The Area of Maximum Effect Resulting from the Lake Almanor Randomized Cloud Seeding Experiment

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(Manuscript received 20 May 1968, in revised form 10 September 1968)

ABSTRACT

A randomized cloud seeding experiment was conducted on the Lake Almanor watershed near Mt. Lassen, Calif., during five winter seasons, 1962–1967. The target area extended approximately 20 mi east-west and 15 mi north-south, and ranged in elevation from 4500–6400 ft MSL. Silver iodide was released from ground-based, acetone solution generators which were located between 6000 and 7400 ft MSL. Silver iodide releases were made for 12-hr periods, these seeding periods being subsequently divided into four weather categories, depending on wind direction and temperature. In three of these categories, which together produce approximately 85% of the total precipitation, no response to the seeding was observed in the target area. In the remaining category, characterized by westerly winds and cold temperatures, the increase peaked at approximately 57% between 5 and 11 mi downwind, and averaged 37% throughout the 21-mi distance. Both results were statistically significant at the 5% level.

1. Introduction

The Pacific Gas and Electric Company has been engaged in cloud seeding since 1953. The evaluation of the early experiments, however, was characterized by unresolvable ambiguities. For example, on one watershed the streamflow analysis indicated a positive effect while the precipitation analysis on the same watershed showed a small negative effect.

In order to resolve these ambiguities, the Company decided in 1960 to conduct a randomized experiment. This experiment was set up on the Lake Almanor watershed during 1960–1962. Five years of testing have been completed, and some of the results are presented in this report.

2. Site description

The Lake Almanor watershed is located in the northern Sierra Nevada Mountains of California, and encompasses approximately 500 mi^2 (Fig. 1). It extends 25 mi east-west and 20 mi north-south. Lake Almanor is located in the southern portion of the watershed, and has an area of approximately 45 mi^2. The elevation of the watershed ranges from 4500 ft at the lake level to 10,467 ft at Mt. Lassen; however, most of the watershed lies below 7500 ft. The area of the watershed used in the experiment lies below 6500 ft, and covers approximately 300 mi^2, extending 20 mi east-west and 15 mi north-south.

There are several good roads in this area which porvide reasonably good access to many of the precipitation gages. However, the high elevation gages and the burner sites can be reached only by use of snow vehicles during most of the winter season.

During the wet season, November to May, there is a high frequency of storms in this area. At Chester, in the central portion of the watershed, the annual precipitation (1931–1952) averages 31.42 inches, ranging from a maximum of 51.56 to a minimum of 16.44. The annual average snowfall is 146.4 inches, and accounts for approximately one-half of the annual precipitation even at the 4500-ft elevation. Since the main ridge of the Sierra Nevada Mountains is located west and southwest of this test area, the wind flow associated with this precipitation traverses terrain which slopes slightly downward toward the test area.

3. Instrumentation

Six silver iodide burners were installed on ridges or peaks within the watershed at elevations between 6000 and 7500 ft. Each burner site included a burner, its control system, two 500-gallon tanks of propane, a radio receiver, a radio tower, a battery pack power supply and an instrument shelter. The burners were completely automated, and were controlled by personnel at the Caribou powerhouse 5–10 mi away. A 4% solution of silver iodide in acetone was burned at a rate sufficient to produce 25 gm hr^{-1} of silver iodide. Both the burners and the control systems proved very reliable.

Continuous precipitation measurements were recorded by U. S. Weather Bureau weighing type gages at 49 locations, for an average network density of one gage per 6 mi^2 of target and control area. An ethylene glycol solution was used to protect the gage catch from freezing, and a light oil reduced the evaporation. To prevent the snow from sticking or capping, each gage

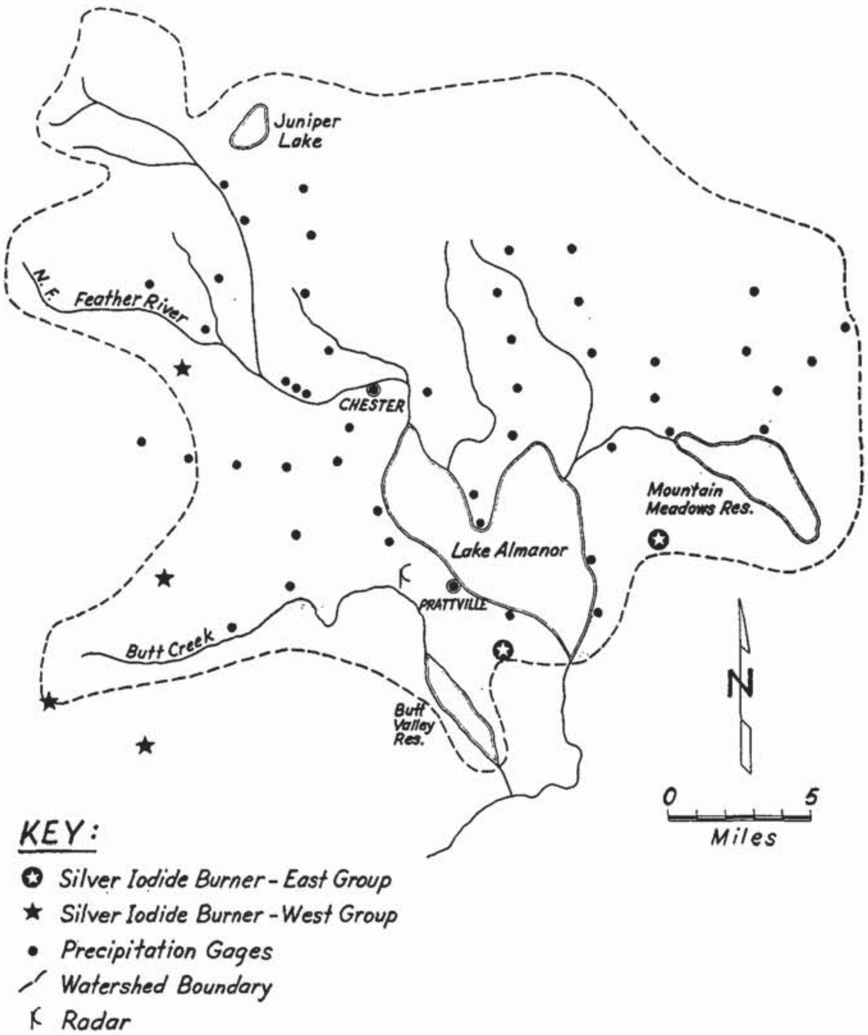

FIG. 1. Lake Almanor cloud seeding experiment instrumentation locations.

orifice was heated with a small propane flame. This heating of the gage orifice caused a slight reduction in the measured precipitation, but the test results were not affected, since both the seeded and the unseeded gages were equally influenced.

The burners and the precipitation gage heaters were designed and fabricated by the Company, and a detailed description of them is contained in a recent paper by Hunsaker and Scott (1967).

Temperature measurements were made at two locations, the Prattville radar site, 5000 ft MSL, and Mt. Dyer, 7500 ft MSL. Temperature soundings were made during the last three years of the experiment at the Prattville location; however, there were many breaks in the record.

Wind measurements were also made at Prattville and Mt. Dyer. An internally heated wind vane at the 7500-ft location provided some good data, but the record was fragmentary due to the severe icing conditions experienced at this site. Continuous good quality records were obtained at the 5000-ft location, but these data were of limited value, because wind observations at ground level are not a reliable basis for estimating the wind direction at higher levels.

Radar scope pictures of precipitation cells and tracks of balloon releases were also made at the Prattville location during the seasons 1964–1967. The quality of these data was high, but again there were breaks in the record.

4. Experimental design

The cloud seeding burners were placed south and southwest of the target area, because southerly or southwesterly flow was expected to be associated with most of the precipitation. The release of the silver iodide from high peaks or ridges, approximately 1000 ft above the target area, increased the likelihood of the silver iodide reaching cloud layers which were colder than −5C, the threshold of its effective range (Fletcher,

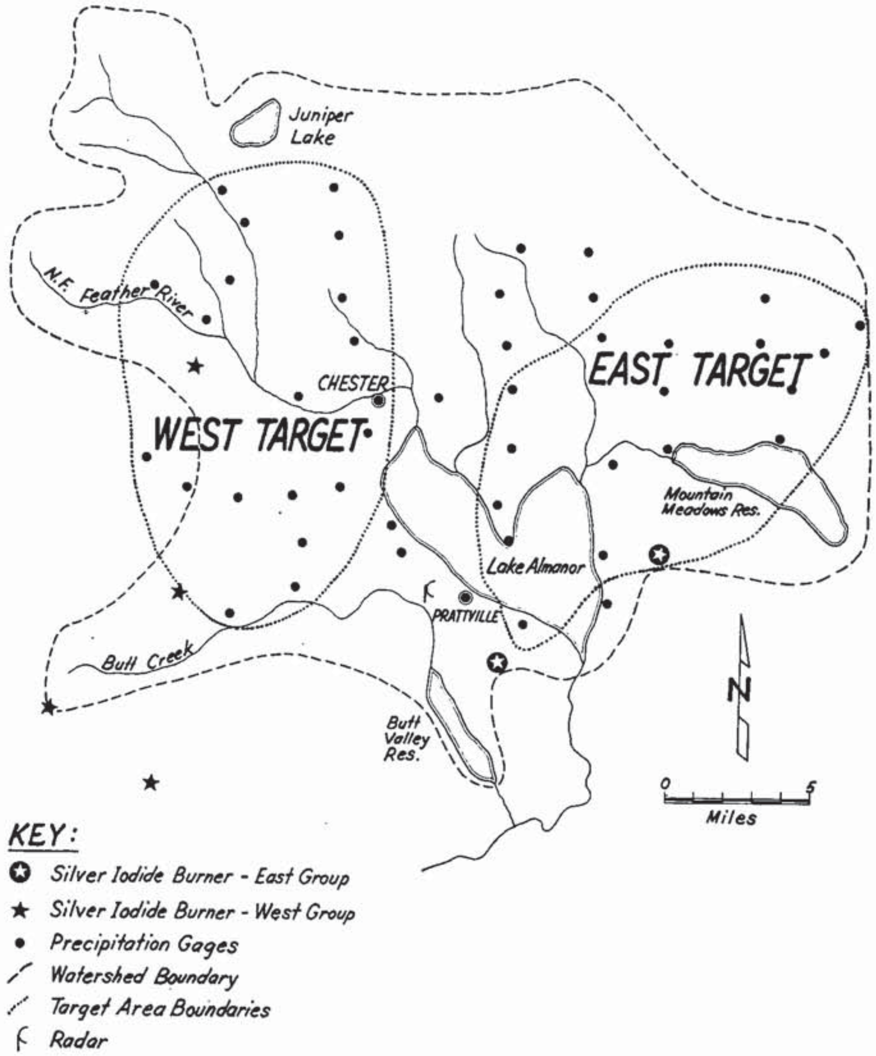

FIG. 2. Lake Almanor cloud seeding experiment target areas, southerly winds.

1962). In fact, during some cold storms, the silver iodide was released directly into this layer of the cloud, and was therefore immediately effective.

The total target area was divided into two approximately equal parts, east and west as shown in Fig. 2. Initially, it was planned that one of these sub-targets would be seeded during every seeding period. The burners which would seed the two target areas were designated the west burner group and the east burner group. Thus, under southerly flow, the two burners in the east group would seed the east target area, and the four burners in the west group would seed the west target area.

During each seeding operation, one of these burner groups was selected according to a set of random decisions made up before the season began. When the forecaster and field meteorologist decided that the weather conditions were favorable for seeding, a sealed order was opened to determine which burner group would be operated. This information plus the starting time of the operation was then transmitted by the forecaster to personnel at the Caribou powerhouse who handled the actual ignition of the burners. If favorable conditions persisted, another sealed order was opened, and the designated burner group was operated. A seeding period consisted of 11 hr of burner operation followed by a 1-hr pause to allow the material time to move out of the area.

The procedure described above was based on the assumption of southerly or southwesterly flow, and it was not until the seeding period had passed that the actual wind flow was known. To utilize the available data when the wind flow had actually been westerly, a different group of precipitation gages (shown in Fig. 3) was used to establish the control and target areas. This target area was defined as the group of precipitation gages which, during westerly flow, might be affected when the west burner group was operated but would not be affected when the east burner group was operated. This control area was defined as the group of

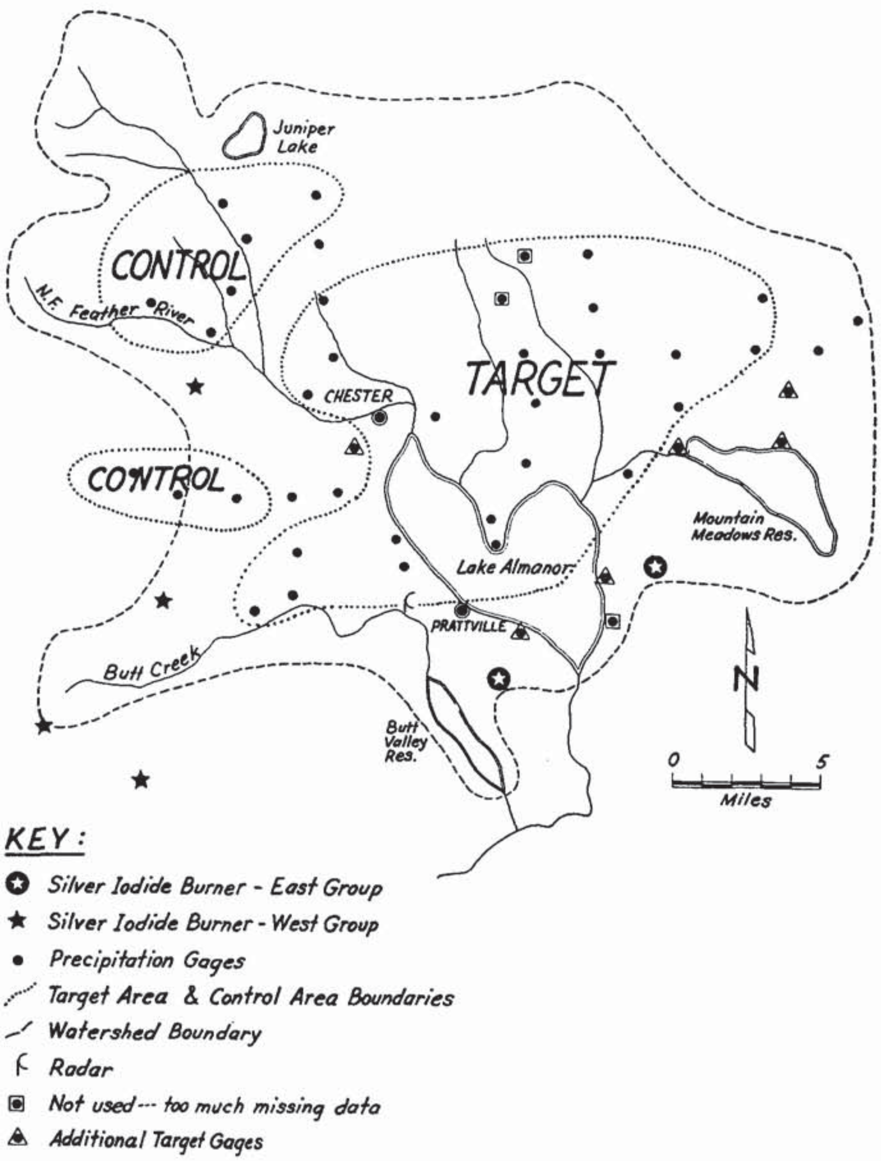

FIG. 3. Lake Almanor cloud seeding experiment target and control areas, westerly winds.

precipitation gages which was never affected by the operation of either burner group during westerly flow. Thus, it was possible to use the data generated during westerly flow, even though the randomization procedure used to select the burner group was based on the assumption of southerly flow.

In summary, when the wind direction was southerly, the double seeding or crossover test was used, i.e., one of the two targets was seeded during every operation. When the wind direction was westerly, the target area was seeded during approximately one-half of the seeding periods, and the control area gages were never seeded.

For the experimental unit, a 12-hr period was chosen. Although a shorter period would have increased the sample size, it would also have decreased the correlation between target and control. These two factors opposed each other in such a manner as to produce an optimum compromise at 12 hr (Eberly and Robinson, 1967).

5. Data reduction

During each of the five test years, 1962–1967, continuous recordings of precipitation, wind and temperature were collected from approximately November–May. The wind and temperature data were reduced as hourly averages. The precipitation data were reduced as hourly totals and recorded on punch cards.

The temperature soundings and winds aloft measurements made during seeding periods were reduced as 1-min averages.

The photographs of the radar echoes of precipitation cells were examined, and the direction of movement was logged.

As a supplement to this on-site wind and temperature data, the direction of mean flow and the height of the −5C isotherm over Northern California were estimated from upper air charts and radiosonde data.

A combination of all available wind data was employed in determining the wind direction in the layer between 5000 and 10,000 ft for each seeding period. When radar and/or data from the Mt. Dyer site at 7500 ft were available, heavy weighting was given to those measurements. For a particular event to be classified as westerly or southerly, the wind direction had to remain within the respective range limits during the entire seeding period.

6. Data analysis

The hourly averages of the temperature data were averaged over each 12-hr seeded period and used as one classification indicator. Each seeded period was classified according to the height of the −5C isotherm. The seeding period was classified as cold if this height ⩽7500 ft, and classified as warm if the height >7500 ft. The hourly averages of the wind direction data were also averaged over each 12-hr seeded period, and the periods were classified to the nearest unit of the 16 point wind scale. If the wind direction was between west-southwest and west-northwest, the period was classified as westerly; when the wind direction was between south-southeast and south-southwest, the period was classified as southerly. Seeding periods with other wind directions or wind direction shifts were omitted from the analysis. Thus, four categories of seeding periods were analyzed, cold-southerly, cold-westerly, warm-southerly, and warm-westerly.

The precipitation gages were grouped according to location with respect to the burners. The precipitation measured at each gage was totalled for each 12-hr seeding period, and these totals were then averaged over the number of gages in each target or control area. Equal weighting was applied to each gage, since they were evenly distributed throughout their respective areas.

Within each of the four categories analyzed, a comparison was made between the average target precipitation with seeding and the same without seeding. In making these comparisons, two statistical methods were utilized, regression analysis and covariance analysis. A detailed description of these methods is given by Eberly and Robinson (1967).

When applied to these data, the covariance analysis involves two treatment effects and one covariate. This involves finding the least-squares estimate of the straight line when the east burners are on,

$$Y_E = b_E + gX,$$

and when the west burners are on,

$$Y_W = b_W + gX,$$

where g is a common slope estimated from all observations.

An F test will determine whether the two lines, forced to be parallel by assumption, are in fact identical, and estimates of the per cent increase due to seeding are possible.

When the equal slope restriction is removed, the analysis is described as a regression analysis. Again, an F test is utilized to determine if the two lines are identical and again estimates of the per cent increase are possible.

7. Results

After each seeded period for the five test years had been classified as previously described, there were only 10 cases in the warm-westerly category. These cases were not analyzed because of the small sample size.

For the 78 seeded periods classified as cold-southerly, the east target was seeded 38 times, the west target 40 times. The comparisons indicated a small negative effect of approximately 3%; however, the level of significance indicated that this was a chance occurrence.

The analysis of the warm-southerly category storms for the five year period has not been completed. However, the data from the first three years, previously analyzed by Eberly and Robinson (1966), indicated no significant effect. Furthermore, there is no theoretical basis to expect more from the warm-southerlies than the cold-southerlies, and the analysis of the latter, as already indicated, showed a small negative effect.

In the cold-westerly storm category, which accounts for approximately 15% of the annual precipitation, the standard target area (Fig. 3), was seeded 30 times and not seeded on 36 occasions. Analysis of these storms indicated a substantial increase, 32% by both the regression method and the covariance method. Both results were significant at the 5% level.

In this category, cold-westerly, a more detailed analysis was undertaken to determine the distance from the burners to the area of maximum effect. The target area was expanded to include a total of 28 gages, and the distance from the burners to the 28 gages used in this target area ranged from 1.5–21 mi (see Fig. 3). These gages were grouped in three different ways. The first grouping consisted of all 28 gages; the second involved three 7-mi distances, and the third roughly four 5-mi distances (0–5, 5.1–11, 11.1–15, and 15.1–21).

Because each sub-area of the total target area contained a unique set of precipitation gages, the dependent variable varied as the target area changed. Regression lines for the seeded and unseeded periods were computed for each of the seven sub-areas and the total target area.

The weighted and averaged values of the slopes and intercepts for the sub-target areas were compared to the respective values for the total target area and are presented in Table 1. The values for the sub-target

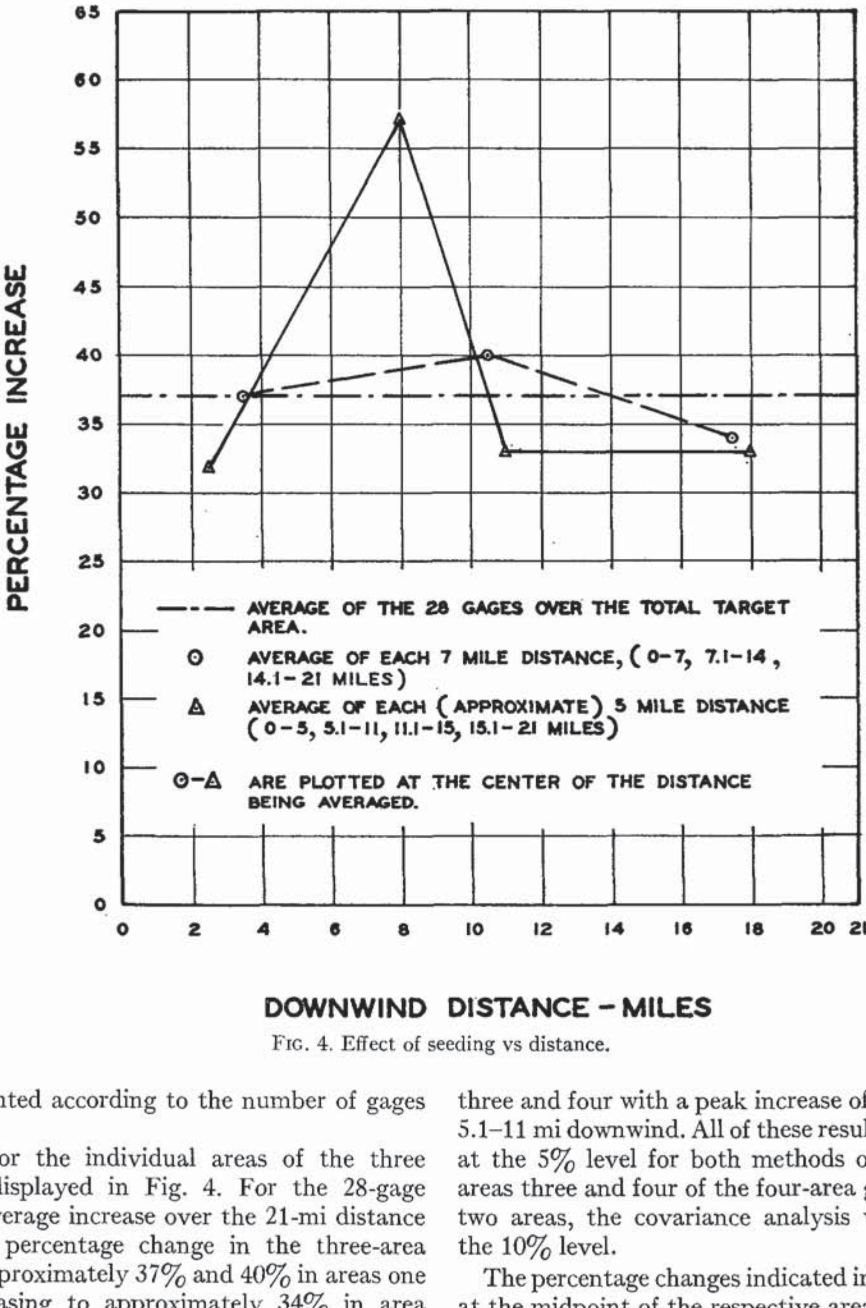

FIG. 4. Effect of seeding vs distance.

areas were weighted according to the number of gages in each area.

The results for the individual areas of the three groupings are displayed in Fig. 4. For the 28-gage grouping, the average increase over the 21-mi distance was 37%. The percentage change in the three-area grouping was approximately 37% and 40% in areas one and two, decreasing to approximately 34% in area three (14–21 mi downwind). In the third grouping of four distances, roughly 5-mi increments, the percentage increase ranged from 32% in area one to 33% in areas three and four with a peak increase of 57% in area two, 5.1–11 mi downwind. All of these results were significant at the 5% level for both methods of analysis, except areas three and four of the four-area grouping. In these two areas, the covariance analysis was significant at the 10% level.

The percentage changes indicated in Fig. 4 are plotted at the midpoint of the respective areas and are a result of the covariance analysis.

TABLE 1. Summary of analysis for westerly-cold category using standard control and 28 gage target area.

	Total area	Three areas averaged	Four areas averaged
Slope g	0.80862	0.80803	0.80812
Intercept-seeded b_w	0.00784	0.00844	0.00850
Intercept-unseeded b_E	−0.03512	−0.03498	−0.03511

8. Discussion of results

The positive effects found in the cold-westerly category are in general agreement with the fact that silver iodide seeding stimulates only the ice-crystal mechanism of the natural precipitation processes, and has no effect on the warm temperature coalescence mechanism (Fletcher, 1962; Mason, 1962). Furthermore, the maximum effect found between 5 and 11 mi downwind is in agreement with the cloud physics. For example, if a silver iodide particle were introduced directly into the

−5C or colder region of a supercooled cloud, the total elapsed time required for it to grow to a snowflake large enough to fall to the ground is on the order of 550–930 sec. If an average wind speed of 10–30 mph is assumed, this elapsed time is equivalent to a distance of 2.0–9.2 mi downwind from the burners.

The elapsed time of 550–930 sec was based on 120–500 sec for growth, the 50 cm sec^{-1} fall rate of powder snow (Mason, 1962), and the average difference in elevation between the burners and precipitation gages of 1000 ft.

However, this theory does not explain the lack of results observed for the cold-southerly category. In this case, there may have been some contamination between the two target areas. For example, they are close together, and wind flow in mountainous regions is often complex. If the silver iodide plume meandered from one target to the other, then both areas would be seeded and a no-effect result would be automatic. It has been suggested that there may be a systematic tendency for a difference in average cloud-base altitude or that there is a probable difference in average stability for the two direction-categories. Neither of these differences could be verified. However, there was some indication from the limited amount of radar data that the cold-southerly storms may be slightly more stable than the cold-westerly storms. On the other hand, the results may be real, and without current explanation.

The lack of results for warm-southerly storms was not totally unexpected since the silver iodide treatment has no effect on the warm precipitation mechanism, and this mechanism most likely dominates during this storm type.

The economically useful aspects of cloud seeding have to be determined on an individual project basis since the value of each percentage point of precipitation increase varies from project to project. The apparent annual precipitation increase on this watershed from seeding cold-westerly storms is only approximately 5% (cold-westerly storms account for approximately 15% of the annual precipitation, the overall increase being approximately 37%), but it would be economically worthwhile and feasible to seed only the cold-westerly storms. A detailed discussion of the economic aspects of the project is presented in the paper by Hunsaker and Scott (1967).

9. Future studies

The Lake Almanor project has been redesigned and testing of the southerly category storms, both warm and cold, will be continued for another five years. The new design will eliminate the possibility of contamination between the target and control areas. New and more reliable wind and temperature sensors have been installed at a high elevation site, and more accurate on-site measurements will therefore be available. The details of the new design are discussed by Hunsaker and Scott (1967).

Acknowledgments. This project represents the joint efforts of several departments of the Pacific Gas and Electric Company. The project was funded by the Electric Department. The design and fabrication of the cloud seeding burners was done by the Gas System Design Department under the direction of C. J. Tateosian. The Department of Engineering Research assisted in the early stages of burner development, and also made an analysis of the burner output. The radio control system was developed by the Communications Department. The original test design, project operations, data collection, reduction, processing and analysis represent the joint efforts of the Meteorological Office Staff headed by F. J. Parsons and later by L. M. Hunsaker. Warren Scott served as the field meteorologist throughout the test period. Special thanks are expressed to L. H. Robinson[1] for his many helpful suggestions in processing and analyzing the data.

[1] Present affiliation: Robinson Associates, Palo Alto, Calif.

REFERENCES

Eberly, D. L., and L. H. Robinson, 1966: Status report of operations: Analysis and results of the Lake Almanor cloud seeding test. Unpubl. manuscript, Pacific Gas and Electric Company.

——, and L. H. Robinson, 1967: Design and evaluation of randomized wintertime cloud seeding at high elevation. *Proc. Fifth Berkeley Symp. Math. Statistics and Probability*, Vol. 5, Berkeley, University of California Press, 65–90.

Fletcher, N. H., 1962: *The Physics of Rainclouds.* Cambridge University Press, 386 pp.

Hunsaker, L. M., and W. L. Scott, 1967: Pacific Gas and Electric Company's weather modification program and accomplishments. Paper presented at ASCE Irrigation and Drainage Div. Conf., Sacramento, Calif. (Copies available from Meteor. Office, PG&E.)

Mason, B. J., 1962: *Clouds, Rain and Rainmaking.* Cambridge University Press, 145 pp.