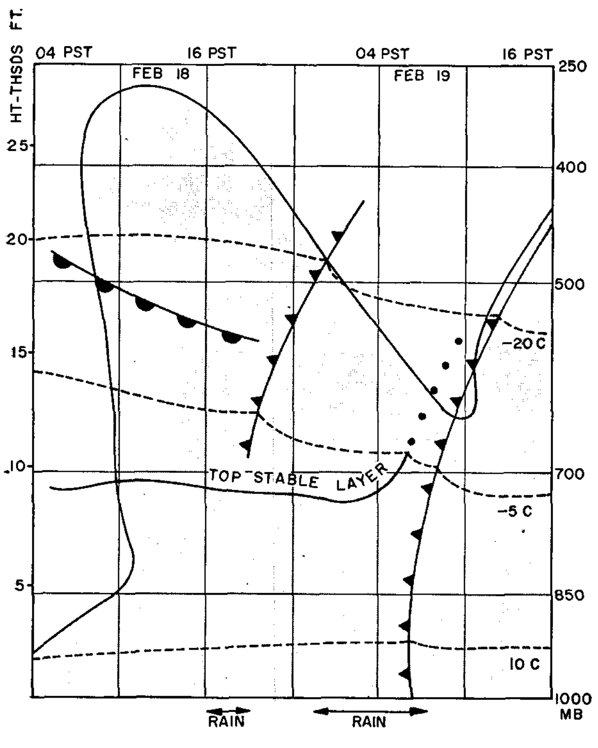

FIG. 4. Vertical time section: Santa Maria, Calif., 18–19 February 1958.

It is not unexpected to find such differences in rainfall distribution depending on vertical storm structure, although it should be pointed out that the downwind distance from the coastal raingage line to the ridge gage line is only about 4 mi. The interpretation of the difference is that the orographic flow over the ridge in the stable case ascends gradually, beginning at a point well offshore. The air aloft does not get much additional lift in passing from the coast raingage line to the ridge line and only small amounts of additional water are condensed out of the rising air. In the convective case the upward motion over the ridge does not begin in an important manner until air reaches the foothills of the ridge, about 2 mi inland from the coast. From this point on, the air ascends rapidly and much more moisture is condensed out over the ridge than over the coastal plain. This is an effect which is dependent on the orographic component of the precipitation pattern and is superimposed on whatever large-scale cyclonic factor may also be contributing to the precipitation.

The importance of the change in coastal-ridge precipitation distribution for the purposes of the present study is that it provides an assessment of the convective-stable character of the flow pattern to compare with the analyses of the vertical structure and radar echo characteristics. Such cumulative curves have been plotted for all storms in the 4-yr project period.

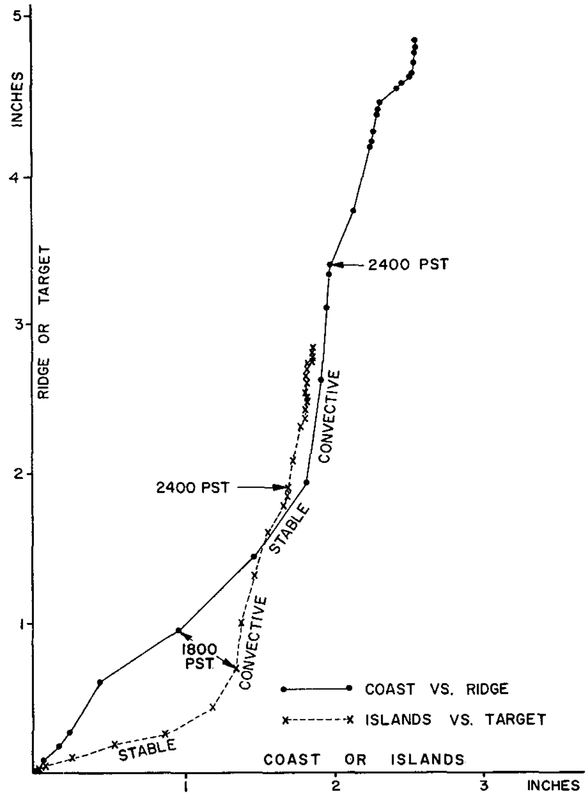

Fig. 5. Cumulative rainfall with stable-convective flow, 25–26 January 1958.

Similar cumulative curves were also plotted for other sectors of the County, but these yield little additional independent information on the separation of convective-stable regimes. Similar cumulative curves for the average of the Channel Islands raingages vs. the average of all of the Santa Barbara County gages have proved useful and examples are shown as dotted lines in Figs. 5, 6 and 7. These curves relate to variations in target-control rainfall and are discussed in a later section.

## 6. Summary of seedability

Adequate criteria on what constitutes a seedable storm are generally non-existent. Bergeron (1949) has suggested that orographic cloud systems with inefficient or inoperative precipitation release mechanisms may offer the best seeding opportunities. Ludlam (1955) has applied this suggestion to typical mountain clouds in Sweden. Thom (1957) reported results of statistical studies which suggest precipitation increases in orographic seeding projects. Elliott (1958), however, argues the case for seeding of convective-type clouds when only a small proportion of the water condensed out in the cloud reaches the ground. For the purposes of the Santa Barbara Project operations, Elliott in Santa Barbara Weather Modification Project (1960) has described the seedability in terms of the height of

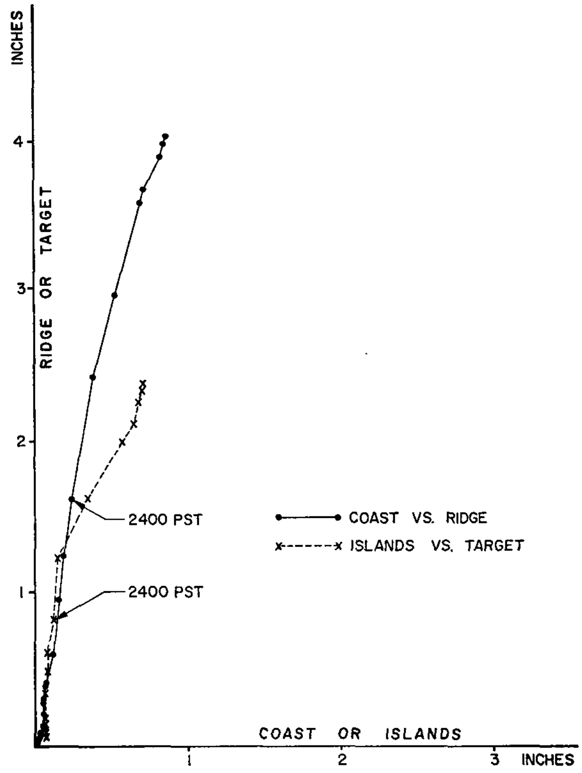

Fig. 6. Cumulative rainfall with convective flow, 2–3 April 1958.

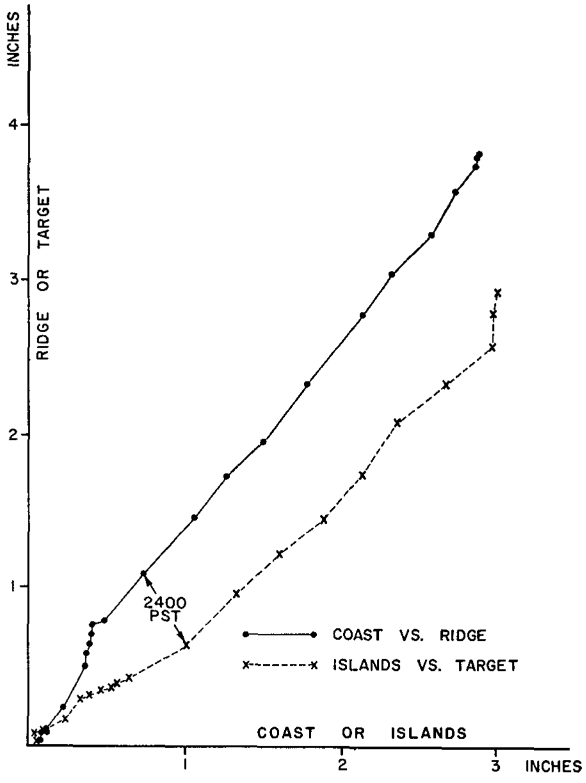

Fig. 7. Cumulative rainfall with stable flow, 18–19 February 1958.

the −5C level and the wind direction at the −5C level. The occurrence of the −5C level at a high altitude implies warm air aloft with considerable stability and relatively poor seeding conditions. A special, favorable category is made for low pressure centers aloft within 200 mi of the Project area. In the present work an attempt has been made to use the radar and storm structure data to develop a rational, qualitative separation of storm seedabilities into favorable and unfavorable categories based on the limited knowledge of such categories that is presently available.

Through the combined use of vertical storm structures, radar echo patterns and coast-ridge precipitation distributions, all storms and portions of storms of the 4-yr project period have been divided into (a) cases of stable flow, efficient precipitation release, (b) stable flow, inefficient precipitation release, and (c) convective flow. Obviously there is frequently not a sharp distinction between efficient and inefficient cases or occasionally even between convective and stable cases. Often one regime gradually transforms into another. However, in order to get an approximate measure of the frequency occurrence of each type, such a distinction has been made in each case. A summary of the occurrence of stable and convective types is given in Table 1 in terms of the total rain on the crest of the coastal ridge which occurred in each of the categories.

TABLE 1. Coastal ridge rainfall.

| Season | Stable | Convective |
|---|---|---|
| 1957 | 9.4 inches | 7.5 inches |
| 1958 | 19.4 | 19.9 |
| 1959 | 8.2 | 10.1 |
| 1960 | 14.5 | 1.8 |

About half of the stable type rain occurred under conditions of patchy, non-uniform horizontal precipitation structure which has been classed as a relatively inefficient release mechanism. The total number of hours, however, for this category is about five times the number of hours classified as efficient release, reflecting the lighter intensity of the inefficient class of stable precipitation.

It is necessary now to consider these categories in greater detail in regard to their possible seedability characteristics. For ground seeding operations there are two conceivable limitations on the usefulness of seeding: (1) the seeding material is not carried upward into the clouds to nucleating levels, or (2) if it is carried upward it may not find itself in a water environment when it reaches nucleating levels. In the latter case, in a snow or ice environment, the seeding would presumably be ineffective.

(*a*) *Convective release mechanism.* The convective category has been confined to those cases where evidence existed of mixing to at least 12,000 ft msl. It is at about this level, apparently, where the coast-ridge precipitation distribution changes from stable characteristics to convective characteristics (Figs. 2 and 5). Under these conditions seeding material released from the ground would be carried upward to nucleating levels rather readily. Also under these conditions, it would be expected that extensive regions of liquid water might exist at the nucleating levels as a result of localized, vigorous updrafts. It can be argued, therefore, that the convective conditions represent good seedability, at least in localized areas.

(*b*) *Stable, efficient release mechanism.* At the other end of the spectrum of possible seeding conditions is the stable flow case with uniform horizontal precipitation structure. Weickmann (1958) and Wexler (1960) have argued that precipitation efficiency is near 100 per cent in such cases of widespread stratiform precipitation. Wexler (1960) points out that for light precipitation of this character, little liquid water exists above −5C. Further evidence of this is given in numerous aircraft soundings by Cunningham and Atlas (1953) where extensive ice-crystal growth was frequently observed without appreciable liquid water above the −5C level. The general presence of the radar bright band in such precipitation is additional evidence of the ice-crystal character of the precipitation above the freezing level.

Under these conditions of limited liquid water content at or above the −5C level, seeding to increase the ice-crystal supply would not appear to be beneficial. The stable character of the flow, in addition, means that mixing from the ground upward does not take place readily to the proper levels for nucleation. Even in an orographic lifting situation such as encountered at Santa Barbara, the smooth, streamline flow over the mountains is not substantially coupled to the flow along the coast under the mountain top level. This is shown by the characteristically strong easterly winds at the surface along the Santa Barbara coast line in stable type storms while the flow at and above mountain top levels is from a southerly or southwesterly direction. Thus seeding material released at ground levels along the coast line would be transported upward so slowly that, if it reached nucleating levels, all semblance of control over the area being affected would be lost. Consequently, both from the standpoint of lack of liquid water at nucleating levels and difficulties in seeding from ground generators, the stable, efficient release type of precipitation is considered to lack seeding potential.

(*c*) *Stable, inefficient release mechanism.* Intermediate between types (a) and (b) is the stable but inefficient release case. Numerous examples are seen on the radar of isolated echo patches, obviously caused by localized streamers of ice crystals falling into the top of a lower cloud mass. In the terminology of Bergeron (1960), the spender or feeder cloud is present but the release cloud is intermittent. Some of these intermittent situations undoubtedly have available liquid water at nucleating levels which can be influenced by seeding. In other cases, it is likely that no liquid water exists at the proper levels and the condition would again be considered unseedable. The fact that approximately one-half of the stable precipitation amounts occur in the intermittent category suggests that further consideration of this type of condition is warranted to determine the extent to which additional ice crystals might be beneficial. The stable nature of the flow in this category presents the same difficulties in ground seeding as mentioned in (b) above. For proper effectiveness and control of the affected area, it is likely that aerial seeding should be employed.

The foregoing seedability discussion hinges around one central thought—i.e., liquid water which is permitted to exist at nucleating levels without freezing for any appreciable length of time may evaporate or shear off and become unavailable for release of moisture stored in the lower level spender cloud. This is particularly true in orographic flow conditions when evaporation may occur rapidly on the lee side or in convective flow where the lifetime of the cell motions may be short. To some extent, the result of seeding this type of orographic flow amounts to a redistribution of precipitation (e.g., from the lee side of the mountain to the windward side) as has been suggested by others. However, a net increase on an extended area basis is possible as illustrated by the simple, special case of seeding-produced precipitation on the windward slope when no precipitation would otherwise have occurred.

Table 1 can now be viewed from the standpoint of the preceding seedability remarks. If effective reasonably accurate targeting by ground seeding operations is insisted upon, only the convective storm cases offer much promise. These cases usually constitute about one-half of the total precipitation occurring on the coastal ridge and about one-half of the total precipitation hours. However, the variations from one year to the next may be very great, as evidenced by the very low amounts of convectively produced rainfall in 1960. Results of the study thus suggest that seeding of all storms leads to a dilution of the data sample with unaffected storms by roughly a factor of two. Under these conditions the time required to detect a given seeding effect is substantially increased.

It has been suggested that seeding might initiate the precipitation earlier than natural mechanisms or might prolong the precipitation after the natural mechanisms had become ineffective. Precipitation in the Santa Barbara area may start from the advection of moisture aloft in the form of ice-crystal clouds as shown in Fig. 2. An alternative initiation of precipitation is typified in Fig. 3 where the increased thickness of the marine layer ultimately permits the coalescence and/or ice-crystal process to operate within the marine air. Due to the stability of the marine inversion it is primarily the case shown in Fig. 3 where seeding might expect to operate prior to the beginning of natural precipitation. A summary of 47 storms at Santa Barbara during the 4-yr period shows that the precipitation was clearly initiated in the marine layer in only four cases. In all other storms there was considerable evidence of the presence of some ice clouds aloft which would have contributed to the early precipitation.

At the end of the precipitation, the typical storm model suggests convective activity which gradually subsides. In this event the natural ice-crystal mechanism would become less and less effective as the depth of the convective activity decreases. In general, the end of the storm is accompanied by a rapid drying of the air aloft as a result of subsidence. For 32 of the 47 storms, this sequence of events occurred and it is likely that seeding would have prolonged the precipitation, although not necessarily by large amounts or extensive periods of time. In the other 15 storms the air aloft did not dry out rapidly as in the typical model storm or convective activity was not prevalent at the end of the storm.

From this brief discussion, it is apparent in the Santa Barbara storms that much more prospect exists of prolonging the precipitation by seeding than of causing earlier initiation than would otherwise be expected.

## 7. Target-control relationships

It has been recognized previously that target-control rainfall relationships may vary depending on the characteristics of the storm influencing the area. Vernon (1955) produced a storm typing system for several target-control regions in California which resulted in families of target-control relations depending on storm type. Typing was accomplished by synoptic scale parameters, i.e., selected surface pressure gradients and the upper level wind direction at Santa Maria, Calif. The present approach makes use primarily of variations in the precipitation mechanism in terms of vertical storm structure characteristics to stratify the Santa Barbara storms according to target-control relationship.

A reasonable, unaffected control area for Santa Barbara County is the Channel Islands region about 25 to 30 mi south of the Santa Barbara coast line. Neyman *et al.* (1960) have used a combination of the Channel Islands and a mainland region to the north of Santa Barbara County as their control area. For the purposes of illustrating the effects of storm structure on target-control relationships only the Channel Islands region has been used in the present study.

Figs. 5, 6 and 7 show, as dashed curves, cumulative hourly precipitation amounts for the average target station plotted vs. the average Islands rainfall. Fig. 5, for example, shows a sharp increase in Islands-target slope occurring near but slightly earlier than the slope change for the coast-ridge rainfall. It is apparent, in this case, that the convective storm structure results in a substantially different Islands-target relationship than the stable structure which preceded it. Comparisons of the dotted curve in Fig. 5 with the convective slope of Fig. 6 and the stable example of Fig. 7 show similar effects of storm structure on target-control relationships.

The division of storms into stable and convective flow types which was used to construct Table 1 has been applied to a comparison of the simultaneous (no time-lag) precipitation in the Islands and the target area of Santa Barbara County. The target area rainfall was computed from an average of 30 rainfall stations with an appropriate area-weighting factor. Results are shown in Fig. 8 separately for the stable and the convective cases. Rainfall amounts are plotted in terms of the square root of the target average vs. the square root of the Islands average. This is in accordance with the procedure of Neyman (1960). Least squares regression lines are further shown for both scatter diagrams. Correlation coefficients in Fig. 8 are 0.82 and 0.81 for the stable and convective cases, respectively. These may be compared with 0.73 for the total combined sample.

Fig. 8 indicates that relatively greater amounts of precipitation occur in the target during convective-type storms than in stable cases. This is apparently the result of numerous high-elevation gage locations in the target. Maximum elevation of any gage in the Islands is 1470 ft msl while about half of the gages in the target are located over 3000 ft msl. A source of considerable difficulty in statistical treatment of the data is that the convective cases show a natural bias in the direction of large target rainfall amounts compared to the entire data sample. It has been suggested earlier that it is primarily these cases where one should look for seeding effects and it is of some importance to eliminate the convective data bias in order to judge the true seeding effectiveness.

Seeded and unseeded storms are designated separately in Fig. 8 for both the stable and unstable cases. It is apparent from the figure that no striking seeding effect is present in either case. Some of the storms not seeded in Santa Barbara County were seeded in Ventura County and no account has been taken of possible effects in Santa Barbara County.

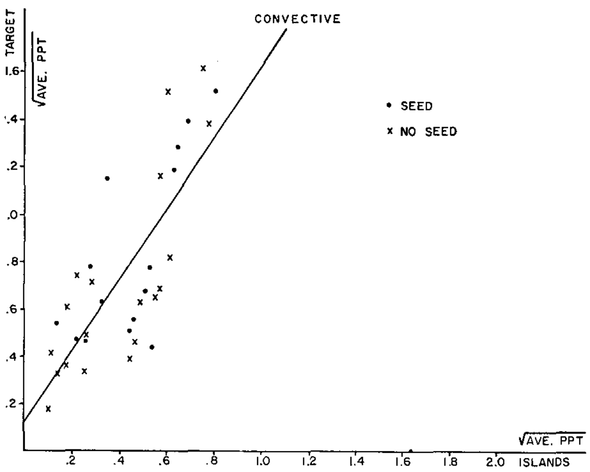

Fig. 8a. Islands-target rainfall regression for convective flow.

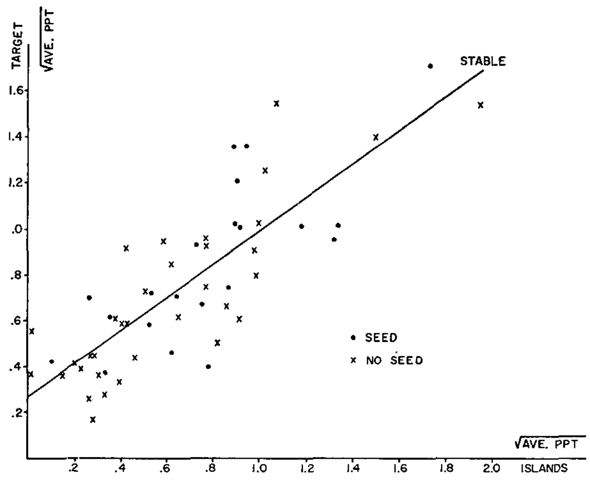

Fig. 8b. Islands-target rainfall regression for stable flow.

## 8. Conclusions

The Santa Barbara Project resulted in an inconclusive test of seeding effectiveness due to excessive variability between target and control area precipitation and a consequent lack of sensitivity in the statistical tests. These difficulties were increased by seeding many storms and portions of storms where the effectiveness of the seeding was likely to have been limited or negligible. This resulted in a dilution of whatever seeding effects may have been produced in the balance of the storms.

Target-control relations were materially affected by variations in vertical storm structure characteristics. Rainfall in Santa Barbara County was much greater relative to a nearby control area (Channel Islands) for storms with convective characteristics than for stable storms. Stratification of the data into convective and stable type storms increases the target-control correlations and thus permits the detection of smaller precipitation increases.

An attempt has been made to describe the relative seedability of each storm during the four-year project period, at least in a qualitative way. The underlying principles of seedability are taken to be 1) seeding material can be transported readily from the ground to nucleating levels, and 2) liquid water exists at nucleating levels which, if not converted to ice promptly, may be lost due to evaporation and become unavailable for release of moisture in the lower levels of the cloud mass. Under these conditions it is shown that about half of the rainfall in the Project area occurs under seedable and about half occurs during stable periods when upward motions are restricted and/or when little liquid water appears to exist at nucleating levels.

In the foregoing, the stratification of storms into seedable and nonseedable categories (convective and stable types) also provides improvements in target-control relations. Improvements in statistical design thus result simultaneously from added test sensitivity and a lack of data dilution due to unaffected storms.

Division of storms into stable or convective characteristics has been accomplished by the combined use of several parameters and is less objective than would be required for rigorous control of a statistical seeding project. The use of RHI radar during the last year of the Project suggests that effects of these various parameters are largely integrated into the vertical structural characteristics of the precipitation. It is suggested that continuous quantitative monitoring of this vertical structure by radar would provide the neccesary objective separation of winter storm classifications.

## 9. Recommendations

The success of the statistical seeding program of Santa Barbara was dependent on the existence of adequate control area rainfall comparisons. The use of 12-hr rainfall units made the determination of adequate control area relations particularly difficult. Rainfall totaled over longer time intervals generally shows higher correlations between adjacent areas. Methods of improving the 12-hr correlations are limited by (1) inadequate physical understanding of the causes of natural rainfall variations in the mesoscale geographical range of 5 to 100 mi, and (2) inadequate criteria for distinguishing between seedable and unseedable storms.

A future seeding program of the Santa Barbara type would benefit from preliminary physical studies on a mesoscale basis prior to the design of the statistical program. These studies should provide (1) an understanding of natural variations in target-control relations, (2) information on the occurrence of seedable conditions, and (3) an understanding of local flow patterns in the area which might influence the transport of seeding material. A better understanding of seedability will require localized seeding, probably by aircraft, as a part of the physical studies. These studies would require the support of area physical measurements by radar, radiosonde, and by surface wind observations to a considerably greater extent than accompanies most seeding programs. The results of such studies and a continuing program of extensive physical measurements during the seeding operations should permit the design of a statistical program optimized through physical understanding to produce definitive results in a calculable interval of time.

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## REFERENCES

Bergeron, T., 1949: The problem of artificial control of rainfall on the globe. *Tellus,* **1**, 32–43.

——, 1960: Problems and methods of rainfall investigation. *Geophys. Monogr. No. 5,* Amer. Geophys. Union, pp. 5–30.

Cunningham, R. M., and D. Atlas, 1953: Growth of hydrometeors as calculated from aircraft and radar observations. *Proc. Toronto Meteor. Conf.,* Toronto, Canada, Amer. Meteor. Soc., pp. 276–289.

Elliott, R. D., 1958: California storm characteristics and weather modification. *J. Meteor.,* **15**, 486–493.

Ludlam, F. H., 1955: Artificial snowfall from mountain clouds. *Tellus,* **7**, 277–290.

MacCready, P. B., T. B. Smith and C. J. Todd, 1958: Discriminations between condensation-coalescence and ice crystal produced precipitation. *Proc. 7th Wea. Radar Conf.,* Miami, Fla., Amer. Meteor. Soc., pp. A17–23.

Neyman, J., E. L. Scott and M. Vasilevskis, 1960: Statistical evaluation of the Santa Barbara randomized cloud seeding experiment. *Bull. Amer. meteor. Soc.,* **41**, 531–547.

Santa Barbara Weather Modification Project, 1960: Interim Report of the Board of Directors, Calif. Dept. of Water Resources, 144 pp.

Thom, H. C. S., 1957: Final report, Advisory Committee on Weather Control, **2**, 25–50.

Vernon, E. M., 1955: *Weather modification operations in California.* California State Water Resources Board, Bull. No. 16, pp. 163–193.

Weickmann, H., 1958: The efficiency of natural rain and its determination. USASRDL Tech. Report 1973, July, 14 pp.

Wexler, R., 1955: Radar analysis of precipitation streamers observed 25 February 1954. *J. Meteor.,* **12**, 391–393.

——, 1960: Efficiency of natural rain. *Geophys. Monogr. No. 5,* Amer. Geophys. Union, pp. 158–163.