Effects of Seeding on the Energy of Systems

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ABSTRACT

Maps of hourly precipitation have been prepared for storms during the 1957–1960 Santa Barbara randomized seeding program. In non-seeded storms, they showed that approximately N–S oriented precipitation bands could be tracked eastward across the area. Similar maps for seeded cases showed that the bands were obscured by a strong stationary E–W oriented orographic band (the mountain range is oriented E–W).

Hourly station reports were arrayed in a table for each hour where row averages revealed the amplitude of the orographic effect and column averages that of the band effect. Row variance is related to the energy of the orographic precipitation-producing circulations, column variance to the band energy, and the residual variance, obtained by subtracting row and column variances from the total variance, to the energy of smaller-scale convective circulations. Attention was confined to the 7 hours of heaviest precipitation in each system.

In comparing seeded to non-seeded periods, the mean precipitation rate was more than double, and the total variance was almost five times as great. The proportion of the total variance in orographic form was more than double, the band variance was essentially the same, while the convective variance was less than a third of the non-seeded proportion.

It is concluded that the distribution of energy was shifted from smaller to larger scale circulation systems in going from non-seeded to seeded cases. The practical implications with respect to cloud seeding are discussed and illustrated by the results from two seasons of single generator tests made in the 1957–1959 period in the San Gabriel watershed near Los Angeles.

1. Comparison of seeded and non-seeded storms

One of the principal features of the Santa Barbara randomized cloud seeding project of 1957 through 1960, was a network of recording rain gages that was installed and maintained by the California State Water Resources Department. The gage density was approximately 1 per 27 mi^2 in the primary target area which lay in the mountainous southeast corner of the county. A network of 25 ground-based propane type silver iodide smoke generators was employed to seed the entire county (approximately 1800 mi^2, and a network of 12 served the primary target (approximately 450 mi^2). The generators burned AgI (and NaI) in acetone solution through a paint spray head at the rate of 6 gm hr^{-1}. They produced approximately 10^{12} nuclei sec^{-1} effective at -15C. More details on the seeding and randomizing procedures have been published by Neyman *et al.* (1960).

The principal topographic features, county boundaries and primary target outline, are shown in Fig. 1. The feature of interest to us is the E–W orientated Santa Ynez range which lies approximately 5 mi north of the coast line and has crest elevations of near 4000 ft.

A recent analysis has been made of hourly precipitation rates at all precipitation stations during seeded and non-seeded storms. Fig. 2 contains maps of hourly amounts (hundredths of an inch per hour) from -3 hours (3 hours prior to peak precipitation) through $+3$ hours (3 hours after peak precipitation) for one typical non-seeded storm. Fig. 3 represents the same type of data for a typical seeded storm. A characteristic feature of the non-seeded maps (Fig. 2) is the approximately N–S oriented band of higher intensity precipitation which moves eastward across the area. This is designated number 3 because two similar bands had been tracked across the area on previous maps. It was possible to track such bands in most of the non-seeded cases, and in a few of the seeded cases. However, in most of the seeded cases, they could not be detected

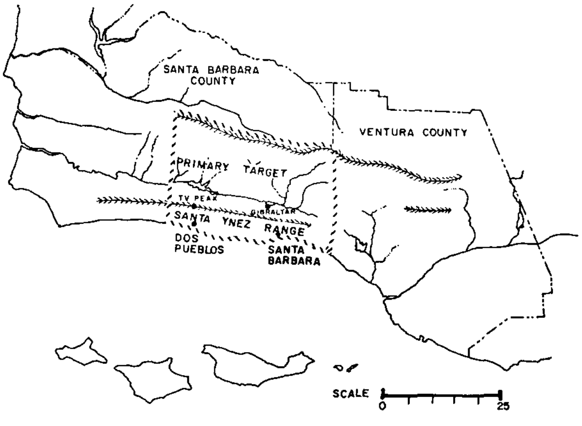

Fig. 1. Map showing principal topographic features and county boundaries, seeded area.

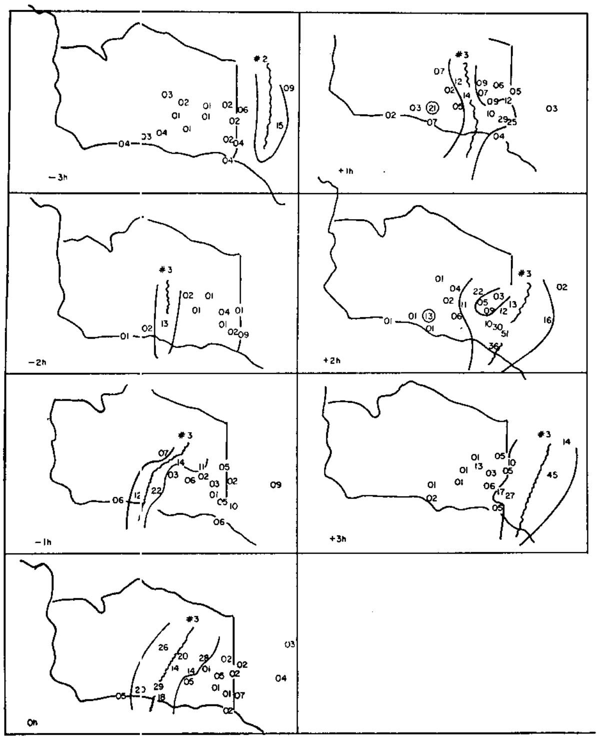

FIG. 2. Hourly precipitation in hundredths of an inch, non-seeded period 1400–2000 PST, 25 April 1957.

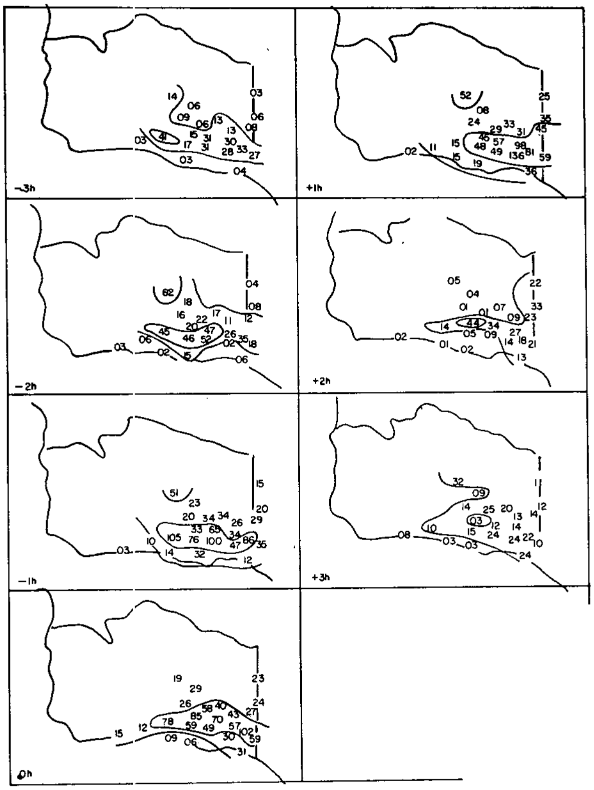

FIG. 3. Hourly precipitation in hundredths of an inch, seeded period 2300 PST 2 April—0500 PST 3 April 1958.

because of the presence of a strong stationary east–west oriented band of heavier intensity precipitation lying over the Santa Ynez range. This situation appears to be the case in Fig. 3. It is seen that hourly amounts are considerably greater than in the unseeded case which was a characteristic of most of the seeded storms. Indeed, the seeded storms showed about four times as many intensities of over 0.40 inch hr^{-1} per storm as did the non-seeded cases.

It was not possible to explain these differences on the basis of synoptic scale patterns. The populations of the storm mean height of the -5C level, the mean -5C wind direction and the mean -5C wind speed were not significantly different for the seeded and non-seeded samples.

It was deemed desirable to obtain some kind of a quantitative measure of this extraordinary difference in pattern. This was achieved by statistical treatment of precipitation in a simple 4-station grid. Two mountain stations, TV Peak (3990 ft) and Gibraltar (1560 ft), the latter actually lying in the valley just north of the Santa Ynez range but in the precipitation spill-over region, were selected to represent the orographic maximum. Two coastal stations, Dos Pueblos and Santa Barbara, each lying approximately south of one of the mountain stations, were selected to represent the "non-orographic" precipitation. These stations had consistent records through the entire four years.

The plan is shown in Fig. 4. The 16-mile east–west spacing was sufficient so that when a precipitation band lay over the western pair, the eastern pair lay between bands, and vice versa. Accordingly, if in any given hour there is strong band activity, then we should expect the two-station average of the precipitation in one column to be either much greater than, or less than, that in the other column. A measure of this difference is the column variance, or twice the sum of the squares of the differences between column means and the grand mean. With strong orographic activity, on the other hand, the row representing the mountain stations has a

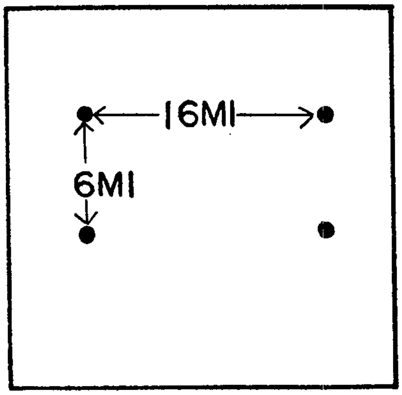

FIG. 4. Precipitation gage network used in precipitation variance analysis.

higher mean than that of the coastal row. In this case, the row variance is a measure of the orographic activity.

If the sum of the column and row variances is subtracted from the total variance (sums of squares of each station departure from the four-station mean), then one obtains the residual variance. In a four-station network such as this, the residual variance is a measure of the difference between diagonal means. If such a difference exists, it would most likely occur when two precipitation cells appear in the network which are not aligned with either the orographic or the band features. Accordingly, the residual variance is considered to be a measure of precipitation activity on a scale less than that of bands or orographic and will be called "convective."

This latter appellation would be of greater significance if the network embraced more stations; however, it was not possible to develop such a network because of missing data at other stations.

Attention was confined to the 7-hr period centered on heaviest target area precipitation. During the January–April 1958 seeding, adjoining Ventura County was not randomized, while in the January–April 1959 and 1960 seeding it was doubly randomized with Santa Barbara. Single randomization occurred in Santa Barbara in January–April 1957. This lack of randomization in Ventura County in 1958 raised some question about the consistency of the experiment and therefore the entire year 1958 was deleted. Only storms where seeding was conducted in Santa Barbara County during the seven hours were classified as seeded, and only those in which there was no seeding in both counties were classified as not seeded. In the actual operations, a randomly selected 12-hr unit of observation had been employed. This meant that some of the 7-hr periods were partially seeded, and these had to be dropped from the sample. Nevertheless, it was possible with these restrictions to obtain a sample of six seeded storms and five non-seeded storms for which data were available at all four stations.

Table 1 displays the pertinent statistics developed from the non-seeded and seeded samples. A ranking test was applied to the array of means for the six seeded and five non-seeded cases and the seeded cases were found to be significantly higher ranked at the 5 per cent level. Up to this point, the analysis parallels that previously reported (Elliott, 1962), but with different gage stations.

Means and variances were computed for each hour and then the averages over 35 non-seeded and 42 seeded hours were computed. These are displayed in Table 1. It is seen that almost 5 times as much total variance per station appears in the seeded than in the non-seeded cases. The table also shows the distribution of variance among the three components: convective (residual), orographic (row) and band (column). It is seen that the percentage in band form is about the same but that in orographic form is more than double in the seeded case vs. the non-seeded case. That in convective form is around a third of its non-seeded value. Thus, the seeding appears to have shifted the activity from smaller to larger scales in the activity spectrum. The meaning of this will now be discussed from both the theoretical and the practical viewpoint.

Table 1. Comparison between non-seeded and seeded rainfall statistics. Means are in inch hr^{-1} and variances in $inch^2\ hr^{-2}$. The means and variances are not for the network as a whole, but per station. Values in parentheses are percentages of the total.

Means and variances		
Precipitation item Mean	Not seeded 0.079	Seeded 0.188
Convective (residual)	0.0023(53)	0.0038(18)
Orographic (row)	0.0010(23)	0.0122(58)
Band (column)	0.0010(24)	0.0051(24)
Total	0.0043(100)	0.0211(100)

2. Theoretical discussion

The various mechanisms responsible for producing the three different precipitation patterns delineated by this analysis can be viewed as essentially circulations in the vertical plane, the orographic one being fixed to the mountain range, the band circulation being migratory, and the smallest one, convective, being both migratory and intermittent. The convective and band cells are driven by convective buoyancy forces, while the orographic is primarily driven by the wind blowing up the slope, but is also partly due to convective buoyancy on this scale.

Lorenz (1955) defines the generation of available potential energy in the atmosphere as

$$G=\int_0^{\bar{P}}\left(\frac{\Gamma_d}{\Gamma_d-\bar{\Gamma}}\right)\frac{\overline{T'Q'}}{T}\frac{dp}{g},$$

where Γ is the lapse rate, T' is the deviation of temperature at a point from the spatial mean at that pressure height and Q' is the deviation of the release of latent heat (in this case). In the convective circulations, the two are correlated, i.e., $\overline{T'Q'}>0$, heat being released in the relatively warmer updrafts, and some evaporation occurring in the downdrafts. Accordingly, available potential energy is being generated. But since there is a quasi-steady state condition, this energy is dissipated frictionally, the energy of the circulation remaining essentially constant. With a given scale, the frictional decay is greater, the greater the kinetic energy of the circulation. Therefore, the kinetic energy of the convective circulation in each scale is related directly to the rate of generation of available potential energy and thus, to the corresponding precipitation variance, the precipitation rate being a direct measure of the release of latent heat. The term "activity" used above then means circulation energy in general terms. It must be kept in mind that the orographic variance is only partly due to convective circulation.

Orographic cloud seeding may enhance precipitation in two ways:

1) Direct effect, by increasing the efficiency with which microphysical processes convert cloud water to precipitation reaching the ground, i.e., by reducing the evaporation to the lee of the barrier.

2) Indirect or dynamic effect. With convection over the barrier, seeding reduces the between-cells evaporation, thus tending to stabilize the air mass (reducing convection) and increasing its mean temperature. This increases the buoyancy on the orographic scale and hence enhances that circulation. The broader-scale upward motion is subject to less dissipation by internal friction than is the assemblage of smaller convection cells of varying sizes, hence the net condensation rate as well as the net precipitation rate is increased. In some instances, the top of the broader scale motion may be lifted and this also would lead to an increased condensation rate.

Let us assume that only the first effect actually occurred. Since the precipitation was 2.38 times as great in the seeded as in the non-seeded sample, we should expect the variances to increase by the square of this, or 5.6-fold. The band variance actually was 5.1 times greater, a little under the expected enhancement; however, the orographic variance was 12.2 times greater and the convective variance was only 1.22 times greater. These results suggest that energy within the orographic circulation could not have been enhanced by process 1) alone. It is worth noting at this point that the coastal, as well as the mountain, mean precipitation rates were greater in the seeded than in the non-seeded sample, and therefore the increase in orographic variance could not be ascribed to a third possibility, namely, reduction of precipitation on the coast with enhancement in the mountains.

A plausible explanation of the observed changes in variance is that seeding did indeed enhance the mountain precipitation rates by means of both mechanisms 1) and 2) operating in the orographic cell; and that process 1) prevailed in the bands.

It should be noted that if the sole change were in the precipitation of the mountain row, then small changes in variance would appear also in band and convective components, simply because the two mountain stations contribute also to their variances in this particular computing scheme. However, the major effect would be in the orographic variance.

The three circulations interact with larger-scale advective processes so that the instability responsible for the energy conversion is maintained and the water lost from the air mass through precipitation is replenished (Elliott and Hovind, 1965). It is pointless to speculate on the more involved changes in the dynamic balance which may occur as a result of this interaction with the larger-scale circulations. It seems likely that mesoscale mixing of properties and internal friction will damp out effects rapidly downwind, especially if only cloud seeding effect 1) occurs; but with effect 2) some type of wave pattern may appear. In any event, it is a gross oversimplification to ignore dynamic effects. Precipitation increases may occur where no silver iodide appears, and no increases may occur where the silver iodide is present.

3. Practical considerations

From the applied viewpoint it becomes necessary to consider the seeding as creating its own circulation mechanism. This is related to the type of dispersal system employed. In this case, the orographic configuration and the pre-seeding circulation mechanisms are part of the initial dispersal system. It appears that later the orographic circulation mechanism may become the dominant influence.

In order better to understand the implications of this, it is necessary to study the area of effect of seeding. This pattern was rather large in the Santa Barbara project because a network of generators was employed. However, seeding was conducted for two years in the San Gabriel Basin near Los Angeles with a single generator in tests preliminary to larger-scale seeding. Area of effect analyses of these operations offer some interesting information.

In 1957–58 a ground-based generator[1] was operated in all suitable storms at San Gabriel dam, a position just inside an inter-mountain valley lying between the E–W oriented front range (4–6000 ft) and the back range (5–10,000 ft). The upper portion of Fig. 5 shows the result of comparing the 7-hr precipitation for seven major seeded storms in this year to that of seven similar major non-seeded storms obtained from the historical record. A four-station control lying in the plains south of the range was employed to sensitize the ratio test employed, i.e.,

$$\text{Ratio}=\frac{T_S}{T_{NS}}\,\frac{\overline{C_{NS}}}{\overline{C_s}},$$

where T is the precipitation at a target station and $\bar{C}$ the mean for the control. A ratio of 1.0 means no difference between seeded and non-seeded precipitation.

A rank test of significance was made for each station by comparing the arrays for individual seeded and non-seeded storms. The asterisks beside the station values on the figures indicate the significance level; 10 per cent for a single asterisk and 5 per cent for the double asterisk. The same large excesses are seen that appeared in the Santa Barbara data analysis. The ratios taper off rapidly to the north, east, west and south of the two adjoining watershed areas outlined by the heavy line. The dashed line represents a plausible boundary of the principal area of effect.

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[1] This generator was in all respects similar to the ones employed on the Santa Barbara project.

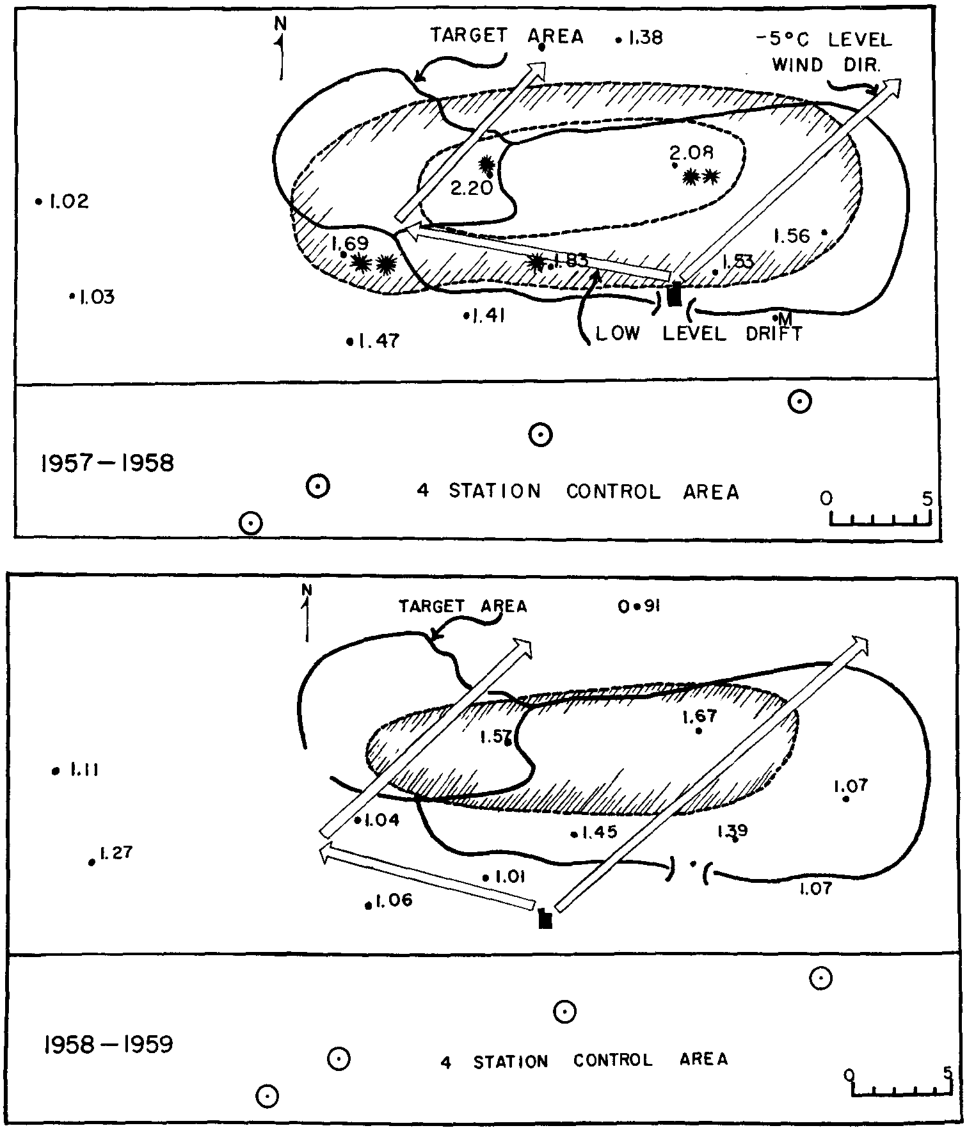

Fig. 5. San Gabriel Basin showing generator locations, ratios and areas of effect.

Now it is convenient to list the following aspects of the seeding process:

1) The low-level drift and diffusion of the plume.
2) Entrainment and further diffusion by convective and larger circulations.
3) Nucleation and fallout.
4) Dynamic effects.

The low-level drift is westward up the inter-mountain valley, as shown. Entrainment occurs all along the low-level drift but there are intervals when the plume may stretch as much as 10 or 15 miles before entrainment develops. The drift during the second and third phases is best represented by the wind at the −5C level. A simple calculation based upon reasonable nucleation and growth rates would indicate some effect as much as 20 or 30 miles downwind, yet the boundary seems to be less than ten miles downwind. It is believed that in this case the orographic circulation is maintained for extensive periods against the basic flow, i.e., cells remain attached to the crests, thus reducing the drift of effects. This tendency is, of course, enhanced by the dynamic effects, phase 4. The total suggested area of effect of the one generator is about 250 mi^2.

The lower portion of Fig. 5 shows the analysis for the 1958–59 season. The generator was operated at Sawpit Dam on the southern flank of the front range, with the thought in mind that the ground drift should be less than in the previous year as the smoke would be forced to ascend the range. However, there remained at least a 10-mi ground drift as shown. The net effect was less than in the previous year and statistical tests showed no significance. The reduced effect may have been due to the different character of the storms in this year, or due to the change in generator placement.

4. Conclusions

It is concluded that a plausible explanation for the observed precipitation distribution in Santa Barbara is that there occurred a seeding-produced indirect, or dynamic effect, which enhanced the orographic circulation. This, in turn, reduced smaller-scale convective circulations and also tended to confine seeding-produced precipitation increases to the mountain bastion. In extrapolating these ideas to other areas, it seems clear that the mountain configuration relative to characteristic storm winds requires careful study in order to anticipate the area of effect. In regions of low relief, more downwind drift could certainly be expected. It is meaningful to deal only with time-averaged drift and diffusion.

It is worthwhile remarking that meteorological conditions in the areas discussed are quite favorable for effective seeding. The orographic barriers are steep and the lower atmospheric layers, which are near sea level, are rich in water content. This may, indeed, represent an optimal area for the seeding of winter storms. In addition, the most favorable 7-hr period has been selected for study which alone should make it easier to sort out seeding effects from the background noise.

Finally, it should be noted that the Santa Barbara precipitation analysis appearing herein was not part of the design of the Santa Barbara randomized seeding project. The intention of this study was to suggest several plausible hypotheses to test in a specific seeding test program which was being planned for another area.

Orographic configuration elsewhere may not provide the simple means for sorting out band effects from orographic effects such as was afforded in this area; however, variations of this scheme might be employed. For instance, with more rain gages in an equally dense or denser network, one might use orothogonal polynomials to represent hourly or sub-hourly precipitation patterns; and use might also be made of precipitation tendency maps to separate the migratory patterns from the fixed patterns.

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