ON THE DESIGN AND EVALUATION OF CLOUD SEEDING EXPERIMENTS PERFORMED BY ELECTRICITÉ DE FRANCE

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1. Introduction

It is desirable to make the title of this paper a little more precise and to circumscribe the discussion that follows. Only the experiments performed under the sponsorship of Electricité de France will be considered, and of these, only those designed to obtain statistical evidence of increase in precipitation due to cloud seeding with silver iodide smoke released from ground based generators. The words "statistical evidence" must be emphasized. The operations not subjected to statistical evaluation are outside of the subject of this paper. Also, we emphasize the words "increase in precipitation." Thus, experiments on hail suppression will not be discussed.

The various experimental projects described here were conducted by Electricité de France which alone performed the statistical evaluation. The development of experimental plans, and the work on the site (including the administration of the network of raingages, recording raingages, and generators) were undertaken in collaboration with other organizations, particularly the Ministry of Agriculture and the National Meteorological Service. During one of the experiments, Tignes, an American firm installed and administered the generators.

This paper consists of four parts:

(1) general remarks on statistical design and evaluation used;

(2) a survey of early experiments, Tignes, Truyere, Maine-Touraine-Beauce, (M.T.B.);

(3) a detailed description of the randomized experiment Cere-Maronne;

(4) comments on the basic elements of the problem of design and evaluation.

2. General remarks on statistical design and analysis

2.1. *Structure of an operation.* The inner structure of an experiment consists of the following elements:

(a) a sufficiently dense network of generators of silver iodide smoke;

(b) a fixed or a variable target, its variability depending on the meteorological conditions at the time of seeding which affect the plume of silver iodide smoke released.

The observable variables subject to analysis are precipitation amounts in the target falling over certain unit time periods of either fixed or variable duration. These precipitation amounts are averages of readings on a certain number of raingages distributed over the target. The choice of the unit time periods is important and must be accomplished at an early stage of planning the experiment. This choice determines the rhythm of seeding. The unit time periods may be of two different kinds.

(1) The unit period may be of a fixed duration (24 hours, 48 hours, and so on). This choice is convenient because it eliminates subjectivity. However, it has the disadvantage of cutting arbitrarily a homogeneous meteorological phenomenon (rainy period), the duration of which is variable. Also, this definition of the unit time period ignores the lack of simultaneity of precipitation occurring at different raingages.

(2) The unit time period of observation may be defined to extend over several successive periods of precipitation, all deriving from the same meteorological origin, from the same group of atmospheric disturbances identified by a forecaster before it reaches the experimental zone. The precipitation amounts collected during such a unit time period correspond to a "rainy period" of variable duration. Obviously, this device of the unit time period is subjective, but not necessarily arbitrary. Also, the subjectivity does not introduce any bias in the evaluation, provided the forecaster determining a unit period is not informed of whether it is going to be seeded or not.

Essentially, the statistical evaluation of the effectiveness of cloud seeding consists of a comparison between the distribution of rainfall from seeded units of observation and that from nonseeded, characterizing the natural conditions. Frequently, such a comparison has been performed using nonseeded precipitation amounts observed during a "historical period" preceding the actual experiment. This method is open to criticism on many grounds. As emphasized by Neyman and Scott [7], the historical method of evaluation may show significant augmentations of rainfall caused by factors that have nothing to do with cloud seeding. These include the changes in number and in geographical distribution of recording and nonrecording raingages, in the manner of performing the observations, and in the subjective choice of rainy periods selected for seeding.

Further, the results of the evaluation may be influenced by the prevalence of certain types of storms which are difficult to identify and yet may increase the precipitation during the experiment compared to that during the historical period of reference. These difficulties can be avoided through a randomized experiment. Later on we shall return to this point.

The documentary value of an experiment depends upon the variability of rainfall measurements. In order to increase the documentary value (or power of the relevant test) of an operation of a limited duration or in order to reduce the duration of an experiment intended to insure a preassigned power of the test, it is important to control the variability of the observations through the use of some predictor variables, possibly the simultaneous precipitation amounts in one or more comparison areas. The comparison areas are chosen so as to insure the closest possible correlation between the precipitation amounts in the target and those in the comparison areas.

2.2. *Statistical tests used.* We shall now describe all the statistical tests used during the Electricité de France's study of the problem. More specifically, we are going to describe the tests ultimately chosen for actual evaluations. All of them are parametric tests based on the assumption that *a transformed variable x of the precipitation amount h from a unit observation is normally distributed.* The transformations considered were

$$x = \sqrt{h}, \tag{2.1}$$

$$x = \sqrt[3]{h}, \tag{2.2}$$

$$x = \log h. \tag{2.3}$$

In evaluations involving one comparison area it was necessary to consider a pair of variables $Y = f$ (h in target), $X = f$ (h in control), where f stands for one or the other transforming functions defined by (2.1), (2.2), or (2.3).

2.3. *Maximum likelihood ratio test.* It is assumed that in natural conditions, that is without seeding, the couple (X, Y) follows a bivariate normal distribution with parameters m_x and m_y, mathematical expectations; σ_x^2 and σ_y^2, variances; and ρ, correlation coefficient.

This is the distribution "of reference." The distribution of seeded precipitation differs from the above by a model of the possible effects of seeding. The assumption used is that this effect is constant and additive. Accordingly, within the framework of the classical theory of tests (Neyman and Pearson), the problem refers to the distribution of (X, Y) for seeded unit periods and here we have the null hypotheses H_0: Normal $N(m_x, m_y;\ \sigma_x, \sigma_y;\ \rho)$ to be tested against the alternative hypothesis H_1: Normal $N(m_x, m_y + a;\ \sigma_x, \sigma_y;\ \rho)$.

Let there be n couples (x, y) available for the period of reference (that is to say, when there was no seeding), and p couples (x, y) for the experimental period (so that here y stands for the seeded precipitation). The test takes into account the likelihood, say $L(x, y, m, \sigma, p, a)$, of the combination of two samples. Using both hypotheses H_0 and H_1 in turn, the intervening parameters can be estimated by the maximum likelihood method yielding, say

$$\hat{L}_0 = \max_{(m,\sigma,\rho)} L(x, y;\ m, \sigma, \rho, a = 0) \tag{2.4}$$

and

$$\hat{L}_1 = \max_{(m,\sigma,\rho,a)} L(x, y;\ m, \sigma, \rho, a). \tag{2.5}$$

The maximum likelihood ratio test leads to the rejection of hypothesis H_0 (asserting no effect of seeding) whenever

$$\lambda = \frac{\hat{L}_0}{\hat{L}_1} < k. \tag{2.6}$$

Here the constant k is computed from the preassigned level of significance α using the distribution of λ as determined by H_0. (It is known that in this case the quantity $-2 \log \lambda$ is distributed as χ^2 with one degree of freedom). We have here

$$\lambda \cong \left[\frac{nS_1^2(1 - r_1)^2 + pS_2^2(1 - r_2)^2}{(n + p)S_0^2(1 - r_0)^2}\right]^2, \tag{2.7}$$

where S_1^2, S_2^2, and S_0^2 are the sample variances of Y for nonseeded precipitation, for the seeded and for the two samples combined, respectively. The letter r with subscripts 1, 2, 0 represents the sample correlation coefficients similarly defined.

2.4. *Regression line test.* This test is based on the conditional distribution of Y given the predictor variable $X = x$. Namely, we write

$$Y_j = \mu_j(x) + \epsilon_j \tag{2.8}$$

with $\mu_j(x) = m_j + \gamma_j(x_j - \overline{x}_j)$ representing the conditional expectation of Y_j given $X = x$. There, the subscript $j = 1, 2$ according to whether one deals with the nonseeded target precipitation or that seeded, respectively. The residuals ϵ_j are supposed mutually independent (for different units of observation) and normally distributed with expectation zero and a fixed variance σ^2. No restriction is imposed on the predictor variable X. For each series of observations, seeded and nonseeded, the parameters involved are estimated using the classical formulas, which with customary notation are

$$\hat{m}_j = \overline{y}_j, \qquad \hat{\gamma}_j = r_j \frac{S_{jy}}{S_{jx}}, \tag{2.9}$$

$$\hat{\sigma}^2 = \frac{nS_{1y}^2(1 - r_1^2) + pS_{2y}^2(1 - r_2^2)}{n + p - 4}. \tag{2.10}$$

The comparison of the slopes of the two regression lines is based on the statistic

$$t = \left[\frac{npS_{1x}^2S_{2x}^2}{nS_{1x}^2 + pS_{2x}^2}\right]^{1/2} \frac{\hat{\gamma}_2 - \hat{\gamma}_1}{\hat{\sigma}}, \tag{2.11}$$

which, on the assumption of no effect of seeding, follows the Student's distribution with $n + p - 4$ degrees of freedom.

The comparison of central positions of the regression lines involves the conditional expectations $\mu_j(x)$ of Y_j given $X = x$. It is possible to determine this x so that the differences $\hat{\gamma}_2 - \hat{\gamma}_1$ and $\hat{\mu}_2(x) - \hat{\mu}_1(x)$ are statistically independent; we have

$$x = \frac{p\overline{x}_1S_{2x}^2 + n\overline{x}_2S_{1x}^2}{pS_{2x}^2 + nS_{1x}^2}. \tag{2.12}$$

Also, this value of x minimizes the variance of $\mu_2(x) - \mu_1(x)$.

The comparison of conditional expectations, corresponding to this particular value of x_1 is based on the statistic

$$t = \left[\frac{np}{(n + p)(1 + q^2)}\right]^{1/2} \frac{\hat{\mu}_2(x) - \hat{\mu}_1(x)}{\hat{\sigma}}, \tag{2.13}$$

with

$$q^2 = \frac{np}{n+p}\left[\frac{(x-\bar{x}_1)^2}{nS_{1x}^2} + \frac{(x-\bar{x}_2)^2}{pS_{2x}^2}\right]. \tag{2.14}$$

On the null hypothesis, the statistic given has a Student's distribution with $n + p - 4$ degrees of freedom. In addition, this particular test has the property of having the same asymptotic power (n and p both large) as the maximum likelihood ratio test.

3. Early experiments

The scientific and economic gains expected from the study of the effectiveness of cloud seeding with silver iodide caused Electricité de France to take close interest in the matter. Accordingly, beginning with 1953, a series of experiments were performed which resulted in an accumulation of experience in this field.

3.1. *Tignes project (1954–57).* In order to benefit from the experience of specialists in the technique of cloud seeding from the very start of experimentation, Electricité de France secured the cooperation of an American commercial company (W.R.D.C.). This company was responsible for running the network of ground smoke generators established for the Tignes project, but the evaluation of effectiveness of seeding was reserved for the E.D.F.

The target area was the Isere (Alps) watershed to the Tignes dam; it extended over 249 km² with altitudes ranging from 1790 to 3800 m.

One of the major defects of this experiment was too few recording raingages which could be used for evaluation: 2 recording raingages in the target area; 6 recording raingages in the control area (the basin of the Arc).

The results of the first season of experiments, winter 1954–55, were used in an American report, Final Report of the Advisory Committee on Weather Control [5], prepared independently of the E.D.F. In view of the low density of raingages, it is out of the question to grant any definite validity to such fragmentary results.

At the end of the experiment a statistical evaluation was performed using the following data: 165 nonseeded experimental units (incidences of rain) during the reference period, October 1949–September 1954; 95 seeded experimental units, October 1954–November, 1957.

The statistical analysis of the data (comparison of slopes of regression lines and the likelihood ratio test based on $\sqrt{h}$) showed no significant increase in precipitation attributable to seeding alone. This is probably due to scarcity of raingages, very low quality of observations, and to a certain number of other circumstances encountered also in the Truyere project discussed below.

3.2. *Truyere project (1954–61).* This operation was performed entirely by the personnel of E.D.F. with the help of a meteorologist engineer especially assigned by the National Meteorological Service.

The target area, originally designated as the drainage basin of the Truyere (a tributary to the Garonne in the Massif Central) to the dam of Sarrans

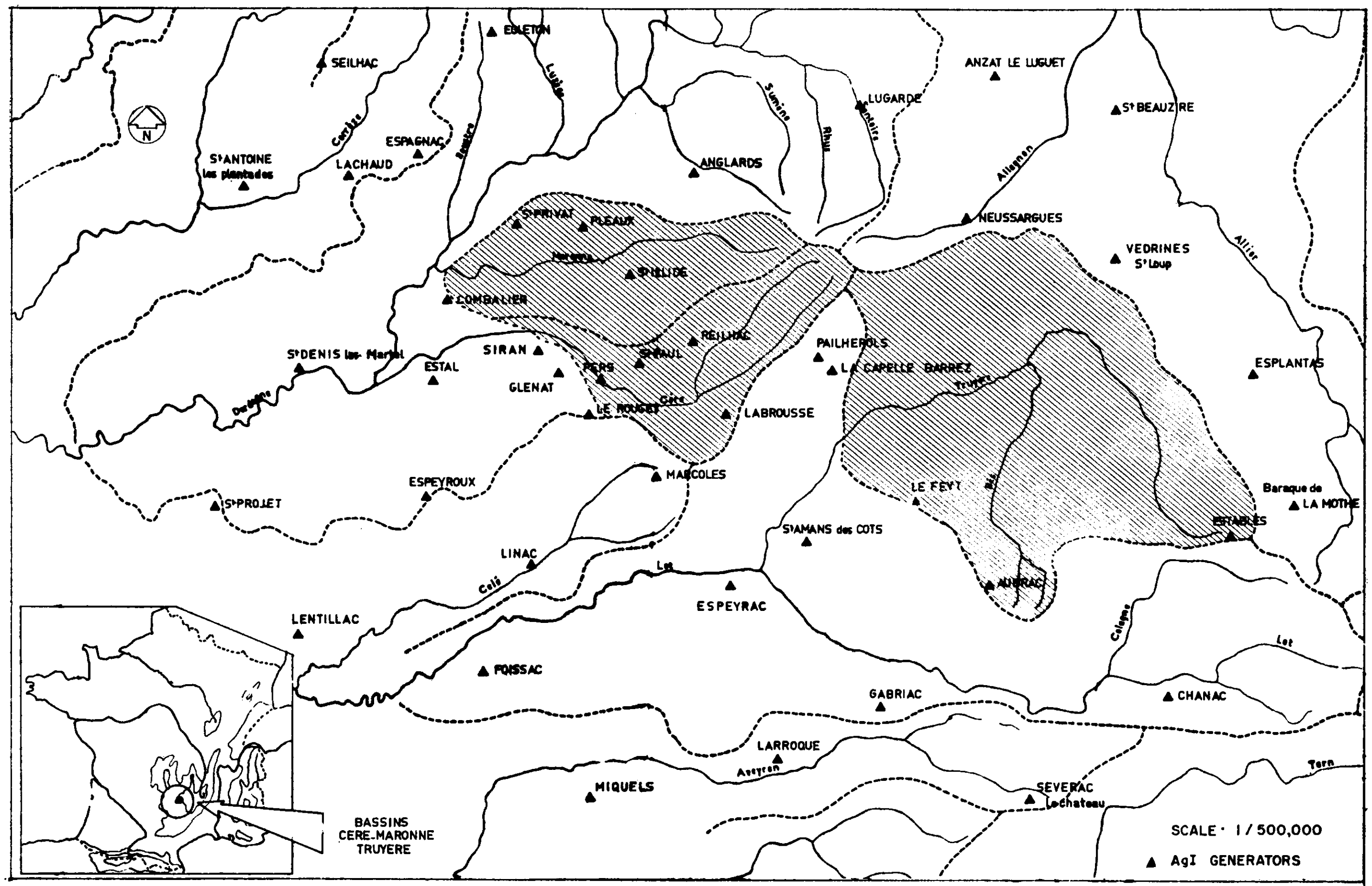

FIGURE 1

Map of Cere-Maronne and Truyere regions, showing locations of silver iodide generators.

(2460 km^2 with a mean altitude of 1040 m), was later enlarged to include the basins of the Cere and the Maronne (tributaries of the Dordogne) with an area of about 1500 km^2 and a mean altitude similar to that of Truyere (figure 1).

As in Tignes, the experimental procedure was to seed at every opportunity using a network of 25 ground generators.

The network of recording gages included 16 gages in the target, and 31 gages in the various comparison areas. The statistical analysis was diversified by the classification of observational units according to the direction, southerly and westerly, of the dominant air flow (winds at low levels, below 6000 m). The available data were: 135 periods of nonseeded rain during the reference period 1950–54; 196 periods of seeded precipitation during the experimental period, 1955–60.

The tests for regression slopes and for maximum likelihood ratio were performed using the cube root transformation. The only effects significant at about 5 per cent were: for southerly air flow the regression slopes differed significantly at 4 per cent level; for only one of the four comparison areas used, for westerly air flow, the maximum likelihood ratio was found significant at the 5 per cent level.

Evaluations of this kind do not escape the criticisms (formulated by Neyman and Scott [7]) of the historical method. In the present case, the following defect should be pointed out.

(a) The experimental conditions certainly underwent an evolution. The seeding was improved by an increase in the number of ground generators and by an increase in their output. The analysis of the meteorological situations became more precise. Nevertheless, there remained a very large heterogeneity in the quality of rainfall observations varying in time and geographically.

(b) The *a posteriori* definitions of periods of rain and the a *posteriori* choice of recording gages to be used in the evaluation are subjective.

In any case, the significance of the final results of the Truyere project is not clear and the methodology of the operation may deserve caution.

3.3. *Maine-Touraine-Beauce, M.T.B. project (1954–56).* This was a cloud seeding operation on level land. In a case of this kind, the absence of orographic effect makes it difficult to expect that the ground based generators will affect a fixed predetermined target. The location of the effect of seeding depends upon the direction and the velocity of the prevailing winds, on the updrift, and on the altitude of the critical isotherm of $-5°$ C.

Three generators were installed at the stations of the National Meteorological Service at Tours, Le Mans, and Alençon. A pulsating technique of seeding was used: 72 hours of continuous seeding followed by 72 hours without seeding. This cycle was repeated continuously with no regard to meteorological circumstances. The control was based on the principle of varying targets.

Taking into account the direction and the average updrift, one computes the average location where the plume of silver iodide crystals reaches the $-5°$ C isotherm, which is the theoretical threshold of effectiveness of silver iodide. The point so determined is considered the center of gravity of the target, a square of area 40,000 km². The controls are contiguous areas half that large on both sides of the target (figure 2).

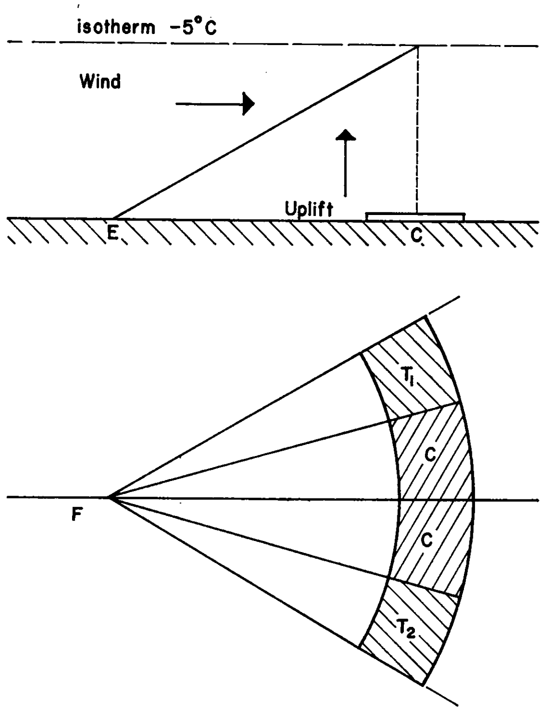

FIGURE 2

Determination of the target region.

The statistical evaluation performed on log h using the regression line technique gave no significant result. In fact, this operation could not be expected to yield significant results for the following reasons:

(a) the intrinsic variability of precipitation over 72 hours was very large;

(b) the number of generators was insufficient;

(c) the determination of targets was not precise.

In effect this determination was based on averages, both over time and over the area, of the altitude of the $-5°$ C isotherm, and, even more important, of the updrift (velocity of ascent of the particles) which, depending upon meteorological conditions, may vary within a very broad range. The area of the target was certainly very large, but the effectiveness of *three* generators in an area of this size is open to question.

4. Detailed description of the "randomized" Cere-Maronne project (from 1961 on)

The experience acquired during the Tignes, Truyere, and M.T.B. projects allowed the determination of the characteristic features of an experiment avoiding the various imperfections previously noticed. These features are:

(a) a fixed target basin of moderate area located in the mountains;

(b) a very dense network of ground generators capable of massive action;

(c) a very dense network of recording and nonrecording raingages, both in the target and in the comparison area, the performance of which could be continuously and critically watched by those responsible for the operation;

(d) randomization of seeding. Whether a rainy spell is to be seeded or not is decided by a random trial. The precipitation from a nonseeded period is used as a control;

(e) the definition of the unit period of observation (a rainy period) is accomplished in complete ignorance of whether this unit was seeded or not.

The Cere-Maronne project was undertaken on the above principles and the actual operation was entrusted to Mr. Tschirhart, an engineer of the National Meteorological Service delegated to the Centre de Recherches of the E.D.F. at Chatou. The statistical evaluation became the responsibility of statisticians at the Centre de Recherches.

4.1. *Description of the target and the control areas.* The target consists of about 1500 km^2 of the drainage basins of the Cere and Maronne rivers, tributaries of the Dordogne. The control area is adjacent and to the west of the target (see figure 3). Thirty three ground generators of silver iodide smoke are located on and about the western boundary of the target. A network of raingages especially established for these experiments consists of 57 gages, 30 in the target and 27 in the control. The readings are made twice a day at 0800 and at 2000 hours. This network is supplemented by 26 recording "tipping bucket" gages. The purpose of the latter is to check the validity of the ordinary gages and, more important, to establish the exact time of showers. However, only the data from ordinary gages have been used in the evaluation.

4.2. *Observational units.* The observational unit chosen is the total amount of precipitation per rainy period. The term rainy period is used to describe a sequence of periods of continuous rain or snowfall in the target and in the control between two consecutive times of reading on the raingages (at 0800 and 2000 hours) *at which times there is no precipitation* (figure 4). An additional condition is that these periods of continuous precipitation belong to the same atmospheric perturbation.

Not all such rainy periods are used for evaluation, but only those, judged favorable for seeding, possessing the following characteristics:

(a) low winds from the quadrant NW to SW (this is in order to avoid accidental seeding over the comparison area);

(b) storm types characterized by the presence of convective clouds, cumulus

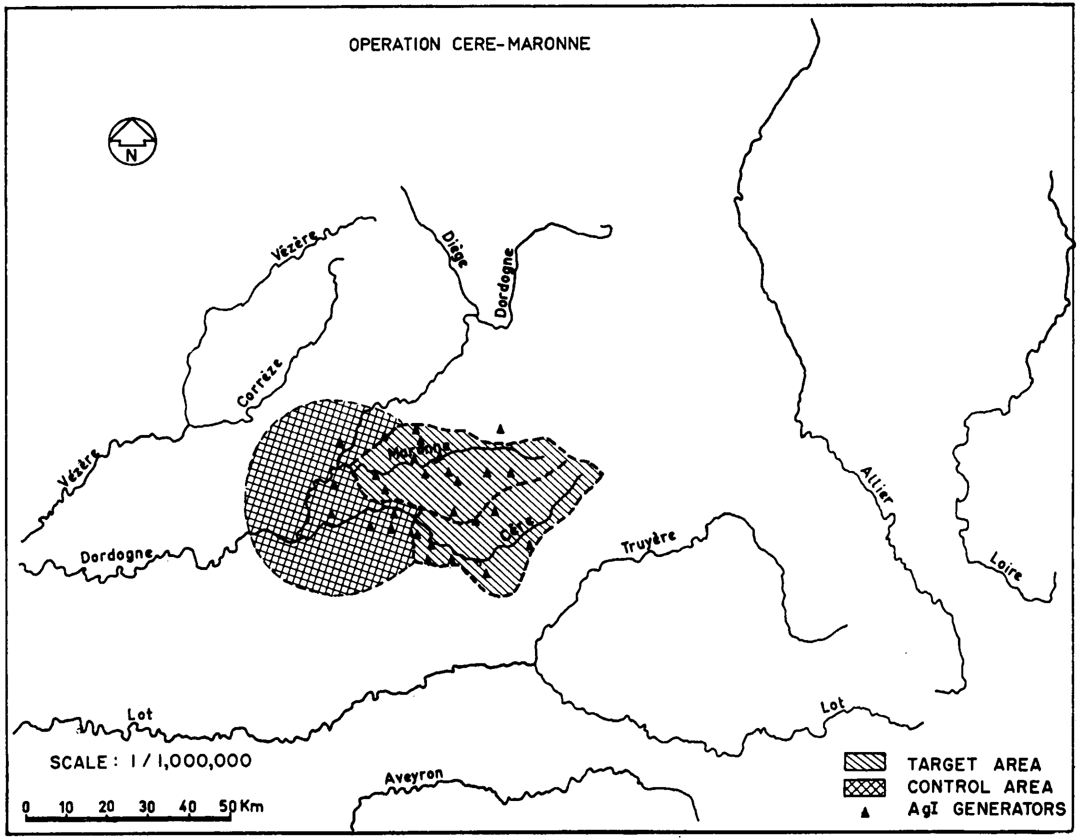

FIGURE 3

The Cere-Maronne operation
showing locations of silver iodide generators.

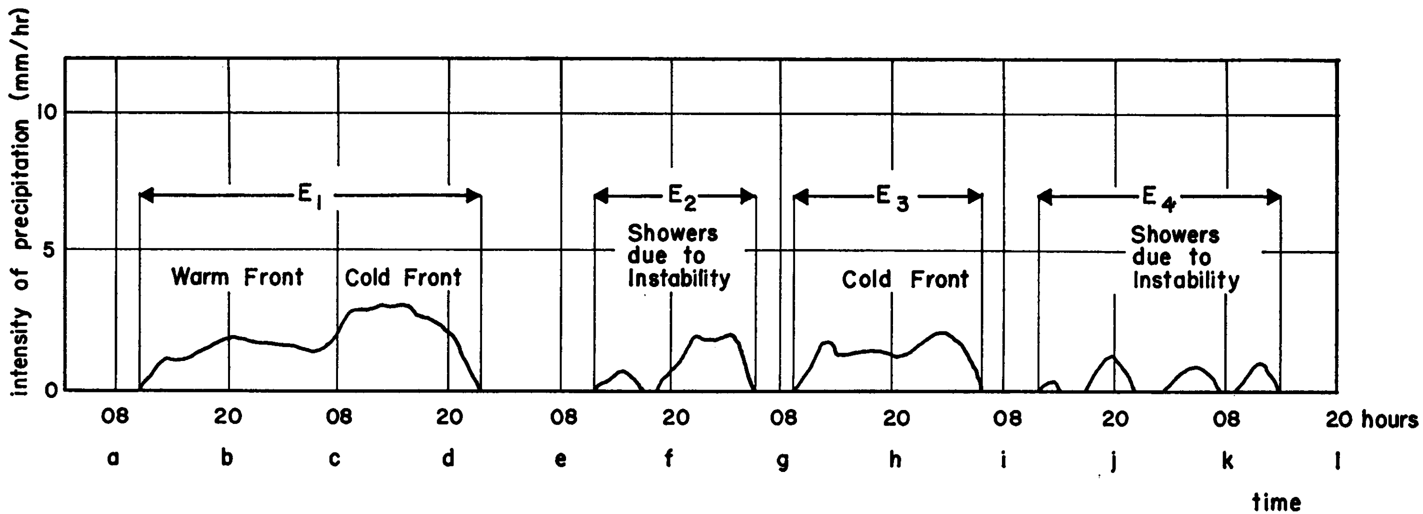

FIGURE 4

The definition of rainy periods:

E_1 (complex period) $= b + c + d + e$;

$E_2 = f + g$; $E_3 = h + i$; $E_4 = j + k + \ell$.

The three rainy periods E_2, E_3, and E_4 are favorable to seeding by silver iodide. On the contrary, E_1 should be excluded.

or cumulonimbus, tied essentially either with a cold front or with an atmospheric instability;

(c) a single storm extending over a rainy period.

Periods not having any of the above characteristics are classified as neutral and are not included in the experiment.

4.3. *Performance of the experiment.* A forecaster located at Chatou performs a continuous fine scale analysis of the meteorological situation in the experimental area. When a situation favorable to seeding presents itself, an order to seed is telephoned to a service agent stationed at the operational bureau at Aurillac at the center of the target. However, the service agent proceeds with massive seeding operations by all the generators only if a random experiment tells him to do so. For this purpose the service agent has a set of numbered

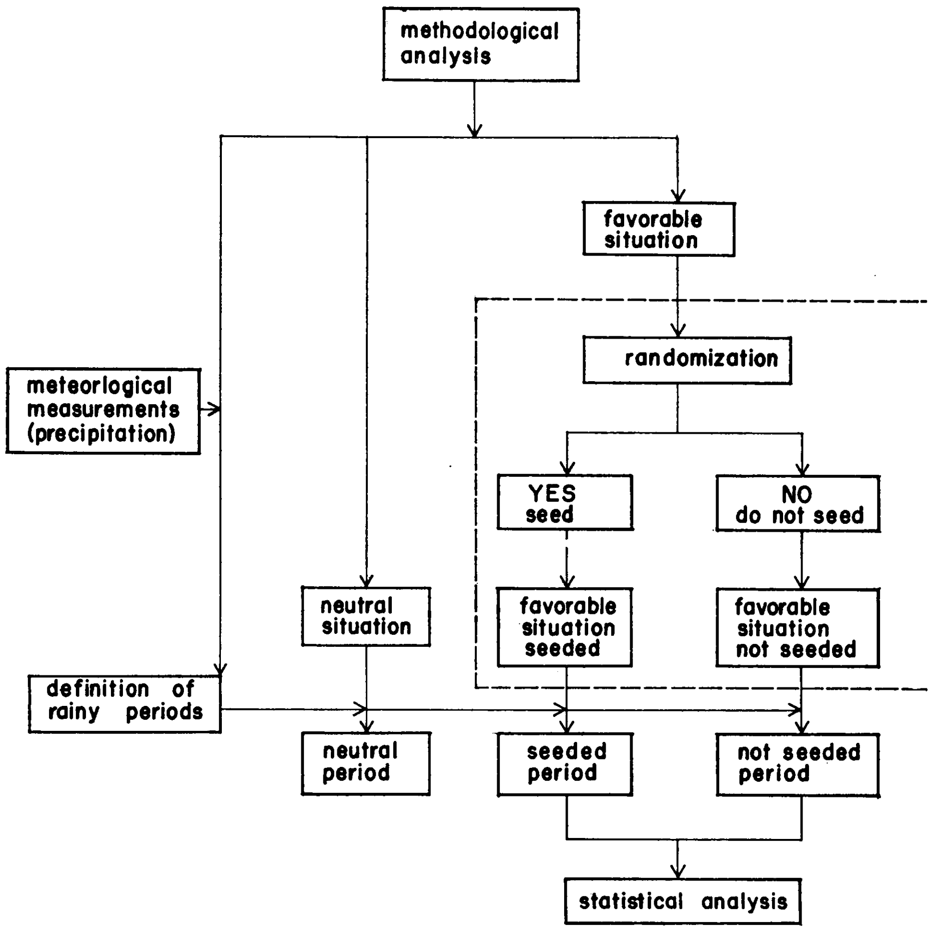

FIGURE 5

Organization chart of the Cere-Maronne operation.

envelopes each containing a card with an inscription either "real seeding" or "fictitious seeding." This series of cards has been prepared in advance using a table of random numbers insuring a probability of one half for each of the two decisions. For each favorable rainy period only one envelope is opened.

The random decision whether the seeding is going to be "real" or "fictitious" is never known to the forecaster responsible both for the definition of the rainy period favorable to seeding and for the decision to discontinue seeding.

Just as soon as the meteorological situation indicates the end of the rainy period, the forecaster telephones the bureau at Aurillac ordering the termination of seeding operations whether they are real or fictitious.

Figure 5 illustrates the scheme of the totality of operations.

The preparatory phase of the experiment, involving the randomization, the definition of "rainy periods," and the establishment of the network of raingages, lasted from March 26, 1962 to April 30, 1963.

The scatter diagram in figure 6 illustrates the target-control correlation of precipitation amounts. Two regression lines are drawn, one for the 27 rainy periods that were seeded and the other for the 29 periods that were not seeded. The calculations were performed using the square root transformation of the original data. The numerical results are

$$\hat{\gamma}_2 = 0.89, \qquad \hat{\gamma}_1 = 1.10, \qquad \hat{\sigma}^2 = 9.72, \tag{4.1}$$

and, for $x = 8.67$,

$$\hat{\mu}_2(x) = 9.22, \qquad \hat{\mu}_1(x) = 9.87. \tag{4.2}$$

The differences, indicating a negative effect of seeding, are not significant.

4.4. *Documentary value of the Cere-Maronne project.* Following the classical procedure, the documentary value of the project is measured by the power $1 - \beta$ of the test used; $1 - \beta =$ the probability of accepting hypothesis H_1 of effectiveness of silver iodide if H_1 is true.

For the two tests (for slopes and for central tendencies of regression lines) applied jointly, the power is given by the following asymptotic formula, valid for large n and p,

$$1 - \beta = \int_{\chi^2}^{\infty} f(u|\nu, \delta^2)\, du, \tag{4.3}$$

where f is the density of the noncentral χ^2 distribution, ν is the corresponding number of degrees of freedom which, in the present case equals two, while

$$\delta^2 = \frac{n + p}{4\sigma^2} [\Delta_\mu^2 + \sigma_\mu^2 \Delta_\gamma^2] \tag{4.4}$$

is the noncentrality parameter with Δ_μ and Δ_γ representing the effects of cloud seeding, and χ_α^2 is the tabled value of the central χ^2 with two degrees of freedom corresponding to the level of significance α, chosen in advance. In numerical calculations of the power, we assumed that, if the experiment is continued, the values of the parameters involved will be close to their estimates obtained from data already available.

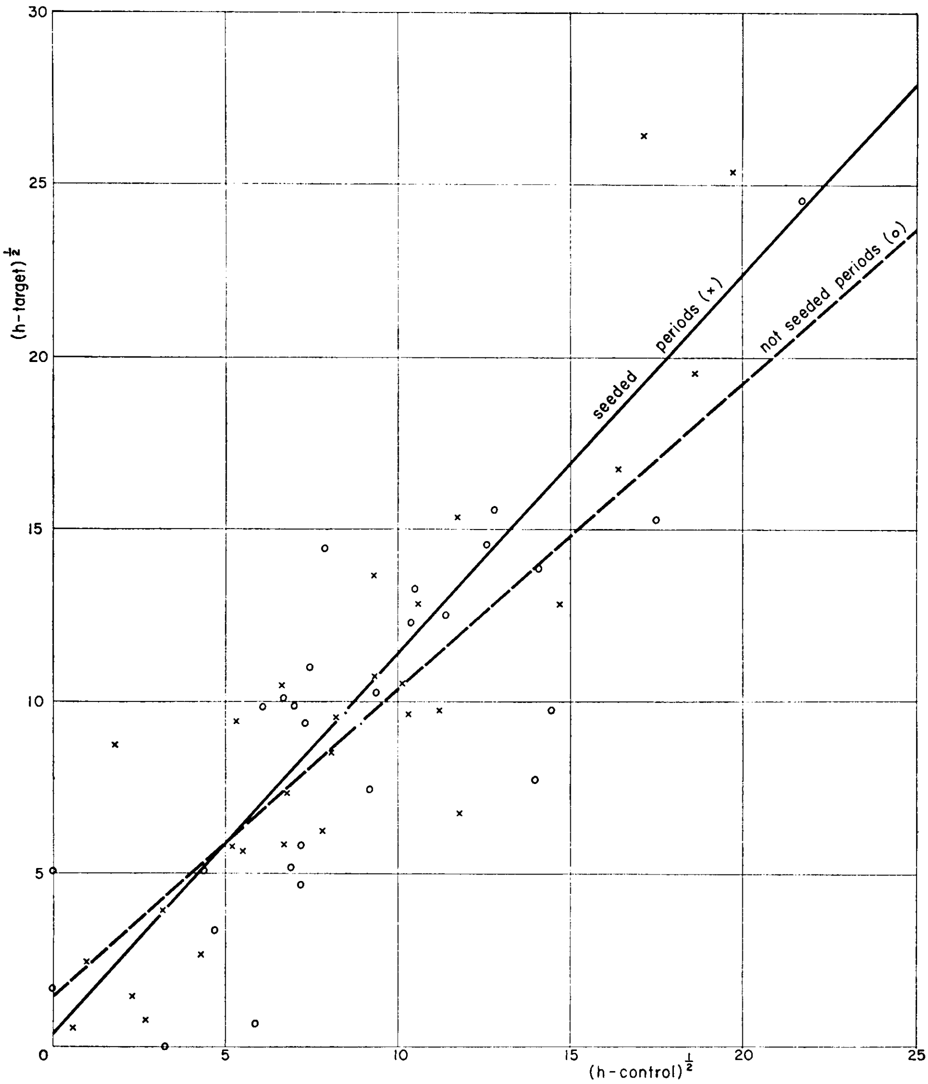

FIGURE 6

Statistical study of the Cere-Maronne operation. Correlation diagram of the square root of the amount of precipitation (in mm) measured in the target and in the control area.

Table I gives estimates of the power $1 - \beta$ computed as a function of the rate, say λ, of the increase in precipitation due to seeding, for several values of $n + p$ on the assumption that this effect is multiplicative.

In order to be clear about the implications of this table, we must remember

TABLE I

POWER $1 - \beta$ OF THE TEST, $\alpha = 0.05$

$n + p$ \ λ	20%	10%	5%
100	0.38	0.13	0.06
200	0.68	0.21	0.08
300	0.87	0.30	0.11

that, as indicated by the current experiment, the average number of favorable rainy periods per year is about 50. We did not evaluate the exact value of the power for the 56 periods obtained thus far, but the figures given in table I indicate clearly that the documentary value of the experimental results now available is very limited.

An increase in the power may be expected from the use of other predictor variables. One of the variables recorded during the experiment is the height of the $-5°$ C isotherm. However, the inclusion of this variable in our evaluations shows no effect. This variable is interesting because of its connection with the effectiveness of cloud seeding. However, this connection is only hypothetical and, thus far, the hypothesis has no empirical support. Here we encounter the difficulty of using predictor variables depending on meteorological factors. It is certain that such variables could diminish the residual variance σ^2 but, in the present state of knowledge of the physical problem, the nature of these factors, the mode of their operation, and their relative importance are little known. As a result, it is uncertain whether the inclusion of any such factors in the statistical evaluation would effectively increase the power of the tests.

5. Comments on the basic elements of the problem

All methods of statistical design and evaluation stem from classical techniques which have been proved in other domains such as agriculture and industry. A comparable effectiveness of these methods could also be expected in experimental meteorology. However, this expectation may be based on an oversight of the fact that the lack of understanding of the mechanism of precipitation and of the factors influencing precipitation forces the statistician to deal with a (statistical) universe in which the variability, the chance fluctuation of the phenomenon studied, is out of proportion to what one finds elsewhere, for example, in agriculture. Furthermore, the probabilistic models capable of representing these fluctuations are far from being known with precision.

5.1. *The role of the basic hypothesis.* The application of a statistical test is based on certain hypotheses, concerned with:

(a) the nature of the probability distribution of precipitation amounts;

(b) the nature of the possible effect of cloud seeding.

5.2. *Distribution of precipitation amounts.* In general, exact control of the two risks of error α and β is possible only when the underlying distributions are well specified. For precipitation amounts these distributions are not well known. This lack of information is an argument in favor of nonparametric tests which insure an exact control of the probability of error of the first kind, without any hypothesis on the actual distribution of the observable variables. However, the actual benefit from a nonparametric compared to a parametric test may be meager if the latter is robust. Here "robust" means the property of certain tests of preserving, approximately, the probability of error of the first kind when the distribution of the observation departs from the hypothesis underlying the test.

The parametric tests used in the evaluation of the E.D.F. projects depend essentially upon the assumption that the deviations of transformed variables from the relevant regression lines are normally distributed. It is known (Scheffé [8]) that such tests are robust, at least when applied to substantial samples. This last condition is also necessary in order to obtain an acceptable power. On the contrary, the assumption that the conditional variance σ^2 is constant is important. If this is not the case in a given application, the conclusions suggested by the test may be biased [8]. From this point of view the interest in the transformations of the type $y = \sqrt{h}$ depends on the degree to which they stabilize the conditional variance.

5.3. *The nature of the possible effect of seeding.* Because of the lack of information on the mechanism of the possible action of silver iodide, any hypothesis regarding the nature of the expected effect of seeding is hazardous. Certain calculations [1] indicate that the power of a test can vary enormously depending upon the type of possible action of silver iodide, on whether it is constant, additive, multiplicative, or random. This latter hypothesis is certainly the most realistic one. Within the framework of normal distributions it is possible to construct tests that are powerful against this latter hypothesis. However, the tests so obtained provide little robustness and are certainly not sufficiently robust to insure that their use on precipitation amounts would not lead to fallacious conclusions. It seems more prudent to rely on regression analysis tests which are sufficiently powerful against the alternatives asserting either additivity or multiplicativity of the effect of seeding. On the other hand, there is no doubt that, in dealing with moderate sized samples, a complex random effect of seeding could escape detection by our tests.

5.4. *Taking account of economic considerations.* In the framework of the classical theory of Neyman and Pearson a test is faced with the null hypothesis H_0: absence of an effect of seeding, and the alternative hypothesis H_1: actual effect of seeding.

It is known that, by fixing *a priori* the significance level, the two hypotheses are treated in a manner which is not symmetric. Is this procedure justified in the present case? In an attempt to answer this question it is necessary to refer to an economic context.

5.5. *Hydroelectric value of an increase in precipitation.* Here we have in mind increases in precipitation that cover the cost of installing and operating a network of generators.

The figures which we are going to quote are a result of a study made by Cappus in 1958. This study gives a comparison of the benefits, from the hydroelectric point of view only, accruing from an augmentation of precipitation, on the one hand, and of the cost of installing and operating a network of generators on the other hand.

Certainly, technical and economic premises have changed since that date. However, it is doubtful whether their order of magnitude has changed significantly. Nevertheless, these results can be regarded only as indications as to the relative importance of certain factors. In calculations of the payoff of this kind, one of the least known elements is the hydrological output of an increase in precipitation. A study of the balance sheet of precipitation, evaporation, and runoff leads to the supposition that, in the cases studied, the output is close to 100 per cent. We repeat that the estimate is one of the most uncertain elements in the calculations and that here we touch upon the weakest points of economic studies of this particular kind.

TABLE II

PROFITABLE INCREASES IN PRECIPITATION

Installation	Watershed (km^2)	Altitude above Sea Level (m)	Mean Annual Precip. (mm)	Profitable Increase (per cent)
Peyrat-Le Chatillon	187	650	1300	7
Bort-Les Orgues	1010	540	1300	1.2
Sarrans	2460	645	900	0.9
Le Pouget	424	600	1100	1.8
Tignes	250	1790	1400	1.2
Bissorte	51	2080	2000	3.1
LeChambon	220	1040	1200	2.7
Serre-Poncon	3600	780	1000	0.8
Pragneres	38	2100	2000	3.9
Puyvalador	134	1420	1200	2.8

It is seen that, in order to be profitable, the increases in precipitation need not be large. It will be noted, however, that the amounts indicated are relative quantities, each referring to the annual precipitation over the whole area of the relevant watershed.

One might think of using the data of table II with reference to the evaluation of cloud seeding experiments in order to construct a rule of choosing between hypotheses H_0 and H_1 while taking into account the consequences which would result. For example, this may be done following the theory of Wald. This would be a fallacious procedure for the following reasons.

(a) Taking into account only the cost of installing the generators and the loss incurred by the rejection of the hypotheses H_1 if, in effect, the increase in precipitation is real and profitable, restrains abusively our sense of the economic universe in which it is appropriate to operate. From a broader economic point of view, there is no doubt that the seeding of clouds with silver iodide enters into competition with other means that have a more "certain" effective profitability of increasing the output of hydroelectric installations.

(b) The "profitable" increases in precipitation refer to a time and area scale (annual precipitation and, frequently, rather a large area of watershed), with which it is impossible to compare the increases that an experiment like that of Cere-Maronne may demonstrate. It is clear that, in order to have a reasonable hope of demonstrating significant increases in precipitation, it is necessary to create special conditions, to control certain sources of variability, to choose certain types of rainy periods, to reduce the size of the watersheds and, in short, to operate in conditions that are restrictive compared with those of a profitable industrial operation.

The above considerations imply that an experiment on the effectiveness of cloud seeding of the type of Cere-Maronne cannot be expected to solve the outstanding economic problem. All it can do is to answer a purely scientific question which has certain rather distant economic implications. With this view, the use of the classical methodology of tests is perfectly justified.

6. Conclusions

Interest in experiments on cloud seeding with silver iodide smoke released from ground based generators should be judged solely from a scientific point of view. At the present time, the economic implications of such experiments are too distant to be taken into account explicitly. With this background the following remarks are relevant.

(a) The importance of an isolated experiment of the type of Cere-Maronne is limited because its results are unavoidably tied to the special local meteorological, climatological, and geographical conditions. However, an extension of such experiments poses the problem of their documentary value. This value cannot be assured other than through the acquisition of a better understanding of factors that operate in the mechanism of precipitation. It is not proved that such understanding will result from the multiplication of similar experiments. To gain such understanding and to study statistically the factors involved, a very complete campaign of measurements appears necessary, a campaign which may be incompatible with cloud seeding experiments.

(b) As to operational methodology, the value of seeding from ground based generators is open to question. Is it possible to find in the zone, which is filled with clouds where the particles of silver iodide might be effective, a sufficient concentration of such particles and a sufficient concentration of those particles that are really effective? Recent experiments with diffusion suggest a negative answer to this question. It follows that one should think of trials involving silver iodide smoke generators operating in the clouds, namely of seeding from aircraft.

(c) The quest for an increased efficiency (in the statistical sense) of experiments leads to the choice (as in the case of the Cere-Maronne experiment) of meteorological situations that are particularly favorable to natural precipitation. However, this amounts to a selection of a particular statistical variable. Thus, it is clear that an experiment of this kind can provide an answer only to a very precise question, namely, (i) does seeding with silver iodide have an effect of increasing rainfall in an incident already underway? This effect is essentially different from that observed in the laboratory, in cold chambers, where (ii) silver iodide particles are introduced into the natural supercooled clouds and provoke or trigger precipitation which would not fall on its own.

From the scientific point of view the establishment of this latter effect (ii) of seeding with silver iodide smoke is just as important as the establishment of the former effect (i) which is the object of the experiments described earlier. However, it is important to realize that the two problems are different. In order to study aspect (ii) of the effect of silver iodide, E.D.F. embarked on a campaign of trials at Mont Ventoux in southern France in which silver iodide smoke is introduced directly into the stationary wave clouds using generators installed in an aircraft. These stationary wave clouds, occurring under a wind crossing a mountain and connected with an oscillatory stationary air flow, the oscillations being caused by the mountain, have the property of remaining stable for a certain period of time without releasing natural precipitation. Various characteristics of these wavy clouds make it easier to study the possible effect of seeding and of the various physical factors that are involved. This series of experiments should increase the understanding of the mechanism of precipitation. Also, it should indicate the domain of validity of Bergeron's theory of the genesis of precipitation which underlies the hypothesis of the effectiveness of silver iodide particles.

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