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## Program Development Plan for an Operational Cloud Seeding Project in Utah With Evaluation Included

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Archives

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PROGRAM DEVELOPMENT PLAN FOR AN OPERATIONAL CLOUD  
SEEDING PROJECT IN UTAH WITH  
EVALUATION INCLUDED

for the

Environmental Research Laboratory  
National Oceanographic and Atmospheric Administration  
Boulder, Colorado 80302

by

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January 15, 1979

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## I. INTRODUCTION

### a) Operational Framework

In the arid climate of Southern and Central Utah, there is a continuing need to augment water supplies. While much of the water is needed for summertime use, particularly for irrigation, most of the available water is supplied by winter storms. Therefore, it is for the augmentation of the water stored naturally as snowpack at higher elevations that cloud seeding can make its greatest contribution.

Over the past several years, an attempt has been made to augment the snowpack by cloud seeding. Although there is a physical basis for expecting an increase in precipitation from a scientifically managed cloud seeding program, the empirical evidence that such increases have actually resulted is inconclusive. If the desired increases have not been achieved, the most likely explanation is that the empirical data necessary to distinguish seeding opportunities adequately have not been collected and applied. Presently, it is worthwhile to design a cloud seeding program in which plans are made beforehand to obtain appropriate field data for use in the execution and evaluation of the program.

Inasmuch as both the clouds available for seeding and the precipitation and storage of water in the form of snowpack are concentrated in the mountains, the area of precipitation augmentation is best confined also to the mountains. Even though the duration of the seeding program may be indefinite, the duration of operation to be evaluated should be defined in advance and carried out as planned. To do otherwise could introduce unwanted bias and doubtful conclusions.

Although an improved operational project with an extensive evaluation included in the design costs much more than that of a simple cloud seeding effort, the benefits will undoubtedly justify the expenditure. The reason is twofold. In terms of immediate benefits, the program will improve determination of which clouds or storms are seedable and concentrate the seeding effort where it will be most beneficial. In the long run, a properly planned and executed evaluation will produce results that will enhance the long term stability of the seeding program as a whole.

Concerning the socio-economic impact of more effective cloud seeding, the benefits of an increased snowpack are likely to far exceed both the cost of the program and any occasional undesirable side effects. However, the disbenefits of the program should not be overlooked. Potential problems include increased flooding during spring runoff, increased avalanche hazard, and increased inconvenience to mountain communities. On the other hand, only artificial increases of precipitation in these occurrences can reasonably be attributed to cloud seeding. Therefore, it is worthwhile to include in the plan sufficient measurements that can be used to deal with such problems on a rational basis. Finally, a public educational effort should be included so that information on all aspects of the cloud seeding program and its reason for being are available to the public.

b) Research Framework

The research associated with this program should be primarily directed toward achieving a definitive evaluation of seeding effects. To accomplish this goal, the evaluation must be specifically designed to do so. Therefore, there are two requirements placed upon the total program, one is to increase precipitation, the other is to clearly demonstrate that precipitation has indeed been increased.

A secondary objective of the research is to develop a knowledge of the actual potential for increased precipitation in the target area. Measurements of relevant parameters over space and time are needed to determine the spatial and temporal variability as well as the frequency of seedable storms. At the same time, the vertical temperature stability at low levels is needed to determine the fraction of time ground seeding generators are effective. In order to increase precipitation efficiently, these measurements are needed anyway. The only extra work needed to improve our knowledge of seeding potential is an analysis of such data as it becomes available.

Research to develop improved methods of indentifying seedability, determine what type of seeding material to use, or decide whether it is better to seed by air or ground requires systematic data collection, but the effort needs to be much more concentrated than appropriate for the general clouding seeding operation and evaluation described here. Such research data collection and evaluation are best left to controlled experiments such as are being conducted at Utah State University.

The present project should, in contrast, emphasize measurements needed in the application of previous research results and evaluation of what is actually achieved by cloud seeding in an operational mode. The technology employed should not include promising methods or approaches still being studied but not yet tested in confirmatory experiments.

## II. OPERATION

### a) Target Area and Length of Project

Although data for evaluation must be gathered on a continuing basis, it is not necessarily desirable to evaluate the information collected after each year. The danger in early analysis and reporting is that when a positive, neutral or negative effect is found, a case will be made to cease the evaluation, if not the operation. Even if the effect found can be demonstrated to be statistically significant, such reaction is unjustified. The period or periods of evaluation should be stated in advance, and sequential evaluations should be recognized only as uncertain indicators of the program's effectiveness.

The same kind of reasoning applies to regional subdivisions used in the monitoring and evaluation. That is, if several areas are evaluated as independent entities, then some will likely show favorable results. If it is indeed desirable to have several separate areas, then it is necessary to take that fact into account in the analysis of statistical significance. Because a longer period of record would be required to establish statistical significance of a given effect when data from multiple areas are used, it would be possible to establish results sooner from a purely statistical point of view with only one area for evaluation. However, important physical considerations suggest that independent evaluation in a few separated areas would be desirable. For example, a front range may cause rather different cloud conditions over a downwind range. Also, over a

large target area there may be significant differences in the type and frequency of seedable storms. Though the former effect may prove to be more important than the latter, allowance should be made for both possibilities.

As an appropriate balance among these considerations, it is recommended that four independent target areas be established in advance. These are shown in Fig. 1. The western most regions are largely unaffected by nearby mountains upwind. The opposite is true for the mountains in the central and northern regions. Furthermore, the northern region is physically separated from the southernmost region by a large distance; storms affecting the southern regions may not reach the northern one and vice versa.

b) Seeding

Both ground and air seeding are recommended. When stability conditions are suitable and all areas are to be seeded for a period of time in excess of about four hours, then ground generators may be used almost exclusively. However, when these conditions are not met, then airborne seeding should be used to augment or replace ground seeding.

To reduce the effect of low level inversions and to increase the flexibility of operation, the use of telemetered control of seeding from high elevations is desirable. The technology for reliable operation of seeding generators by remote control is well established. Trapping of ice nuclei by low level inversions would be greatly reduced and the timeliness of the flow of nuclei into the clouds would be increased. These factors lead to the recommendation that the majority of ground generators be placed at high elevations and operated remotely if necessary. The general location of ground-based seeders is shown in Fig. 2.





Fig. 1. Target area with subdivisions and rawinsonde locations.



Fig. 2. Zone of ground-based seeding, solid curve. (Target area dashed.)

Airborne seeding must be sufficiently flexible to place material into clouds over the limited regions where it will do the most good. Therefore, seeding aircraft should be controlled by radar. A dedicated control radar should be placed atop a high elevation with a view over the entire airborne seeding release zone. Two radars should be used if one has insufficient coverage.

Project design and the method of evaluation are inseparable parts of the whole program. For example, if additional instrumentation is used to obtain data for evaluation of some treatment effect, then matching data for some untreated situations must also be obtained. Otherwise, unwanted biases will surely arise. One of the most effective ways to obtain data properly representing both treated and untreated situations is to employ randomization. Since the instrumentation available to the operational weather modification project in Southern Utah is to be augmented, it is strongly recommended that randomization or some equivalent procedure be employed as a basis for evaluation. If randomization were used, the decision whether to seed specific storms should be made in several steps. First, information from rawinsondes and aircraft should be used to decide whether a cloud area is seedable. If the conditions are declared favorable and a definite seeding period decided, then another decision should be made as to whether to carry out the seeding or to leave the target area unseeded as a deliberately selected untreated situation in the randomization process. The choice should be made randomly with the odds pre-fixed so that there will be about  $m$  seeded storms for every  $n$  unseeded storms during the course of a single season. For example with  $m = 3$  and  $n = 2$ , 60% of the suitable storms would be seeded and 40%

unseeded. For each storm, the declaration of intent to seed should be reported to the evaluator and the choice of whether to seed or not is then reported back to the operator.

Another possibility would be to state in advance that  $p$  days would be open for seeding if conditions were suitable. That is, seeding is permitted but not required. Then after 1 purge day, there would be  $q$  days following in which no seeding would be permitted. Such a cycle would be repeated throughout the winter season. As an example, with  $p = 11$  and  $q = 6$  each cycle would last 18 days including the purge day. Precipitation in the  $p$  days would be considered as seeded and precipitation in the  $q$  days as unseeded. We shall call this approach "programmatic seeding" as differentiated from "randomized seeding." For reasons which will be discussed later, this is the method recommended for establishing unseeded periods of precipitation to be used in evaluating this project.

c) Seedability

The critical question concerning seedability is what criteria should be used to decide whether the addition of ice nuclei, and in particular, silver iodide will increase precipitation. Certainly, the presence of supercooled water is a prerequisite for increasing precipitation by cloud seeding. All indices for seedability must ultimately rest their worth on how well they act as an indicator of supercooled water. Of course, other indices may be used to measure how well seeding material is dispersed, its direction of travel, and the trajectories of augmented precipitation.

There is substantial evidence that the criterion found in the Climax experiments cannot be applied successfully at most other locations. A

fixed level temperature is likely to be very poorly correlated with the amount of supercooled water present.

Cloud top temperature has been widely used as a measure of seedability. Cold cloud tops are believed to contain abundant supplies of ice particles, and warm cloud tops, a relatively small supply of ice particles. If the cloud top is too warm, the effectiveness of silver iodide is diminished. Thus, physical reasoning suggests that cloud top temperature would serve as a useful index of seedability. Several experiments, mostly of the post hoc variety, tend to support this contention. However, a number of factors suggest that cloud top temperature is a rather weak indicator of seedability. For example, there is a lack of studies which actually demonstrate a relationship between supercooled water concentrations and cloud top temperature. Apparently, a better indication of seedability is direct measurement of supercooled water, and its temperature if silver iodide is to be used. Thus, the presence of substantial amounts of supercooled water at temperatures which can be affected by silver iodide would be expected to constitute a highly seedable situation.

But even though these latter criteria appear optimal, the combined criteria of supercooled water and temperature have not been tested. Such tests are in the preparatory stage at USU. In the meantime for an operational seeding and evaluation program, the system should be designed to utilize indicators that have both a physical basis and some experimental validity. Therefore, it is suggested that the seedability criterion should be cloud top temperature rather than supercooled water.

d) Measurements Required for Seeding Operations

Measurements of variables related to targeting of precipitation are needed in addition to those required for seedability determination. Low level stability measurements are needed to ascertain whether seeding material released from the ground will disperse into the clouds. Winds at levels where seeding material is expected to be found are required. Nearly continuous measurements of cloud top heights in the vicinity of the mountains are needed to find the cloud top temperature. Cloud detection units similar to the Air Force TPQ-11 are recommended along with rawinsondes. Airborne measurements of cloud top temperature should also be made to augment the ground based measurements. However, the combined data used to determine seedability should not be separated later into sub-categories for separate evaluations.

e) Suspension Criteria

Provisions should be made for suspending seeding operations, if environmental conditions become or could become hazardous. These situations include the presence of abnormally deep snowpack, threat of flooding especially at lower elevations and avalanche danger. Unusually strong convection conditions might also be considered unsuitable for seeding.

## III. DESIGN AND EVALUATION

## a) Design Framework

Much of the design has already been defined by the general requirements previously discussed. Randomized or programmatic seeding is needed for evaluation purposes. Seeding is accomplished both by ground based and airborne released silver iodide. Seedability is to be determined primarily on the basis of a cloud-top temperature window, presumably from about  $-10^{\circ}\text{C}$  to  $-24^{\circ}\text{C}$ . Consideration is also given to low level stability and wind flow, so that proper placement of seeding material is achieved.

## b) Precipitation Control

Although extensive measurement of precipitation within the scope of the operation is justified solely on the basis of evaluation of seeding effectiveness, the interaction of those measurements with the project design must be considered. The ultimate success of the project is measured by how much the precipitation is increased in the target area compared to how much precipitation would have fallen in the absence of treatment. This added precipitation can be much more readily detected if substantially well-correlated variables are used. Covariates can take the form of control-area precipitation measurements or control-area aerological measurements, or both. Our recommendation is that only precipitation be used as a covariate for reasons discussed later. Precipitation measurements in the control area should be at the higher elevations where the snowpack is greatest. Correlations with target precipitation will be much higher at the high elevations compared to measurements

radar  
for  
forecasting

at low elevations. Some predetermined time lag between control and target area precipitation should also be employed. The general area of the control measurements is shown in Figure 3 along with the ground seeding and target areas.

Whatever approach is selected to establish controls for evaluation, the choice should be made prior to the start of the operational phase. Therefore, it is suggested that the first season of the program be set aside for an intensive period of measurement without any seeding. From these measurements the gages to be used as covariates may be chosen. Control area precipitation measurements found to be highly correlated with target precipitation should then be designated as the controls for the project evaluation. During the operational periods, whether designated seeded or unseeded, both control and target area measurements should be taken on a regular prescribed basis. New correlations and relationships between target and control precipitation would be established as part of the evaluation of seeding effectiveness.

c) Duration of Seeding

The duration of individual operational periods needs to be established. If randomization were not used, and some area control were used instead as the only basis for evaluation, then a variable period of seeding strictly suited to the requirements of individual storm events could be employed. The final test of seeding effectiveness would rest with the seasonal totals.

If randomized seeding were to form the basis of an evaluation, wherein precipitation measured in both the target area and control area is used to evaluate seeding effectiveness, then the duration of individual events may still be varied according to the individual storm at hand, but the





Fig. 3. Control area (labeled C) with seeding and target areas also shown.

choice of event duration must be made in advance of the randomized seeding decision. Otherwise a seeded wet storm could be continued, or a seeded dry storm could be discontinued. Another option would be to make all storm periods of equal duration. Because the duration of storms varies greatly, it would seem clear that a variable duration, decided in advance of each operational event would be far better than a constant duration.

On the other hand, it would be highly desirable for the operator to have the flexibility of starting or ending seeding as needed, but not having to make such a decision in advance when available data and the ability to forecast seedability conditions are inadequate for the task. Such flexibility can be achieved by the programmatic seeding wherein fixed intervals of seeded and unseeded periods follow cyclically. We therefore, recommend this strategy for developing seeding controls.

d) Location of Control Areas

If control areas were needed in evaluating individual storms, it would be virtually necessary to have the areas close to the target, that is within a 100 km or so. Otherwise, storm time and path variations would greatly reduce the correlations as the distance becomes greater. On the other hand, the control areas must be located such that seeding material does not enter into them. One approach is to utilize only control areas upwind of the target. Thus, for example, a southern control area would be used for southerly flow. The difficulty would then be that the northern target area is far removed from that control area, and its usefulness would be marginal.

With programmatic seeding, the control area may be placed further away, so that contamination is unlikely. Since up to several periods of

precipitation may occur within one seeding cycle, the correlations of a somewhat more distant target would still be fairly high, say 0.7 - 0.8, especially if time lagged correlations are used. For an average upwind distance of around 200 km, a time lag of about 6 hours would probably be close to optimum. During the course of a single season, about 9 seeded/unseeded cycles could be generated between November 1 and April 11.

e) Analysis of Seeding Effectiveness

It is recognized that programmatic seeding results in the inclusion of untreated storms or portions of storms which fall into periods of permitted seeding. This dilution effect is also present in any non-randomized design using a control area for evaluation. On the other hand, the operator is freed from other constraints which may seriously reduce the effectiveness of seeding even though only the seeded portions are included in the evaluation.

Another practical benefit of programmatic seeding is that better planning is possible. Also, the operator can concentrate on determining seedability conditions at the moment, and not be required to anticipate seedability.

With the recommended seeding design, 9 pairs of precipitation data for each target area are obtained each year. Covariate correlations in the vicinity of 0.7 or 0.8 might be expected. After five years there would be an accumulation of 45 data pairs. A crude estimate of the resolving power of this data yields a detection level of seeding effectiveness as low as a 5% increase at the 5% level of statistical significance.

#### IV. EQUIPMENT AND MEASUREMENTS

To accomplish the tasks described in the foregoing plan of operation and research, a variety of measuring equipment is needed. These are outlined as follows:

a) Seeding

It is suggested that about 60 ground generators be used to cover the target area. Most of these should be located at high elevations, and because of a likelihood of inaccessibility, they should be operated by remote control. Other seeders at lower elevations could be located at convenient places and be operated manually.

Two or three seeding aircraft should be operated to augment or replace ground generators when low level inversions exist or when seedable clouds are particularly deep.

A cloud physics reconnaissance aircraft should be equipped to measure ice nuclei, liquid water content and cloud top temperature. However, the liquid water data should not be made available to those doing the seeding, otherwise the project's results will become ambiguous, and it would not be known whether to attribute success to the liquid water or the cloud top temperature measurements. It is the latter measurements which comprise most of the seedability data collection effort and expense for determining seedability in accordance with previous discussion. On the other hand, it would still be worthwhile to collect liquid water content measurements for later analysis and interpretation in conjunction with research such as that ongoing at USU.

Two radar control stations are needed to allow seeding aircraft and the reconnaissance aircraft to cover the area desired. Telemetering facilities should be added for remote control of the ground seeders. Four rawinsonde/TPQ-11 sites should be set up for monitoring cloud conditions, one in each target subarea.

A central weather station should be available for collecting and interpreting local and national weather. Telephones and radio communication are also needed for contact with seeder operators, radar and telemetering sites, project aircraft, and rawinsonde/TPQ-11 sites.

b) Evaluation

About 60 recording precipitation gages should be placed within the target area at elevations generally above 2000 m. A similar number of gages should be placed over a wide region to the west of the target by about 200-250 km in an arc shape somewhat enclosing the target, but sufficiently limited so that artificial ice nuclei drifting out of the target area do not enter this control area.