DESIGN AND EVALUATION OF RANDOMIZED WINTERTIME CLOUD SEEDING AT HIGH ELEVATION

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1. Introduction

Silver iodide crystals have been released in a controlled test on the Lake Almanor watershed in northeastern California to determine the effects of seeding wintertime Pacific storms. The Lake Almanor watershed has an average elevation between 5000 and 6000 feet. It encompasses the headwaters of the North Fork of the Feather River and is situated among mountain peaks. The highest of these is Lassen Peak at 10,467 feet elevation.

In designing the test, provisions were made for subdividing periods of precipitation into categories with similar temperature and wind patterns. It was reasoned that silver iodide seeding should not be equally effective in all weather situations and, as others are now beginning to realize [1], [2], the problem is in isolating the kinds of weather where increases in precipitation are possible and conversely the conditions where precipitation might even be decreased.

In the preliminary work on the test design, emphasis was placed on obtaining definitive answers on the effectiveness of cloud seeding as quickly as possible. This report describes the operation, outlines the details of the test, and describes the analysis of the data collected in 1963, the first year of the test.

2. Description of burners

Silver iodide is releasable from six different sites. The sites are located at or near mountain tops (7000 feet ±) on the southeast, south, and west sides of the watershed. Equipment at a burner site includes the burner, a programmer and controls, the radio receiver, battery power, instrument shelter, propane fuel, and a supply of chemical. The burners are remote, operated by radio from the Caribou Powerhouse located about 12 miles south of Lake Almanor.

The burner consumes a 4.5 per cent solution of silver iodide in acetone at the rate of 0.17 gallons per hour, equivalent to 27 grams of silver iodide. Each gram produces approximately 10^{15} crystals [3] of silver iodide ranging in size from about 0.01 to 0.2 microns. The threshold temperature where silver iodide begins to act as an ice nucleus is $-4°$ C. At $-10°$ C there are approximately 1.4×10^{14}

crystals per gram that are active as ice nuclei. At $-15°C$ almost all silver iodide crystals are active.

A 50 gallon supply of silver iodide solution is installed at each site. Thus, 300 hours of operation are possible before the supply must be replenished. Propane is consumed at the rate of about 700 gallons per season. Propane was used initially to pressurize the solution as well as the fuel to support the silver iodide acetone flame. However, after extended periods under pressure, the propane tended to go into solution in the silver iodide. The use of nitrogen corrected this problem and has been substituted for the propane in pressurizing the system.

A purge of acetone is made before and after each seeding operation.

Although the burner is completely automatic, servicing is required at least once a month. With each servicing any deposits are cleaned from the pilot lights and the burner chamber, all voltages are checked, proper pressures on regulators are maintained, temperature charts changed, instruments serviced, radio controls checked, and the burner cycled to insure that all lines are clear. Consumption of fuel and chemicals is noted and any necessary adjustments to the system are made. Careful maintenance has resulted in an excellent performance record for the burners.

3. Silver iodide burner operations

From January 28, 1963 through May 14, 1963, 76 orders to cloud seed were issued by the Pacific Gas and Electric Company weather forecaster in San Francisco. Of the 76 orders, actual seeding was accomplished 70 times. This was equivalent to 1826 hours of burner operations. Equipment failure and/or breakdown in communications resulted in six cases of a seeding order not being carried out.

Seeding operations were normally conducted in periods of precipitation. The weather forecaster determined the beginning of each period, attempting to start the seeding two hours before the expected onset of precipitation.

Every order was a command to seed in the sense that one of two groups of burners was to be operated. Whether or not an order specified the east group (two burners) or the west group (three to four burners) was a random decision, made before the season started, and of which the duty forecaster had no prior knowledge. The latter, once he had decided to seed, opened the next in a sequence of numbered envelopes, learned which burner group to operate, transmitted, dated, signed, and filed the order.

Seeding orders were given to the Caribou Powerhouse operator who handled the actual ignition of the burners. The powerhouse operator transmitted by radio a tone signal that turned the appropriate burners on and off.

4. Instrumentation, measurements, and data

Wind, temperature, and precipitation are the principal measurements being made on the watershed. Precipitation is the variable being tested for effects from cloud seeding; wind and temperature are used to stratify the different seeded periods into like categories.

Precipitation is often in the form of snow in the vicinity of Lake Almanor. Thus, the gages must be able to sense both liquid and solid forms of precipitation. This factor, plus the remoteness of the gage locations, limited the choice of gages to the weighting type. This gage has a delicate calibration and requires experienced maintenance. It was necessary to heat the gages with a propane flame to prevent snow from clogging the orifice.

The heating of the orifice results in a loss of catch. One location has been specially instrumented with a trio of gages, one heated, two unheated, to measure this effect. This factor does not affect the results of the test because all gages are heated and presumably all are affected similarly. The test design which is described later looks at the difference in the catches of seeded gages and nonseeded gages, all of which are heated.

There are 51 gages spaced at intervals of approximately two miles on the watershed. Gages are visited once every two weeks. These instruments require constant checking and servicing to achieve a level of performance which is considered satisfactory.

When a gage is serviced, the precipitation catch since the last visit is discarded. Ethylene glycol for protection from freezing and a light oil to prevent evaporation are added. Heaters are checked and adjusted. The chart is changed, the pen is inked, and batteries for the clock movement are checked or replaced. Notes are made on each chart to aid in interpretation of the record.

Temperature is measured at the burner sites and at Prattville. In addition, temperature soundings in the free air are made at times during the seeded periods.

Temperature measurements have always been adequate to determine the approximate level of different isotherms.

Wind is measured at two levels on the watershed: 5000 feet and 7500 feet. As would be expected, the 5000 foot equipment has a better performance record than the 7500 foot instrument. Also, radar echoes of precipitation cells are photographed and the movement with time determined. This represents the average wind for the cloud layer. Another source of wind information is the orientation and spacing of lines of constant height on the daily upper air weather charts for North America. These give the average mean flow in the free air for different heights over northern California and Lake Almanor.

All this information, which includes on site observations, is combined to provide an estimate of the wind direction for the period of seeding. Figure 1 is a map of the project showing the location of equipment and instrumentation.

A classification of seeding operations is given in table I. A "flow chart" summary of these events is given in figure 2. Table II lists all 76 events, each with the related meteorological and operational detail. As much information as possible is displayed, and the table is nearly complete.

Twenty five events out of seventy six were deleted from further analysis for

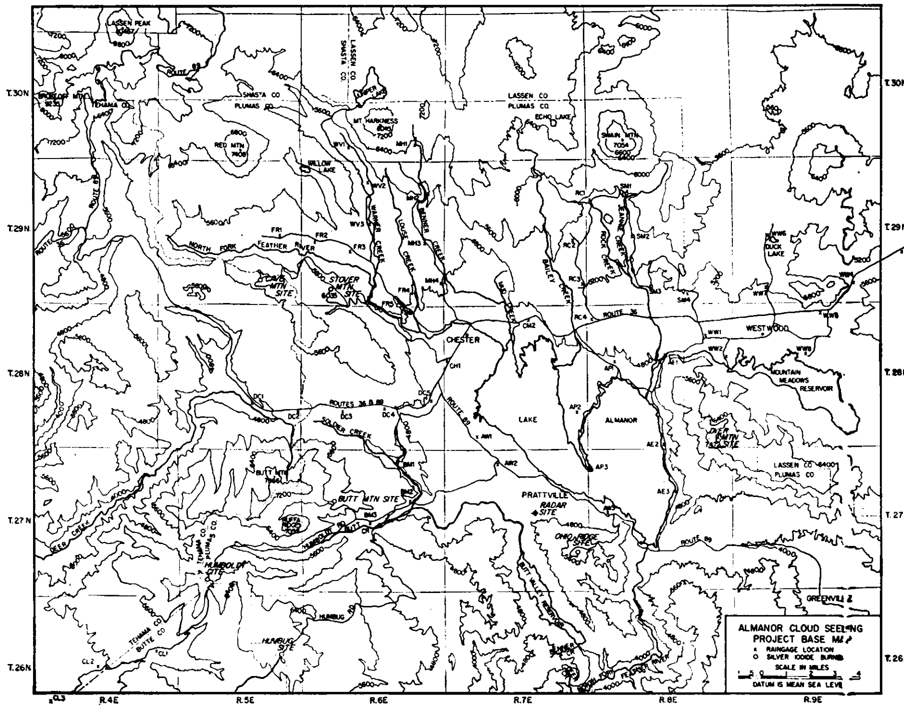

FIGURE 1

Almanor cloud seeding project base map.

some or all of the following reasons: burner malfunction; radio malfunction; missing precipitation records; inappropriate wind direction. Table I also gives the distribution of deleted events. Thirteen, just over 50 per cent of those deleted,

TABLE I

DISTRIBUTION OF EVENTS 1962–63

	South	So/ Warm	So/ Cold	West	West/ Warm	West/ Cold	Total So + We
Usable east burners on	16	6	10	11	3	8	27
Usable west burners on	12	9	3	12	1	11	24
All usables	28	15	13	23	4	19	51

	South	So/ Warm	So/ Cold	West	West/ Warm	West/ Cold	South-west	Other Dirs.	Shear, Variable or Missing	All Deletes	All Usable	Total for Year
Summary of deletions	12	6	6	0	0	0	5	5	3	25	51	76

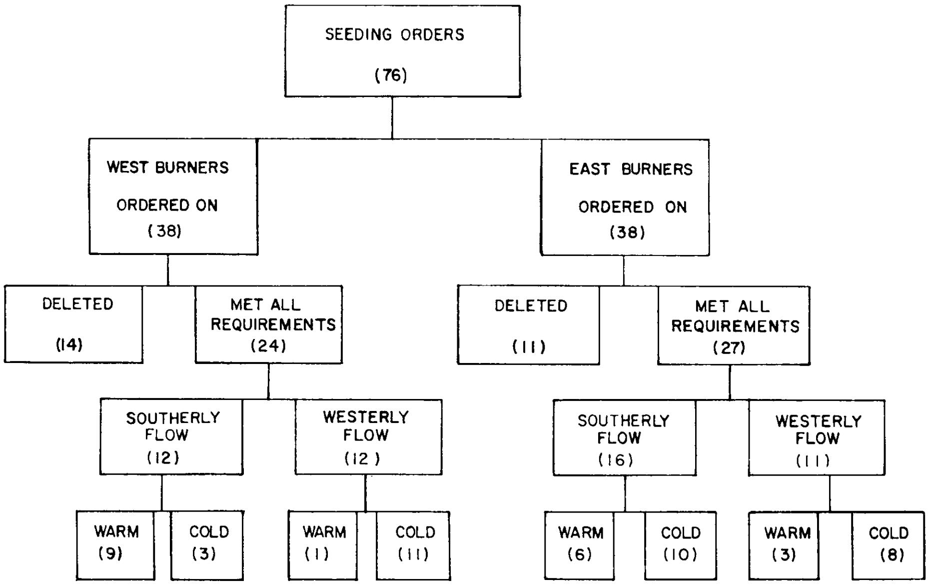

FIGURE 2

Distribution of 12 hour seeded periods.
January to May 1963.

were not usable because of an inappropriate wind direction. Ten of the remaining twelve deleted were the first ten orders issued. No precipitation records were available for those initial events due to project "start up" problems.

The meteorological data in table II are all derived from after the event analyses. Since the forecaster was not required to randomize the operation within blocks of forecasted wind direction, a certain amount of unbalance occurs in table I. For example, compare sample sizes in like wind categories when the east burners were on and when the west burners were on. The randomization plan contained boundary conditions that limited the degree of unbalance to moderate proportions. In the usual statistical sense the randomization scheme was more like that for a completely randomized design than a randomized block design. The opposite is true for the analysis, although neither term precisely characterizes either the randomization or analysis.

Wind direction is the basis for distinguishing between two key situations: southerly and westerly. Although the analysis is formally the same for both, there are important differences in the interpretation of the seeding effects and in the computation of percentage increases based on these effects. Some terminology, definitions, and derivations are given in the methods of analysis section to further develop the discussion in the next several paragraphs.

If south winds (160 through 220 degrees) predominate during the seeded period, the event is classified southerly flow. In this case, the target area down-

TABLE II

SUMMARY OF SEEDING EVENTS INCLUDING OPERATIONS AND METEOROLOGICAL DETAILS 1962–63 SEASON

	Operation			Wind		Temperature		Precipitation (Averages)				
								South Wind Cases		West Wind Cases		
Order No.	Date/Time	Burner Group	Burners Operated	Mean Wind Direction	Wind Group	Mean −5°C Level (ft)	Temp. Group	East Target	West Target	Target	Control	Unit Status
63– 1	1/28, 17:00– 1/29, 03:00	West	None	South Southwest	South	6000	Cold	M	M	M	M	Delete
63– 2	1/28, 05:00–16:00	East	O, D	South	South	7000	Cold	M	M	M	M	Delete
63– 3	1/29, 17:00– 1/30, 04:00	West	None	South	South	6500	Cold	M	M	M	M	Delete
63– 4	1/30, 05:00–17:00	East	O, D	South	South	11000	Warm	M	M	M	M	Delete
63– 5	1/30, 17:00– 1/31, 04:00	West	None	South Southwest	South	12000	Warm	M	M	M	M	Delete
63– 6	1/31, 05:00–16:00	East	O, D	Southwest		12000	Warm	M	M	M	M	Delete
63– 7	1/31, 17:00– 2/1, 04:00	East	D	Southwest		10000	Warm	M	M	M	1.470	Delete
63 –8	2/3, 06:00–17:00	East	O, D	South Southwest	South	>11000	Warm	M	M	M	.064	Delete
63– 9	2/4, 04:00–15:00	East	O, D	South	South	11000	Warm	M	M	M	.238	Delete
63–10	2/4, 16:00– 2/5, 03:00	West	None	South	South	8000	Warm	M	M	M	.081	Delete
63–11	2/16, 10:00– 2/16, 21:00	East	O, D	South	South	7800	Warm	0	.008	T	.013	Usable
63–12	3/2, 17:00– 3/3, 04:00	West	B, S, Hu	Northeast		6000	Cold	0	.024	.006	.036	Delete
63–13	3/5, 05:00–16:00	West	B, S, Hu	South Southwest	South	8500	Warm	0	0	0	0	Usable
63–14	3/5, 17:00– 3/6, 04:00	East	O, D	South Southwest	South	7000	Cold	.006	0	.004	0	Usable
63–15	3/6, 05:00–16:00	West	S, Hu	South	South	8000	Warm	0	0	0	0	Usable
63–16	3/6, 17:00– 3/7, 04:00	East	O	South Southeast	South	7500	Cold	0	0	0	0	Usable
63–17	3/14, 04:00–15:00	East	O, D	West	West	6500	Cold	.207	.305	.225	.374	Usable
63–18	3/14, 16:00– 3/15, 03:00	West	Ht, B, S, Hu	West	West	4500	Cold	.035	.049	.031	.067	Usable
63–19	3/15, 04:00–14:30	West	Ht, B, S, Hu	Northwest	West	5500	Cold	.018	.011	.014	.009	Usable
63–20	3/15, 17:00– 3/16, 04:00	East	O, D	South Southwest	South	5000	Cold	.105	.304	.212	.311	Usable
63–21	3/16, 05:00–16:00	East	O, D	South Southwest	South	5250	Cold	.283	.387	.366	.348	Usable
63–22	3/16, 17:00– 3/17, 04:00	West	Ht, B, S, Hu	Wind Shift		4000	Cold	.051	.028	.042	.019	Delete
63–23	3/17, 05:00–16:00	East	O, D	North		6000	Cold	.006	.003	.005	.002	Delete
63–24	3/17, 20:00– 3/18, 07:00	West	Ht, B, S, Hu	North		4500	Cold	0	0	0	0	Delete
63–25	3/21, 19:00– 3/22, 06:00	West	S, Hu	South	South	8500	Warm	0	0	0	0	Usable
63–26	3/22, 07:00–18:00	East	O, D	South	South	9000	Warm	.008	.029	.019	.034	Usable
63–27	3/22, 19:00– 3/23, 06:00	West	S, Hu	West	West	7000	Cold	.603	.564	.701	.453	Usable
63–28	3/23, 10:00–21:00	East	O, D	South Southwest	South	<7000	Cold	.077	.115	.102	.146	Usable
63–29	3/26, 14:00– 3/27, 01:00	East	O, D	South Southwest	South	8500	Warm	.004	.012	.004	.014	Usable
63–30	3/27, 02:00–13:00	West	S, Hu	South	South	8000	Warm	.838	1.172	1.096	1.078	Ussble
63–31	3/27, 13:00–24:00	West	S, Hu	South	South	7000	Cold	1.435	1.624	1.626	1.564	Usable
63–32	3/28, 01:00–12:00	West	O, D, B, Hu	South	South	<7000	Cold	.178	.267	.217	.313	Delete
63–33	3/28, 13:00–24:00	West	O, D, Hu	South	South	7500	Cold	.216	.177	.190	.204	Delete
63–34	3/29, 01:00–12:00	East	O, D	West Southwest	West	7000	Cold	.086	.067	.069	.085	Usable
63–35	3/29, 13:00–24:00	West	S, Hu	West Southwest	West	7500	Cold	.111	.134	.130	.146	Usable
63–36	3/30, 01:00–12:00	East	O, D	West Southwest	West	<7000	Cold	.042	.173	.068	.240	Usable

63-37	3/30, 13:00-24:00	West	S, Hu	West	West	7500	Cold	.044	.153	.077	.192	Usable
63-38	3/31, 01:00-12:00	East	O, D	West Southwest	West	7000	Cold	.096	.211	.123	.251	Usable
63-39	3/31, 13:00-24:00	West	Ht, S, Hu	Wind Shift		<6000	Cold	.091	.065	.086	.052	Delete
63-40	4/1, 01:00-12:00	East	O	Wind Shift		5000	Cold	.004	.006	.001	.010	Delete
63-41	4/3, 08:00-19:00	West	None	South	South	10000	Warm	.001	.005	.002	.007	Delete
63-42	4/6, 10:00-21:00	East	O	West Southwest	West	9000	Warm	.644	.659	.651	.714	Usable
63-43	4/6, 22:00- 4/7, 09:00	West	Ht, S, Hu	West Southwest	West	7500	Cold	.518	.488	.488	.577	Usable
63-44	4/7, 10:00-21:00	East	O	Southwest		7000	Cold	.321	.314	.343	.342	Delete
63-45	4/7, 22:00- 4/8, 09:00	East	O	South Southwest	South	6000	Cold	.035	.037	.042	.036	Usable
63-46	4/8, 10:00-21:00	West	None	South Southwest	South	6300	Cold	.081	.104	.079	.134	Delete
63-47	4/9, 08:00-19:00	West	Ht, B, S, Hu	West Southwest	West	6500	Cold	.170	.175	.221	.156	Usable
63-48	4/9, 20:00- 4/10, 07:00	East	O	South Southwest	South	6000	Cold	.102	.194	.176	.159	Usable
63-49	4/10, 08:00-19:00	East	O	West Southwest	West	6000	Cold	.311	.229	.302	.211	Usable
63-50	4/10, 20:00- 4/11, 07:00	West	Ht, B, S, Hu	South Southwest	South	4800	Cold	.085	.093	.097	.088	Usable
63-51	4/11, 21:00- 4/12, 08:00	West	Ht, B, S, Hu	South	South	8000	Warm	0	.031	.006	.044	Usable
63-52	4/12, 09:00-20:00	East	O	South	South	10500	Warm	0	.002	.002	.001	Usable
63-53	4/13, 10:00-21:00	West	Ht, B, S, Hu	South	South	11500	Warm	.042	.142	.087	.162	Usable
63-54	4/14, 10:00-21:00	East	O	South Southwest	South	7000	Cold	.407	.510	.503	.526	Usable
63-55	4/14, 22:00- 4/15, 09:00	West	Ht, B, S, Hu	West	West	<6000	Cold	.264	.371	.341	.376	Usable
63-56	4/18, 16:00- 4/19, 03:00	East	O, D	West	West	6000	Cold	.323	.483	.365	.616	Usable
63-57	4/19, 04:00-15:00	East	O, D	West	West	<6000	Cold	.222	.312	.237	.350	Usable
63-58	4/19, 16:00- 4/20, 03:00	West	Ht, B, S, Hu	West	West	4000	Cold	.008	.011	.006	.014	Usable
63-59	4/20, 04:00-15:00	West	Ht, B, S, Hu	West	West	4500	Cold	.027	.022	.021	.033	Usable
63-60	4/20, 16:00- 4/21, 03:00	East	O, D	Northeast		4500	Cold	.002	.004	.004	.003	Delete
63-61	4/21, 04:00-15:00	East	O, D	Northwest	West	5300	Cold	.001	.001	0	.002	Usable
63-62	4/24, 22:00- 4/25, 09:00	West	Ht, S, Hu	South Southwest	South	7000	Cold	.055	.004	.032	.002	Usable
63-63	4/25, 10:00-21:00	East	O, D	South	South	7000	Cold	.011	.013	.011	.016	Usable
63-64	4/25, 22:00- 4/26, 11:00	West	Ht, S, Hu	North		6500	Cold	0	0	0	0	Delete
63-65	5/3, 08:00-19:00	East	O, D	South	South	9500	Warm	0	0	0	0	Usable
63-66	5/4, 10:00-21:00	West	Ht, S, Hu	South	South	10000	Warm	0	0	0	0	Usable
63-67	5/7, 09:00-20:00	East	O, D	South Southwest	South	10000	Warm	.012	.038	.013	.060	Usable
63-68	5/7, 21:00- 5/8, 08:00	West	B, S, Hu	South	South	8000	Warm	0	0	0	0	Usable
63-69	5/8, 09:00-20:00	West	O, D	Southwest		8000	Warm	.434	.453	.446	.478	Delete
63-70	5/8, 21:00- 5/9, 09:00	East	O, D	Southwest		7000	Cold	.047	.013	.031	.016	Delete
63-71	5/9, 11:00-22:00	West	B, S, Hu	South	South	8000	Warm	0	.001	.001	0	Usable
63-72	5/10, 08:00-19:00	East	O, D	South	South	7000	Cold	.034	.100	.066	.118	Usable
63-73	5/10, 20:00- 5/11, 07:00	West	B, S, Hu	Northwest	West	7000	Cold	.256	.176	.269	.146	Usable
63-74	5/11, 08:00-19:00	East	O, D	Northwest	West	8000	Warm	.123	.034	.107	.033	Usable
63-75	5/13, 14:00- 5/14, 01:00	East	O, D	West	West	11000	Warm	.009	.014	.010	.020	Usable
63-76	5/14, 02:00-13:00	West	B, S, Hu	Northwest	West	11000	Warm	0	.001	.001	0	Usable

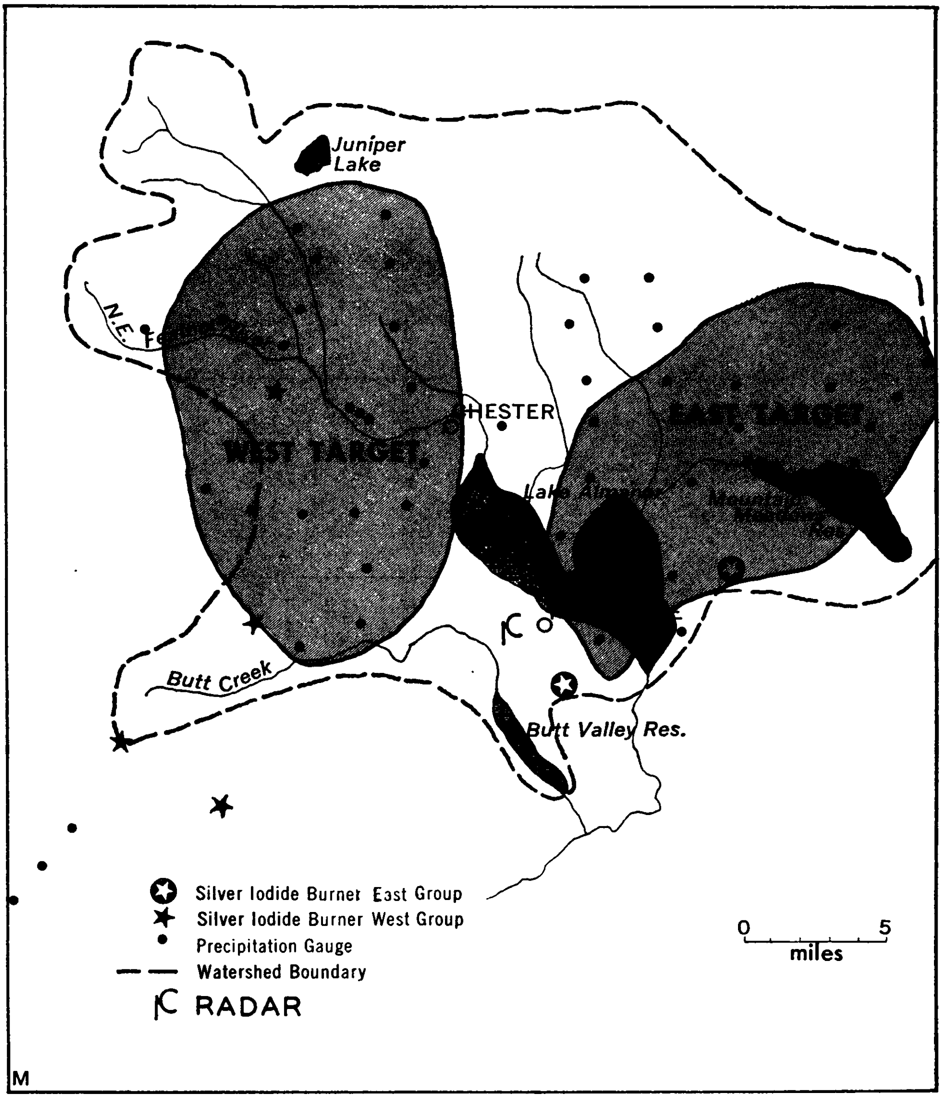

FIGURE 3

Lake Almanor cloud seeding test.
Southerly winds.

wind from the burner group operated is assumed to be seeded and a crossover test is used to evaluate the results of seeding (see figure 3). Basically this involves comparing the precipitation in the seeded target area with the target area that was not seeded. With southerly winds, either the east target or the west target has been seeded. The data obtained for the two targets is further subdivided

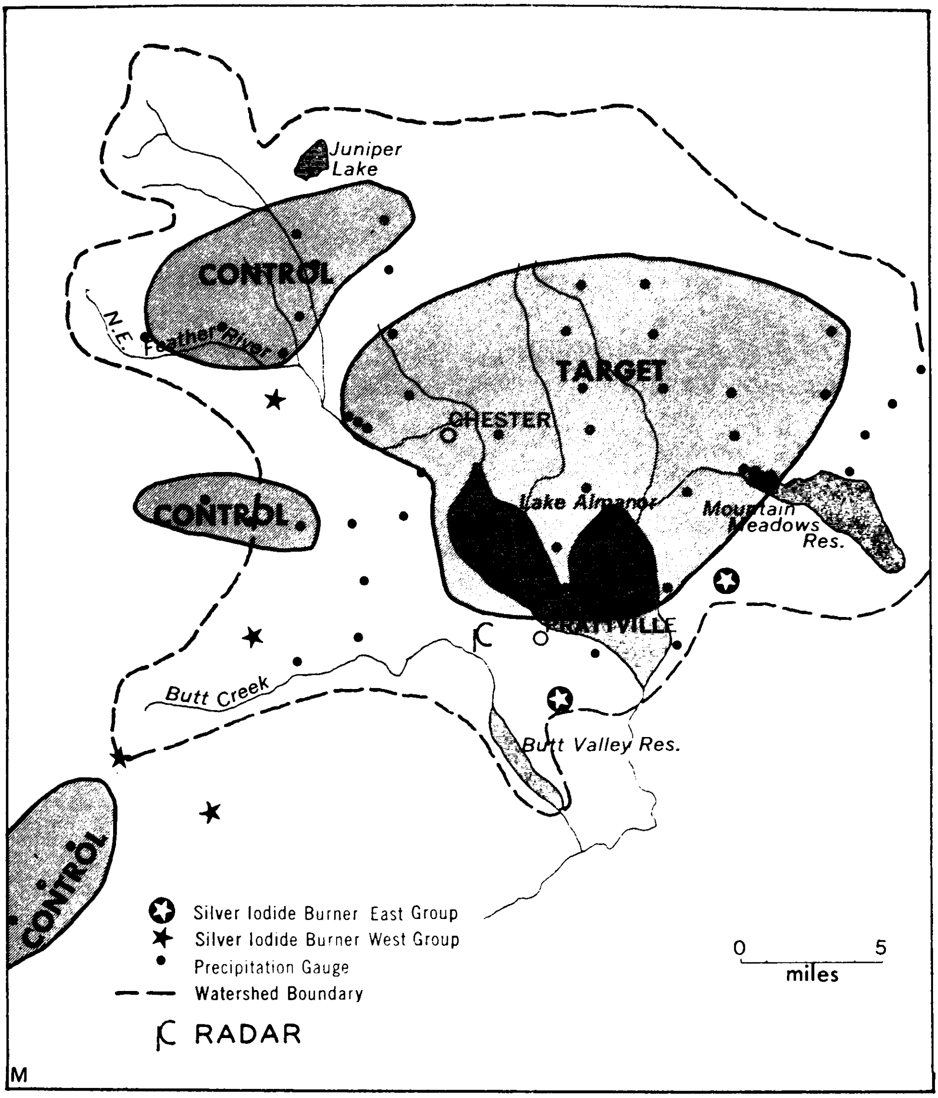

FIGURE 4

Lake Almanor cloud seeding test.
Westerly winds.

into categories of cold temperatures (−5° C level under 7500 feet) and warm temperatures (−5° C level above 7500 feet).

If west winds (230 through 300 degrees) predominate during the seeded period, the event is classified as westerly flow. In this case, if the east burners are used, *no* target gages are seeded. If the west burners are operated, the target area *is* seeded (see figure 4). Thus, a target-control regression can be computed for the events where the target has been seeded and another regression computed for the periods when the target was not seeded. As in the southerly cases, the events are further subdivided into the two categories of temperature.

There are four basic weather types that are being analyzed for effects from seeding. They are: (1) south winds, warm temperatures; (2) south winds, cold temperatures; (3) west winds, warm temperatures; and (4) west winds, cold temperatures.

5. Methods of analysis

The problem of experimental design and evaluation of seeding trials has not been neglected by statisticians [4]. Their recommendations might be summarized as follows: randomize the treatment; use a control; stabilize the (residual) variance; apply covariance analysis. The meteorologist, of course, must furnish comprehensive information on the physical factors likely to affect the response, execute the project, evaluate the results and, ultimately, update physical theory to account for the observed effects.

The factors most likely to affect the response are discussed next, then some statistical methods.

5.1. *Variation of effect with temperature—warm and cold effects.* The height of the $-5°$ C level is a factor that could have an obvious influence on the seeding effect, since silver iodide is known to be inactive at warmer temperatures. This possibility is the justification for choosing a dividing line between warm and cold events at 7500 feet (the approximate elevation of the highest burner). An alternative procedure would have been to introduce the height of the $-5°$ C level directly as a covariate in the regression analysis.

5.2. *Variation of effect with time—the "Australian" effect.* Australian workers were among the first to report an apparently uniform decrease in seeding effect when individual successive events were analyzed. This is additional justification for showing the event by event breakdown in table II.

5.3. *Variation of effect with wind direction.* Since it is so important to the analysis, some simple notation is introduced to formalize the notion of variation of seeding effects with wind direction.

Let (y, z) be a pair of numbers where, y = mean natural precipitation over all events and gages for a group of gages in the east half of the watershed, z = mean natural precipitation over all events and gages for a group of gages in the west half of the watershed.

Let the subscript 1 indicate the average precipitation over all events and gages when the east burners operated. Let the subscript 2 indicate the average precipitation over all events and gages when the west burners operated.

Let Δy_1 be the change in y due to treatment 1, east burners on.
Let Δz_1 be the change in z due to treatment 1, east burners on.
Let Δy_2 be the change in y due to treatment 2, west burners on.
Let Δz_2 be the change in z due to treatment 2, west burners on.

Assume a southerly wind (SSE, S, or SSW) and a seeding effect (Δy and Δz not zero), then the downwind layout of gages with respect to burners implies that,

$$(5.1) \qquad (y_1, z_1) \cong (y + \Delta y_1, z), \quad (y_2, z_2) \cong (y, z + \Delta z_2).$$

Similarly assume a westerly wind (WSW, W, and WNW) and a nonzero seeding effect; then the downwind relation of gages to burners implies that,

$$(5.2) \qquad (y_1, z_1) \cong (y, z), \quad (y_2, z_2) \cong (y + \Delta y_2, z).$$

Thus, two quite different situations are possible, depending on wind direction. The southerly case corresponds to a double target or crossover type of design as discussed by Moran [10]. The westerly case corresponds to the more familiar target, control setup.

A convenient naming convention that will be adhered to in this report (except in tables IVb and Vb) will be to let the letter y, with or without subscripts or superscripts, always denote an easterly region of the watershed, sometimes referred to as the east target, or simply, the target. Similarly the letter z, with or without subscripts or superscripts, will always denote a westerly region of the watershed, referred to as the west target, when winds are southerly, and as the control when winds are westerly.

5.4. *Variation of effects in space; gage grouping to investigate cross contamination and distance maximum effects.* Within the general framework of an east, west division of the watershed, different gage combinations may be specified that allow for the possibility of detecting cross contamination (east burners affecting west target and *vice versa*) or the location of maximum effect as a function of downwind distance from the burners. To examine these possibilities, several arrangements were defined in addition to the "standard" arrangement. This initial arrangement incorporated as many as possible of the 51 gages into the basic east, west division, although the actual gages involved differ for southerly and westerly flow. Since, in both cases, allowance had to be made for a buffer zone, gages within this zone had to be excluded.

As an aid to constructing the standard arrangement, downwind isopleths of silver iodide concentration were drawn from each burner site for southerly and westerly flow. The diffusion calculations, made in 1962, followed a plume model and methodology due to Meade [5] and Pasquill [6]. The computations have not been repeated although improved methods have since been developed [7].

The other arrangements are identified in the following list:

BB) Southerly Case—similar to the standard, except that buffer zone was enlarged.

B) Southerly Case—similar to the standard and BB groups, except with buffer zone enlarged to maximum size.

BT) Westerly Case—buffer zone enlarged, target limited to those gages most likely to show an effect (center portion of standard target).

C) Southerly Case—similar to standard, except that only those gages closest to burners are included.

F) Southerly Case—similar to standard, except that only those gages farthest from burners are included.

TABLE III

GAGE GROUPINGS

FR7 designates the heated gage in the group of three gages, FR4, FR5, and FR6.

	Standard Group			BT Group		CT Group		FT Group	
	Target		Control	Target	Control	Target	Control	Target	Control
	AE1	SM1	DC1	AE2	DC1	BM1	DC1	AE1	DC1
	AP1	SM2	DC2	AP3	FR2	BM2	DC2	AP1	DC2
	AP2	SM3	DC3	AW2	MH1	BM3	DC3	SM1	DC3
	AP3	SM4	FR2	BM2	WV1	FR7	FR2	SM2	FR2
	AW1	WW1	FR3	FR7	WV2	MH3	FR3	SM3	FR3
	AW2	WW6	MH1	MH4		MH4	MH1	SM4	MH1
Westerly flow	BM1	WW7	WV1	KC3			WV1	WW1	WV1
	BM2		WV2	RC4			WV2		WV2
	CH2		WV3	SM2			WV3		WV3
	FR7			SM3					
	MH3			SM4					
	MH4								
	RC3								
	RC4								

	Standard Group		B Group		BB Group		C Group		F Group	
	East	West	East	West	East	West	East	West	East	West
	AE1	AW1	AC2	DC1	AE1	BM1	DC2	AE2	CH1	AE1
	AE2	BM1	AP3	DC2	AE2	DC1	DC3	AP3	DC1	AP1
	AP1	BM2	AW3	DC3	AP3	DC2	DC4	AW3	FR7	RC4
	AP2	BM3	WW1	DC4	AW3	DC3	FR2	WW1	MH2	SM3
	AP3	CH1	WW2	FR2	WW1	DC4	FR3	WW2	MH3	WW6
	AW3	DC2	WW7	FR3	WW2	FR2	WV3		MH4	
	RC4	DC2			WW3	FR3				
	SM3	DC3			WW4	FR7				
Southerly flow	SM4	DC4			WW7	WV3				
	WW1	FR2			WW8					
	WW2	FR3								
	WW3	FR7								
	WW4	MH1								
	WW5	MH2								
	WW6	MH3								
	WW7	MH4								
	WW8	WV1								
		WV2								
		WV3								

CT) Westerly Case—similar to standard, except that only those target gages closest to west burner group are included.

FT) Westerly Case—similar to standard, except that only those target gages farthest from west burners are included.

Table III lists the individual gages in each group.

5.5. *The analysis of covariance.* A random crossover type analysis and target, control type analysis may both be considered special cases of the fixed effects model for the analysis of covariance, as discussed by Scheffé [8]. The analysis of covariance (ANOCOVA for short) as applied to these data involves two treatment effects and one covariate. In Scheffé's terminology the model equation is

$$y_{ij} = \beta_i + \gamma z_{ij} + e_{ij}, \qquad i = 1, 2; j = 1, \cdots, J_i. \tag{5.3}$$

More simply, this reduces to finding the least squares estimates of the straight line when the east burners are on,

$$y_E = b_E + gz, \tag{5.4}$$

and when the west burners are on,

$$y_W = b_W + gz, \tag{5.5}$$

where g is a common slope estimated from all observations.

An F test will decide whether the two lines (constrained to be parallel by assumption) are in fact identical. In any case, estimates of the per cent increase due to seeding are possible, although the procedure will differ for southerly and westerly situations.

5.6. *Regression analysis.* If the equal slopes restriction is removed, the analysis is usually described as a regression analysis. The general theory for a fixed effect model still applies for testing if the lines are identical. As in the ANOCOVA case, estimates of the per cent increase are also possible.

5.7. *Bivariate analysis of variance.* In the fixed effects model for regression and covariance analysis, Scheffé states ([8], pp. 195–196) that only y and e are assumed to be random in the model equation. If z is, in fact, also random, he suggests that the analysis must be made conditional on the observed values of z. In the data of table II it is difficult to suppose z is any less random than y. This dual randomness is handled quite naturally in a bivariate analysis of variance (BIANOVA for short). The assumption now is that the vector,

$$(y_{ij}, z_{ij}) \qquad i = 1, 2; j = 1, \cdots, J_i, \tag{5.6}$$

is random, sampled from one of two bivariate normal distributions with different means but with common standard deviations, and correlation coefficient. The mean vectors, correlation coefficient, and standard deviations must be estimated. Anderson [9] describes the test which is based on either Hotelling's T statistic or the F statistic. He also describes a method for constructing a confidence ellipse about the vector difference.

5.8. *Moran's common effect test.* P. A. P. Moran [10] gives a test for the crossover design which is asymptotically most powerful when the effects are common to both targets,

$$\Delta y_1 = \Delta z_2 = \Delta \neq 0. \tag{5.7}$$

Moran uses a linear transformation of the data to obtain a test statistic that does not depend upon a naming convention. Thus, the definitions of y and z may be interchanged and the test statistic will still have the same value. While Moran gives arguments for believing in a common effect, it is nevertheless an uncomfortable assumption because (i) increments that depend strongly on wind direction and target definition, and (ii) imbalance in the manner of treatment (two east burners compared to three or four west burners) give considerable weight to the possibility of unequal or even reverse effects. Estimates of these effects should not be excluded *a priori*.

Moran has stated that when the correlation between y and z is high and

$$\text{Var}\,(y) \cong \text{Var}\,(z); \tag{5.8}$$

the relative efficiency of the asymptotic power of his common effects test and an analysis of covariance tends to unity. Due to the proximity of the targets these conditions are usually satisfied so that the loss of power is of minor concern.

5.9. *Power.* With only two variables, it seems clear from the simple geometry involved that a crossover design should be more powerful than a target, control design. In the ANOCOVA case, any crossover effect forces the parallel lines for target and control farther apart; in the BIANOVA case, the difference between the mean vectors becomes greater.

5.10. *Ratio methods.* An *ad hoc* test is possible by forming the ratios

$$y_i/z_i, \qquad i = 1, 2. \tag{5.9}$$

The appropriate test for the crossover case may be obtained as follows:

$$r_1 = y_1/z_1 \cong (y + \Delta y_1)/z, \tag{5.10}$$

$$r_2 = y_2/z_2 \cong y/(z + \Delta z_2). \tag{5.11}$$

If Δy_1 and Δz_2 are comparable, then r_1 should usually be greater than r_2.

An estimate of an average per cent change can be obtained by a sort of dimensional analysis type of argument. Form

$$q = r_1/r_2 \cong (y + \Delta y_1)(z + \Delta z_2)/yz = (1 + p_1)(1 + p_2). \tag{5.12}$$

The expression on the right may be interpreted as a product of two ratio increases corresponding to the two treatments. Their geometric mean is $\sqrt{q} \cong 1 + \bar{p}$, where $\bar{p} = (p_1 + p_2)/2$. The average per cent increase due to both treatments is then,

$$\bar{p} \cong 100(\sqrt{q} - 1). \tag{5.13}$$

For the target control case the appropriate ratios are the same

$$r_1 = y_1/z_1 \cong y/z \tag{5.14}$$

for east burners on, and

$$r_2 = y_2/z_2 \cong (y + \Delta y_2)/z \tag{5.15}$$

for west burners on, but now r_1 will usually be less than r_2.

To get an estimate of an average per cent change, form

$$q^{-1} = r_2/r_1 \cong (y + \Delta y_2)z/yz = 1 + p_2, \tag{5.16}$$

then

$$p_2 \cong 100(q^{-1} - 1). \tag{5.17}$$

Table Va shows r_1, r_2, and $\bar{p}$ for southerly flow, standard gage arrangement. Table IVa shows r_1, r_2, and $\bar{p}$ for westerly flow, standard and BT gage groupings.

6. Estimates of per cent increase due to seeding by ANOCOVA and regression methods

Once the F test has established the uniqueness of the regression lines (regardless of any parallelism assumption) for the two treatments, a very great interest centers on estimating the per cent increase or decrease. A ratio percentage estimate has been discussed. A more generally recommended method is to use the regression lines for this purpose; the three procedures used are described as follows.

6.1. *Procedure 1*—ANOCOVA *case, southerly flow.* Four regression lines are available:

$$L_1\colon \hat{y}_1 = \hat{\beta}_1 + \hat{\gamma}z^{(1)}, \quad \text{where } \hat{\beta}_1 = y_1 - \hat{\gamma}z_1, \tag{6.1}$$

$$L_2\colon \hat{y}_2 = \hat{\beta}_2 + \hat{\gamma}z^{(2)}, \quad \text{where } \hat{\beta}_2 = y_2 - \hat{\gamma}z_2, \tag{6.2}$$

$$L_3\colon \hat{z}_1 = \hat{\beta}_1' + \hat{\gamma}'y^{(1)}, \quad \text{where } \hat{\beta}_1' = z_1 - \hat{\gamma}'y_1, \tag{6.3}$$

$$L_4\colon \hat{z}_2 = \hat{\beta}_2' + \hat{\gamma}'y^{(2)}, \quad \text{where } \hat{\beta}_2' = z_2 - \hat{\gamma}'y_2. \tag{6.4}$$

Lines L_3 and L_4 are obtained by interchanging the roles of y and z and recalculating the intercepts $\hat{\beta}'$ and slope $\hat{\gamma}'$, both primed to distinguish them from the estimates in lines L_1 and L_2. Hats and superscripts distinguish variables from their corresponding means.

The procedure is to calculate the per cent change in the east target when it is seeded and the per cent change in the west target when it is seeded and average the two percentages. The first step is to calculate the average unseeded precipitation in the east target and west target. Four means are available, (y_1, z_1) and (y_2, z_2), where by definition,

$$\bar{y} = (J_1 + J_2)^{-1}(J_1y_1 + J_2y_2), \tag{6.5}$$

$$\bar{z} = (J_1 + J_2)^{-1}(J_1z_1 + J_2z_2). \tag{6.6}$$

Supposedly the effect of seeding is to shift line L_1 above and line L_2 below some parallel, intermediate, unseeded line,

$$Ly\colon \hat{y} = \hat{\beta} + \hat{\gamma}z. \tag{6.7}$$

A similar line,

$$L_z\colon \hat{z} = \hat{\beta}' + \hat{\gamma}' y \tag{6.8}$$

may be defined for the interchanged case, where an opposite effect has occurred; that is, line L_3 is shifted below line L_z by operating the east burners and line L_4 is shifted above L_z by operating the west burners.

In (6.7) $\hat{\gamma}$ is taken to be the $\hat{\gamma}$ of equations (6.1) and (6.2) and $\hat{\beta}$ is taken to be

$$\hat{\beta} = (J_1 + J_2)^{-1}(J_1\hat{\beta}_1 + J_2\hat{\beta}_2) = \bar{y} - \hat{\gamma}\bar{z}. \tag{6.9}$$

Similarly in (6.8) $\hat{\gamma}'$ is taken to be the $\hat{\gamma}'$ of equations (6.3) and (6.4) and $\hat{\beta}'$ is taken to be

$$\hat{\beta}' = (J_1 + J_2)^{-1}(J_1\hat{\beta}_1' + J_2\hat{\beta}_2') = \bar{z} - \hat{\gamma}'\bar{y}. \tag{6.10}$$

Lines L_y and L_z are not parallel. They intersect at the point $(\bar{y}, \bar{z})$.

The average unseeded precipitation in the east target y may be calculated from (6.5) when y_1 is replaced by,

$$y_1^c = y_1 - (\hat{\beta}_1 - \hat{\beta}). \tag{6.11}$$

Similarly the average unseeded precipitation in the west target z may be calculated from (6.6) when z_2 is replaced by,

TABLE IVa

SUMMARY OF ANALYSIS FOR WESTERLY FLOW CASES USING STANDARD AND BT GAGE GROUPINGS, 1962–63 SEASON

I. RATIO ANALYSIS

Size of warm sample is too small for analysis.

	Standard Gage Groupings			Gage Grouping BT		
	Combined	Warm	Cold	Combined	Warm	Cold
I. Ratio Analysis						
Sample size, seeded	12	1	11	12	1	11
unseeded	11	3	8	11	3	8
Correlation coefficient, seeded	0.9030		0.8950	0.8486		0.8367
unseeded	0.8991		0.8251	0.8697		0.7833
Coefficient of variation						
Target seeded, target	1.120		1.033	1.160		1.072
control	1.007		0.9196	0.9351		0.8475
Target unseeded, target	0.9338		0.6899	0.9286		0.7196
control	0.8586		0.6600	0.8628		0.6710
Average 12 hour precipitation						
Target seeded, target	0.1915		0.2088	0.1859		0.2028
control A′	0.1806		0.1971	0.1923		0.2098
Target unseeded, target	0.1961		0.1736	0.1845		0.1619
control A″	0.2634		0.2663	0.2955		0.3008
Ratio effects						
Seeded target/control A′	1.055		1.061	0.9688		0.9667
Unseeded target/control A″	0.7452		0.6541	0.6271		0.5382
Percentage change due to seeding	41.6		62.2	54.5		79.6

TABLE IVb

SUMMARY OF ANALYSIS FOR WESTERLY FLOW CASES USING STANDARD AND BT GAGE GROUPINGS, 1962–63 SEASON

II. REGRESSION ANALYSIS: REGRESSION OF SEEDED TARGET ON CONTROL, UNSEEDED TARGET ON CONTROL, SLOPES NOT NECESSARILY EQUAL

III. COVARIANCE ANALYSIS: REGRESSION OF SEEDED TARGET ON CONTROL, UNSEEDED TARGET ON CONTROL, SLOPES ASSUMED EQUAL

IV. BIANOVA

Size of warm sample is too small for analysis.

	Standard Gage Groupings			Gage Grouping BT		
	Combined	Warm	Cold	Combined	Warm	Cold
II. Regression Analysis						
Y intercept, seeded	−0.001		−0.001	−0.0097		−0.012
unseeded	0.004		0.024	0.012		0.026
Slope, seeded	1.064		1.065	1.017		1.023
unseeded	0.728		0.562	0.585		0.452
Average unseeded precipitation	0.1643		0.1511	0.1534		0.1381
Percentage change due to seeding	41.7		52.8	53.9		75.1
Standard errors:						
Seeded line	0.1009		0.1064	0.12495		0.1317
Unseeded line	0.0886		0.0781	0.0935		0.0836
Lines identical	0.1032		0.1126	0.1224		0.1339
Observed F	2.82		4.19	3.22		4.06
Degrees of freedom	2, 19		2, 15	2, 19		2, 15
Chance of F	8.8		3.5	6.4		3.9
III. Covariance Analysis						
Y intercept, seeded	0.035		0.039	0.044		0.046
unseeded	−0.032		−0.056	−0.033		−0.063
Slope	0.867		0.861	0.737		0.747
Average unseeded precipitation	0.1586		0.1391	0.1448		0.1225
Percentage change due to seeding	42.4		68.1	53.5		88.8
Error sums of squares $\times 10^2$						
when Y intercepts equal	22.37		21.57	31.44		30.47
unequal	19.88		17.56	28.18		25.28
Observed F	2.50		3.66	2.31		3.29
Degrees of freedom	1, 20		1, 16	1, 20		1, 16
Chance of F	13.3		7.6	14.8		9.0
IV. BIANOVA						
Observed F	1.71		2.19	1.77		1.86
Degrees of freedom	2, 20		2, 16	2, 20		2, 16
Chance of F	21.2		14.8	20.2		19.3

$$z_2^c = z_2 - (\hat{\beta}_2' - \hat{\beta}'). \tag{6.12}$$

The per cent increase in the east target when the east burners are on becomes

$$\hat{p}_1 = 100(\hat{\beta}_1 - \hat{\beta})/y. \tag{6.13}$$

TABLE Va

SUMMARY OF ANALYSIS FOR SOUTHERLY FLOW CASES USING STANDARD GAGE GROUPINGS, 1962–63 SEASON

I. RATIO ANALYSIS

	Combined	Warm	Cold
I. Ratio Analysis			
Sample size, East seeded	16	6	10
West seeded	12	9	3
Correlation coefficient, East seeded	0.9595	0.9756	0.9504
West seeded	0.9924	0.9974	0.9996
Coefficient of variation, East seeded, East	2.127	1.193	1.204
West	2.040	0.919	1.024
West seeded, East	2.127	2.679	1.227
West	2.040	2.436	1.297
Average 12 hour precipitation, East seeded, East	0.0677	0.0039	0.1060
West	0.1094	0.0152	0.1659
West seeded, East	0.2045	0.0978	0.5247
West	0.2555	0.1495	0.5735
Ratio effects, East/West, East seeded	0.6188	0.2566	0.6389
West seeded	0.8004	0.6542	0.9149
Percentage change due to seeding	−12.1	−37.4	−16.4

TABLE Vb

SUMMARY OF ANALYSIS FOR SOUTHERLY FLOW CASES USING STANDARD GAGE GROUPINGS, 1962–63 SEASON

II. COVARIANCE ANALYSIS: REGRESSION OF EAST TARGET ON WEST TARGET OR OF WEST TARGET ON EAST TARGET, WHEN SLOPES ASSUMED EQUAL

III. BIANOVA

	Combined	Warm	Cold
II. Covariance Analysis			
Y intercept $\times 10^2$, Y is East target seeded	−2.152	−0.06997	−3.375
unseeded	−0.3867	−0.9378	4.158
West target seeded	1.038	1.383	−3.937
unseeded	2.825	0.9790	4.209
Slope when East is Y	0.8155	0.7169	0.8424
West is Y	1.199	1.387	1.168
Average unseeded precipitation, combined			
East targets	0.1307	0.05967	0.2160
West targets	0.1764	0.09481	0.2744
Percentage change in East target, East burners on	−5.79	2.39	−8.05
West target, West burners on	−5.79	1.71	−22.8
Percentage change due to seeding	−5.79	2.05	−15.4
Regression of East on West			
Error sums of squares $\times 10^2$, Y intercepts equal	5.75977	0.3421	3.349
unequal	5.554	0.3401	2.255
Observed F	0.9244	0.06827	4.853
Degrees of freedom	1, 25	1, 12	1, 10
Chance of F	35.2	79.8	5.3
III. BIANOVA			
Observed F	0.986	0.363	3.90
Degrees of freedom	2, 25	2, 12	2, 10
Chance of F	38.8	70.4	5.6

The per cent increase in the west target when the west burners are on becomes

$$\hat{p}_2 = 100(\hat{\beta}_2' - \hat{\beta}')/z. \tag{6.14}$$

The overall average increase is then,

$$\bar{P}_s = \frac{1}{2}(\hat{p}_1 + \hat{p}_2). \tag{6.15}$$

6.2. *Procedure 2—*ANOCOVA *case, westerly flow.* Only regression lines L_1 and L_2 from Procedure 1 are used. The effect of seeding is now to shift L_2 above L_1 where L_1 is analogous to L_y in Procedure 1; that is, it serves as the unseeded control line.

As before, y, the average unseeded precipitation in the target, may be calculated from (6.5), but with y_2 replaced by,

$$y_2^c = y_2 - (\hat{\beta}_2 - \hat{\beta}_1). \tag{6.16}$$

Note that,

$$y = (J_1 + J_2)^{-1}(J_1 y_1 + J_2 y_2^c) = \hat{y}_1(z) = \hat{\beta}_1 + \hat{\gamma} z \tag{6.17}$$

where $z = \bar{z}$ is defined by (6.6). The per cent increase in the target when it is seeded is then,

$$\bar{P}_w = 100(\hat{\beta}_2 - \hat{\beta}_1)/y. \tag{6.18}$$

6.3. *Procedure 3—regression case, westerly flow.* Two regression lines are available

$$\hat{y}_1 = \hat{\beta}_1 + \hat{\gamma}_1 z^{(1)}, \tag{6.19}$$

$$\hat{y}_2 = \hat{\beta}_2 + \hat{\gamma}_2 z^{(2)}. \tag{6.20}$$

The average unseeded precipitation in the control z is defined by (6.6),

$$\bar{z} = (J_1 + J_2)^{-1}(J_1 z_1 + J_2 z_2). \tag{6.21}$$

The average unseeded precipitation in the target is then,

$$\hat{y}_1(\bar{z}) = \hat{\beta}_1 + \hat{\gamma}_1 \bar{z}. \tag{6.22}$$

The effect of seeding is taken to be

$$\hat{\Delta} y_2 = \hat{y}_2(\bar{z}) - \hat{y}_1(\bar{z}). \tag{6.23}$$

The per cent increase is then,

$$\bar{P}_{w,R} = 100\hat{\Delta} y_2/\hat{y}_1(\bar{z}). \tag{6.24}$$

It is clear that many estimates similar to equation (6.24) can be defined by replacing $\bar{z}$ with any observed value of z.

An alternate approach that avoids this difficulty and in fact, one of the earliest used in cloud seeding evaluations, is to compute

$$d_k = y_k^{(2)} - \hat{y}_1(z_k^{(2)}), \tag{6.25}$$

for the K seeded events $k = 1, \cdots, K$. These are the differences between the seeded value of y and its unseeded value as predicted by the control line. Let

(6.26) $$\bar{d} = K^{-1} \sum_{k=1}^{K} d_k.$$

The estimate becomes

(6.27) $$\bar{P}'_{w,R} = 100\bar{d}/Y,$$

where Y is some estimate of the average unseeded target precipitation, possibly from equation (6.22) or historical records.

7. Transformations

No square root, logarithmic, or other transformations of the basic data have been made. Other investigations have employed such transformations, mainly to stabilize the residual variance as required by the theory, although this desirable end has the bad side effect of complicating the estimation procedures. In particular, biased estimates must be corrected [11]. Estimation of the per cent increase is a central issue in any evaluation of cloud seeding. It is so important that the analysis very likely should be handled as an estimation problem with confidence intervals developed for what are essentially, in all procedures, ratio estimates.

8. Computer processing

The analyses discussed in the next sections are based on about 150,000 gage hours of accumulated precipitation data, of which about 25,000 gage hours were nonzero. Readings for each individual gage were punched on cards, each card containing 24 hourly values at least one of which was nonzero. (No cards were punched for rainless or snowless days.)

This file of about 2500 cards was then checked, matched, merged, and processed with a deck of 76 event cards containing all the meteorological and operational data. Total precipitation for each 12-hour event was calculated for each gage and output as a gage detail file for each gage and event processed. These 12-hour totals were combined for all gages within a particular target or control area and divided by the total gages in the target or control. This information was output as an area average file for each area and event processed. The precipitation data listed in table II were obtained from this output. Thus the numbers represent area wide 12-hour totals, divided by the number of gages in the area.

The gage detail file also includes, for each event, 12-hourly averages, standard deviations, and coefficients of variations, sorts of each of these, and a frequency distribution of the total gage record for each 0.01 inch increment of precipitation.

Since areas (and events) could be redefined with ease, it was quite simple to investigate modified target and control areas. In fact, a modern digital computer with large memory is almost indispensable to relieve the tedium and remove the errors in these computations. The work was done on an IBM 7094 in the Fortran language.

Once the precipitation data had been boiled down to the events of interest, standard and modified regression programs were employed to calculate the results in tables IVb and Vb.

9. Summary of analysis of westerly wind cases

As pointed out earlier, each seeded period is stratified into categories of wind direction according to the standard 16 point rose. This section describes the results of the analysis of the cases that were determined to be associated with a west wind over the Lake Almanor watershed.

Twenty three usable 12-hour periods with winds from WSW through NW occurred during the season. Of these 23 cases, the east burner group was used in 11 cases and the west burners used in 12 cases. This resulted in target precipitation gages being seeded 12 times and not seeded 11 times.

With the standard gage groupings, the ratio, regression, and covariance analyses showed an increase in precipitation when the clouds were seeded prior to moving over the target gages; that is, when the west burners were on. This increase is largest for the westerly cases when the $-5°$ C level was at or below 7500 feet. The chance of erroneous identification of distinct regression lines in this cold situation is, for the regression analysis, less than five per cent. This result is the main significant effect to be reported (see table IVb.)

The per cent increases for the westerly cold cases are by the ratio method, 62.2 per cent; by the regression method, 52.8 per cent; and by the covariance method, 68.1 per cent, so that in round numbers the increase is 60 per cent.

With warm and cold combined into one sample, the ratio, regression, and covariance percentage estimates are respectively 41.6, 41.7, and 42.4 per cent, or 40 per cent in round numbers. Regression analysis showed a difference in seeded and unseeded lines significant at the 10 per cent level. The covariance analysis was significant at the 15 per cent level, the bivariate analysis of variance at the 25 per cent level.

As described earlier, several different groupings of gages have been used to investigate the distribution and magnitude of any increase. Table IV shows the results of the analysis of the gage grouping which was thought to represent gages most likely to be seeded; that is, arrangement BT. Increases of 54.5 per cent using the ratio method, 53.9 per cent using the regression method, and 53.5 per cent using the covariance method were observed for combined westerly cases. The increases for the cold cases were, for the same analyses, respectively, 79.6, 75.1, and 88.8 per cent. Significance of these results is about the same as for the standard gage group.

Data from the other gage groupings are not included in this summary. The most interesting result of the other grouping analyses was the fact that the target gages closest to the burners showed more of an increase than the gages farthest from the burners.

10. Summary of analysis of southerly wind cases

For 28 usable events associated with southerly winds, 15 were identified as warm and 13 were identified as cold. The east burners seeded the east target 16 times and the west burners seeded the west target 12 times.

Estimates of per cent changes due to seeding along with the elaborating statistics are shown in table V. No effects of interest comparable to the westerly cold situation were detected. In particular, no positive changes were observed that could be identified with significantly different seeded and unseeded regression lines. Covariance analysis and bivariate analysis of variance were both used; regression analysis was not performed because of time limitations and the unpromising prior results. (The basic data for analysis is, of course, available in table II.) Regression analysis is not likely to detect any significance either, except perhaps for the cold cases. Unfortunately this small sample is highly unbalanced.

On the whole, an excess of negative signs occurs in the estimated effects. There is little doubt, however, that this is a chance occurrence, although the temptation might exist to postulate a minus effect in warm cases.

No improvement was detected in the level of significance for the different groupings of the target gages. This is to say, no changes were observed which could be confidently attributed to seeding when investigations of just the gages closest to the burners, gages farthest from the burners, and so forth, were made.

11. Discussion of results

Statistical analysis of the meteorological data appears to have isolated the general weather conditions where seeding has been effective. This has led to an investigation of the physical mechanisms which might be operating to cause an increase in precipitation.

Reviewing briefly the results of the statistical analysis, a positive change was observed in the standard target area during seeding when the winds were from the west. In round numbers, the increase was 40 per cent for all westerly cases and 60 per cent when only the cold cases were analyzed. When the peripheral target gages were eliminated from the analysis and the buffer zone increased, the increases became about 54 per cent for all cases and about 80 per cent for the cold cases. The target gages were further divided into close in targets and targets farthest from the burners. This analysis showed a bigger increase close in than was observed in the farthest target.

The implication in the above result was that a distance effect relationship was occurring. To investigate this further, individual gages were analyzed downwind, under westerly flow, of two different burners, Stover Mountain and Butt Mountain. Results of this study are shown in figure 5.

Average gage catch was normalized to the catch of the control gages and plotted for the seeded periods and for the unseeded periods. The solid line is

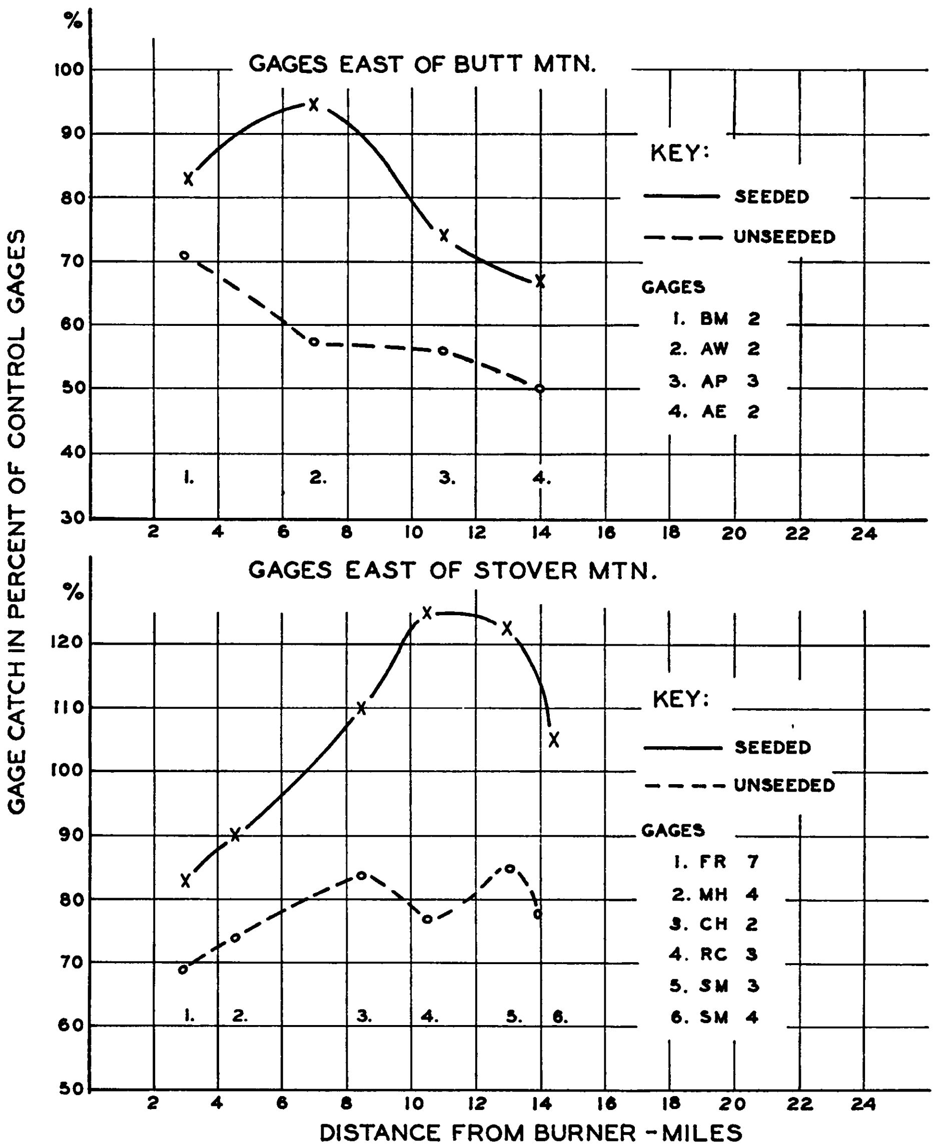

FIGURE 5

Analysis of the effects of seeding under westerly flow downwind of two individual silver iodide burners, 1963 data.

the seeded catch. The broken line is the unseeded catch. In both cases the precipitation was observed to decrease with distance when no seeding was carried out. A rise in terrain at about ten miles from the Stover burner accounts for the increase at that distance.

Seeded cases showed the opposite pattern; that is, precipitation was observed to increase out to about seven miles and then decrease. In every case, the seeded precipitation catch was more than would have been expected.

Under westerly flow the Almanor watershed is in the lee of the Sierra; that is, the mountains are highest to the west of the watershed. The watershed drains to the Pacific through the deep Feather River Canyon which is south and southwest of the basin.

Air moving from the west to the east passes the crest of the Sierra and begins a gradual descent which averages at least 1000 feet in 10 to 20 miles. Compression of the air increases both the pressure and temperature of the parcel, causing evaporation of the cloud particles.

In the mountains the flow becomes complicated and successive waves are often produced in the lee of the mountain. However, at Almanor the overall tendencies will be for the air to be sinking over the watershed with superimposed waves downwind of the crest of the Sierra under westerly flow.

Discussed below are three physical mechanisms which are probably contributing to increasing the precipitation under westerly flow when the clouds are seeded.

(a) Freezing the subcooled (temperatures less than 0° C) drops in a cloud will allow the individual drops to grow larger than a water drop could grow from condensation alone under the same atmospheric conditions. This is possible because the vapor pressure over ice is smaller than over water; thus, ice can attract more vapor from the air and can cause the adjacent water droplets to evaporate with this vapor also being attracted to the ice. By growing larger, the ice crystals can begin to fall through the cloud (having overcome the buoyant effect of the cloud), and still grow by sweeping up other cloud particles.

(b) Freezing of the cloud particles increases the expected life of a cloud particle. More energy is required to evaporate an ice particle than is required to evaporate a liquid drop. Also, because the vapor pressure is lower over ice than over water, the gradient of available vapor below a cloud would permit ice particles to fall farther before they would start to evaporate. The saturation pressure over water at -5° C is 4.22 millibars while over ice at the same temperature the saturation pressure is 4.03 millibars.

(c) Latent heat is released to the atmosphere when water freezes. From calculations, the available heat from this source would appear to be large enough to greatly increase the buoyancy of the seeded parcel of air. For example, if the assumption is made that seeding will convert a cloud downwind of a burner that is 3.4763×10^8 meters^3 in volume (the approximate seeded volume of air with temperature less than -5° C out to about 1.5 miles from the burner) and that the average water content of the cloud is 1 gram per meter^3, then approximately 1.16398 $\times 10^{11}$ joules of heat would be released. This is enough heat to raise the temperature of such a volume of dry air by 3° C. An increase of temperature of a volume of air over the temperature of the surrounding air would have the effect of displacing the warmed air in an upward direction until the surrounding air mixes sufficiently with the warmed air to bring it into equilibrium. Thus, the seeded parcel of air, being more buoyant than the surrounding air, resists the downward motion in the lee of the crest preventing evaporation of the cloud particles and maintaining the cloud for a longer period of time.

The analysis of individual gages downwind of burners referred to earlier suggests that the effect of these physical mechanisms is to increase and displace the precipitation to the east with a maximum increase occurring at about seven miles from the burner. This appears to be a physically reasonable possibility.

No statistically significant result was detected from seeding clouds associated with southerly flow over the Almanor watershed. One factor which is thought to be an active suppressant of any effect is the thermally stable air often associated with southerly flow. This is in contrast with westerly flow where the atmospheric conditions usually are measured to be unstable.

Stable flow could prevent or retard the silver iodide from reaching the clouds at the levels and in the concentrations required for effective seeding. Also, the release of latent heat under stable conditions is less likely to be sufficient to induce vertical motion.

The possibility has been suggested that the increase under southerly flow might be occurring farther downstream. There is no support for this case. The diffusion of smoke from a point source would reduce the cloud concentration of silver iodide to a level below one particle per liter in less than ten miles. The same analysis was completed for the southerly cases as was described above under westerly flow; that is, only close in gages were analyzed, only gages farthest from the burners were analyzed, and so forth. This comprehensive work gave no clue to any effects.

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