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CLOUD SEEDING IN CALIFORNIA: AN EVALUATION OF THE RAINSHADOW EFFECT OF WEATHER MODIFICATION PROJECTS

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Rainmaking has existed for tens of thousands of years as a part of ritual, religion, and tribal politics (Lewis-Williams 1977). In historical times, a variety of methods have been used in an attempt to increase rainfall, but modern rainmaking began in 1946 when a chance laboratory observation suggested that the introduction of dry ice into a supercooled cloud would stimulate the natural precipitation process. Later that year, two General Electric scientists successfully seeded cumulus clouds in New Mexico with dry ice (Fleagle 1968), and silver iodide crystals were discovered to be efficient ice-forming nuclei for promoting precipitation processes. Although many cloud seeding experiments have claimed success in enhancing precipitation in target areas, the effects of cloud seeding on precipitation patterns downwind of target areas have been debated since the beginning of modern weather modification activities. Brier and Kline (1966) reported positive precipitation anomalies up to 240 kilometers downwind of target areas, and Gabriel and Mather (1986) concluded that summer precipitation was relatively high downwind from seeding areas. In contrast, rainshadow enhancement was detected downwind from a

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northern Sierra Nevada cloud seeding location (U.S. Bureau of Reclamation [USBR] 1974) and downwind of cloud seeding projects in Mexico and Arizona (Weather Modification Advisory Board [WMAB] 1978). Both positive and negative precipitation effects downwind of a seeding operation were reported by others (National Research Council 1973).

Among concerned citizens and public officials, a widespread perception persists that a downwind rainshadow is created by cloud seeding. The Ecological Society of America, in its study of potential downwind effects of weather modification, advocated that all cloud seeding cease until extra-area impacts on long-term weather patterns could be fully appreciated (National Science Foundation [NSF] 1966). Approximately 25 percent of all public comments on a proposed snow augmentation program in the northern Sierra Nevada concerned the possibility that downwind areas would be robbed of precipitation they would otherwise receive (USBR 1974). Residents of Colorado's San Luis Valley were so convinced that cloud seeding activity had created a rainshadow and resultant drought in their area that they destroyed the weather modifier's equipment in protest (Lambright 1984). In 1989, officials in Utah's Uinta Basin expressed concern that upwind cloud seeding had reduced annual rainfall in their watershed. Given the inadequacy of the current level of understanding of cloud seeding processes and results, such concerns may have merit.

Much of the early scientific information on cloud seeding and downwind influences was based on single experiments, programs extending over a season, or project durations of a few years. Today, some cloud seeding projects have been operating for thirty years or more; and these long-term programs provide an improved data base for assessing the spatial influences of cloud seeding activities. The purpose of this paper is to test the hypothesis that cloud seeding in one locale results in the creation of a rainshadow effect, that is precipitation deprivation downwind from the target area of the cloud seeding activity. Two long-term cloud seeding projects in California are analyzed.

The Rainshadow Effect of Cloud Seeding

The term "rainshadow" refers to the area on the leeward side of a topographic barrier where precipitation is less than on the windward side. Although a rainshadow effect is often a naturally occurring phenomenon, such as the rainshadow of the Sierra Nevada in California and Nevada, in theory human weather-modification efforts to increase precipitation in one locale could create a rainshadow downwind of that locale even in the absence of an orographic barrier. Such efforts could also intensify a naturally-occurring rainshadow effect. This theory rests on the assumption that, all other factors remaining static, artificial removal of atmospheric moisture from a cloud or cloud system results in less atmospheric moisture available for precipitation as the cloud or cloud system moves downwind.

Unfortunately, all other factors do not remain static; and the processes of precipitation and storm segregation make it difficult for the researcher to isolate any one factor for analysis (Flueck 1984). Moreover, it is generally recognized that atmospheric moisture is rarely a limiting factor in precipitation processes. It is estimated that 10 percent or less of the moisture in most storms is extracted in the precipitation process; so even with seeding there should be substantial moisture available for downwind areas (USBR 1974). Nonetheless, the theoretical consequences of a cloud-seeding induced rainshadow on ecology and agriculture are significant enough to merit investigation (NSF 1966).

If cloud seeding does deprive downwind areas of precipitation, the precipitation changes caused by an extensive-area, long-term, well-controlled cloud seeding program could alter the local environment in a number of important ways. Environmental changes linked to cloud seeding could include altering the historic climatic variability of the downwind area; altering trends in soil formation, erosion, and retention; shifting rates of growth and production of plant communities (with possible extinction or migration of plant species); and changing the hydrologic elements of the climate system, including changing patterns in runoff, stream discharge, sediment flow, water temperature, and turbidity. In addition, Simpson and Dennis (1974) have concluded that the extended-area effects of cloud seeding go beyond changes in precipitation patterns to include changes in radiation and energy budgets, momentum transports, boundary layer processes, severe weather manifestations, and wind circulation patterns. Such precipitation changes and their consequences are of particular concern in arid environments because such environments are comparatively more sensitive to precipitation variability (Cooper and Jolly 1969). Hence, a decrease in downwind precipitation in an arid area, such as the leeward side of the Sierra Nevada, would have a severe impact on agriculture, water supply, flora, and fauna in dry years.

The California Study Areas

Cloud seeding has occurred in parts of California annually since 1947, primarily for increasing the water supply, but also for hydroelectric generation, recreation (snow skiing), research, and suppression of fire, lightning, hail, and fog (Figure 1)(Roos 1988a). The two oldest, continuing precipitation augmentation programs in California are the Lake Almanor Project, designated here as the northern study area, and the Upper San Joaquin River Project, used here as the southern study area (Figure 2).

The Lake Almanor Project. The Lake Almanor Project is operated by the Pacific Gas & Electric Company in the northern Sierra Nevada, targeting the Lake Almanor watershed. The purpose of the project is to increase high elevation snow pack and subsequent dry-season runoff for storage in hydroelectric installations (Marler 1988). A structured program of

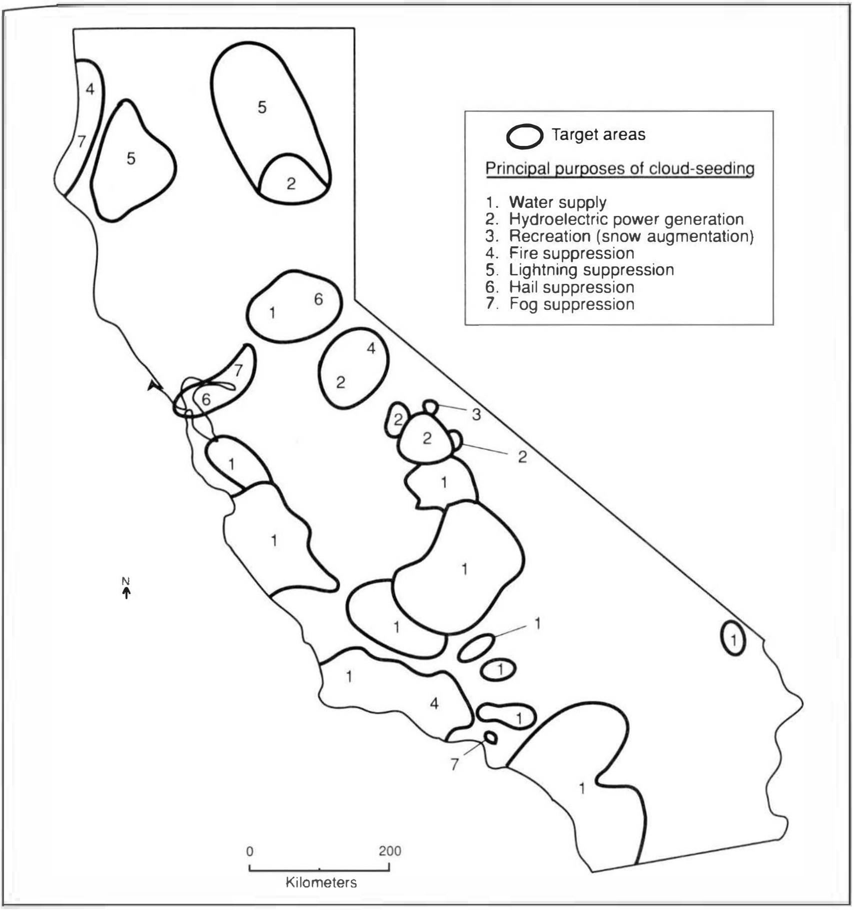

Figure 1. Target areas of weather modification projects in California, 1947-1988.

cloud seeding was established in 1954, but seeding had been conducted in the area as early as 1951 (Bartlett et al. 1975), and randomized cloud seeding programs have been conducted periodically at Lake Almanor. The seeding is effected by the use of six to eight automatic, radio-operated ground generators using silver iodide-in-acetone burners (Marler 1988).

The Lake Almanor watershed occupies 1,295 square kilometers and ranges in elevation from 1,370 meters to 3,190 meters at Mt. Lassen. The target area for the project is a 777 square kilometer area located below 1,980 meters. There is a high frequency of storms in the area from November to May. Snowfall accounts for one-half of the annual precipitation, and the winds are predominantly westerly and southwesterly (National Research Council [NRC] 1973).

The Upper San Joaquin River Project. The Upper San Joaquin River Project, operated by Southern California Edison Company, is also intended to enhance water storage for hydroelectric purposes. The project began in 1951 and is the longest continuously operated cloud seeding project in the world (Elliott 1975).

The target area is the watershed of the upper San Joaquin River and its tributary streams in Fresno County in the southern Sierra Nevada. The project operates twelve to fifteen radio-controlled ground-based generators which emit silver iodide; beginning in 1971-1972, aircraft have been using pyrotechnics to disperse silver iodide crystals into clouds at selected elevations (Elliott 1975).

Methodology

Precipitation data were collected at three stations in the northern study area and three stations in the southern study area (Table 1). Although a dense observational network of stations in each study area would have been preferable, there are few weather stations in the target areas or downwind areas with long precipitation records. Because the analytical method employed in this paper is to compare precipitation patterns before and after cloud seeding activities began, a pre-cloud-seeding calibration period for each station was required. This eliminated the use of most stations because records are short or sporadic. As a result, only the stations with the longest precipitation records were used to represent precipitation in each of the target areas and the downwind areas. No feasible proxy data are available to substitute for weather station data. Furthermore, the resolution of proxy data, such as tree rings, is not sufficient to re-

Table 1. LOCATION AND PRECIPITATION INFORMATION

STATION NAME	Elevation	Location (Vis-à-vis	Range in Mean Monthly Precipitation for 1931-1951 (in centimeters)		
Northern Sites	**(Meters)**	**seeding)**	**February**	**April**	**December**
Chester	1379	Target	00.9–30.0	00.4–19.0	00.1–41.0
Greenville	1085	Downwind	01.0–40.0	00.7–21.7	00.5–56.8
Doyle	1292	Downwind	00.0–08.4	00.0–09.6	00.0–11.0
Northern Sites					
Auberry	652	Target	00.0–32.0	00.2–27.0	00.3-43.0
Bishop Airport	1252	Downwind	00.0–03.3	00.0–41.0	00.0–04.7
Deep Springs College	1593	Downwind	00.0–08.4	00.0–09.6	00.0–11.9

veal precipitation changes on a seasonal or monthly basis as is required here.

In each study area one station is located in the target area of the cloud seeding activity and two stations are located in a downwind transect from the target station. Most researchers agree that determining what is "downwind" of a target area is one of the most difficult aspects of weather modification experiments (Lackner 1971), particularly since cloud seeding can itself affect wind circulation patterns (Simpson and Dennis 1974). Using an "area of effect" model developed to predict the area influenced by seeding of winter storms over an orographic barrier, Elliott and Brown (1972) concluded that precipitation patterns in winter systems observed in the western United States, whether or not seeded, moved west to east. The "downwind area" of cloud seeding activities as measured by fallout of seeding particles and other criteria was generally found to be due east of the primary area of effect.

Based on the prevailing winter winds in the study areas and on the research results concerning what constitutes "downwind" as reported by others (Elliott and Brown 1972; American Meteorological Society [AMS] 1975; Young and Gall 1975), it is assumed for purposes of this study that "downwind" is essentially due east of each of the target areas. This assumption is confirmed by the consistent reporting of westerly winds at various elevations in the few weather modification reports which identify wind patterns in the northern and southern target areas (Department of Water Resources 1957-1988).

Each downwind station is within 150 kilometers of the respective target areas. Most studies have concluded that downwind effects, if any, extend to a maximum of 240 to 320 kilometers downwind of the target area (Lackner 1971; NRC1973). Neither study area is downwind of any known cloud seeding project except the Lake Almanor Project and the Upper San Joaquin River Project, respectively.

Precipitation data are used rather than runoff data or some other parameter of the hydrologic cycle because the basic means of evaluating the effectiveness of cloud seeding is the measurement of the amount of precipitation before and after cloud seeding. In addition, precipitation data do not involve the lag effect inherent in runoff data (Flueck 1984).

Monthly precipitation data were compiled for the years 1931 to 1980, for the months of February, April, and December. In addition, the number of days in each of these months in which cloud seeding occurred was tallied (Table 2). The months of February, April, and December were selected because most cloud seeding in California occurs from December to April (Roos 1988a). Summer cumulus clouds are low in moisture, have poor vertical development and high bases, and thus are not good candidates for seeding (St.-Armand and Ennis 1978). In selecting the months of greatest cloud seeding activity, the data will be more likely to show a discernible effect from cloud seeding.

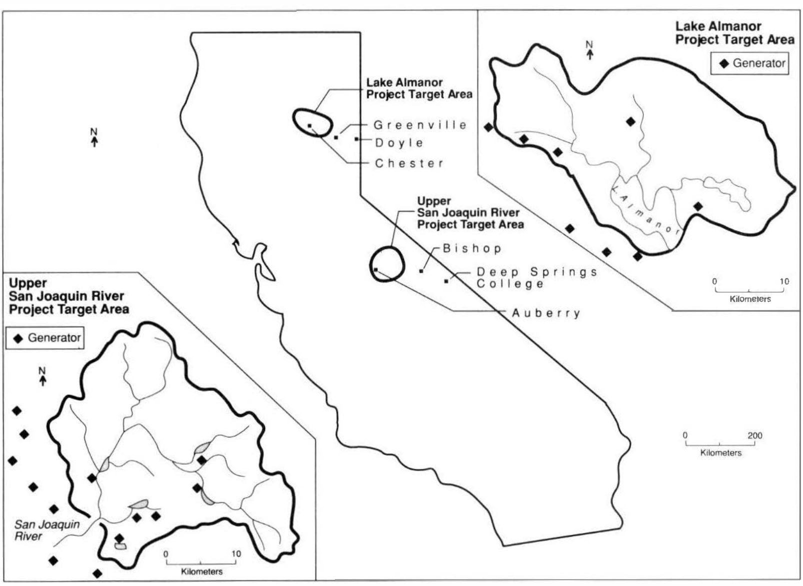

Figure 2. Study areas and weather station locations.

Table 2. NUMBER OF CLOUD SEEDING DAYS IN EACH AREA

	Lake Almanor			Upper San Joaquin		
Year	Feb.	Apr.	Dec.	Feb.	Apr.	Dec.
1952	8	0	4	0	0	0
1953	2	10	0	0	0	0
1954	6	9	12	0	8	15
1955	9	17	11	10	23	12
1956	7	11	2	0	7	6
1957	22	12	8	12	9	13
1958	8	0	1	14	0	8
1959	5	2	9	13	4	2
1960	8	8	2	6	9	4
1961	3	4	0	9	4	3
1962	•	•	2	10	•	0
1963	6	21	2	5	19	6
1964	•	1	11	8	5	13
1965	4	11	8	2	8	11
1966	7	5	7	14	4	10
1967	4	17	7	7	20	9
1968	8	4	13	5	4	20
1969	2	1	4	5	•	10
1970	9	4	10	1	8	•
1971	2	3	12	•	•	14
1972	2	9	6	13	10	10
1973	15	5	8	9	1	6
1974	10	1	2	5	18	9
1975	2	11	6	8	4	13
1976	7	7	4	1	9	4
1978	12	8	2	14	13	1
1979	8	7	0	11	1	•
Mean	7	7.14	6	7.44	8.54	8.39

• = no data available

The northern study area consists of three stations in the northern Sierra Nevada (Figure 2). Chester is in the target area and in the central portion of the Lake Almanor watershed. This is the preferred location for determining the mean annual precipitation in the central watershed (NRC 1973). Greenville is 30 kilometers downwind of the target area and in a valley between mountain ridges that trend east to west. Doyle is 100 kilometers downwind of the target area in a valley 200 meters higher than Greenville. A series of northwest to southeast trending mountain ridges separate Doyle from the target area.

The southern study area stations are widely dispersed (Figure 2). Auberry, at an elevation of 652 meters, is in the cloud seeding target area on the west side of the Sierra Nevada and on the extreme western edge of the southern study area. A more centrally-located station is not available for this project area. Bishop is 95 kilometers downwind and 600 meters higher than Auberry and is on the lee side of the Sierra Nevada. Deep Springs College occupies a site 130 kilometers downwind from the target area and 300 meters higher than Bishop, and is partially blocked from the target area by the southern tip of the White Mountains.

The northern study area has one downwind station, Doyle, in the rainshadow of the Sierra Nevada. Greenville has no significant topographic barriers separating it from the northern study target area. In contrast, both downwind stations in the southern study area are in the rainshadow of the Sierra Nevada and have arid conditions which, theoretically, would be aggravated by a cloud-seeding enhanced rainshadow.

Data Analysis

Natural Variability of Precipitation. Precipitation data for the months of February, April, and December for each of the stations are divided into two segments. The years 1931-1951 represent the control period or period before cloud seeding. The twenty-nine years from 1952-1980 represent the period of continuous cloud seeding.

The range in mean monthly precipitation for the years prior to cloud seeding (Table 1) indicates the natural cycle of precipitation variability at each of the stations. Monthly precipitation varies considerably with a range of 0.0 to 3.3 centimeters at Bishop in February, to a range of 0.5 to 56.8 centimeters at Greenville in December. These data show that the range can be large at an arid site (for example, Bishop's April range of 0.0–41.0 centimeters). Because of this variability in the natural precipitation input, it is difficult to demonstrate that cloud seeding has a downwind effect unless a significant or consistent precipitation difference is detected in the could-seeding period. Any detectable differences may simply reflect either a sampling fluctuation or the natural variability of precipitation at the station.

A comparison of the precipitation data over the twenty-one-year period before cloud seeding began and the twenty-nine-year period of continuous cloud seeding in the target areas yields inconsistent results. The mean monthly precipi-

Table 3. MEAN MONTHLY PRECIPITATION
(In Centimeters)

STATION NAME	Feb. 1931-1951	Feb. 1952-1980	Apr. 1931-1951	Apr. 1952-1980	Dec. 1931-1951	Dec. 1952-1980
Auberry	12.27	10.35	5.56	6.60	13.59	10.44
Bishop	9.40	0.88	2.77	1.98	8.86	0.78
Chester	13.18	13.61	5.77	5.16	14.76	14.07
Deep Springs	0.41	2.25	1.96	1.55	1.32	1.92
Doyle	3.81	2.25	1.35	1.41	3.96	5.27
Greenville	13.77	15.88	6.81	6.91	16.64	18.20

tation for each station before and after cloud seeding is given in Table 3. After commencement of cloud seeding activities, both positive and negative precipitation effects are seen at both target and downwind stations. The exceptions are the two downwind stations of Greenville, which has a consistent positive effect, and Bishop, which has a consistent negative effect. This comparison does not indicate a clear pattern of rainshadow effects.

Comparison of Mean Monthly Precipitation. T-tests are applied to the mean monthly precipitation data to test the null hypothesis that the mean monthly precipitation at each station in each February, April, and December before cloud seeding was the same as after cloud seeding. For this test, and all tests described below, a 0.10 level of significance was chosen in order to maximize the probability that any positive seeding effect would be revealed in the analysis. Analysis of the t-tests provides mixed results (Table 4). In two-thirds of the cases, there is a high probability—ranging from 25 percent to 92 percent—that the means are from the same population. Thus, there is no basis to reject the null hypothesis because there is no significant change in the sample means.

However, in the remaining one-third of the cases there is evidence that the change in the mean precipitation is significant at the 0.10 level. One of these cases is December precipitation at Auberry. A significant positive change is expected from the 1931-1951 control period to the 1952-1980 period of continuous cloud seeding because the Auberry station is located in the cloud seeding target area. However, the change identified is a decrease in precipitation. In the other five cases (Bishop's February and December precipitation; Deep Springs College's February precipitation; and Doyle's February and December precipitation) the significant changes are at stations, and during months of normally low precipitation, where small changes in monthly precipitation values have a large effect on the monthly mean. For exam-

Table 4. Test Values for Statistical Tests of Precipitation and Cloud Seeding

Station	Month	t-Test Values	Probability (2-tail)	Kendall's Correlation Coefficient	Correlation Coefficient "r"
Chester	February	0.248	0.81	0.150	0.223
	April	-0.800	0.43	**0.296**	**0.564**
	December	-0.352	0.73	0.022	0.013
Greenville	February	1.064	0.30	0.193	0.199
	April	0.105	0.92	**0.300**	**0.459**
	December	0.585	0.56	0.014	0.065
Doyle	February	**-3.125**	0.01	0.138	0.248
	April	0.438	0.66	0.177	0.041
	December	**-3.651**	0.01	0.200	0.239
Auberry	February	-1.178	0.25	0.175	0.213
	April	0.965	0.34	0.145	**0.401**
	December	**-1.798**	0.08	-0.051	0.172
Bishop	February	**-43.428**	0.01	0.138	0.203
	April	-0.558	0.58	0.138	0.051
	December	**-38.307**	0.01	0.191	0.309
Deep Springs	February	**3.718**	0.01	0.138	0.199
	Aprii	-0.933	0.36	0.177	0.121
	December	1.092	0.28	0.200	0.282

Values in bold type are significant at the 0.10 level.

ple, such variability could be caused by isolated storms with heavy rainfall unrelated to cloud seeding activity. Three of these five cases are decreases, rather than expected increases in precipitation.

Correlation between Cloud Seeding and Precipitation. Kendall's rank correlation coefficient is used to test the degree of association between the two paired variables of the number of cloud seeding days and monthly precipitation to determine the correlation between cloud seeding and precipitation at each of the stations. If there is a rainshadow effect from cloud seeding, the results would tend toward a coefficient of –1 for downwind stations, indicating a perfect inverse correlation between cloud seeding activity and downwind precipitation. A coefficient of +1 at the target stations would indicate a perfect direct correlation between cloud seeding and enhanced precipitation at the target station.

In all but two cases the correlation coefficient is low (+0.014 to +0.2) and not significant at the .10 level (Table 4). The two cases that produced a significant coefficient occurred in April. Chester has a correlation of +0.296, which is expected at a target station and indicates the possibility of enhanced precipitation due to cloud seeding. Greenville has a correlation of +0.3, indicating a significant but unexpected correlation with an increase in precipitation at a downwind station. It is important to keep in mind, however, that even a high correlation coefficient does not prove a causal relationship, since a third factor could be responsible for a significant change in mean monthly precipitation.

Regression Analysis. A least squares regression analysis is performed to determine how well cloud seeding activity predicts precipitation in the target area and downwind. Moderate relationships are found between Chester's April precipitation and cloud seeding days (correlation coefficient of 0.564) and Auberry's April precipitation and cloud seeding days (correlation coefficient of 0.401), which are not unexpected for target stations. A correlation coefficient of 0.459 is found between Greenville's April precipitation and cloud seeding days, which is significant at the 0.10 level. No other significant correlation is found and very low correlation values—ranging from 0.013 to 0.459 (Table 4)—indicate an approximation which is so general as to be useless in making predictions of precipitation based on cloud seeding.

Correlation between Target Precipitation and Downwind Precipitation. The hypothesis that increased precipitation in the target area results in decreased precipitation downwind is tested by computing a series of Wilcoxon signed-rank tests for each study area to determine if increased precipitation at the target station is related to decreased precipitation downwind during the same period. By looking for significant differences between the paired values of precipitation at target and downwind stations, the test identifies the probability that the distribution of the target station precipitation data is related to the distribution of the downwind precipitation data. If the hypothesis is true, the Wilcoxon test would yield low "Z" values, indicating a relationship between the two distributions of precipitation data. In fact, in all cases the "Z" scores were so high (the lowest was 3.16), and the associated probabilities so small (in all cases less than 0.003), that the hypothesis could be rejected at the highest level of significance (Table 5).

Table 5. WILCOXON "Z" VALUES

	STATIONS			
MONTH	Chester & Greenville	Chester & Doyle	Auberry & Bishop	Auberry & Deep Springs
February	3.16	4.78	4.70	4.66
April	4.09	3.41	4.09	4.09
December	3.91	4.63	4.78	4.57

None of the values are significant at the 0.10 level.

Limitations on the Methodology

There are various general and specific limitations on the data and methodology used in this study. The general limitations relate to the difficulty of modeling or analyzing the results of any cloud seeding activity. Cloud seeding takes place in a short-term, small-scale atmospheric event, such as a thunderstorm or cloud, and is thus hard to monitor in any fashion. Efforts have been made to analyze the effects of cloud seeding on particular segregated storms or clouds based on non-randomized storm events in which specific seeded storms were compared with non-seeded storms (Brown and Elliott 1968). The generalized conclusions drawn from these studies have been criticized for lack of data and appropriate controls (NRC 1973; Martner 1984).

Results of cloud seeding in areas with strong topographic gradients, such as Doyle and Bishop, are more difficult to interpret because of the myriad of variables affecting the precipitation pattern (Houghton 1969). McDonald (1968) described the complexity and difficulty of analyzing precipitation patterns as follows: "[O]ur atmosphere is a physical system characterized by many degrees of freedom and exhibiting enormous variability. And it defies attempts at execution of 'controlled experiments.' " Adding the analysis of the additional factor of deliberate human intervention in the atmospheric processes almost negates the use of random, independent samples. Cloud seeding operations tend to be opportunistic by nature: their location, operation times, and techniques are related to the particular precipitation pattern developing, which is the variable under investigation, making appropriate study and sampling difficult.

The special limitations in this study relate to data collection. The seeding unit "seeding days per month" was used rather than other units such as "seeded storms," "generating hours," and "volume of seeding agent used." None of these latter units is used consistently or continuously by weather modifiers. "Generating hours" refers to the total hours of seeding-generator operation and aircraft-seeding equivalent, and has recently become the most universally used index to describe amounts of cloud seeding activity (Marler 1988). However, although "seeding days per month" is not as accurate a representation of the actual amount of cloud seeding effected in a month as "generating hours" or the other units, it is the only unit reported in each of the California cloud seeding reports (Department of Water Resources 1957-1988).

The sparse rain gauge network restricted the number and choice of stations available for study. The location of climatic stations has a distinct lowland bias (Flaschka, Stockton, and Boggess 1987) which is reflected in the paucity of Sierra Nevada precipitation stations with a long historical record. The use of only a few stations as a measure of precipitation causes a problem because even adjacent gauges will differ due to slight differences in exposure, construction, operation, and interpretation (Wegman and DePriest 1980). A vast network from which an average could be obtained is preferable. Furthermore, great topographic irregularity in the study areas means precipitation patterns will show pronounced local variations which can be effectively averaged only by a several-fold increase in the gauge network (Houghton 1969; Cooper, Cox, and Johnson 1974).

As a result of these limitations, this study used the approach taken by most researchers faced with a severe lack of data for a definitive statistical analysis of cloud seeding effects: dealing with differences in precipitation patterns based on normal precipitation data collected at a limited number of stations (Caouette 1980).

Discussion of Results

It is difficult to arrive at unequivocal answers by purely statistical methods. Any conclusions about the effectiveness of cloud seeding based on this study would at best have to be made with extreme caution. Any conclusion reached would likely be supported by some segment of the weather modification community as there is no consensus on downwind precipitation impacts due to cloud seeding. Various studies around the globe have reported increases and decreases in precipitation downwind of target areas and upwind areas as well (Adderly and Twomey 1958; Henderson 1966; AMS 1972; Gagin and Neumann 1974). In this study, few significant differences were found in precipitation patterns after commencement of cloud seeding activities. With respect to those few significant differences which were found, it cannot be stated without qualification that cloud seeding operations produced the differences.

Analysis of the data herein does not support the hypothesis that cloud seeding in one locale produces a rainshadow effect downwind, as there is no conclusive evidence that cloud seeding treatments resulted in detectable differences in downwind precipitation patterns. This is in accord with the only other study of the downwind effects at either the northern or southern study areas (Marler 1981), which concluded that the calculated, quantitative changes in precipitation at both target and downwind stations associated with specific cloud seeding events were small and not statistically significant. Without long-term, well-controlled, randomized weather modification experiments, it is not possible to separate clearly the influences responsible for either variations in long-term precipitation patterns or relations between precipitation in target areas and downwind areas.

Conclusions

A great deal of uncertainty exists as to the areal effects of weather modification projects. The inability to demonstrate these effects, as well as target area effects, constitutes a principal inhibition in the formulation of state and national weather modification policies and represents a major hurdle in the practical economic matter of evaluating liability for changes in precipitation patterns. A better understanding of the downwind impacts of cloud seeding is necessary if prudent policies to regulate weather modification projects are to be developed. Otherwise, there is a possibility that projects designed to enhance various aspects of water supply, demand, storage, and distribution, agricultural practices, multi-purpose planning, and water systems and capital costs in one area will result in a detrimental impact on those same concerns in another area. Moreover, adequate knowledge and prudent regulation could help prevent unintended climate modification, such as rainshadow effects, from occurring as a result of intended weather modification. Those involved in the nascent weather resource management efforts should collaborate with those whose research focuses on long-term, large-scale climate change. This may be particularly important since weather modifiers have made recent advances in technology which may greatly enhance their ability to extract moisture from the sky (Marler 1988; Boos 1988b).

Brown (1984) has stated that weather modification was born in an industrial laboratory and raised in the tough neighborhood of entrepreneurs and free enterprise. Research followed application and effectiveness was assessed by interested parties, not by objective scientists. After four decades of cloud seeding the promise is great, but the concrete results are few and modest with neither the nature, magnitude, nor areal extent of cloud seeding having been established (Simpson and Dennis 1974). As late as 1984, a review of over thirty cloud seeding experiments in four continents showed that none had produced credible statistical evidence of a precipitation increase in the target area (Flueck 1984). Proven results are limited to single cloud experiments (Martner 1984; Simpson and Dennis 1974).

What is needed are modeling advances, detailed measurements of precipitation, wind speed and direction, and other relevant data, and judicious application of statistics. Current cloud seeding models are not capable of predicting effects of a seeding operation, or of designing cloud seeding projects to produce maximum benefits with minimum unintended consequences. The downwind anomalies found to date, such as in this study, call for further research into the causes of these anomalies.

The ideal analytical structure for the study of downwind effects of cloud seeding would include data focussing on a limited area with a high number of stations and instruments, backed by a model that links the various elements in the target area to downwind spatial precipitation processes. This will not be easy as numerous and complex factors influence the precipitation pattern downwind from a weather modification project, including natural climatic variability, variation in precipitation mechanisms, and variations in cloud seeding practices. Such further research and experimentation will surely prove helpful, but for now it remains unresolved whether cloud seeding leaves a detectable precipitation footprint downwind.

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