Santa Barbara Pyrotechnic Cloud Seeding Test Results 1967–70[1]

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ABSTRACT

Tests of the effectiveness of ground-released pyrotechnics in enhancing precipitation in storms in Santa Barbara County were conducted during the three winter seasons of 1967–68, 1968–69 and 1969–70. The mode of operation and the type of pyrotechnic device remained fixed through the three years in order to develop a large sample of data. The observation unit employed was a convective band embedded within a general storm system. A series of pyrotechnic candles of the LW-83 formulation were ignited just prior to and during the passage of convective bands over the seeding site, located on a 3500-ft mountain ridge in the Santa Ynez mountains. The bands were detected upwind of the test area and tracked into the test area by use of telemetered raingages and weather radar. Out of a total of 85 bands, 43 were seeded and 42 not-seeded. The selection of bands to seed was made on a random basis following declaration of the approach of a seedable band.

Over 60 recording raingages extending over an area of $\sim$1500 mi^2 provided the basic evaluation data. Soundings taken with a GMD-1 system just prior to band passage into the test area provided useful air mass documentation. The cases were stratified by stability and 500-mb temperature categories.

The statistical analysis shows that there was a statistically significant difference between the distributions of seeded and not-seeded band precipitation totals for stations distributed over a several hundred square mile area downwind of the point source of nuclei. Indications were that precipitation was increased by 50% or more. The effect was greatest in the case of the warmer and more unstable categories.

When the overall precipitation is considered, including the between-band (not-seeded) component, the net increase is about 32%. Precipitation between bands was not significantly changed by seeding.

A computerized seeding-area-of-effect model was employed to predict an envelope of areas of seeding effect for the various categories of seeded bands. The bulk of the stations for which seeded precipitation distributions were significantly different from the not-seeded distributions fell within these areas.

The test results show the value of seeding winter convective orographic systems with this pyrotechnic device. The test results also demonstrate the value of employing the convection band as a natural unit of seeding and of observation. The sensitivity of the statistical evaluation was greatly enhanced through the use of this approach.

1. Background

This article presents the results of three winter seasons, 1967–68, 1968–69 and 1969–70, of testing the effectiveness of ground-based seeding with pyrotechnic devices for producing precipitation increases over a mountainous watershed. The test area was the rugged back country of Santa Barbara County in the northern portion of Southern California. The tests were conducted for the Earth and Planetary Sciences Division, Naval Weapons Center, China Lake, Calif., through contract with North American Weather Consultants.

A number of previous weather modification projects and tests had been conducted in this general area since the early 1950's. The most notable previous test was the Santa Barbara project of 1957–60 (Neyman *et al.*, 1960), a cooperative program during which a randomized test was made of the effects on precipitation of a network of approximately 30 ground-based silver iodide smoke generators distributed at low valley locations generally upwind of the mountainous region. In this test, a 12-hr unit of observation was employed. The results indicated some effect of the seeding on precipitation, but a question was raised concerning differences in the sample from season to season. There was a strong implication of the need for more collateral physical observations to be used in stratifying the data in meaningful ways.

Subsequent field studies of storm structure in the Santa Barbara area clearly identified the existence of

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TABLE 1. Composition of the nucleant agent LW-83.

Material	Percentage by weight
Silver Iodate	78
Aluminum	12
Magnesium	4
Binder	6

convective cells grouped into bands that passed through the area during most storms (Elliott and Hovind, 1964). A more recent field study has revealed similar structure in the northeastern United States (Kreitzberg and Brown, 1970). The presence of updrafts and associated supercooled cloud water within the bands provided ideal conditions for entraining and distributing the nucleant smoke and for artificial nucleation. A post analysis of the Santa Barbara seeding data (Elliott, 1962) showed that by focusing on periods of heaviest precipitation (corresponding to convection band activity), some interesting apparent effects of seeding were revealed.

During the same period that this clarification of the mesoscale processes relevant to cloud seeding was underway, a great deal of attention was being devoted to developing new nucleating agents and devices. In particular, pyrotechnic seeding devices were developed which generated orders of magnitude higher outputs of nuclei effective at warmer temperatures.

2. Project design

With this background, it was first decided to design a test program which would exploit the existence of convection bands, and second, to incorporate into the operational procedures the new and more effective seeding devices. Under the first goal, the convection band was employed as a seedable unit to be treated or not-treated according to random selection. Comparable samples of seeded and not-seeded bands could be built up over a period of time. By avoiding the mixture of precipitation mechanisms which occurs when a whole storm or some arbitrary fixed time period is employed as a unit, the seeding would have a clear-cut physical significance and be more sensitive to statistical tests.

An even sharper evaluation of effects might be expected if single convection cells were the unit of observation. However, this would require aerial seeding under difficult and hazardous flight conditions over rugged terrain, a situation which was not feasible at the time of the experiment. The smallest and most definite practical natural test unit was therefore the convection band.

Convection bands usually take from one-half to one and one-half hours to pass over a point. During this time they produce rainfall of several tenths of an inch up to over an inch. Rates may be as high as several inches per hour for 5–10 min as individual cells move overhead. Bands are usually spaced 3–4 hr apart. Between bands there is light, or even no precipitation in the valleys, and generally light precipitation in the mountains.

In a post analysis, bands can best be identified and tracked by a detailed analysis of all recording raingage records. In operation, however, it was found necessary to employ telemetered raingages located at key points upwind of the test area in order to identify the convection bands in real time and track them into the test area. Weather radar was used to supplement the telemetered gage tracking procedure. A local sounding system was also employed to determine air mass characteristics within each band.

In a further effort to sharpen the definition of the physical treatment of seedable systems, it was decided to employ a single fixed source of nuclei. Furthermore, this source was located on a 3500-ft mountain ridge, at the highest location available immediately downwind from the coastline.

With a single source it was not possible to adjust the seeding mode so as to take into account the time variations in wind flow as it affects targeting. However, it was felt that this disadvantage could be counteracted through the use of a numerical seeding model which would predict the likely area of enhanced precipitation under seeding conditions for a given wind flow pattern and air mass structure.

Under the second goal, the use of a more effective seeding device, a pyrotechnic device, was employed which emitted almost pure AgI smoke. The reason for this choice was to avoid the disadvantages of the silver iodide-sodium iodide complex.

It had earlier been supposed that the complex was active as a freezing agent at temperatures near −5C. If the effluent from these devices were to be introduced into a relatively warm cloud base, it is conceivable that only a limited amount would be effective at temperatures > -14C. The complex $NaI \cdot 2AgI$ is deliquescent and upon being transported in air at relative humidities $>35\%$ will soon begin to take up water, forming a series of hydrated complexes from which AgI may or may not precipitate. If entrained in an updraft, liquid droplets soon form on the particles because they act as condensation nuclei. Following adequate dilution, the complex breaks down and AgI is precipitated. The freezing point is determined by the size of the largest AgI particle precipitated. On the other hand, relatively pure AgI does not undergo these transformations. Because of its limited solubility in water, only the very smallest particles are destroyed, the great proportion of them surviving for long periods in liquid water.

The devices used in the experiment were pyrotechnic fusees designed by the Naval Weapons Center and produced by Wilson Weather Control Corporation. A full description is given by St. Amand *et al.* (1970). The composition is shown in Table 1.

The smoke produced is 78% AgI with minor amounts of Al_2O_3 and MgO balanced to produce spinel. Each fusee dispersed 400 gm of AgI smoke over a 3-min period.

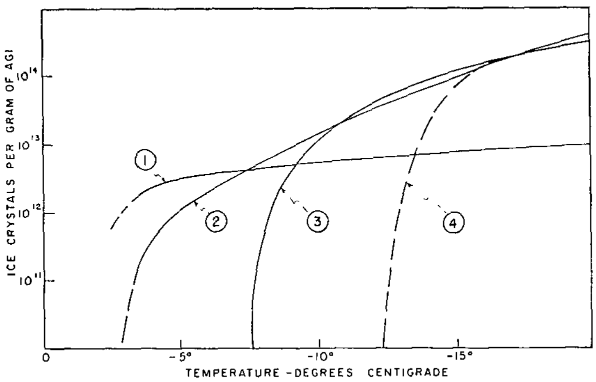

FIG. 1. Comparison of number of effective nuclei per gram of AgI as a function of temperature for different nucleating agents: curve (1) is the basic LW-83 pyrotechnic, curve (2) $2AgI \cdot NH_4I$ in acetone, and curve (3) $2AgI \cdot NaI$ in acetone, the first three being based on cold box tests. Curve (4) shows how $2AgI \cdot NaI$ is hypothesized to behave following wetting if it were introduced into the base of a cloud at a relatively warm temperature.

The activity of the smoke has been characterized by Donnan *et al.* (1970); their results for this and for two types of acetone burner products are shown in Fig. 1. While the cold box results may not be the same as would be obtained in a cloud, the same dosage rate liquid water content was used.

The LW-83 nucleant [curve (1) of Fig. 1] has been tailored to produce an almost monodispersed smoke active at as warm a temperature as possible. The activation temperature lies between −2.0 and −2.5C, with the particles being somewhat larger than those from an acetone burner. Curve (2), showing the results for an acetone burner using ammonium iodide as a solubilizing agent is similar, and although less effective at temperatures > -7C, is more productive at lower temperatures. Its behavior at warmer temperatures could be improved by increasing the concentration of the AgI in the solution. This agent should be equally as effective as LW-83.

Curve (3) is for the 2 AgI-NaI complex in the same AgI concentration as in (2). The maximum effective temperature is about −7.5C. Curve (4) shows the behavior hypothesized for the $2AgI \cdot NaI$ complex after it has been subjected to extended traverse through the lower part of a relatively warm cloud. By using a relatively pure AgI, it was believed that a freezing agent could be activated between −2.0 and −3.0C. Upon introduction into an updraft, condensation probably occurs on all but the smallest particles.

The basic meteorological and operational decisions were made by the meteorologist designated as Project Director who was located at the Project Control Center at Santa Barbara Airport in Goleta. At this point he had available, in addition to standard meteorological data received via weather teletype circuits and facsimile, telemetered raingage data, radioed weather radar reports, and the latest local sounding data. He identified and tracked the bands and made the decision as to their seedability just before they entered the test area. Once identified as seedable, the Project Director treated every band as though it was being seeded although the actual decision as to which band would be seeded was made at the seeding site through reference to a book of pre-prepared randomly selected yes or no decisions. The ratio of yes to no decisions was approximately one. Up until the time that data analysis was completed, the Project Director and other personnel not at the seeding site did not know which bands had been seeded. The observational routines were continued through each band passage as though it had been seeded.

Fig. 2 shows the principal topographic features of Santa Barbara and western Ventura Counties. Santa Barbara County consists of a series of west-to-east oriented mountain ridges with valleys between. The range peaks are over 6000 ft to the east, sloping down to near sea level in the west and northwest. The south coastal strip runs west to east south of the Santa Ynez range, the southernmost range in Fig. 2, and contains the cities of Santa Barbara (stations 225 and 234) and Carpinteria (station 208). This is outside the anticipated area of effect of the program. Other reference points are Santa Maria (raingages 213 and 235) and Lompoc (raingages 2 and 215) in the western portion of the county. The test area and control area boundaries are marked on the map.

Initially, four telemetered upwind gages (nos. 1–4) were installed over the western portion of the Santa Ynez valley and in the Santa Maria area. This network was later expanded to include a gage to the southwest of the seeding site (no. 18) and two gages within the anticipated area of effect (nos. 6 and 15). Sixteen gages were installed for the project to determine the effects of the seeding program throughout the Santa Ynez valley, on the South Coast, and in the interior mountain sections. Raingages in Ventura County are identified in Fig. 2 by the letter V preceding the gage circle. These additional gages, which cover all of Santa Barbara County and the western portion of Ventura County, bring the total of gages employed in the analysis of the data to over 60.

A modified 3-cm marine radar was installed and operated from the 3500-ft ridge location and is shown by the solid triangle on Fig. 2. It offered an unobstructed view of the upwind areas. During the second year it was moved northward across the Santa Ynez valley to a site on Figueroa mountain (site C-2) at the 4500-ft level. During the last season it was again operated at the original site. The seeding was conducted at the original radar site throughout the three years.

A GMD-1 rawinsonde receiver was established at the Project Control Center (designated by the solid square on Fig. 1) at the Santa Barbara airport and rawinsonde balloons were released during band passage at headquarters.

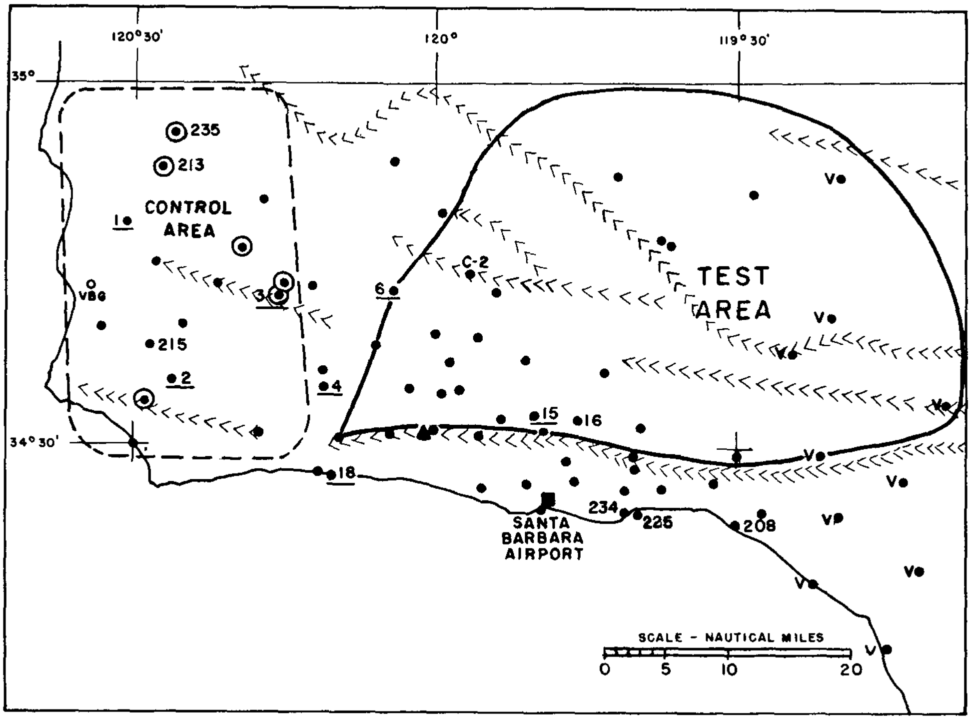

FIG. 2. Santa Barbara pyrotechnic seeding and control test areas. The test area boundary is marked by a solid heavy line, the control by a dashed line. Mountain ranges are designated by vee hatched lines. Raingage sites are designated by solid circles, with control raingages being open ringed and telemetered gages underlined. Numbered gages are those discussed in text. The seeding and radar site is indicated by a solid triangle, and Project Control Center by a solid square.

3. Operational procedures

Weather situations were monitored in the Project Control Center, and on the approach of a storm, project personnel were alerted and assumed their posts. The Project Director then examined his upwind telemetry and weather radar reports for the approach of the first convection band. When this band appeared, and was confirmed by tracking across the control area, the seeding technician was informed when to ignite the first seeding flare.

Typically, the operation would occur in two stages: 1) a band alert stage, and 2) a band confirmation stage. A band alert was called when any one of the telemetered stations reported 0.02 inch in a 15-min period or when the radar operator reported a banded echo approaching the target area.

If the band was detected by radar, the band was confirmed when any telemetered station recorded 0.02 inch (15 min)$^{-1}$ provided this coincided with the radar position of the band. If the band was detected from raingage data, the band was confirmed either by a radar report of the band or by a subsequent precipitation report of 0.02 inch (15 min)$^{-1}$ from any other telemetered station. For tracking purposes, the most important feature was the continuity of similar events at the various upwind telemetered gages. Once the band was confirmed and tracked to a position just upwind of the test area, it was declared seedable. Such a declaration was made regardless of prior information suggesting that the base of convection might lie above the seeding site. Following declaration of seedability, a field technician referred to the book of prepared randomly made decisions to determine whether or not to seed the band. The first ignition was timed to occur just prior to onset of band precipitation. Other units were ignited every 15 min until the meteorological decision was made that the band had passed the site.

The routine of band recognition, subsequent seeding or simulated seeding, and observation continued throughout each storm period or until termination of operations because of unfavorable wind direction or technical reasons.

During a portion of the winter seasons of 1968–69 and 1969–70, additional airborne measurements and observations were made during and between storms by personnel from Weather Science, Inc., Norman, Okla., under a separate contract from the Naval Weapons Center. These data included in-flight ice nucleus measurements, cloud physics measurements, and cloud top photography of band and storm structure.

The flight observations have confirmed indications determined from the scattered observations in previous years, namely, that within the convection bands the cloud top extends 8000–13,000 ft above the cloud top between bands. The tops in bands showed considerable evidence of ice, and in strong bands (heavier precipitation), this ice obscured the band pattern and considerably reduced the value of the on-top photographic work. In weaker bands, individual anvils could be seen protruding up from below.

Between bands the tops had a rough cumuliform appearance, but the elements were smaller than within the bands, resembling closely packed cumulus congestus. There were usually some breaks through which the ground could be seen.

Typical cloud tops in the bands were 20,000–25,000 ft while tops between bands were 7000–12,000 ft.

4. Analysis procedures

The first step in the analysis was the tracking of the precipitation band pattern across the gage network on the basis of plots of all available precipitation and radar information. This was achieved by a meteorologist skilled in the analysis of precipitation bands. In order to insure a lack of subconscious bias, the meteorological analyst was uninformed as to which bands were seeded. Once a rational analysis for the band movement was obtained, each station was assigned a total precipitation value for that band. A second meteorologist, who was not aware of either the seeding schedule or the band analysis results, made an evaluation of the air mass characteristics of each band from the sounding data taken at the Santa Barbara Airport and at Vandenberg Air Force Base. Vandenberg (VBG on Fig. 2) is 30 n mi west-northwest of the seeding site.

The soundings taken during the passage of the bands were classified according to four categories of air mass stability (Table 2). The lower air mass is assumed to be lifted orographically over the Santa Ynez crest (about the 900-mb level). In the convectively unstable air mass the base and top of the positive area for the parcel lift method are located, and identified as convective instability base (CIB) and convective instability top (CIT). Radar echo tops have shown a good correlation with the CIT in Southern California. The total number which fell in each category are also shown in the table.

The most seedable cases fall into category 1. In these cases the ground level smoke plume has a high assurance of being entrained into convection, a necessity if the nucleant is to reach the −4C level.

Bands falling into category 2 are considered to be marginally seedable since the CIT is above the seeding site. If local heating is present near the seeding site or if there is strong mechanical turbulence over the ridge, then the nucleant may be entrained into convection.

Table 2. Aerological stability categories.

Category	Definition	Number in category
1. Unstable, low CIB*	CIB $\leqslant$ 900-mb level	54
2. Unstable, high CIB	900-mb level $<$ CIB $\leqslant$ 800-mb level	21
3. Stable (A)	800-mb level $>$ CIB	5
4. Stable (B)	Entirely stable or CIT < -4C level	5

* Convection instability base.

Table 3. 500-mb temperature classes for stability category 1.

Category	T_{500} (°C)	Number of cases
1. Warm	$-17.5 \geqslant T \geqslant -12.8$	17
2. Medium	$-17.5 > T > -22.5$	19
3. Cold	$-22.5 \geqslant T \geqslant -32.0$	18

Bands falling into categories 3 and 4 are not considered seedable from the 35-ft level source. Category 4 usually occurs in association with the wind shift line of a sharp frontal zone.

In the analysis discussed herein, the seeding data are presented either in pooled form (all bands), or in category 1 form. The other categories are listed in Table 1 only for the sake of completeness. The individual analysis of categories 2, 3 and 4 tended to indicate a trend toward less seeding effect with increasing category number but the limited sample size combined with the lessened effect provided little information having statistical significance.

Recent interest in the relation between cloud top temperature and seeding effects (Grant and Mielke, 1967) prompted a further categorization by temperature. Following Grant's lead, the cases were stratified on the basis of the 500-mb temperature, which is near the average CIT in this area. The 54 cases in stability category 1 were subdivided into three approximately equal classes, as shown in Table 3.

The basic test statistic used to determine the area of effect and magnitude of the precipitation increase for a given category was the double ratio

$$R=\frac{\bar{T}_s/\bar{C}_s}{\bar{T}_{ns}/\bar{C}_{ns}}, \tag{1}$$

where $\bar{T}_s$ is the test station seeded band average precipitation, $\bar{C}_s$ the control area seeded band average precipitation, $\bar{T}_{ns}$ the test station not-seeded band average precipitation, and $\bar{C}_{ns}$ the control area not-seeded band average precipitation.

This provides a simple way of comparing seeded and not-seeded precipitation ratios, corrected for the natural intensity of a given band as measured by the control area average precipitation.

In order to test the statistical significance of the observed precipitation distributions, a non-parametric ranking test (Mann-Whitney U Test) was applied to the distribution of the seeded and not-seeded target to control ratios. In the present study, the null hypothesis is that seeded and unseeded band precipitation at each station are drawn from the same population. The seeded and not-seeded band precipitation ratios were

TABLE 4. Number of bands during the three years 1967–68, 1968–69 and 1969–70.

Year	All categories Seeded	All categories Not seeded	Category 1 Seeded	Category 1 Not seeded
1967–68	11	11	10	11
1968–69	19	22	6	9
1969–70	13	9	11	7
All	43	42	27	27

separated into the two independent groups. These were then ranked and U values calculated for each station. These U values were then compared to the critical U values to determine the level of significance. For a more complete treatment of this test, the reader is referred to Siegel (1956).

The seeding model was employed as an adjunct to the statistical evaluation. The particular computerized model employed is known as the area-of-effect model and the details of its construction may be found elsewhere (Elliott, 1969). In this article only a brief resume of its principle features will be given. The model is employed to predict the areas of effect in orographic seeding. It is a steady-state model in which the nucleant is dispersed in a plume drifting with the low-level flow until entrained into convection. The maximum drift time was 1 hr. On rising to lower temperatures after entrainment, nucleation occurs in a series of 2C steps. Short-period stepwise computations are made of the growth by diffusion and accretion of the sets of ice particles thus formed. The downward flux of particles through the side of a tilted convection column, and their drift on descent to the ground is computed. The model includes a sub-model of the wind flow over the barrier and a parameterized version of motions within convective cells and of convection cells within bands.

In particular, the model predicts the boundary of the first possible ground-level seeding-produced precipitation enhancement downwind of the source under its basic assumptions. It provides a less clear-cut definition of the downwind limit of effects because a large number of small ice particles trail off in the downwind side.

In application an envelope of the area of effect is determined for all of the cases falling into one of the analysis categories. Because of the variation from band to band, the composite area of effect is much broader than that computed for a single band.

5. Results

The program during the 1967–68 season began in late January 1968 and a relatively small data sample was obtained in a below-normal precipitation year. Based on the experience of the first year's program, a few raingage locations were changed and the site of the weather radar was moved, but all other aspects of the test program were retained during the next winter season. While the 1968–69 season experienced much above normal precipitation, it was necessary to stop seeding entirely during the period of heaviest precipitation when the watershed became saturated; thus, the sample was again reduced. The winter season of 1969–70 was much like that of 1967–68 with below normal precipitation observed throughout the county although all possible storms were sampled.

The 1967–68 season sample contained relatively cold storms, in contrast to the second year which produced many warm storms moving up from lower latitudes and containing many bands with high convection bases. The third year again contained a large percentage of cold storms with unstable air masses.

Table 4 displays the number of seeded and not-seeded bands in each year, and for the three years as a whole.

The double ratio for the 43 seeded and 42 not-seeded bands, representing the total three year sample of 85 bands, is shown in Fig. 3. Ratios of over 1.5 (indicating 50% more precipitation in the seeded cases) lie along a north-south oriented axis about 25 n mi to the east of the seeding source. There also appears to be an extension of higher values westward along the Santa Ynez ridge as far west as the seeding site. Thirteen of the stations showed the null hypothesis to be invalid at the 5% level of significance (indicated by an asterisk on the figure), according to the Mann-Whitney U Test (one-tailed). This signifies a high likelihood of a real difference in distribution of precipitation between the seeded and not-seeded sample.

The composite of the area-of-effect envelope computations for the seeded cases is shown by the heavy dashed line. It should be noted that 12 of the 13 stations which showed significance at the 5% level lie within the area of effect boundary.

The center of this area is closer to the upwind boundary of the envelope than to the downwind boundary. The model predicts such a distribution of precipitation, the particles falling out far downwind being relatively small.

On the basis of the model calculations, it is unreasonable to expect any precipitation to appear as far west as the high ratio shown near the nuclei source. If there is indeed an increase in precipitation at this location due to seeding, it would have to be the result of some dynamically produced effect, or possibly due to an initial drift of the nuclei in the upwind direction under the influence of some low level eddy.

Fig. 4 displays the double ratios for stability stratification 1, those cases considered most seedable. The pattern of double ratios is quite similar to the pattern of Fig. 3, but the area including ratios of over 1.5 is somewhat larger. Fifteen of the stations, all with positive ratios, indicated rejection of the null hypothesis at the 5% level of significance. Thirteen of the 15 significant stations lay within the boundary of the area of effect.

Fig. 5, the analysis for the bands with the warmest 500-mb temperature, shows high double ratios over a

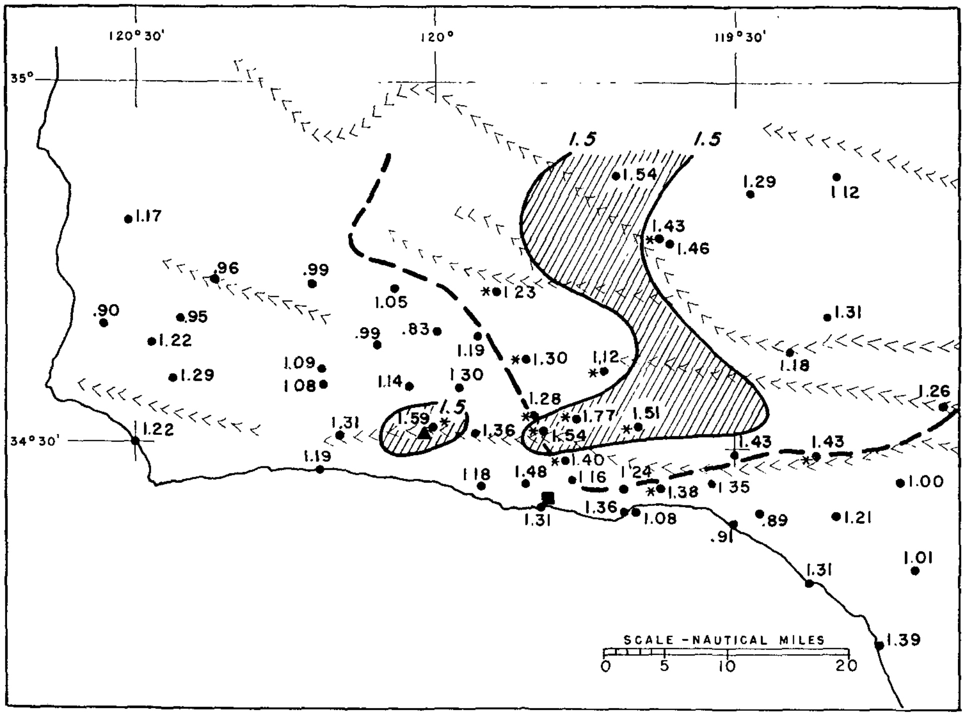

Fig. 3. Double ratio and computed area of effect, 1967–70, for all bands. Forty-three bands were seeded, 42 not seeded. The heavy dashed line describes the envelope of the computed areas of effect for the seeded cases. Thin solid lines show the analysis of the double ratios with areas of 1.5 or greater indicated by hatching. Stations marked by an asterisk indicate significance at the 5% level.

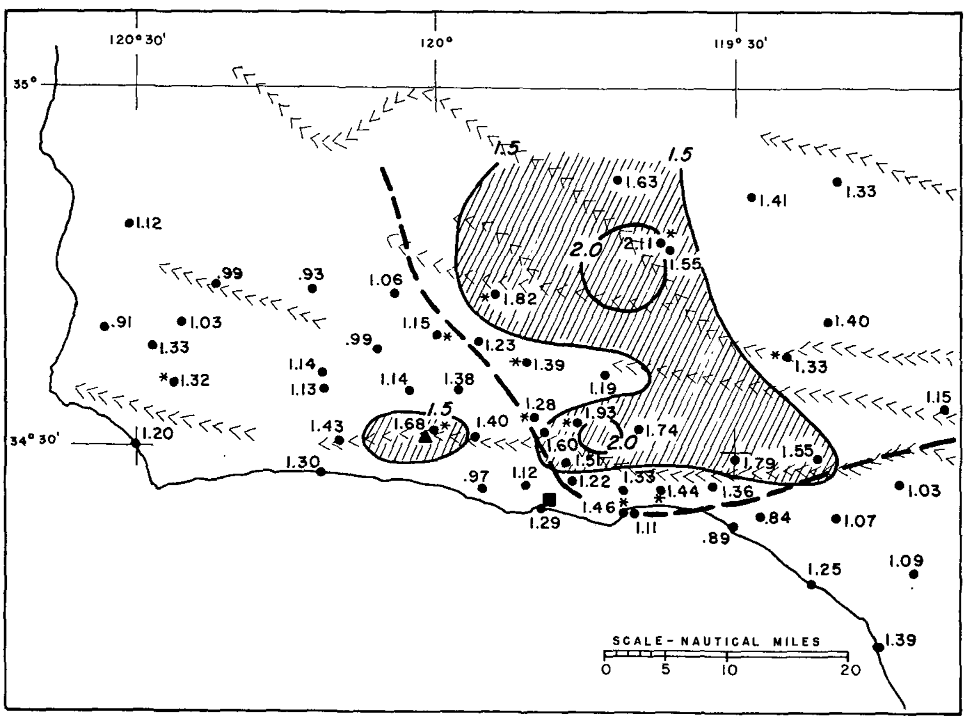

Fig. 4. Double ratio and computed area of effect, 1967–70, for category 1, unstable low CIB. Twenty-seven were seeded, 27 not-seeded. Analysis and symbols are the same as in Fig. 3. See text for category definition.

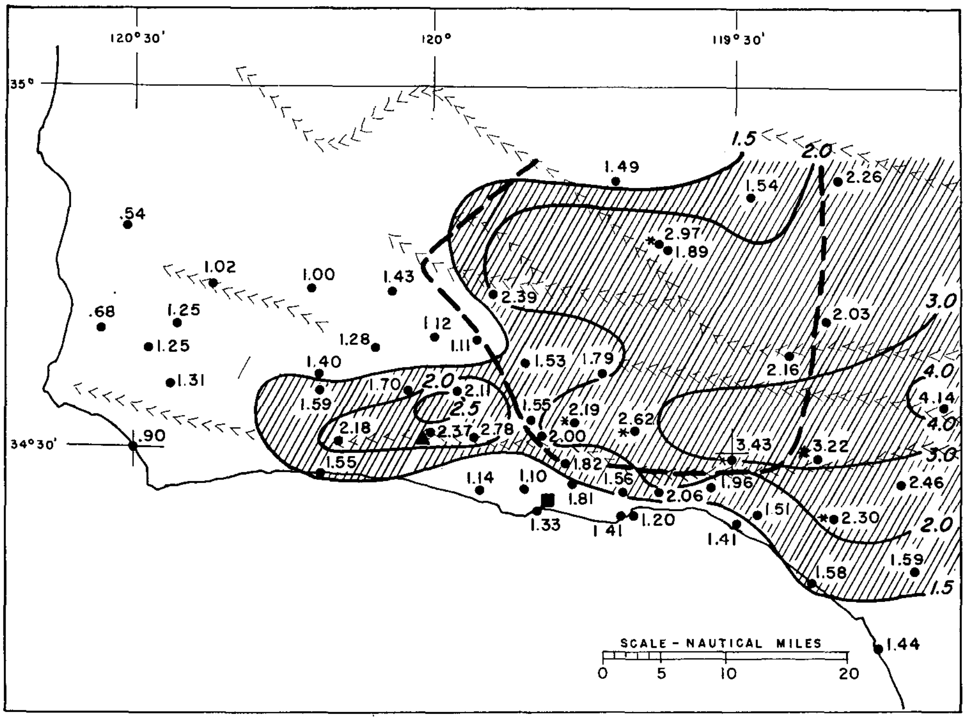

FIG. 5. Double ratio and computed area of effect for the warmer class ($-17.5 \geqslant T_{500} \geqslant -12.8$C) in the unstable, low CIB category. These include 7 seeded and 10 not seeded cases. Analysis and symbols are the same as in Fig. 3. See text for category definition.

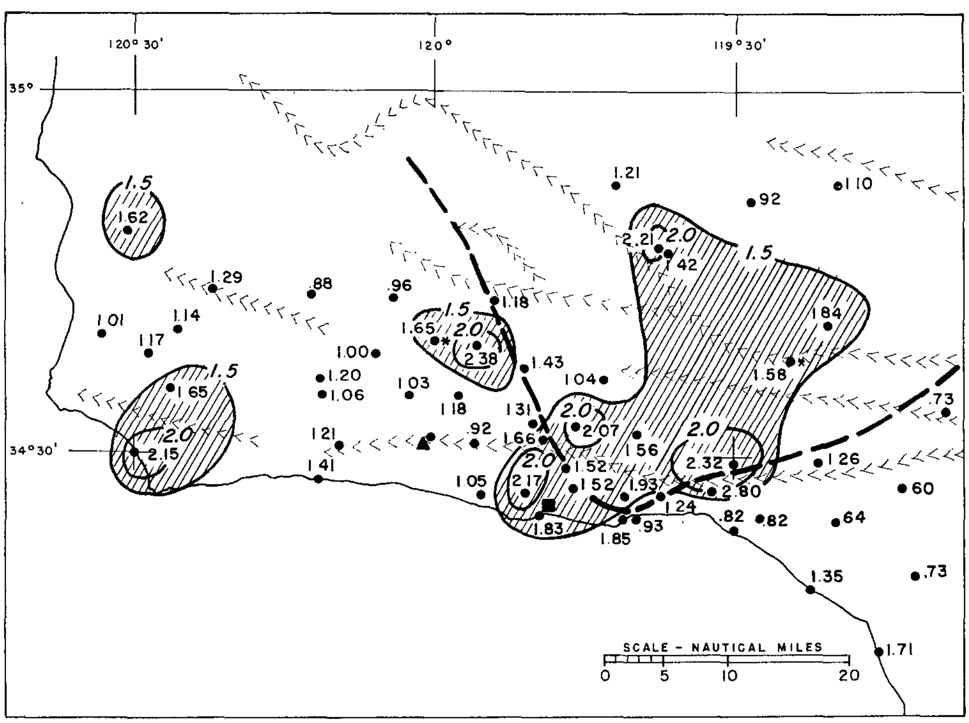

FIG. 6. Double ratio and computed area of effect for the middle class ($-17.5\text{C} > T_{500} > -22.5$C) in the unstable, low CIB category. There were 10 cases seeded and 9 not-seeded. Analysis and symbols are the same as in Fig. 3.

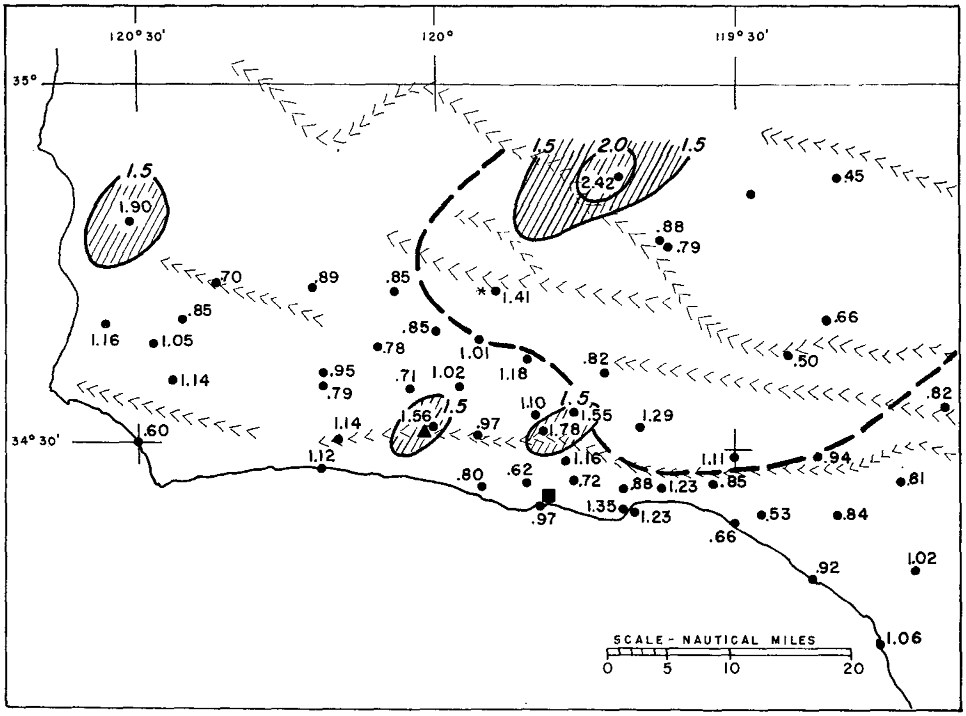

FIG. 7. Double ratio and computed area of effect for the cold class ($-22.5 \geqslant T \geqslant -32.0$C) for the unstable, low CIB category. There were 10 seeded and 8 not-seeded cases. Analysis and symbols are the same as in Fig. 3.

large area to the east and northeast of the seeding site. In fact, the highest ratio (>4.0) lies beyond the area of effect model boundary. The area showing ratios >2.0 is quite large, extending from western Ventura County westward to 10 mi east of the seeding site, and northward toward the Santa Barbara County line. Another area with ratios >2 begins just west of the area of effect boundary and extends westward to Gaviota Pass some 10 mi west of the seeding site. Six of the stations are statistically significant on this map. The fact that there were only 17 bands in the entire sample may account for the reduced number of statistically significant stations in the face of the larger numbers of high double ratios.

Examination of Fig. 6, for bands with 500-mb temperatures between -17.5 and -22.5C, shows double ratios considerably lower than for the warm class; nevertheless, a definite center still exists 25–35 mi east and northeast of the seeding site. Ratios in the eastern portion of the test area have dropped off to around 1.0.

A considerably different pattern appears in Fig. 7, for the cold class ($T_{500} \leqslant -22.5$C). Double ratios over the eastern half of the area of effect are generally under 1.0 with values as low as 0.45. There are a few spotty areas of relatively high ratio, but no consistent pattern as in the preceding figures. The overall pattern suggests that over-seeding could have reduced precipitation in the region of primary effect, but that just upwind and to either side there is a positive effect. However, essentially no statistically significant differences were found between seeded and not-seeded samples.

The two warmest classes, both of which had extensive areas with ratios of over 1.0, were combined and the results shown in Fig. 8. Ratios >1.5 extend over most of the downwind regions. In this figure, eleven stations showed significance at the 5% level. The ratios were larger in the warmest class (Fig. 4) but there were fewer stations showing significance at the 5% level. This may be accounted for by the greater number of cases in the combined sample.

On the maps the ratios appearing in the vicinity of the six control stations have values not far from 1.0. This does not necessarily imply that there is no seeding effect in this vicinity, positive or negative. One way in which to test for this possibility is to compare the distribution of precipitation values directly, rather than the double ratios, for the seeded and not-seeded bands. When this was done for the six control stations, the seeded and not seeded mean values differed by approximately 10%. According to the Mann-Whitney U Test the two distributions were not different at the 10% level.

6. Conclusions

The combined results of the three years of testing the LW-83 pyrotechnic seeding device, ignited on a 3500-ft

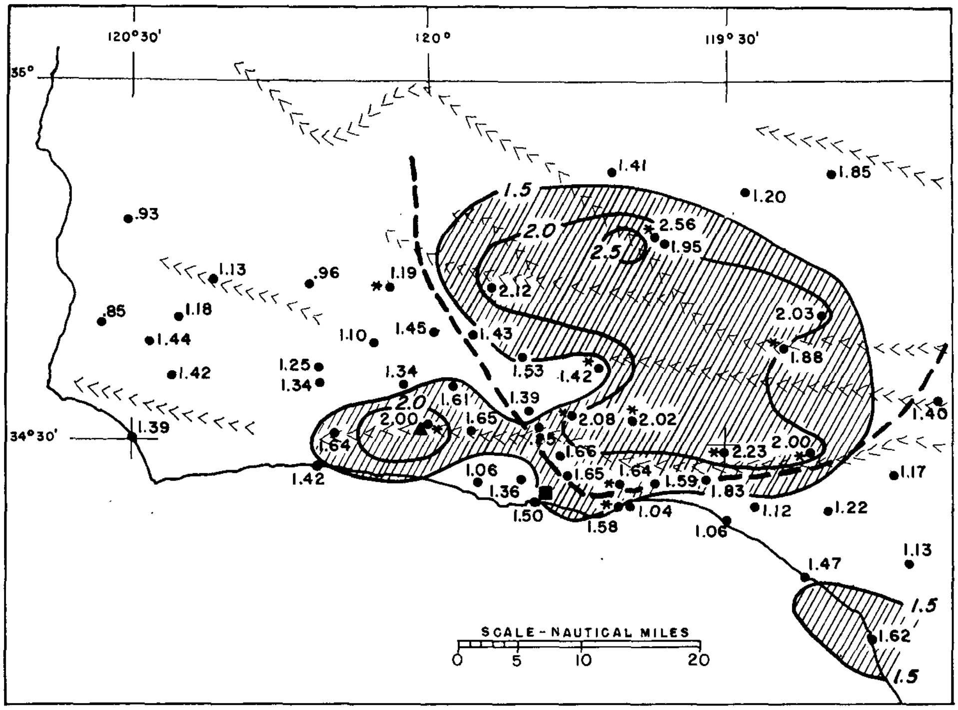

FIG. 8. Double ratios and computed area of effect for warm and middle classes combined ($-22.5 \geqslant T \geqslant -32.0$C) for the unstable, low CIB category. There were 17 seeded cases and 19 not-seeded cases. Analysis and symbols are the same as in Fig. 3.

mountain ridge with convection band passages, has provided abundant evidence that:

1) The seeding device used in the mode employed was highly effective in increasing precipitation downwind from the seeding site. For the most seedable bands, i.e., warm and unstable, the maximum ratio of seeded to non-seeded precipitation was $\sim$4.0. The average ratio was more than 2 over an area $>$1000 mi^2. Only in the case of the colder bands ($T_{500} \leqslant -22.5$C) did it appear that overseeding and a reduction of precipitation may have occurred. The combined results of all of the most seedable bands, regardless of temperature, showed the seeded precipitation to be twice that of the non-seeded over several hundred square miles. When all of the bands were combined, regardless of seedability, increases $>$50% were indicated for the seeded bands over a large area.

2) The purposeful seeding of convection bands can be done when there is available suitable upwind information. Upwind telemetered raingages are most helpful in defining intensities, while durations of approaching convection bands and reports from weather radars can also be useful. If radiosonde data were available sufficiently upwind from the seeding site to allow analysis of the data prior to the band passing the seeding site, only the most productive bands (based on stability and temperatures) should be seeded.

According to the working definition of convection bands employed for this project, their primary characteristic is the regular movement of a band of higher precipitation intensity across the control area and into the test area. Physically, this could be caused by convective instability arranged in band structure, or occasionally by the passage of a very sharp front in a stable air mass. Higher intensities resulting from orographic lifting form more of a steady component of precipitation superimposed upon the unsteady band component. It is in the convective activity within the bands that the greatest abundance of supercooled water suitable for seeding exists. The updraft also provides a means for distributing the nucleant upward into the region of supercooled cloud. The seeding was purpose-

TABLE 5. Average total not-seeded band precipitation and between band precipitation for the period 1967–70.

	Precipitation (inches)		Precipitation (% of total)	
	Mean band	Mean between-band	Band form	Between bands
Los Prietos Ranger Station	0.214	0.122	64	36
Santa Maria Airport	0.175	0.035	83	17

fully confined to these promising (from the seeding viewpoint) portions of each storm.

Table 5 shows the average total precipitation for not-seeded bands, and for the between-band period at two key stations. This precipitation is spread over an interval of from 30 min to 1 hr or more in the case of the bands, and over several hours in the between-bands region.

It is seen that at the typical valley station, Santa Maria (Station 213, Fig. 2), the between-band component, consisting primarily of remnants of precipitation from cloud forms extruded from the bands, is only 17% of the total. At Los Prietos Ranger Station (No. 16, Fig. 2), in the orographic "carryover" precipitation region, it is 36% and represents a true orographic component.

On the basis of the observed frequencies of occurrence and the observed average ratios lying within the calculated areas of effect, and assuming no seeding effects between bands, the net increase in overall precipitation was approximately 32%. The detection of a real increase of this magnitude using a longer period unit of observation which does not fit a definite physical mechanism such as a band would have required many more years of testing than three years.

The question can legitimately be asked: What happened, if anything, to the precipitation falling between bands as a result of seeding? This was investigated by comparing between-band precipitation for the four cases: 1) a seeded band followed by a seeded band, 2) a seeded band followed by a not-seeded band, 3) a not-seeded band followed by a seeded band, and 4) a not-seeded band followed by a not-seeded band. The first two cases showed higher mean precipitation values than the latter two in much of the test area; however, the ranking tests indicated that these differences were not significant at even the 10% level.

The precipitation distribution in the region lying downwind of the boundary of the gage network is being investigated in a separate study to determine if there are any discernable downwind effects.

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