SOME OUTSTANDING PROBLEMS RELATING TO RAIN MODIFICATION

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1. Introduction and summary

This paper deals with two aspects of the problem of rain modification by cloud seeding: the meteorological aspect, concerned with the rainfall itself and with the possibility of its being affected by cloud seeding, and with the statistical aspect, concerned with the methodology particularly suitable for the treatment of the meteorological problem. The conclusions presented stem from an analysis of five major American rain stimulation experiments and of a Swiss hail suppression experiment Grossversuch III.

Our basic premise in discussing the meteorological problem is that, as documented below, there exist two (at least two) sets of synoptic conditions, say A and B, in which the seeding of clouds has opposite effects: in conditions A it increases the precipitation and in conditions B it decreases the precipitation. In a series of storms (or "rainy incidents") passing over a given locality these conditions A and B are mixed in varying proportions and we hypothesize that it is this varying frequency of conditions A and B that is responsible for the disappointing results of a number of cloud seeding experiments: too many days with conditions B were included so that the net effect is negative or zero.

Thus far, the identity of conditions A and B is not established and there are only certain vague hypotheses regarding them. However, and this is our second premise, these two sets of conditions appear identifiable in terms of the usual meteorological parameters such as pressures, wind velocities, fronts, and so forth.

In the light of these two premises, the foremost outstanding substantive problem of rain modification by cloud seeding is the identification, or the definition, in terms of meteorological parameters of the conditions A and B. Most probably these definitions will be relative, referring to the local orographic conditions and to the method of seeding.

Unambiguous indications that cloud seeding can increase rain come from Grossversuch III [1], [2]. Specifically, on the 103 days selected for the experiment by one of the forecasters, Mr. F. Ambrosetti, seeding appears to have produced an overall increase in precipitation amounting to about 80 per cent

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and this result is significant (two tail) at four per cent. For another forecaster, Mr. O. Lüthi, who selected 26 days for the experiment, the estimate of the increase amounts to 246 per cent. Because of the relatively small number of observations, this estimate is somewhat shaky and, probably, overestimates the true effect. However, it corresponds to a significance probability of six per cent.

The apparently positive effect of seeding is not uniform over the target of Grossversuch III. Increases in rain due to seeding are most pronounced in the northern part marked with very high mountains and deep valleys and canyons. Here, the two tail significance probabilities reach two per cent. On the other hand, in the southern foothills of the Alps, no significant effect of seeding was found. Since the moisture bearing air flow is predominantly from the south, this distribution of effects is, perhaps, not surprising. However, it conceivably may be connected with the differences in the intensity of seeding, high in the south and somewhat weaker in the north.

The evidence that cloud seeding can decrease rainfall comes from five American experiments. One of them indicates an apparent increase in rain due to seeding and the other four are unanimous in indicating decreases ranging from 20 to 50 per cent of normal. While in several cases the original experimental data are not available and while the original evaluations are subject to some doubts, an effort at a summary evaluation of the five experiments indicates that in one or more of them the effect of seeding must have been a decrease in rainfall.

The evidence cited above indicates that on Mr. Ambrosetti's experimental days and also those of Mr. Lüthi, there must have been frequent cases where conditions A prevailed in the northern part of the Swiss target. On the other hand, in at least one of the five American experiments, and probably more, conditions B must have been prevalent.

Indications that conditions A and B are probably identifiable in the usual meteorological terms come also from Grossversuch III. In addition to strong evidence of increases in precipitation on days selected by Mr. Ambrosetti and Mr. Lüthi, the data provide mild indications that on the 80 days selected by another forecaster, Dr. E. Zenone, there was a 44 per cent decrease in rainfall. Also, an overall analysis shows that the risk of error in rejecting the hypothesis that the true effect of seeding on days selected by the five different forecasters was the same amounts to seven per cent. This suggests that the relative frequency of conditions A and B on days selected by the different forecasters, each following his own system and perhaps intuition, must have been different. For example, conditions B must have been more frequent on Dr. Zenone's days than on Mr. Ambrosetti's days. If so, then the two meteorologists must have identified the conditions A and B, at least partially, even though they are not aware of the fact.

Eventually, the definition of conditions A and B will have to be determined through special experiments. However, a comparative analysis of the several already completed experiments is likely to provide useful working hypotheses or clues. Here Grossversuch III offers excellent promise for the reason that the indicated differential effect of seeding cannot be due to anything else but to the variation in synoptic conditions, since everything else remained fixed.

Of the clues thus far collected regarding the conditions A and B the following may be mentioned.

(i) Seeding seems to increase rainfall when the winds aloft are strong but not when they are weak. (Actually, this is an *a priori* hypothesis communicated to us by Mr. James Hughes. It appears to be confirmed by data in Grossversuch III.)

(ii) As indicated by Grossversuch III, seeding during the early part of a rainy period, as well as during the late part, appears to decrease the precipitation.

In this connection, the following observation occurs to us. The five American experiments, and also the Australian and Israeli experiments reported in this volume, may be divided roughly into two categories: those in which an effort appears to have been made to begin seeding so to speak in advance of the anticipated natural rain (SCUD, Whitetop, and the two experiments in Arizona) and those in which seeding was done only in the presence of clouds judged "ripe for seeding" (ACN experiment in Washington-Oregon, the four experiments in Australia, and the Israeli experiments). It may or may not be significant that the indicated effects of seeding in all four experiments of the first category is a decrease in rain, whereas in four out of the six experiments of the second category there is an indicated increase.

In order that an experiment provide definitive information regarding conditions A and B, it must be planned on principles different from those underlying the classical experiments. (See appendix.) In the latter, the seeding was conducted only in strictly preassigned conditions (perhaps when cloud tops were sufficiently cold or when the precipitable water was sufficiently high, and so forth) under which the experimenter expected the desired effects of seeding. Trials of this kind can *prove*, or fail to prove, the soundness of the experimenter's preconceived ideas, but are not effective means to *explore*. An exploratory experiment, leading to the identification of conditions A and B, must be richer than the classical experiment and must involve seeding in a variety of conditions. Also it must involve observations not only on rainfall but also on a number of other weather characteristics.

The difficulty of experimentation with weather control depends very much on the variability of the weather manifestations, including rainfall. As a result, experiments likely to detect effects that they are supposed to detect must last several years in favorable conditions and several decades in unfavorable conditions. This circumstance makes it important to use in the evaluations those statistical procedures that are efficient. Several statistical procedures in frequent use are not efficient and the use of the best of them, compared to the use of an efficient test indicated in this paper, is equivalent to the loss of about 35 per cent of the available observations. While the problem of an optimal test appears to be solved with reference to certain experimental situations, it is far from being solved for a number of others.

The precision of rain stimulation experiments depends very much on many details of the design, such as the size and shape of the target, the unit of observation, and so forth, and particularly on the availability of predictor variables. The planning of future experiments should be based on a thorough study of meteorological data relating to a historical period, leading to the selection of the most favorable elements of the design.

2. Evidence of decreases in precipitation due to seeding

The American literature on artificial rain stimulation presents a remarkable contrast. On the one hand, there are highly optimistic accounts of increases in precipitation produced by commercial nonrandomized cloud seeding operations. On the other hand, as a result of five completed randomized experiments of unchallenged reliability, each conducted over several years with considerable care and foresight, there is just one for which the original evaluation lists a highly significant effect, and this effect is a decrease in precipitation due to seeding. The estimated decrease is quite large and amounts to 53 per cent of normal precipitation. The significance of this decrease is unusually strong, at one third of one per cent. In addition, there is this remarkable fact: out of the remaining four experiments, the results of which were not found statistically significant, only one indicates increases in precipitation ascribable to seeding and the remaining three indicate decreases.

Overwhelmingly, the tone of the relevant reports suggests that the motivation for conducting the experiments was to prove that cloud seeding can increase precipitation. Accordingly, in a number of cases, the authors, faced with the necessity of reporting decreases in precipitation due to seeding, appear to take comfort in noting that the indicated effects are not significant and that they "do not preclude the possibility" that seeding has a moderate positive effect on rainfall. With reference to each particular experiment, statements of this kind are justified. However, if experiment after experiment show apparent negative results of seeding, even if in each particular case this effect is not significant, the accumulated evidence may become heavy. The purpose of the present section is, then, to present a summary evaluation of all the reliable American experiments. Specifically, our purpose is to test the hypothesis that in not a single experiment seeding had any real effect (whether positive or negative) on precipitation.

To our knowledge, there were six major cloud seeding experiments performed in the United States. Unfortunately, certain incidents described elsewhere ([3], pp. 55–56 and [4], pp. 598–599) indicate that the data resulting from one of these experiments may not be reliable. The following evaluation is based on five experiments only, summarized in table I.

TABLE I

SUMMARY OF FIVE PRINCIPAL RAIN STIMULATION EXPERIMENTS IN THE UNITED STATES

	Original Evaluation		Reevaluation		
	Percentage Estimated Effect $100\,[S - C]/C$	Significance	Percentage Estimated Effect $100\,[S - C]/C$	Significance Two Tail P	Fisher's Test $-2 \log_e P$
Experiment	1	2	3	4	5
1. ACN 1953–54 Washington-Oregon					
Targets I	+13	"No signif. results from seeding"	+13	0.697	0.722
Targets II	+34		+34	0.935	0.134
Targets III	+109		+109	0.079	5.077
2. SCUD 1953–54 East Coast					
RI	−6	"Effect too small to be detected"	−20	0.127	4.130
RII	−33		−2	0.974	0.053
Rt	−16		Only 16 observations		
3. Whitetop, 1960–64 Missouri-Arkansas					
Missouri Plume	−53	0.0034	No data for reevaluation		11.368
Chicago Plume	−39	0.150			3.794
Out of Chicago Plume	−24	0.060			5.626
4. Arizona 1957–60	−30	0.60, 0.90	−30	0.171	3.532
5. Arizona 1961, 62, 64	−30	0.34, 0.58	No data for reevaluation		(3.532)

Columns 1 and 2 in table I give, respectively, the estimated effect of seeding and the appraisal of significance taken directly from the original reports on the particular project. Entries in columns 3, 4 and 5, as far as they differ from those in the earlier columns, are the results of reevaluations for which the present authors are responsible. The methodology used, explained in three papers [5], [6] and [7], consists in the application of the so called optimal $C(\alpha)$ tests of the hypothesis that the seeding has no effect, against the alternative that, if this effect exists then it is multiplicative. For experiments 3 and 5 no data are available for reevaluation. For experiments 1 and 4 only the average amounts of target precipitation on seeded and control days are published and these were used to obtain the two tail significance probabilities given in column 4. In these cases, then, column 3 repeats the estimate of the effectiveness of seeding given in column 1:

$$100\,[\text{mean seeded} - \text{mean not seeded}]/\text{mean not seeded}.$$

The report of Project SCUD includes values for three predictor variables, M, T, and L. These were used both in order to obtain the significance probability in column 5 and the maximum likelihood estimate of the effectiveness of seeding given in column 4.

Certain details regarding experiments are given in the notes [8] and [9]. Here the following brief remarks must suffice.

Experiments 1 and 2 were pioneer efforts at randomized experimentation with weather control and the two experimenters, Ferguson Hall and Jerome Spar, respectively, deserve warm congratulations.

The report on experiment 1, published by Hall [10], describes the definitions of three kinds of targets and gives the results of six different evaluations. All three types of targets were "adjustable" to the direction and the velocity of winds prevailing during periods of seeding as well as during the control periods. Targets I were relatively long, narrow, fan shaped strips downwind from the line followed by the aircraft that performed the seeding, to the distance of about 100 miles. Targets II were small sections of target I expected to contain the maximal effect of seeding. Targets III were of comparable size, averaging about nine raingages per target and were also devised to include the maximal effect of seeding. They were quite elaborately defined, apparently wider than target I but substantially shorter.

Hall's report contains indications that, for some reason, he was uncomfortable about targets III. One such indication is that, while publishing the average amounts of precipitation in targets I and II, separately for seeded and not seeded experimental units, namely,

	Targets I	Targets II
Seeded	13.58	12.76
Not seeded	11.98	9.53

with seeded precipitation exceeding that unseeded, the much more impressive averages corresponding to targets III, namely, 15.40 seeded and 7.36 not seeded, are not published. The amount of arithmetic performed by Hall on his data is tremendous and the assumption that the averages for targets III were not computed is hardly credible. Their absence in the paper, as well as the absence of any comment on the more than doubling of precipitation ascribable to seeding, produces the impression that Mr. Hall intended to deemphasize targets III. Mr. Hall's own statistical evaluations [7] were most elaborate and, in our opinion, arbitrary and not convincing. The significance probabilities given in column 4 were computed by the optimal $C(\alpha)$ test applied to single amounts of average precipitation in each target without any predictors. If predictor variables were available, the test could have been more powerful. However, given that the targets, particularly targets II and III, were defined purely on *a priori* grounds (that is, without reference to information on rainfall either numerical or qualitative), and given that the observational data are reliable, the indicated significance probabilities are also reliable.

The report on project SCUD is published by Spar [11]. See also [9]. Evaluations were performed using rain data denoted by RI, RII and Rt. The first two refer to two giant fixed areas. One area, on the East Coast of the United States, is about 1000 miles long and 200 to 400 miles wide, extending roughly from northern Florida to Massachusetts. The other fixed area is farther north, including Labrador and Newfoundland. Since all the cloud seeding was performed south of New York, the idea that it could affect the precipitation in Labrador seems a little far fetched. Thus, it is not surprising to find that (see column 4 of table I) if one attempted to attach significance to such effects as the observed 33 per cent decrease in precipitation *RII* estimated by Spar, or to the much smaller 2 per cent decrease estimated by us, one would be risking errors in about 974 cases out of a thousand. In the study of the totality of evidence in table I, we are inclined to ignore the evaluation based on *RII*. However, we emphasize that the reason for this inclination is not the significance probability 0.974, but the *a priori* considerations. We would be similarly inclined to ignore the evaluations, if such were performed, of the effect of Dr. Spar's seeding on precipitation in Argentina or in Australia.

The symbol *Rt* refers to rain in "adjustable targets" on the East Coast of the United States. Unfortunately, only sixteen experimental periods are available so these were not reevaluated. In our opinion the significance of project SCUD lies not only in providing evidence of the effectiveness of seeding, but also in the invention, and publication, of predictor variables which allow a very considerable increase in the precision of evaluation. This is discussed in some detail in the appendix and in [9]. Our reevaluations are based on these predictor variables.

The data in table I for the Whitetop experiment are based partly on the handout [12] which Wayne L. Decker distributed at the meeting of the American Meteorological Society held in Reno, Nevada, in October, 1965, and partly on his article [13] joint with Schickendanz in the present *Proceedings*. The handout contains the value of the t test for the evaluation of "Missouri Plume."

The Whitetop experiment was performed over an "experimental area," a circle with a 60 mile radius. "Missouri Plume," somewhat like targets I in experiment 1, means a narrow strip of land downwind from the seeding aircraft. "Chicago Plume" is a wider area, supposed to enclose all points affected by silver iodide smoke at least at some time during the experimental unit. In addition, calculations were performed for the "Out of Plume Area" which is the complement of Chicago Plume to the circular experimental area.

In interpreting the significant decrease in the Missouri Plume, Decker [13] emphasizes that the seeded Missouri Plume rain does not differ significantly from that in Out of Plume, which he considers as a no treatment area. Decker concludes that not seeded days were favored with rain, in spite of randomization.

The Whitetop experiment was organized and executed by Professor Roscoe R. Braham. Speaking before the United States Senate Committee on Commerce, Professor Braham stated [14]: "Perhaps I can speak . . . with reference to an operational seeding project which we have only recently concluded . . . in southern Missouri. We felt that our major problem, scientific problem, was to determine the conditions under which the modest increases in precipitation might occur. It didn't occur to us that there might be situations in which we could have an unfavorable result.

"Yet, as a consequence of that long series of studies, we now come to realize that indeed there may be periods in the weather, certain weather situations in southern Missouri, in which our seeding, using standard seeding techniques, resulted in decreases in the precipitation in that region."

On our part, we believe that the conclusion reached by Dr. Decker is partly due to the complexity of his tables and partly to the significance he attaches to the area to area comparisons. These we think are irrelevant. From the point of view of the question of effectiveness of cloud seeding, the only relevant comparisons are between seeded and not seeded precipitation amounts in properly defined areas. Our own preference would be a fixed target, perhaps coinciding with the entire circular experimental area. However, in principle, there are no objections to adjustable targets. The three considered by Dr. Decker arrange themselves in the following logical order: Missouri Plume, Chicago Plume, Out of Plume. The first is the narrowest and, supposedly, 100 per cent affected by the silver iodide smoke. The second is wider, and includes the first. Supposedly it contains all points with some influence of seeding. The third area, the Out of Plume, contains all points of the experimental area that are not included in Chicago Plume. Also, supposedly, the Out of Plume area is not affected by seeding. We emphasize the "supposedly" because, as Dr. Decker admits, the boundaries of the particular areas are subject to error. After this preamble, let us consider the experimental data collected from Dr. Decker's tables, arranged in what appears to us a logical order.

TABLE II

RECAPITULATION OF THE RESULTS OF WHITETOP EXPERIMENT IN UNITS OF INCHES PER "FAIR HOUR"

	Missouri Plume	Chicago Plume	Out of Plume
Average seeded	0.0045	0.0063	0.0065
Average not seeded	0.0105	0.0104	0.0085
Difference	−60	−41	−20
P	0.0034	0.15	0.06

With this arrangement of data, the interpretation appears unique: (i) the closer one comes to the center of the plume, the stronger the negative effect of seeding; and (ii) the negative effect of seeding extends beyond the Chicago Plume. As to the reliability of these conclusions, Professor Decker expresses certain doubts as to the method by which his significance probabilities have been computed. We are inclined to share his doubts. However, until the observational data on the Whitetop experiment become available for reevaluation, the two tail significance probabilities of table I and table II are the only basis for judgment. They are impressive.

Experiment 4 is described in a report by L. J. Battan and A. R. Kassander, Jr. [15]. In this experiment and in experiment 5, the target was fixed, a relatively small area in the Santa Catalina Mountains. For the observed 30 per cent decrease in rain ascribable to seeding, the application of two inefficient tests yielded significance probabilities of 0.60 and 0.90, respectively. However, the report contains the original observational data, for which the optimal $C(\alpha)$ test determined the significance probability of 0.17.

The information on experiment 5 is taken from the article [16] by Battan and Kassander. Experiment 5 differs from experiment 4 by a stricter selection of experimental days, and by a somewhat smaller target with a denser network of raingages. The indicated decrease in precipitation ascribable to seeding in the two experiments is the same. However, the significance probabilities obtained by Battan and Kassander for experiment 5 are substantially smaller than those for experiment 4. For experiment 5 no data are available for reevaluation, but the comparison of significance probabilities for experiments 4 and 5 suggests to us that the adoption for experiment 5 of the two tail significance probability of 0.17, the same as for experiment 4, is both realistic and conservative.

Reflecting the fact that weather modification in general, and rain stimulation in particular, represents a colossal new area of study, the five experiments summarized in table I are far from representing a single system. On the contrary, somewhat haphazardly, the five experiments differ in many important details: in method of seeding, in the chemical used, in the location, character and size of target, and, finally, in the method of selecting weather patterns judged appropriate for seeding. In spite of all this heterogeneity, it is interesting to inquire whether, with an acceptable risk of error, the existing evidence justifies the assumption that in at least one case the seeding had an effect on precipitation, whether positive or negative. For this purpose, we use a special test, originally invented by R. A. Fisher [17] and subsequently found to have an optimal property by E. S. Pearson [18].

The test is applicable to the results of several independent experiments. Its machinery consists in computing for each experiment $-2 \log_e P$ and the sum total of these quantities. This sum is the test criterion, to be compared with the percentage points of the χ^2 distribution with the number of degrees of freedom equal to twice the number of experiments. The requisite values of $-2 \log_e P$ are given in the last column of table I and the only problem, and a delicate one, is to decide which evaluations, supposed independent, to include in the application of the summary test. Obviously, the three evaluations for experiment 1 and the three for experiment 3 are not mutually independent. Here there are several possibilities and the choice among them is bound to be somewhat subjective. One limitation on this choice is important: the particular evaluations to be included into the summary test must be selected for reasons other than the numerical values of P. Alternatively, one might select the two extremes and then make up one's mind about an appropriate intermediate.

On our own part, we have no hesitation on the following points. For experiment 1 we select targets I for the reason of the relative simplicity of their definition and because they are much larger than the others. For experiment 2 we select the evaluation based on *RI*. For experiment 5 we have no hesitation in hypothesizing that a realistic value of P is at most equal to that corresponding to experiment 4, that is, $P = 0.17$. As to experiment 3 we are in some doubt. As mentioned, our preference would be to use the evaluation based on the total rainfall in the whole experimental area, an evaluation that has not been performed. As things stand, we perform three separate summary tests, one with Missouri Plume data, one with Chicago Plume data and one with Out of Plume data. The results with obvious notation, are

$$\begin{aligned} &\chi^2_M = 23.3, \qquad \chi^2_C = 15.7, \qquad \chi^2_0 = 17.5, \\ &P_M = 0.010, \quad P_C = 0.108, \quad P_0 = 0.064. \end{aligned} \tag{2.1}$$

Taking into consideration these three significance probabilities, and the way they were computed, we believe that the risk of rejecting the hypotheses tested

TABLE IIa

REEVALUATION OF PROFESSOR DECKER'S DATA

COMMENT *1.* It looks a little as if seeding increased the frequency of noticeable rain (not significantly) and it is interesting to see whether this is confirmed by radar data. However, the amount of rain reaching the ground was (significantly) diminished, so much that the final effect is negative.

COMMENT *2.* The above reevaluation of Dr. Decker's data did not influence materially our conclusion that in at least one of the five experiments in table I the seeding had some effect and that this effect was a decrease in precipitation.

	Missouri Plume		Chicago Plume		Out of Chicago Plume	
	Seeded	Not S	Seeded	Not S	Seeded	Not S
I FREQUENCY OF NOTICEABLE RAIN						
Rainy days	42	34	59	51	72	62
Dry days	60	62	43	45	30	34
Per cent rain	41	35	58	53	71	65
P	0.492		0.600		0.453	
II PRECIPITATION PER RAINY DAY						
Mean (inch/fair hour)	.0123	.0286	.0109	.0195	.0093	.0131
Per cent increase	−57		−44		−29	
P	0.014		0.040		0.120	
III PRECIPITATION PER EXPERIMENTAL DAY						
Mean (inch/fair hour)	.0051	.0101	.0063	.0104	.0066	.0085
Per cent increase	−50		−39		−22	
P	0.076		0.111		0.291	

is small, probably substantially less than five in a hundred. We adopt, then, the alternative hypothesis, which is, that in at least one of the five experiments, seeding did have some effect. As to what this true effect of seeding might have been, the predominance of negative estimates in table I is impressive. We believe, then, that there is little risk in assuming that at least in one of the five experiments, and probably more, the true effect of seeding was a decrease in precipitation.

Note. We are indebted to Professor Wayne L. Decker for sending us the data that led him to the evaluation discussed above. The following summary of our reevaluation attempts to answer three questions: (i) did the seeding influence the frequency of noticeable rain? (ii) did the seeding influence the average amount of precipitation per rainy day? (iii) did the two effects (i) and (ii) combine to produce a change in the average precipitation per experimental day? The data received give precipitation amounts averaged over "fair hours" of an experimental day and, therefore, our "dry day" does not necessarily mean a day without any rain in the experimental area.

3. Evidence of increases in precipitation due to seeding

As mentioned in the introduction, the selection of experimental days in Grossversuch III was done by several forecasters at the Osservatorio Ticinese at Locarno-Monti. The forecasting was done each afternoon for the next day during the summer months of 1957 through 1963. Because the purpose of the experiment was to demonstrate whether cloud seeding can suppress hail, the forecaster's attention was concentrated on the question as to whether on the morrow hail storms were to be expected or not. There was no single person especially assigned to the work on Grossversuch III and it was serviced with some kind of rotation by all the meteorological staff of the observatory. Unavoidably, there were inequalities in the work done for Grossversuch III, with two persons working on fewer than ten days.

Table III is similar to table I and gives the results of the evaluations performed on "noticeable precipitation" averaged over the whole target of Grossversuch III. "Noticeable precipitation" means precipitation with the target average exceeding 0.05 millimeters. The table is divided into three parts. First there are separate evaluations made for the five forecasters who classified more than 20 days each as experimental days. It will be noticed that there are three substantial increases ascribable to seeding, one significant at 3.6 per cent and another at 6.3 per cent. Fisher's summary test yields $\chi^2 = 23.20$, which is significant at 2.8 per cent. Here, then we have the first unambiguous evidence of effectiveness of seeding. Furthermore, seeding appears to have increased rainfall.

The second part of table III, containing only two lines, refers to the section of the total Grossversuch III composed of 94 days with noticeable rain included in the experiment by the five forecasters who selected not more than 30 days each: Balmelli, Lüthi, Zeller, Thams, and Valco. The first line gives the evalu-

TABLE III

APPARENT EFFECT OF SEEDING ON DAYS SELECTED BY PARTICULAR FORECASTERS
ENTIRE TARGET, GROSSVERSUCH III, NOTICEABLE RAIN

Forecaster	No. of Experimental Days		Mean Rain in mm	Estimated Effect Percentage	Two Tail P	$-2 \log_e P$
1. Ambrosetti	Seeded	39	18.6	+79	0.036	6.48
	Not seeded	46	10.3			
2. Balmelli	Seeded	17	12.8	−29	0.490	1.43
	Not seeded	13	18.1			
3. Lüthi	Seeded	10	27.9	+246	0.063	5.53
	Not seeded	13	8.1			
4. Zeller	Seeded	16	14.2	+115	0.202	3.20
	Not seeded	12	6.6			
5. Zenone	Seeded	31	9.6	−44	0.117	4.29
	Not seeded	32	17.1			
6. Thams and Valco	Seeded	7	5.2	−39	0.321	2.27
	Not seeded	6	9.9			
Summary 1, 2, 3, 4, 5, 6			$\chi^2 = 23.20$	$P(\chi^2) = 0.028$		
Forecasters 2, 3, 4, 6	Seeded	50	15.2	+40	0.258	2.71
	Not seeded	44	10.9			
Summary 1, 5, (2, 3, 4, 6)			$\chi^2 = 13.48$	$P(\chi^2) = 0.036$		
All days with noticeable rain	Seeded	120	14.9	+21	0.143	
	Not seeded	122	12.3			
Zero rain	Seeded	25				
	Not seeded	25				

ation for "five forecasters" and the second the value of χ^2 and the corresponding P computed for the three major parts of Grossversuch III, composed of days selected by Ambrosetti, by Zenone, and by the five other forecasters combined. Here again Fisher's summary test indicates that in at least one of the three groups of experimental days the seeding had a real effect. The last part of table III gives the evaluation for all the experimental days of Grossversuch III, irrespective of the forecaster.

The five evaluations in table III differ considerably from evaluations in table I. While the evaluations in table I refer to different experiments, with differently located and differently defined targets, some small and some colossal, and while the method of seeding in all these experiments was not the same, all these elements were identical for all the evaluations in table III. The only thing that changed from one evaluation to the next was the identity of the forecaster, each with his own ideas as to the symptoms of approaching stormy weather. Another characteristic of table III is important: this is that all the five evaluations are mutually independent; they refer to different days.

Table III refers to the evaluation performed for the whole target of Grossversuch III, a roughly triangular area in Switzerland, south of the Alps. The base of the triangle is running approximately from west to east, on the crest of the Alps. The vertex of the triangle is south. The whole area is heterogeneous to the extreme and, therefore, the experimenters divided it into four zones or subtargets, numbered from south to north. The southernmost zone 1 had just one raingage located at the edge of the Po Valley. Zone 2, immediately north of zone 1, had six gages located on the floor of a deep valley oriented north to south and located between chains of mountains reaching 2000 meters. Zone 3 is farther north, also in a deep valley. However, this valley is oriented roughly from WSW to ENE and is separated from the Po Valley by a barrier of high mountains. Zone 4, north of zone 3, is very mountainous, with a series of deep and narrow canyons oriented mostly north and south. Some of the raingages are at the bottom of the canyons at elevations below 400 meters. Several are above 1000 meters. Because of this heterogeneity of zone 4, we decided to divide it into two subzones, labeled 4 low and 4 high, according to whether the gages are below or above 1000 meters.

Because the predominant flow of moisture is from directions south to west, the above differences in orographic conditions indicated the possibility that the effects of seeding will not be the same in the five parts of the target. With this in mind table IV was constructed giving separate evaluations for the five subtargets with the subdivision of days into three groups: those selected by Ambrosetti; those selected by Zenone; and those selected by the five other forecasters. In addition, table IV reflects a little deeper analysis of the data.

Cloud seeding may have two kinds of effects on rainfall. First, it may trigger rain which would not fall otherwise. Also, conceivably, cloud seeding may decrease the frequency of rainfall. Second, the seeding may increase or decrease the average amount of noticeable precipitation. Table III refers only to the possible change in the average amounts of noticeable precipitation due to seeding, per rainy day. Contrary to this, table IV, divided into three parts IVa, IVb, and IVc, attempts to answer the following three questions.

(a) Does seeding alter the frequency of days with noticeable rain?

(b) Does seeding affect the average amount of noticeable rain, per rainy day?

(c) Does the seeding affect the total rainfall in the particular subtargets by either of the two mechanisms (a) or (b) or both?

Turning first to table IVa, we see that on seeded days selected by Ambrosetti, the frequency of noticeable rain is higher than on not seeded days in all subtargets except in zone 4 low. Exactly the opposite is seen for days selected by Zenone and by the five other forecasters. However, the values of P, in particular those given in the last column, show that the indicated effects may easily be due to chance fluctuations. Thus, the available evidence is not sufficient to assert that seeding affected the frequency of noticeable rain.

This is not the case for table IVb, referring to the amount of precipitation per rainy day. The results of Fisher's summary test exhibited in the last column

TABLE IVa

DOES SEEDING AFFECT THE FREQUENCY OF DAYS WITH NOTICEABLE RAIN?
NUMBER OF DAYS WITH RAIN, PERCENTAGE OF RAINY DAYS, AND
SIGNIFICANCE PROBABILITY

Boldface numerals mark the effects that are significant at better than 10 per cent.

	Forecaster	Ambrosetti		Zenone		Five Others		All		
Zone		S	NS	S	NS	S	NS	S	NS	Summary
1	Rain	29	25	15	24	30	27	74	76	
	No Rain	18	31	25	16	28	24	71	71	
	% Rain	62	45	38	60	52	53	51	52	
	P	0.128		**0.074**		0.948		0.997		0.150
2	Rain	35	37	22	25	38	37	95	99	
	No Rain	12	19	18	15	20	14	50	48	
	% Rain	74	66	55	63	66	73	66	67	
	P	0.480		0.650		0.560		0.836		0.745
3	Rain	35	37	19	25	35	34	89	96	
	No Rain	12	19	21	15	23	17	56	51	
	% Rain	74	66	48	63	60	67	61	65	
	P	0.480		0.261		0.629		0.565		0.533
4 Low	Rain	36	44	29	28	43	33	108	105	
	No Rain	11	12	11	12	15	18	37	42	
	% Rain	77	79	73	70	74	65	74	71	
	P	0.998		1.000		0.390		0.649		0.930
4 High	Rain	39	44	26	31	44	42	109	117	
	No Rain	8	12	14	9	14	9	36	30	
	% Rain	83	79	65	78	76	82	75	80	
	P	0.755		0.323		0.554		0.446		0.676
Entire	Rain	39	46	31	32	50	44	120	122	
	No Rain	8	10	9	8	8	7	25	25	
	% Rain	83	82	78	80	86	86	83	83	
	P	0.882		1.000		0.789		0.919		0.994

indicate that there is very little risk of error, from $P = 0.016$ to $P = 0.034$, in asserting that in the three mountainous zones of the target there was a real effect of seeding. On the other hand, no such effect is noticeable either in the flat zone 1 or in foothill zone 2. Turning our attention to particular forecasters, we see consistent and consistently significant increases in precipitation on days selected by Ambrosetti. To a lesser extent this also applies to the days selected by the five "other forecasters." On the other hand, an opposite tendency is noticeable on days selected by Zenone.

Table IVc was constructed using the optimal $C(\alpha)$ test of the hypothesis that the seeding does not affect the total average amount of precipitation per experimental day, even though it may affect (in opposite directions) the frequency of noticeable rain and the amount fallen.

The general picture presented by table IVc is very much the same as that in table IVb. As indicated by the significance probabilities given in the right margin, no effects of seeding are noticeable in the two southernmost subtargets. On the other hand, the chance of error in asserting the existence of effects in the three subtargets in the mountains is about 2 in 100. Turning to the main

TABLE IVb

DOES SEEDING AFFECT THE AVERAGE AMOUNT OF PRECIPITATION ON DAYS WITH NOTICEABLE RAIN?
MEAN PRECIPITATION PER RAINY DAY FOR SEEDED AND NOT SEEDED DAYS, PERCENTAGE INCREASE, AND SIGNIFICANCE PROBABILITY
Boldface numerals mark the effects that are significant at better than 10 per cent.

Zone	Forecaster	Ambrosetti	Zenone	5 Others	All	Summary
1	Mean Seeded	18.81	18.19	18.00	18.36	
	Mean Not S	19.57	15.90	13.60	16.29	
	% Increase	−4	14	32	13	
	P	0.901	0.742	0.372	0.536	0.836
2	Mean Seeded	21.35	15.70	18.03	18.71	
	Mean Not S	15.52	23.44	16.61	17.93	
	% Increase	38	−33	9	4	
	P	0.275	0.264	0.780	0.810	0.452
3	Mean Seeded	25.41	15.87	25.74	23.50	
	Mean Not S	13.14	25.09	14.18	16.62	
	% Increase	93	−37	82	41	
	P	**0.031**	0.256	**0.053**	**0.061**	**0.017**
4 Low	Mean Seeded	18.72	10.55	18.07	16.27	
	Mean Not S	9.73	18.96	12.90	13.19	
	% Increase	92	−44	40	23	
	P	**0.016**	0.104	0.306	0.240	**0.019**
4 High	Mean Seeded	14.62	8.20	15.80	13.56	
	Mean Not S	8.92	14.33	9.45	10.54	
	% Increase	64	−43	67	29	
	P	**0.053**	0.133	**0.085**	0.138	**0.022**
Entire	Mean Seeded	18.55	9.61	15.23	14.86	
	Mean Not S	10.35	17.13	10.90	12.32	
	% Increase	79	−44	40	21	
	P	**0.036**	0.117	0.258	0.287	**0.034**

body of the table referring to the mountainous subtargets, it is seen that increases in precipitation are quite distinct for days selected by Ambrosetti. For Zenone's days there are substantial decreases with significance probabilities ranging from 0.064 to 0.157. The combined experience of the five other forecasters is a substantial increase in rainfall. However, the reliability of this result is substantially less than that for Zenone.

Our working hypothesis is: *in the mountainous regions of Grossversuch III there was a real effect of seeding; at least on days selected by Mr. Ambrosetti this effect was a substantial increase in precipitation.* While the noted effectiveness of seeding occurred in the mountainous regions of the target, it should be mentioned that, judging from the disposition of raingages, the intensity of seeding is not uniform and appears to have been less in zone 4.

4. Evidence of differential effects of cloud seeding by a fixed method and in the same target

Comparing the results of Grossversuch III with those in table I, we have to admit that, depending upon circumstances, cloud seeding may increase the

TABLE IVc

DOES SEEDING AFFECT THE AVERAGE AMOUNT OF PRECIPITATION PER EXPERIMENTAL DAY? MEAN PRECIPITATION PER EXPERIMENTAL DAY, PERCENTAGE INCREASE, AND SIGNIFICANCE PROBABILITY

Boldface numerals mark the effects that are significant at better than 10 per cent.

Zone	Forecaster	Ambrosetti	Zenone	5 Others	All	Summary
1	Mean Seeded	9.86	8.77	9.41	9.43	
	Mean Not S	10.26	7.75	7.11	8.37	
	% Increase	−4	14	32	13	
	P	0.440	0.467	0.482	0.634	0.592
2	Mean Seeded	14.92	9.22	12.41	12.43	
	Mean Not S	10.85	13.77	11.43	11.91	
	% Increase	38	−33	9	4	
	P	0.170	0.191	0.951	0.938	0.325
3	Mean Seeded	17.76	8.73	16.29	14.89	
	Mean Not S	9.18	13.80	8.98	10.53	
	% Increase	93	−37	82	41	
	P	**0.019**	0.101	0.150	0.167	**0.012**
4 Low	Mean Seeded	14.54	7.52	12.60	11.87	
	Mean Not S	7.56	13.51	8.99	9.62	
	% Increase	92	−44	40	23	
	P	**0.031**	0.157	0.177	0.190	**0.029**
4 High	Mean Seeded	11.78	5.84	12.46	10.50	
	Mean Not S	7.19	10.21	7.45	8.16	
	% Increase	64	−43	67	29	
	P	**0.045**	**0.064**	0.173	0.283	**0.019**
Entire	Mean Seeded	15.31	7.57	13.14	12.31	
	Mean Not S	8.54	13.49	9.40	10.21	
	% Increase	79	−44	40	21	
	P	**0.043**	0.115	0.276	0.315	**0.040**

precipitation and may decrease it. However, the range of possibilities encompassed by the word "circumstances" is very broad and includes variation in the nature of the target and in the method of seeding, not to speak of the synoptic situations. On the other hand, the particular columns of table IV refer to the same target and to the same method of seeding and differ only by the identity of the meteorologists who selected the particular days for inclusion in the experiment. In the foregoing inspection of the results, the evaluation strongly indicates increases in precipitation in the mountains recorded on days selected by Ambrosetti and, much less distinctly, decreases on days selected by Zenone. The question arises whether this difference is simply due to chance or reflects a real difference in the method of forecasting. If the latter possibility be true, then the analysis of weather situations frequently selected by Ambrosetti and those frequently selected by Zenone may provide important clues regarding the dependence of the effects of seeding on synoptic conditions. In effect, this would mean a contribution to the understanding of the mysterious processes in the atmosphere following the release of silver iodide smoke.

With the above in mind, an optimal $C(\alpha)$ procedure deduced by Davies and Puri [19] was used to test the hypothesis that the true effects of seeding on the three groups of days, selected by Ambrosetti, by Zenone, and by five other forecasters, were the same. The analysis was limited to days with noticeable rain. The significance probability resulting from this test procedure is 0.07. In other words, if in similar circumstances one asserts the existence of real differences, one can be wrong as frequently as once in about 14 cases. While this frequency is not negligible, we consider it sufficiently low to justify further analysis of Grossversuch III, with the idea of identifying classes of synoptic conditions A and B where cloud seeding, by the methods of Grossversuch III, tends to increase or tends to decrease precipitation.

5. Hypothesis of effects of winds aloft

The first tentative hypothesis considered in an effort to define the conditions A and B was that, through a particular mechanism [20], seeding may be depressing precipitation when the winds aloft are weak. On the other hand,

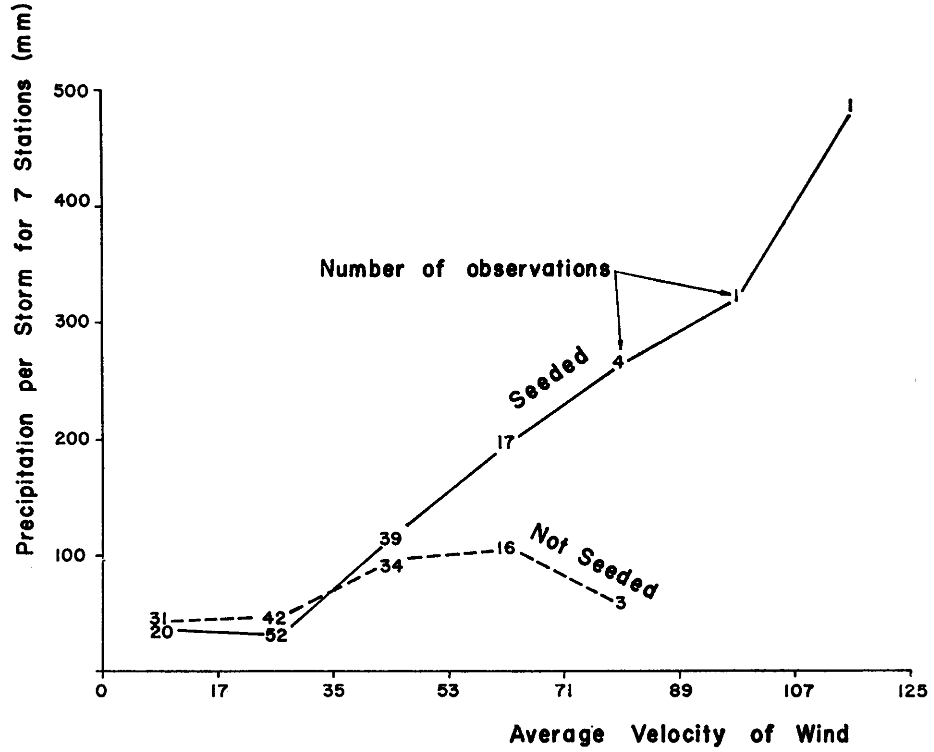

FIGURE 1

Comparison of seeded and not seeded precipitation for varying velocity of noon wind, for case of zone 4, altitude <1000 km. Number of observations at each velocity is shown.

according to the same hypothesis, with strong winds aloft the seeding would increase precipitation. Figure 1 represents plots of average amounts of seeded and of nonseeded precipitation in subtarget 3 in the Swiss experiment against the wind velocity at Milan at noon of the experimental day, averaged over two levels of 1500 and of 5500 meters above sea level. The data are taken from the annual reports on Grossversuch III.

The two graphs in figure 1 do tend to confirm the hypothesis considered. In fact, with average wind velocities below some 35 km/hr, the average seeded precipitation is slightly below that observed without seeding. For stronger winds the situation is reversed.

Unfortunately, when the idea of the relevance of wind velocity was pursued further, the situation became much less clear than is suggested by figure 1. Some of the possible reasons for this will be discussed below. The study is continuing.

6. "Optimism" and "pessimism" in forecasting

Conferences in Locarno-Monti revealed that the meteorologists at Osservatorio Ticinese are aware of a difference in forecasting by Messrs. Ambrosetti and Zenone. The essence of this difference could not be defined precisely except that Mr. Ambrosetti is considered as an "optimist" and Dr. Zenone as a "pessimist." Apparently, if it rains on a particular afternoon, Dr. Zenone is more likely to forecast rain on the morrow than Mr. Ambrosetti. Figures 2 and 3 represent an effort to substantiate this interpretation of optimism and pessimism. Both are based on the readings of the recording gage at Locarno-Monti and indicate the frequency distribution of the first half hour of rain following the beginning of the "experimental period" at 0800. The shaded rectangle on the right indicates the relative frequency of experimental days without any rain at Locarno-Monti. Figure 2 refers to Mr. Ambrosetti and figure 3 to Dr. Zenone.

The two figures indicate the following interesting details. Looking first at the graphs relating to nonseeded experimental days, it will be noticed that on Dr. Zenone's days the rain started between 0800 and 0830, or before ("early rain") more frequently than on days selected by Mr. Ambrosetti. This is consistent with the suggestion that experimental days forecast by Dr. Zenone included more cases of dissipating storms than those forecast by Mr. Ambrosetti. Next, comparing panels for seeded days with those corresponding to nonseeded we see essentially no difference in frequency of early rain on Dr. Zenone's days. On the other hand, on Mr. Ambrosetti's days the seeding beginning at 0800 seems to have stimulated early rain.

Figures 4 and 5, similarly constructed, give the frequency distribution of the last hour of rain for the two forecasters.

The impression one obtains from figures 4 and 5 is that, in the case of Mr. Ambrosetti, seeding delayed the last hour of rain. On the other hand, if anything, in the case of Dr. Zenone, seeding may have advanced the cessation of rain.

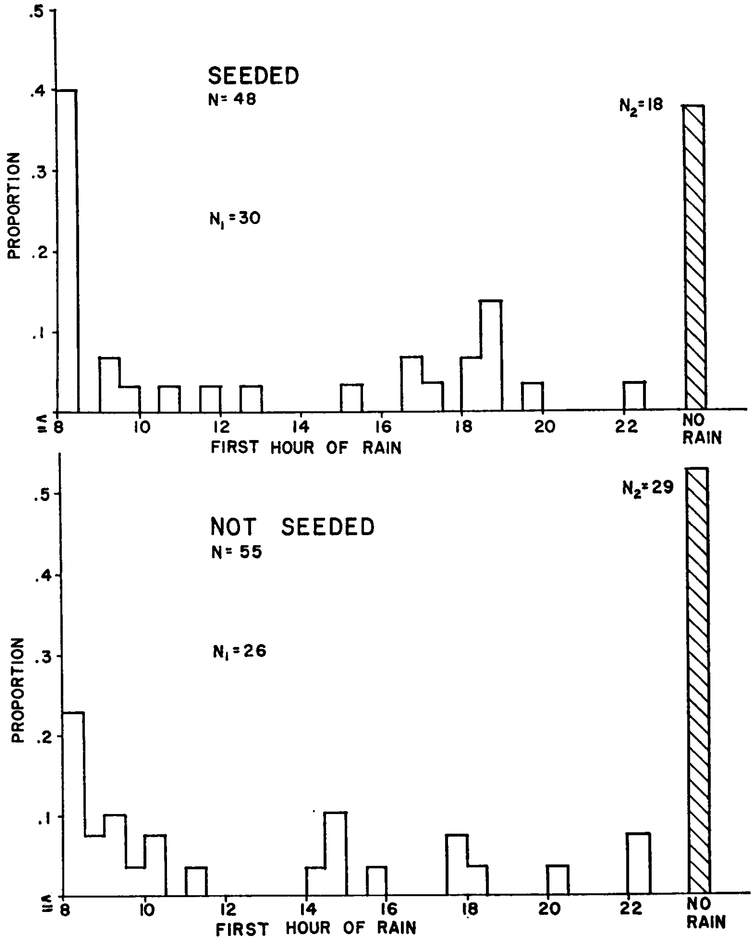

FIGURE 2

Distribution of time of first hour of rain
at Locarno-Monti, 1957–63, for Ambrosetti
(in half hour intervals except 2300 to 0800 shown at 0800).
Seeded and not seeded experimental days.

As mentioned, figures 2 to 5 were constructed using the data of just one recording gage, at Locarno-Monti, which was in operation over the whole duration of the experiment, 1957–63.

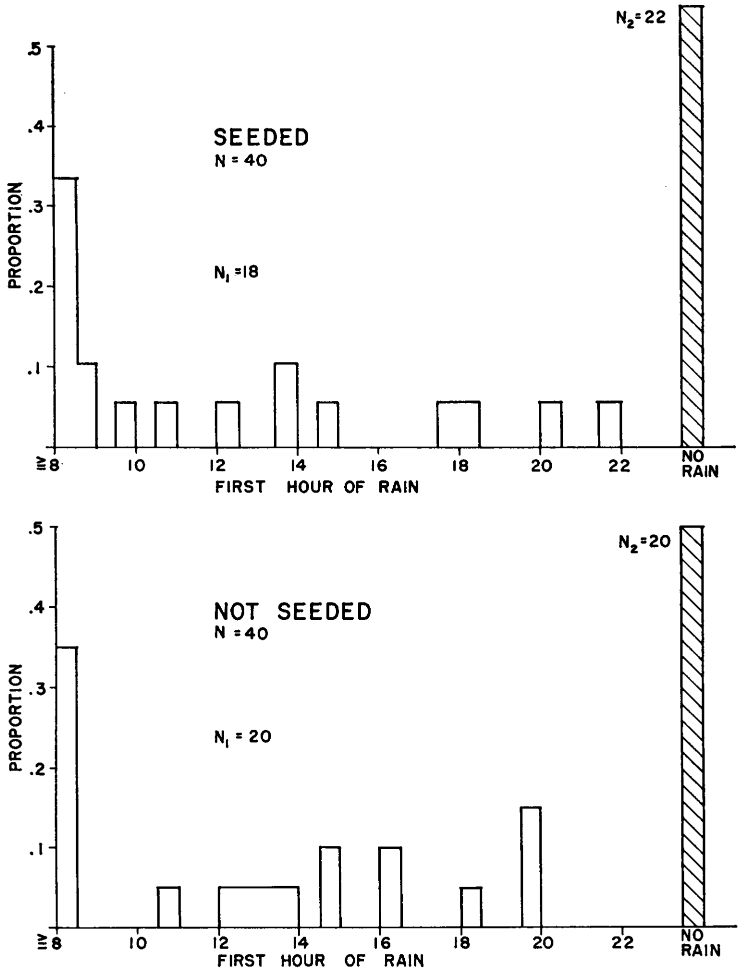

FIGURE 3

Distribution of time of first hour of rain
at Locarno-Monti, 1957–63, for Zenone
(in half hour intervals except 2300 to 0800 shown at 0800).
Seeded and not seeded experimental days.

7. Hypothesis of "incipient" and "dissipating" storms

The above and other similar studies of the seeded and not seeded rainfall on days forecasted by Messrs. Ambrosetti and Zenone suggested the following hypothesis regarding the differential effect of seeding:

(1) the period of an incipient storm is characterized by an increase in turbulence; hence the silver iodide smoke released from the ground at the time of a

gathering storm quickly reaches high levels and stimulates precipitation. On the other hand,

(2) the period of dissipation of a storm is characterized by a decrease in

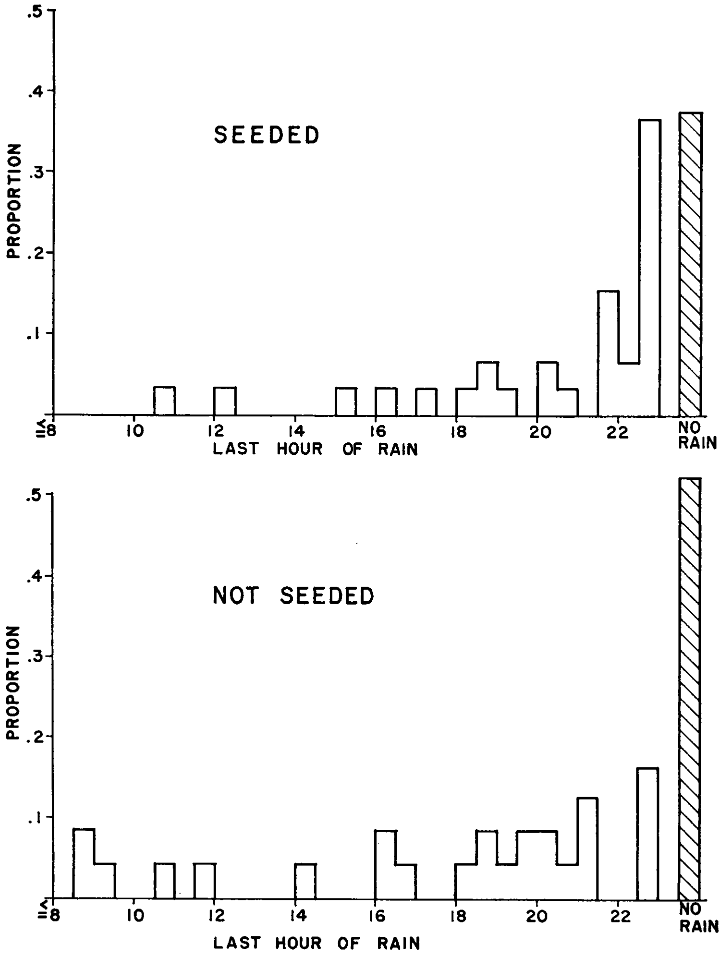

FIGURE 4

Distribution of time of last hour of rain at Locarno-Monti, 1957–63, for Ambrosetti. Seeded and not seeded experimental days.

turbulence; through some mechanism, the seeding of dissipating storms contributes to the speed of dissipation.

The first part of the hypothesis is definitely not new. In fact, various remarks in the writings of R. Braham indicate his opinion that, in order to achieve at least modest increases in precipitation, cloud seeding should begin somewhat in advance of the expected onset of atmospheric turbulence. Similar ideas appear to have influenced the operations of SCUD and the two experiments in Arizona. On the other hand, the description of the experiment of Ferguson Hall (no. 1 in table I) and also of those conducted in Australia and in Israel, suggest an effort to seed only those clouds that "are ripe for seeding," an apparently opposite tendency.

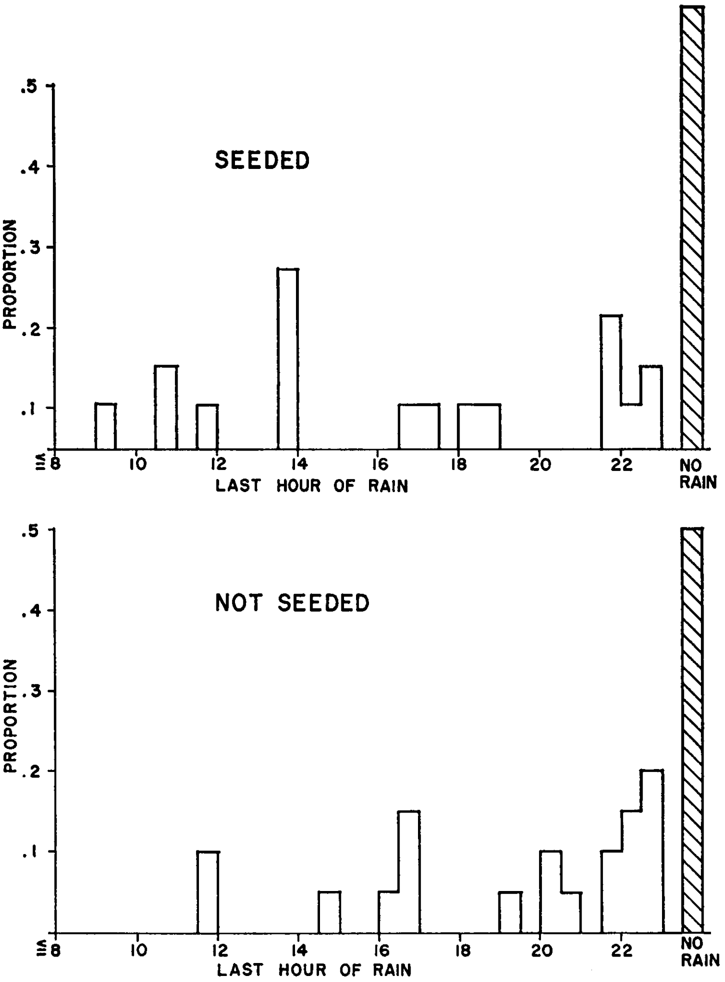

FIGURE 5

Distribution of time of last hour of rain at Locarno-Monti, 1957–63, for Zenone. Seeded and not seeded experimental days.

Whether the idea that the seeding during the period of dissipation of a storm may be harmful is new, we are not sure; conceivably it may be involved in the requirement of "ripeness for seeding."

It must be obvious that the proper way of testing the hypothesis of incipient and dissipating storms is through the analysis of synoptic situations that prevailed during the period of Grossversuch III, involving the study of weather maps, and so forth. Because of the absence of such data, all that was possible to do was to proceed by an admittedly very crude method.

By inspecting the day by day precipitation data relating to the general region south of the Alps, an attempt was made to identify groups of consecutive days marked by rainy weather. The first day of such group was labeled day of an incipient storm, the last day the day of a dissipating storm and all the rest the middle days of storm. Then evaluations were performed for experimental days of the three categories "incipient," "middle storm," and "dissipating storm" days. Some of the days so classified were experimental days selected by particular forecasters. These, then, served for the evaluations. On the other hand, a few experimental days are lost in this classification for the reason that, as reflected in precipitation data, these days could not be assigned to any storm. In fact, these days appear to have happened during periods of persistent dry weather.

The subdivision of all experimental days into the three categories, incipient, middle, and dissipating, combined with the cross subdivision according to the identity of the forecaster responsible for the inclusion of the particular day into the experiment, unavoidably results in the necessity of dealing with small groups of observations. Because of the asymptotic character of the optimal $C(\alpha)$ tests used, the significance probabilities for classes of the nine way classification must be taken with caution. Also, it must be clear that the chances of finding a significant effect are rather slim, even if this effect is large.

As indicated in the tables that follow, the hypothesis of incipient storms as well as the hopes that this will explain the difference in the effects of seeding on Ambrosetti's and Zenone's days proved false. The presumption was that positive effects of seeding on days selected by Mr. Ambrosetti are due to his avoidance of dissipating storms and his favoring incipient storms. On the other hand, it was expected that among Dr. Zenone's days there will be relatively more "dissipating" than "incipient" storms. Table V shows that these expectations were disappointed.

However, the results that are most relevant to the hypothesis of incipient and of dissipating storms are exhibited in tables VIa, VIb, and VIc. These tables are similar to tables IV, but are limited for brevity to evaluations for the entire target and for zone 3.

As expected, the subdivision of data into three separate groups resulted in a scarcity of significant effects. However, what significant effects there are, all refer to periods of incipient storms and all indicate decreases in precipitation due to seeding!

As far as the frequency of noticeable rain from incipient storms is concerned,

TABLE V

THREE CATEGORIES OF DAYS AMONG THOSE SELECTED BY PARTICULAR FORECASTERS

Category	Ambrosetti		Zenone		Other Forecasters	
	Days	Per Cent	Days	Per Cent	Days	Per Cent
Incipient	28	28.9	23	35.4	22	22.2
Middle	45	46.4	27	41.5	45	45.5
Dissipating	24	24.7	15	23.1	32	32.3
Totals	97	100.0	65	100.0	99	100.0

significant changes are noted for zone 3, but not for the entire target. With the exception of days selected by Mr. Ambrosetti, these changes are very substantial decreases. For all forecasters combined, the decrease in frequency is from 74 per cent to 41 per cent and is significant at better than one per cent.

TABLE VIa

INCIPIENT, MIDDLE PARTS AND DISSIPATING STORMS
DOES SEEDING AFFECT THE FREQUENCY OF DAYS WITH NOTICEABLE RAIN?
NUMBER OF DAYS WITH RAIN, PERCENTAGE OF RAINY DAYS, AND SIGNIFICANCE PROBABILITY

Boldface numerals mark the effects that are significant at better than 10 per cent.

Target	Storm	Forecaster	Ambrosetti		Zenone		Five Others		All		Summary Test
			S	NS	S	NS	S	NS	S	NS	
Entire	Incip.	Rain	7	17	14	8	10	11	31	36	
		No Rain	2	2	0	1	1	0	3	3	
		% Rain	78	90	100	89	91	100	91	92	
		P	0.817		0.824		1.0		0.802		0.992
	Middle	Rain	26	19	13	14	25	19	64	52	
		No Rain	0	0	0	0	1	0	1	0	
		% Rain	100	100	100	100	96	100	98	100	
		P	1.0		1.0		0.875		0.911		1.000
	Dissp.	Rain	6	10	4	10	15	14	25	34	
		No Rain	3	5	0	1	0	3	3	9	
		% Rain	67	67	100	91	100	82	89	79	
		P	0.665		0.629		0.272		0.435		0.630
Zone 3	Incip.	Rain	7	13	2	6	5	10	14	29	
		No Rain	2	6	12	3	6	1	20	10	
		% Rain	78	68	14	67	46	91	41	74	
		P	0.952		**0.038**		**0.067**		**0.009**		**0.061**
	Middle	Rain	26	18	13	14	25	18	64	50	
		No Rain	0	1	0	0	1	1	1	2	
		% Rain	100	95	100	100	96	95	98	96	
		P	0.875		1.0		0.618		0.845		0.975
	Dissp.	Rain	2	6	4	5	5	6	11	17	
		No Rain	7	9	0	6	10	11	17	26	
		% Rain	22	40	100	46	33	35	39	40	
		P	0.665		0.246		0.798		0.824		0.667

TABLE VIb

Incipient, Middle and Dissipating Storms
Does Seeding Affect the Average Amount of Precipitation on Days with Noticeable Rain?
Mean Precipitation per Rainy Day for Seeded and Not Seeded Days, Percentage Increase and Significance Probability
Boldface numerals mark the effects that are significant at better than 10 per cent.

Target	Storm	Forecaster	Ambrosetti	Zenone	5 Others	All	Summary Test
Entire	Incip.	Mean Seeded	4.11	1.72	2.46	2.50	
		Mean Not S	4.11	7.38	4.20	4.86	
		% Increase	0	−77	−41	−49	
		P	0.999	**0.025**	0.230	**0.030**	0.113
	Middle	Mean Seeded	26.37	20.20	28.34	25.88	
		Mean Not S	20.45	30.82	21.16	23.50	
		% Increase	29	−34	34	10	
		P	0.333	0.191	0.302	0.551	0.245
	Dissp.	Mean Seeded	1.53	2.78	1.91	1.96	
		Mean Not S	1.76	5.75	2.22	3.12	
		% Increase	−13	−52	−14	−37	
		P	0.825	0.496	0.762	0.216	0.887
Zone 3	Incip.	Mean Seeded	4.03	5.45	3.88	4.18	
		Mean Not S	5.68	10.52	4.08	6.13	
		% Increase	−29	−48	−5	−32	
		P	0.548	0.567	0.925	0.333	0.869
	Middle	Mean Seeded	33.03	22.07	33.90	31.14	
		Mean Not S	21.82	37.04	21.77	36.06	
		% Increase	51	−40	56	19	
		P	0.217	0.210	0.185	0.367	0.145
	Dissp.	Mean Seeded	1.15	0.95	6.82	3.65	
		Mean Not S	3.23	9.10	8.25	6.73	
		% Increase	−64	−90	−17	−46	
		P	0.435	0.113	0.821	0.294	0.379

Taking separately the effect of seeding on average amounts of precipitation per rainy day (table VIb), significant effects are limited to the entire target. Here, the seeding of incipient storms on days selected by Dr. Zenone resulted in a 77 per cent decrease in noticeable rain, significant at 2.5 per cent. Also, the evaluation for all forecasters combined indicated a 49 per cent loss of rain from incipient storms, significant at 3 per cent.

The combined effect of the change in the frequency of noticeable rain and in the average precipitation per rainy day, is reflected in table VIc. Here significant decreases due to seeding incipient storms are noted for both the entire target and for zone 3.

Curiously, while tables VIb and VIc indicate very substantial decreases in the average amount of precipitation from dissipating both per rainy day and per experimental day, none is significant. One might perhaps say that our hypothesis of dissipating storms is not contradicted by the data.

TABLE VIc

INCIPIENT, MIDDLE PARTS AND DISSIPATING STORMS
DOES SEEDING AFFECT THE AVERAGE AMOUNT OF PRECIPITATION PER EXPERIMENTAL DAY?
MEAN PRECIPITATION PER EXPERIMENTAL DAY, PERCENTAGE INCREASE, SIGNIFICANCE PROBABILITY
Boldface numerals mark the effects that are significant at better than 10 per cent.

Target	Storm	Forecaster	Ambrosetti	Zenone	5 Others	All	Summary test
Entire	Incip.	Mean Seeded	3.20	1.72	2.24	2.28	
		Mean Not S	3.68	6.56	4.20	4.49	
		% Increase	−13	−74	−47	−49	
		P	0.786	**0.041**	0.164	**0.031**	0.107
	Middle	Mean Seeded	26.37	20.20	27.25	25.48	
		Mean Not S	20.45	30.83	21.16	23.50	
		% Increase	29	−34	29	8	
		P	0.333	0.191	0.380	0.619	0.281
	Dissp.	Mean Seeded	1.02	2.78	1.91	1.75	
		Mean Not S	1.17	5.23	1.83	2.47	
		% Increase	−13	−47	5	−29	
		P	0.843	0.572	0.929	0.389	0.952
Zone 3	Incip.	Mean Seeded	3.13	0.78	1.76	1.72	
		Mean Not S	3.89	7.01	3.71	4.56	
		% Increase	−19	−89	−52	−62	
		P	0.741	**0.044**	0.197	**0.021**	0.121
	Middle	Mean Seeded	33.03	22.07	32.59	30.66	
		Mean Not S	20.67	37.04	20.62	25.06	
		% Increase	60	−40	58	22	
		P	0.165	0.210	0.179	0.312	0.118
	Dissp.	Mean Seeded	0.26	0.95	2.27	1.44	
		Mean Not S	1.29	4.14	2.92	2.66	
		% Increase	−80	−77	−22	−46	
		P	0.251	0.457	0.800	0.359	0.573

Without documentation, which is lacking, it is difficult to be definite about which of the already performed experiments involved seeding of incipient and of dissipating storms. As already mentioned, incipient storms appear to have been seeded in SCUD, in Whitetop, and in the two Arizona experiments. This judgment of ours is based on such statements as the following: "Present plans call for seeding for a six hour period starting at 1000 CST in order to slightly precede the period of anticipated afternoon convection." Also, because of the apparent brevity of summer storms with which both the Whitetop and the two Arizona experiments were concerned, it seems likely that in both cases periods of dissipation may have been seeded. Thus, it may not be entirely a coincidence that the indicated effect of seeding in these four experiments is a decrease in rain.

A tendency to seed only clouds "ripe for seeding" is manifest in the ACN Washington-Oregon experiment, in the Israeli experiment, and in the four experiments in Australia. In four out of these six experiments the indicated effect of seeding is an increase in rain. Is this a mere coincidence?

The tentative conclusions suggested by the above analysis are as follows.

(i) The distinction among incipient, middle parts, and dissipating storms does not contribute to the explanation of the difference in the effects of seeding on days selected by Ambrosetti on the one hand and by Zenone on the other.

(ii) During an early part of a storm, perhaps only of a storm of a particular category, a mechanism appears to operate in the atmosphere such that the injection of silver iodide smoke during this period tends to dissipate the storm or to decrease the rainfall. Something similar may be happening during the end period of the storm.

8. Some outstanding statistical problems of rain stimulation

All the statistical problems relating to weather modification experiments are concerned with the difficulty mentioned above when we were concerned with the hypothesis of the relevance of winds aloft to the effectiveness of seeding. This difficulty is connected with the extreme variability of rainfall whether seeded or not seeded. The importance of this difficulty is enhanced by the circumstance that the time required to accumulate a sizable number of observations is inordinately long. The Swiss experiment was conducted over seven consecutive years and accumulated 292 experimental days of which only about 180 were with some rain in the target. In the Whitetop experiment in Missouri, 198 experimental days were accumulated over a period of five years. The first four year experiment in Arizona yielded 138 experimental days. The second experiment, of three years' duration, yielded 74 days. This experience indicates something like a 30 to 40 experimental day rate per year of experimentation.

The general statistical problem, then, is to devise the methodology for using the precious experimental data in the most efficient manner so as not to waste the information these observations contain.

The above statement is formulated in terms that, hopefully, will appeal to the intuition, but in terms that are vague. A more precise but somewhat more involved description of the situation is as follows.

To every statistical procedure used in some particular circumstances, for example, in testing whether seeding has any effect on precipitation, there corresponds a set of probabilities that this procedure will lead to correct or to erroneous conclusions.

With reference to testing the effectiveness of seeding, and considering the simplest version of the problem, the conclusions expected from an experiment are two: (i) there is no noticeable effect or (ii) yes, there is some effect of seeding. Theoretically, conclusions (i) and (ii) could be made without error if one could use an infinity of data. Practically, this would mean experimenting over a prohibitively long time and, in actual practice, we have to accept nonzero probabilities of both errors, the error in asserting (i) and the error in asserting (ii).

As mentioned, to each test procedure, and to each system of circumstances of experimentation, there corresponds a set of probabilities, technically called power function, that this procedure will lead to the assertion (ii) when, in fact, the seeding has an effect of a specified magnitude.

The rational selection of a statistical procedure for use in some specified experimentation must be made after a careful consideration of the power function corresponding to the various procedures that are available. The situation is illustrated [6] in figure 6.

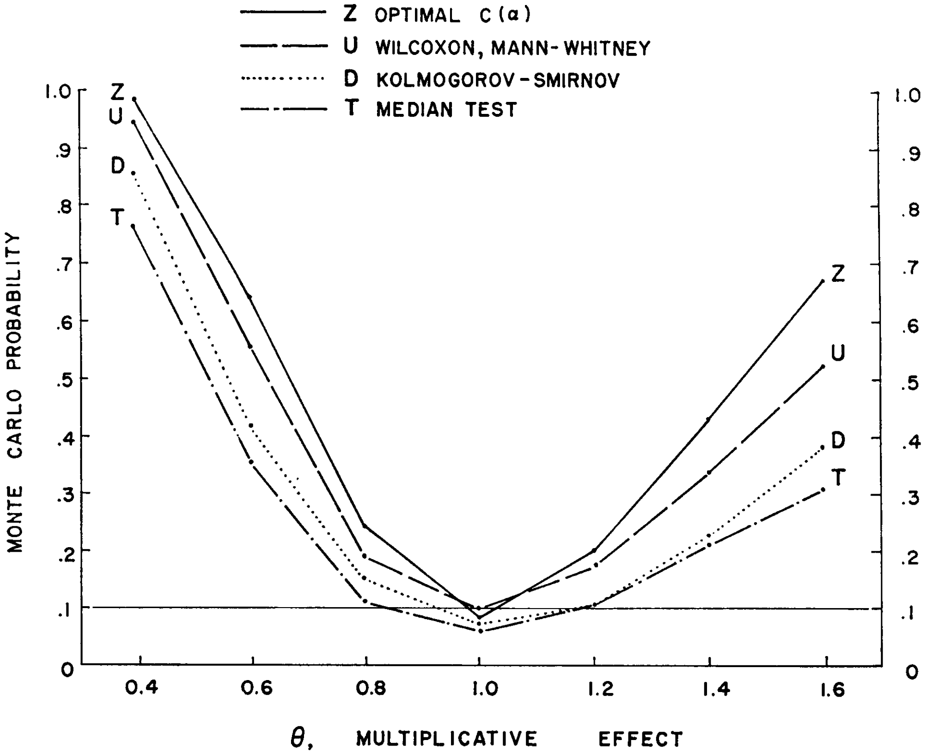

FIGURE 6

Comparison of Monte Carlo power functions corresponding to $\alpha = 0.10$, two sided tests, $N = 100$ observations.

In accordance with the presumption of a number of meteorologists that, if seeding has an effect on precipitation, then this effect must be multiplicative (see, for example [11]), the quantity measured on the axis of abscissae is the factor θ, by which, hypothetically, the seeding multiplies the average precipitation that would fall without seeding. Thus, $\theta = 1$ means no effect of seeding, while $\theta = 1.4$ means a 40 per cent increase in precipitation due to seeding, and so forth. The quantity measured on the vertical axis is the probability that the given statistical test will lead to the conclusion (ii): yes, there is an effect of seeding. If $\theta = 1$, then this will be the probability of an error. If $\theta \neq 1$, this will be the probability of a correct conclusion.

The four curves drawn in figure 6 refer to four alternative test procedures. Three of these are the procedures that we found used in certain evaluations of cloud seeding experiments, the two sample Kolmogorov-Smirnov test, the Mann-Whitney test and the median test. The fourth test is new and has been deduced [6] to be asymptotically locally most powerful in the circumstances considered. These circumstances are: (i) whether seeded or not seeded, the nonzero precipitation amounts follow a Gamma distribution, with density

$$p(x|\gamma, \delta) = \frac{\delta^\gamma}{\Gamma(\gamma)} x^{\gamma-1} e^{-\delta x}; \tag{8.1}$$

(ii) the possible effect of seeding is multiplicative; and (iii) there are no "predictor variables." It is, of course, uncertain whether formula (8.1) holds universally. However, our own experience indicates that with targets of moderate size and with time periods of moderate duration, this formula fits the observations excellently. Figure 7, referring to Grossversuch III, may serve as an illustration. Also, we refer to a paper by H. C. S. Thom [21], reporting a similar experience.

The four tests illustrated in figure 6 are adjusted to correspond to 100 observations and to the intended level of significance 0.1. That is to say, a systematic use of any of the four tests, each based on 100 unrestrictedly randomized experimental days, is expected to insure the same frequency of one in ten of asserting the effectiveness of seeding when, in fact, this effectiveness is nil. This long run frequency, imposed on all the tests compared, is a kind of common denominator adopted conventionally. The ordinates at other values of θ can be treated as probabilities that the tests will "discover" the effectiveness of seeding when this effectiveness corresponds to the given value of θ.

The origin of curves, really polygons, in figure 6 is empirical. The ordinates of dots representing the vertices of the polygons are relative frequencies of cases where the given test rejected the null hypothesis in a long series of "synthetic" trials, simulated by the high speed digital computer. With the exception of the curve corresponding to the Mann-Whitney test, at $\theta = 1$ all the other curves are somewhat below the intended level $\alpha = 0.1$. This divergence has two assignable sources. One is that the intended level α was used to adjust the available asymptotic distribution of the relevant test criterion. The other source of deviation is the unavoidable random sampling error. Each of the dots in figure 6 is a frequency of rejection in 400 trials performed independently. With that many trials, the standard deviation of the relative frequency corresponding to probability p is $[p(1 - p)]^{1/2}/20$. With $p = 0.1$ this amounts to 0.015. Thus, a difference between the probability of one tenth and the corresponding relative frequency amounting to one or two units in the second digit should not be surprising.

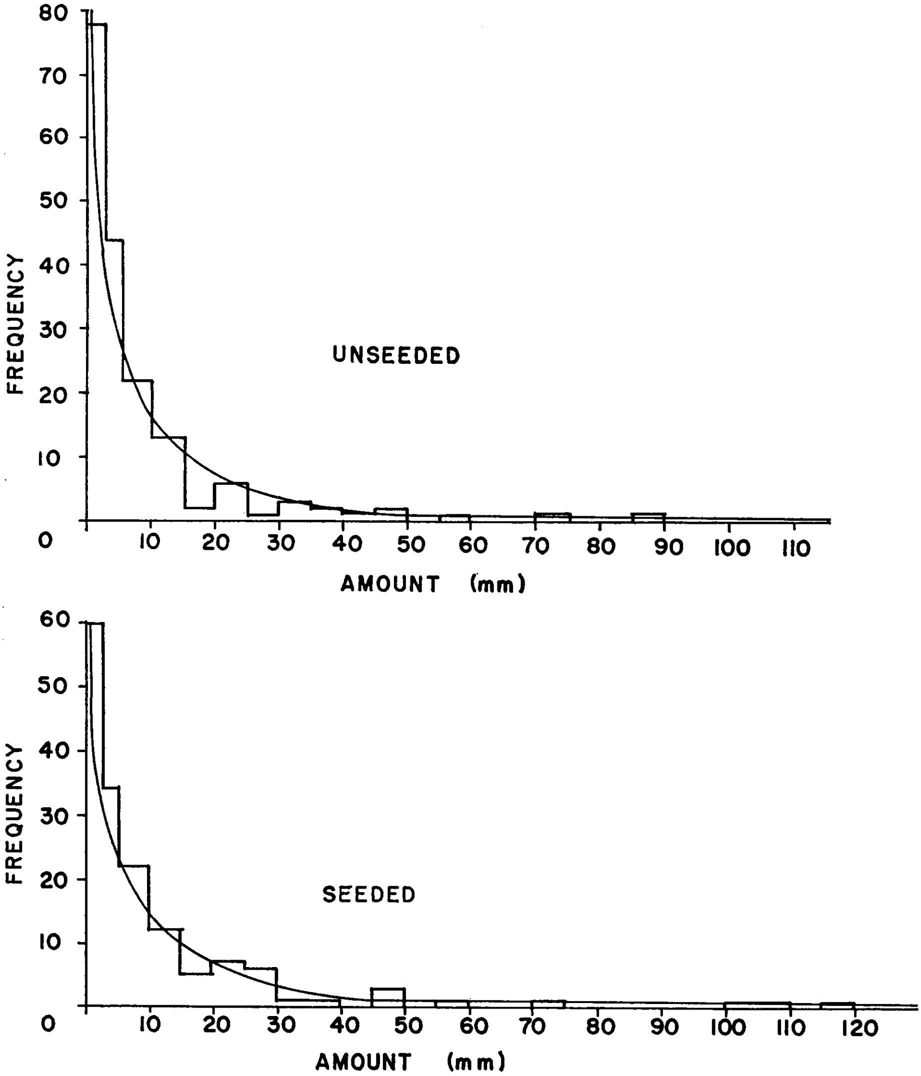

Figure 7

Comparison of observed distribution of nonzero precipitation with Gamma distribution fitted by maximum likelihood. These data correspond to nonzero precipitation in Swiss zone 4, altitude >1000 km, 1957–63.

Figure 6 illustrates the following facts: (a) the four tests differ considerably in their power, that is, in their ability to detect the effectiveness of seeding if such exists; (b) the new test, termed the optimal $C(\alpha)$ test, insures a substantially higher frequency of detecting the effectiveness of seeding than the alternative tests; (c) the power of even the more effective optimal $C(\alpha)$ test is discouragingly low. The power at 40 per cent increase is of the order of one half. With other tests, this power is even lower.

In the statistical literature there are two values of the level of significance that are often used, namely, five and one per cent. Customarily, but purely conventionally, an effect with significance probability larger than five per cent is considered nonsignificant and, frequently, dismissed from further consideration. Figure 6 indicates that with reference to cloud seeding experiments, performed in circumstances to which this figure corresponds, this practice is unreasonable. In fact, theory and practice indicate that a decrease in the level of significance means a decrease in power. Thus, if in cloud seeding experiments without predictor variables and extending over some one hundred experimental days with rain, it is insisted that the level of significance be five per cent or lower, then the chances that this experiment will discover the real and substantial effect of seeding will be so small as to make the experiment and/or its evaluation of questionable value.

To a meteorological audience, the discussion of power functions may seem somewhat esoteric. However, there is nothing esoteric about them and, given a little patience and the use of a high speed computer, the conclusions just enumerated can be verified easily by tangible experience. All that is involved in the construction of the four curves in figure 6 is the following.

A program for the computer is constructed (it is available in Berkeley) to produce random samples from the Gamma distribution of equation (8.1) with parameters γ and δ, both positive, fitting the conditions of interest. Further, the program includes the splitting of the sample into two parts, one part to represent the nonseeded precipitation and the other that affected by seeding. The amounts of seeded precipitation are obtained by multiplying the figures of the second subsample by the selected factor θ. Next, the program includes the performance of the test of interest on the two sets of "synthetic" experimental data obtained as indicated. The procedures involved in the three classical tests are described in textbooks. The procedure of the $C(\alpha)$ optimal test is given in the appendix to the present paper. The final stage of the computer program is the counting of cases in which the test in question rejects the hypothesis of no effect of seeding. In spite of some intricacy of the program, the whole operation is really routine. The nonroutine part is the deduction of a test which, for a given set of circumstances, is in some sense optimal. As explained below, quite a few problems of this kind are still unsolved.

The discouraging features of figure 6 raise the question: what is a possible remedy? One answer is clear: we should use efficient tests and, if we are forced to deal with experiments without predictor variables, we should use a level of significance more lenient than 0.05, possibly 0.10. Since this last answer amounts to an adjustment to, or acquiescence with, the difficulty rather than its resolution, it is appropriate to proceed further. The real remedy is the use of predictor variables, and the search for good predictor variables is a very important study of an empirical statistical climatological character.

The predictor variables customarily used in the evaluation of commercial cloud seeding operations are precipitation amounts in control areas. Unfortunately, to our knowledge at least, very little has been published on this matter thus far. The questions are: what are the general rules governing the strength of correlation between simultaneous precipitation amounts in two areas? How does this correlation depend upon the number and/or the distribution of raingages over the areas concerned? How does this correlation depend upon the type of storm [4], and so forth?

However, comparison areas are not the only source of predictor variables. Here we have in mind the ingenuity of Spar [11], who invented three meteorological parameters denoted by him as T, M, and L, that do not represent precipitation amounts, but show a reasonable correlation with precipitation in the target area I, a wide strip along the East Coast of the United States. One of these quantities, defined as the rate of flow of moisture over a certain perimeter, is particularly inspiring. Figure 8 in [9] gives the relevant scatter diagram. As calculated in the appendix, the use of these three predictor variables, compared to no predictor variables at all, is equivalent to multiplying the number of observations by a factor of 4.6. In other words, with the use of these predictor variables, the power of an evaluation of the experiment with only 40 observations is about equal to that based on 184 observations, without any predictor variables.

The predictors devised by Spar may be contrasted with "precipitable water" which, in the Arizona experiment at least, does not appear to correlate with precipitation.

While the optimal $C(\alpha)$ test appears to solve the methodological statistical problem for experiments without predictor variables, the more important problem of an optimal test for experiments with predictor variables does not appear to be satisfactorily solved and is the subject of our preoccupation.

What has been done thus far is limited to the situation where the original observations of rainfall, following a skew distribution exemplified in figure 7, are transformed somehow so as to approach normality. As is well known, a number of transformations are used from time to time, such as the square or cube root, and the logarithmic transformation. If one postulates that the transformation is satisfactory, then a solution of the estimation problem (eliminating the bias introduced by the transformation) is given in [22] and [23] and a solution of the hypothesis testing problem (through an optimal $C(\alpha)$ test) is available in [5]. However, and here we share the attitude of a number of statisticians, the use of a transformation without a conceptual chance mechanism to back it up is not convincing. What one would like to do is to pursue the ideas of LeCam developed in his paper [24], delivered at the Fourth Berkeley Symposium of 1960, perhaps with some simplifications, and to treat the rainfall in the two areas as the sums of amounts of precipitation from "elementary showers."

Unfortunately, while conceptually attractive, the idea leads to complicated formulas with which we have not been able to cope thus far. The statistical part of the audience is cordially invited to join us in this interesting and practically very important field of study.

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