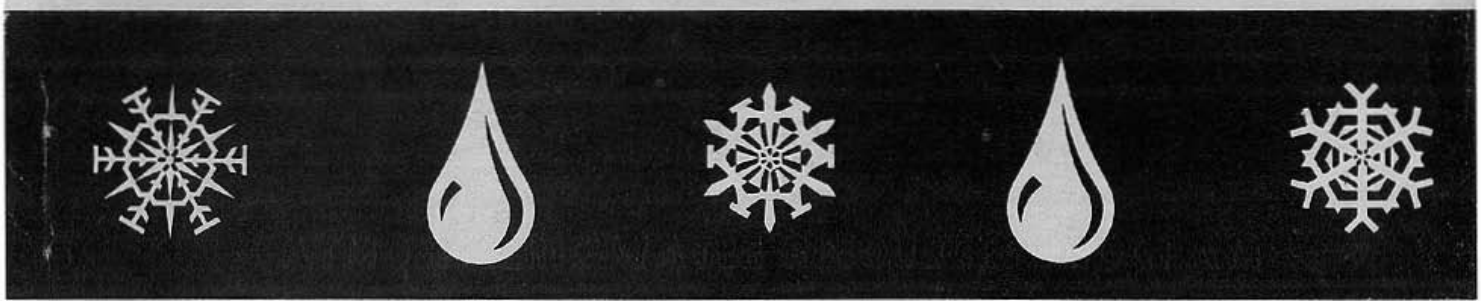
Chuck Robertson

ATMOSPHERIC WATER RESOURCES PROGRAM

PROJECT SKYWATER

1968 ANNUAL REPORT

Volume II: Contractor Reports



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UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
OFFICE OF ATMOSPHERIC WATER RESOURCES

JANUARY 1969

PROJECT SKYWATER

1968 Annual Report

Volume II

Contractor Reports

ATMOSPHERIC WATER RESOURCES PROGRAM

UNITED STATES
DEPARTMENT OF THE INTERIOR

BUREAU OF RECLAMATION

January 1969

TABLE OF CONTENTS, VOLUME II

	Page
Preface	iii
University of Arizona	1
Colorado State University (hydrology)	7
Colorado State University (equipment)	33
University of Denver	41
Fresno State College Foundation	59
Montana State University	81
University of Nevada, Desert Research Institute	99
University of New Hampshire	121
New Mexico State University	127
New York University	135
Pennsylvania State University	143
South Dakota School of Mines and Technology	163
Texas A&M University	183
University of California at Los Angeles	187
Utah State University	207
University of Wyoming	223
Aerometric Research, Inc.	239
T. G. Owe Berg, Inc.	257
E. Bollay Associate, Inc.	267
Loren W. Crow	285
EG&G, Inc.	291
Meteorology Research, Inc.	303
North American Weather Consultants, Inc.	335
Travelers Research Center	347
Illinois State Water Survey	369
State of Washington Department of Water Resources	375
Environmental Science Services Administration	391

PREFACE TO VOLUME II

This is the second annual report of Project Skywater. Volume I summaries the historical development, present activities and future plans of the Atmospheric Water Resources Program. Volume II contains reports describing the fiscal year 1968 activities of the Project Skywater contractors.

Some of the reports were reproduced exactly as received from the contractors. Others, because of their length, were summarized by personnel of the Office of Atmospheric Water Resources. The contractors have not reviewed the summaries, but in almost all cases the summaries consist of essentially verbatim extracts from the contractor reports. The Bureau of Reclamation summaries are identified as such on the cover sheet of each report.

Several research programs were started late in the fiscal year. Reports of the activities of these programs have not been included in this volume. The contractors involved are Colorado State University (one contract to investigate diffusion, using a wind tunnel model, and another contract for planning the Upper Colorado River pilot project), University of Denver (cloud physics research), and the University of Michigan (ecology). In addition, reports from the Soil Conservation Service, Geological Survey and the Forest Service have not been included because the primary role of these groups is providing equipment and data.

Citation of trade names or commercial firms does not constitute an official endorsement or approval of the use of such products or firms by the U.S. Department of the Interior, Bureau of Reclamation.

Legal Aspects

of

Weather Modification

UNIVERSITY OF ARIZONA

College of Law

This summary, prepared by the Bureau of Reclamation, contains the introductions to the four interim reports and the summary of a special report concerning legal guidelines for atmospheric water resources management. The reports themselves cannot easily be reduced to a size suitable for the Project Skywater Annual Report.

INTRODUCTION

The law, like the atmosphere, stubbornly resists computerization; yet each has its parameters, and men have chosen the task of defining them. In the nature of things, elaboration of atmospheric science theories has preceded description of the legal effects of their implementation. The time, though, is now ripe for an overall examination of the law of weather modification. The Weather Modification Law Project at The University of Arizona College of Law is such a study. This is the first interim report from the study.

The term "weather modification," as used in those state statutes which attempt to define it, and in the regulations of the National Science Foundation, covers changes in the composition, behavior, or dynamics of the atmosphere which are artificially and intentionally induced. It is customary to think of weather modification as being on a lesser scale of size and permanence than climate modification. The primary focus of this study is upon artificial changes in clouds and fogs and the legal implications of such alterations.

The effects of weather modification may be considered on a temporal basis; that is they may be divided into those taking place initially and those that are cumulative. Artificial weather operations may also be compartmentalized in light of their geographical impacts. The Weather Modification Law Project will consider both kinds of classification of effects.

This report concerns the presently existing law of weather modification. Its primary division is into a consideration of the legal problems arising from the initial effects of weather modification and an exploration of those problems arising from the cumulative effects of weather modification. There is also a recitation of the state of the art and an inquiry into the complex problems of "legal cause" that pervade most of the legal questions resulting from weather modification.

Two later interim reports will delve into questions concerning the possibilities of adjustment in weather modification law through future legislative activities. They will be divided upon the basis of geography. The January report will consider the domestic impact, both interstate and intrastate, of weather modification; the April report will focus upon the international consequences of artificial weather changes. Both reports will cover the governmental power to act and possible norms that might be established.

This interim report and the other two are segments of an overall study of the law of weather modification. They will lead to the final report which will incorporate their substance. Hence they are not intended as complete and final statements concerning the

areas of law covered. They will be supplemented by closer examination of many of the problem areas that they raise. Suggestions and criticisms are invited. They will be taken into consideration in preparation of the final report. Also the authors contemplate making changes in light of future inquiry and reflection. There is an awareness that forecasting the law, or even guiding its direction, may be akin in difficulty to forecasting the weather - or in guiding its direction.

The goals of modern weather modification are to make artificially and intentionally such changes in the composition, behavior, and dynamics of the atmosphere as would alter precipitation patterns, disperse transportation inhibiting fog, suppress hail and lightning, and eventually diminish the disasterous effect of severe storms. Governmental regulation of activities designed to achieve these goals is now directly imposed, to greater or lesser extent, in some 26 states and has been proposed on a federal level. Weather modification regulation should facilitate efficient use of the atmosphere as a national resource, provide for equitable distribution of the benefits thereby derived, and promote fair assessment of the costs and liabilities.

The Weather Modification Law Project at the University of Arizona College of Law involves an overall examination of the law of weather modification. In order to conduct the research more efficiently, the study has been divided into three main areas: The presently existing law of weather modification, possibilities for future regulation of the domestic consequences of this new technology, and potential control of its international consequences. The October interim report concerned the present law; this report relates to the domestic regulatory possibilities; the March report will involve the international aspects. In addition to these quarterly reports, two series of papers are being prepared. The first, which should be available in February, concerns water resources acquisition and management problems inherent in weather modification. The second will deal with specific liability problems.

This interim report deals initially with the powers of the federal, state, and local governments to regulate weather modification. It then considers possible types of regulation and potential agencies for effectuating governmental controls. Consideration is given to present patterns for regulation of somewhat analogous activities, state weather modification statutes, federal weather modification bills, and proposals for regulation advanced by weather modifiers, governmental agencies, and legal writers. There has been no effort made, however, to predict or to dictate the future course of regulation. The conclusions reached herein are only tentative.

Very helpful suggestions concerning the first interim report have been received from some of the persons studying it. Comments and criticisms regarding this report are also solicited. They will be considered in preparation of the final report. In addition the authors expect to make changes in these materials in light of future inquiry and reflection. Exploration of the intricacies of atmospheric technology is a complex matter; so, to, is examination of the law that will be applied to it.

Weather respects no international boundaries. Men are bound to respect them, however; and when men alter the weather, international legal complications develop. This report explores them.

International weather relationships will develop in two directions: Adverse and cooperative. International law itself falls into two categories: public and private. Large-scale weather modification will bring about combinations of these. Analysis of the problem is complicated by the absence of weather modification activity on an intentionally international scale and the absence of directly applicable international law.

But, our problems have begun: At one time 80,000 Canadians petitioned their government to put a halt to cloudseeding operations in New York State. More problems loom ahead: Our Project Lake Effect, whose goal is to benefit our eastern states by interfering with storms east-bound across the Great Lakes, may lead us to conclude we need Canada's cooperation in seeding north of the border. On the other hand, our efforts to increase runoff in the Colorado River Basin may bring Mexican claims against us to the increased water supply.

Similarly, in the private sector, weather modifiers may join generators across borders, or unilaterally cause weather effects across borders, with benefit or damage to governments or to private individuals. Military applications of weather modification have not gone unnoticed.

This report proceeds on a statement about public international law, international types of law such as admiralty and air law which are potentially applicable to weather modification, and private international law, then analyzes the types of international weather modification problems which may come about and international legal solutions which may be applied - present and future.

A. Study Setting

This fourth quarterly interim report to the Office of Atmospheric Water Resources of the Bureau of Reclamation by the Weather Modification Law Project at the University of Arizona College of Law explores questions of the law of indemnity, insurance, and indemnification as they relate to precipitation management planning and

activities. Its central theme is protection, through law, of both private and public interests from financial losses that might arise due to weather modification.

The previous three quarterly interim reports of the Weather Modification Law Project have examined the variety of legal problems potentially arising from weather modification activities in the complex and far-reaching public, private, and international legal frameworks of today. Two mimeographed sets of papers - one on liability issues and the other on analogies between atmospheric and surface and ground water law - have also been produced as part of the University of Arizona College of Law's contribution to Project Skywater. Although these prior materials by their nature neither attempt in-depth analysis of potential problems nor present guaranteed pat solutions, they nevertheless document the cause for interest in the weather modification community for finding legal security while exploring this challenging area of science.

As with the earlier reports and papers, this document purports only to examine a few trees in a large forest. The entire contents of these materials will be totally superseded by this project's final report to the Bureau of Reclamation and its booklet for Project Skywater contractors containing legal guidelines for atmospheric water resources management. And, as with prior papers and reports, this report is circulated to a limited group of weather modifiers, legal scholars, and governmental officials who are knowledgable concerning the applicable parameters, with the express purpose of soliciting from them comments and criticisms which, coupled with additional research and analysis by this project staff, will contribute to making the final report to the Bureau and the booklet of guidelines authoritative, up-to-date documents of benefit to all concerned.

B. Legal Setting

Many legal uncertainties confront the weather modifier, just as many meteorological uncertainties confront the lawyer. Certainly, as weather modification becomes ever more predictable of result, so will its legal implications. But even now, some of the legal uncertainties are theoretical in nature, the practical questions being whether particular weather modifiers are immune from liability, or, if they are exposed to the possibility of liability (whatever the legal theory), how they may protect themselves from financial losses associated with that liability through insurance or indemnity agreements.

The public, too, may acquire financial protection through insurance, and in some areas possibly applicable to weather modification, through indemnity by Government program.

This report explores these matters, commencing with a discussion of immunity, to lay the groundwork for determining which classes of weather modifiers are most exposed to chance of financial loss and who may be most benefited by insurance or indemnity protection.

SUMMARY OF GUIDELINES

Planning and Preparation for Weather Modification Activities

Contracts. There are three major kinds of contracts that have legal significance to participants in Project Skywater: Federal procurement contracts between the Bureau of Reclamation and the weather modifiers, indemnification agreements, and liability insurance contracts. In all three instances contractors should become aware of thier legal rights and obligations under the agreements.

Licensing. Although Federal contractors may be immune from state licensing, it is sound policy to comply. State agencies have the necessary forms and applications for professional licenses and operational permits. The statutes of some states require various types of advance notice prior to conducting weather modification operations.

Conducting Weather Modification Activities

Operating Delivery Systems. When conducting weather modification activities upon government or private lands, obtain permission from the governmental agency involved or the owner of the private lands. Seeding by aircraft is subject to governmental controls generally applicable to air flights.

Dispersing Seeding Agents. Although good public relations will mitigate concern of people over dispersal of silver iodide in the air, there may be those persons who will sue. They will have a difficult time establishing to the satisfaction of a court that the seeding caused measurable damage.

Evaluation of Consequences of Weather Modification Activities

Instrumentation and Evaluation. A person claiming injury resulting from weather modification must establish that he suffered a loss and that the modifier's activities caused it. Difficulty in bearing the burden of this proof will, as a practical matter, limit the number of instances when claimants will win lawsuits. In negligence cases there is the additional burden of proving proximate cause. Under the proximate cause doctrine, there is no recovery when unforeseeable intervening causes break the causal chain. Proof of causation may be made by use of expert and lay witnesses, by physical and statistical evaluation, and by the weather modifier's own records.

Atmospheric Consequences. The atmosphere is essentially an unowned resource, hence atmospheric property rights are uncertain. For alleged interference with such rights, a modifier may be sued for trespass (interference with possession of property), private nuisance (interference with use of property), negligence (carelessness), and upon the theory of strict liability, i.e., liability for ultrahazardous activity. Outcome of the cases will depend in large part upon their specific facts, upon whether what has been done fits within the technical requirements of the theories used.

The weather modifier may protect his activities by using remedies against interference with his equipment and personnel and intentional interference with his business relations.

A defendant in a legal action will win the lawsuit when he proves a defense. Among the defenses available to weather modifiers, depending upon the facts of the case, are consent, immunity, privilege, and waste.

Hydrologic Consequences. Claimants asserting that they have been flooded or have had access to their property blocked by the consequences of weather modification efforts will usually be able to prove the flood and the interference with access; they will, however, have a very difficult time establishing that weather modification was enough of a causal factor in the flood or blockage to be legally significant.

Reporting Consequences of Weather Modification Activities

Contractual, statutory, and administrative requirements stipulate that weather modifiers must keep records, make various reports, and, in some states and under some contracts, render evaluations of their weather modification activities.

the freezing level lifted to over 10,000 feet, and for the majority of days in February was over 6,000 feet. The result was substantial snow melt from late January, through March, as reflected by stream flows for the period.

If both target and control groups were approximately the same elevation, revision of the analysis would be unnecessary. Early melt would, in that case, be reflected equally in both areas. However, two of the three target stations are below 5,000 feet, while only one of the four control stations is below this level. Average elevation of the control group is about 600 feet higher than the target group. Thus, target area snowpack is over-forecast in a season such as the past, when melting and runoff occurs unusually early at lower elevations.

To correct for this, two additional snowcourses, Upper Holland Lake, and Trinkus Lake, are incorporated into the target group, for a total of five. Average elevation of the revised target group is nearly equal to the control group, 5,640 feet versus 5,600 feet. Historical records of these two additional stations of March 1st measurements are not as complete as the other stations, so the historical sample size is somewhat reduced. It is for this reason these stations were not used in the 1966-67 analysis.

The decrease in sample size is however, offset by an increase in correlation between target and control groups. With the previously used three station target set the correlation coefficient was .827, while the revised five-station set yields a coefficient of .868 against the same four-station control. Although April 1st data gives an even higher correlation ($r = .903$), it was decided to adhere to March 1st data for continuity of analysis with the previous year.

The modified analysis indicates an increase in the target area snowpack water content of 9.3 percent for 1966-67, 3.5 percent for 1967-68, and a 2 year combined increase of 7.1 percent, with a probability of .19 that the increase was due to natural variability.

Silver in Snow

Further effort was expended last winter in an attempt to more accurately delineate the area of seeding effect. A portion of this included the collection of snow samples in and around the target area for silver content analysis. Analysis was conducted by the same agency as before, the Desert Research Institute (DRI), University of Nevada, and their analytical methodology was essentially the same as the previous year.

The first set of 25 samples was collected in mid-January. An additional 10 samples were collected in March, and one in April; this second set was sent to DRI in early April.

Upon inspection of the data, several disturbing things are apparent. Exluding the five samples taken in the Swan Valley near generator locations, where it is probable that some direct AgI washout occured, all other samples, with two exceptions, show concentrations lower than the lowest ranked sample from the 1966-67 season. Both target and control samples alike show only background concentrations, and, equally important, the background is approximately an order of magnitude less that the previous year. The median of 20 control samples taken in 1966-67 is 3.35×10^{-10} gm/ml, while the median of 19 target and control samples taken in January 1968, is 1.18×10^{-11} gm/ml.

There are several hypotheses which might explain this difference. The most direct is the possibility that background concentrations vary, by the amount observed, from year to year as a result of natural causes. If this be the case, comparison of target-control concentrations within a given year can be made, but year-to-year concentrations would not be directly comparable because of the high noise level. This hypothesis is not supported by the results of a sampling program in the Reno, Nevada region in 1966-67, which showed background concentrations of about $1\text{-}4 \times 10^{-11}$ gm/ml, about in line with the Hungry Horse 1967-68 concentrations (1967). However, Project Hailswath in South Dakota showed unseeded concentrations as high as 7.1×10^{-10} gm/ml (1967), so the question of absolute background levels remains an open one.

A second hypothesis is that the collection and/or analytical procedures were significantly changed from one year to the next. This possibility is difficult to assess, but a check with the DRI is being made.

Turning to the 1967-68 data for single season target-control relationships, we find other difficulties. Two sampling modes were employed: freshly fallen new top snow, and core sampling. There is no apparent difference in silver concentration between the two modes, nor is there a significant increase in target area concentrations. This indicates little or no direct nucleation at any of the sample sites. There is, however, physical justification why this may indeed be the case.

Prior to January 11, when the target samples were collected, there were four periods of general seeding: December 16, January 4, January 7-8, and January 9-10. It is certain that snowfall from December 16th was not sampled, since the ground was clear of snow at Hungry Horse Dam on December 24th. Seeding effects from the operation on January 4th were expected to be confined to that portion of the target area south of the reservoir, since winds from the surface to 10,000 feet were from the northwest.

During the third seeded period, January 7-8, winds in the layer from surface to 10,000 feet were south to southwest, and the area of effect should have extended over the reservoir area. However,

there are two reasons why increases in silver content should not be expected as a result of this storm. The first is that the front did not produce heavy amounts of precipitation. At Hungry Horse Dam, .14 inch was recorded, a total of one inch of new snow. Secondly, between the 8th and the time of sample collection, January 11, temperatures reached 42° at Hungry Horse Dam, and approximately one-half inch of rain prior to frontal passage on January 10. Any high concentration of silver in this top snow could possibly have been washed down through the older snow, distributed throughout the 2-foot pack below, and diluted to near background concentrations.

Effects during the fourth period are more difficult to assess. Frontal passage through the area occured about 0600 on January 10, and produced locally heavy amounts of precipitation in the mountain areas. Hungry Horse Dam reported .93 inch of precipitation in the 24 hours ending at 9 a.m. January 10, Columbia Falls .30 inch, and Big Mountain (top), 7 inches new snow. From the hourly precipitation record at FCA, it is probable that most or all of this fell within several hours of frontal passage. Surface winds were southeast prior to frontal passage, and became light northwest-northeast directly following. Winds above the subgradient level were general southwest both pre- and post-frontally, as inferred from the Spokane sounding. The silver iodide plume was defintely reaching FCA for 12 hours prior to frontal passage, so a prefrontal northward drift, from each generator site, of at least 9 miles was certain. Directly after frontal passage, however, nuclei counts at FCA quickly dropped to background, suggesting large scale entrainment into the cloud structure of the frontal zone. It would seem that conditions were very good for producing nucleation over the reservoir area, yet silver concentration above background were in fact not observed. Any conclusions at this point, however, should be approached with caution. All of the prefrontal precipitation occurred as rain at Hungry Horse Dam, and the samples of new snow collected at Hungry Horse Dam, Wounded Buck Point, Anna Creek, and Elam Creek, undoubtedly consisted of postfrontal snowfall which fell after the surface windshift had occurred. It is thus quite possible that while these sites were affected by nucleated precipitation falling as rain prefrontally, and washing into the old snowpack, that post-frontal precipitation was not nucleated in this area, but further south in the Bob Marshall Wilderness area.

The conclusion drawn is thus a limited one, i.e., for the storm of January 10, there is no evidence that post-frontal precipitation which fell on the western side of Hungry Horse reservoir was the result of artificial nucleation. In addition, although washout of silver iodide particles, direct nucleation, or both, near the CNG sites is indicated, resultant silver concentration still is within the background range obtained the previous year.

Nuclei Climatology

An important factor in the proper design and efficient control of any cloud seeding project is knowledge of naturally occurring freezing nuclei concentrations. Accordingly, provision was made at the beginning of the project for an investigation of local nuclei climatology. Results of the first year indicated that, (1) background concentrations generally agreed with those at other locations in the western states, (2) extended low level drift of the silver iodide plume produces high concentrations of artificial nuclei at considerable distances from the generation source under certain conditions, and (3) that massive entrainment of the low level plume probably occurs at or near frontal passage for active systems. All three indications are further substantiated by data from the past season.

A total of 10 seeded periods were covered, some partially, with the ice nuclei counter. Increased counts to over 100 times normal background were observed during 5 of the 10 periods, and strongly suggest plume detection. On one other occasion, an increased count was observed, but was of such short duration, that its significance is uncertain. Of the five periods mentioned, well defined fronts passed the airport during two of them, and within a short period of time the nuclei counts returned to background range.

Diurnal variations in low level stability may result in significant variations in background concentrations. To check this possibility, average counts by time of day were determined. Only days in which the counter functioned continuously for 24 hours were used, and all periods where there was a possibility of contamination from concurrent or previous seeding were rejected. Dramatic variations are not apparent, and are not of sufficient magnitude of justify changes in generator operation procedures. However, peaks near 0800 and 1900, with lower than average counts between 1000 and 1700, are indicative of expected patterns. Nighttime cooling would tend to concentrate available nuclei through stabilization of the ground layer, with daytime destabilization through heating reducing concentrations.

A temperature dependence curve was obtained from a composite of data obtained on a number of unseeded days. Although scatter is quite large, it does appear that the nuclei-temperature relationship is verified as logarithmic. Average background is about .1 per liter. The number of effective nuclei increases approximately one order of magnitude for each 5^{o} C of cooling.

Temperature dependence curves were also obtained during several seeded periods when it was thought that the silver iodide plume was reaching the airport. The curve obtained February 2nd shows a nuclei concentration at -20^{o} C more than two order of magnitude higher than average background. The shape of the curve closely matches the production curve for NAWC's propane-type silver iodide generators, as determined by Grant and Steele (1966). A minor

difference, however, is the temperature at which the effective nuclei count begins to increase at a lower than logarithmic rate. The production curve begins to flatten at -13° C, while the observed FCA nuclei curve appears as logarithmic to -16° C. The significant aspect of these curves is the similarity of the temperature variation of nuclei per liter in the plume to that of the effective nuclei per gram produced by the generators.

Seeded data obtained on March 28th are not as meaningful. It is probable that within the time taken for the variable temperature run, about 2 hours, a minor windshift or other change in meteorological conditions, reduced absolute nuclei concentrations at the sampling point. This would explain the near independence of effective nuclei on temperature at colder temperatures, and is supported by the entirely different curve obtained with chamber temperature increasing during the latter half of the run.

An attempt to relate periods of high counts at FCA during seeded periods to prevailing stability conditions has not been completely successful. Few definitive conclusions are to be expected, because no direct measurements of upper air parameters are made within 200 miles of Kalispell. An exception is, of course, the tentative conclusion that post-frontal instability is responsible for concentration reduction, presumably through stronger upward transport of the plume.

EQUIPMENT DESIGN AND CONSTRUCTION

Telemetered Generator and Observing Network

The first phase of the planned 5-year program provides for complete systems engineering analysis and design of the network, plus construction and installation of three elements in the first year. Work continues toward fulfillment of the finalized System Functional Requirements, enumerated in the following sections.

System Functional Requirements

This part of the specification outlines the functional requirements at each general type of station, and some of the overall system functional capabilities.

A. Kalispell Control Center

The base station and control center located at Kalispell shall be capable of the following functions.

1. Insertion of a 1 to 4 decimal digit combination address and command instruction by means of manually operated switches.
2. Conversion of a binary coded equivalent of the 3 decimal digits to a three frequency audio signal of the return-to-zero FSK type.

3. Transmission of the three frequency FSK data group as a frequency or phase modulated signal over a VHF communication type radio transmitter.
4. Reception of a VHF radio signal of 16, 32, 48, or 64 binary digits in the form of a frequency shifted return-to-zero three frequency audio tone, carried on the VHF carrier frequency as a frequency or phase modulated signal.
5. Storage of the incoming information in a buffer storage register for purposes of printout or retransmission.
6. Parity error check of each group of 16 binary digits received on an incoming transmission.
7. Teletype printout of the day of the year, time of day, interrogated station number, and received data stored in the buffer storage register.

B. Swan Peak Repeater-CNG-Weather Station

The equipment located at Swan Peak shall be capable of the following general functions:

1. Reception of a VHF radio communication of the type described in A.3 above.
2. Storage of the received message in a buffer storage register capable of holding up to 16 bits of digitally coded data.
3. Retransmission of the stored data on a different frequency (repeater operation).
4. Execution of certain commands contained in the data if the first 4 binary digits are the identity code of the Swan Peak station.
5. Conversion of various sensed analog variables to a digitally coded form and storage of these digitally coded variables in a buffer storage register.
6. Generation of a error check digit for each group of 16 binary digits.
7. Transmission of the contents of the buffer storage register as a three frequency return-to-zero audio signal frequency or phase modulated on a VHF radio transmitter carrier.
8. Transmission of certain trouble diagnosis messages when called for by command signals as mentioned in B.4.
9. Audio transmission by use of a microphone and one or more manually operated push-to-talk buttons.
10. Standby or monitoring operation shall be done with a minimum current drain. All switching and command execution shall be done with keyed on power initiated by the receiption of an incoming message, or manual pushbutton operation.

C. Meadow Creek Weather Station

The equipment located at Meadow Creek shall be capable of the following general functions:

1. Reception of a VHF radio communication of the type described in A.3.

2. Storage of the received message in a buffer storage register capable of holding up to 16 bits of digitally coded data.
3. Execution of certain commands contained in the data if the first 4 binary digits are the identity code of the Meadow Creek Station.
4. Conversion of various sensed analog variables to a digitally coded forms and storage of these digitally coded variables in a buffer storage register.
5. Generation of an error check digit for each group of 16 binary digits.
6. Transmission of the contents of the buffer storage register as a three frequency or phase modulated on a VHF radio transmitter carrier.
7. Transmission of certain trouble diagnosis messages when called for by command signals of the type mentioned in C.3.
8. Audio transmission by use of a microphone and one or more manually operated push-to-talk buttons.
9. Standby or monitoring operation shall be done with a minimun current or power drain. All switching and command execution shall be done with keyed or power initiated by the reception of an incoming message or manual pushbutton operation.

D. System Operation

The system being built will have functional capabilities beyond that of just transmitting weather information. It must be capable of causing specified remotely controlled action at the hydromet station.

Since one of these actions involves turning on a Cloud Nucleating Generator with attendant possible effects on weather conditions, it is desirable that the possibility of inadvertent operation be made as remote as possible. For this reason, a dual frequency keying signal will be used to "key" on the selected remote station. Use of high "Q" filters at the receiving end will necessitate that these tones be held on for a period of up to one-half second to insure detection. This long integrating time will allow filtering of sporadic noise bursts or other undesired signals.

At the completion of the one-half second tone transmison, additional binary digits will be transmitted as a three frequency FSK type of signal. These data will be transmitted at a rate of approximately 250 bits per second and will be stored in a control register at the remote station.

The selection of the transmitted information will be made by means of three thumbwheel switches at the base station. The first of these 3 digits will select the desired remote hydromet station. The second digit will select which parameters are involved in the transmission. After selection of the desired parameter, the third

digit can be used for further control purposes. All of the various operations will not be connected in on the initial equipment, since many parameters are not available at the particular stations.

A standard interrogation signal will occur when the FSK data is all zeroes (or no FSK data is transmitted). This will result in the remote hydromet stations transmitting from one to four groups of meteorological data, each group consisting of 16 binary digits.

Receipt of the groups of 16 binary digits at the base station will result in loading buffer storage registers with the received information. From these buffer registers, it is gated out to a teletype printer. At a later date, it may be transferred out serially for retransmission, although more probably this retransmission will be done as received without the need for interim storage.

E. Diagnostic Procedures

Previous experience with equipment used for remote sensing and telemetering of data has shown that it is very desirable to be able to partially determine the nature of any trouble which may occur.

F. Audio Tone Transmissions

The tentative tones have been selected and manner in which they are to be used has been defined. The tone modules are designated for possible tone transmission of eight bit parallel alphanumeric information. For the present installation, the switches of two tone channels will be used in parallel for switching the FSK tone carrier. Since less than eight stations will be on the system for some time, only five tones will be used, so in effect, a two-out-of-five code will be used.

The tone switches are made up of FET switches operated by compatible microcircuit gates.

Annual Report

on

POTENTIAL FEASIBILITY OF UTILIZING THE ATMOSPHERIC WATER RESOURCE IN THE CONNECTICUT RIVER BASIN

by

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TABLE OF CONTENTS

Section	Title	Page
1.0	INTRODUCTION	1
2.0	APPROACH	3
2.1	Background	3
2.2	Technical Approach	5
3.0	STATUS OF RESULTS	10
3.1	Overview of Supply and Demand	10
3.2	Estimate of the Potential Atmospheric Water Resource	12
4.0	FUTURE PLANS	17
5.0	REFERENCES	18

COLORADO STATE UNIVERSITY

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July 1, 1967 to June 30, 1968

Atmospheric Water Resources Research

Bureau of Reclamation

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A. INTRODUCTION

The purpose of this report is:

1. To summarize the activities sponsored by the Bureau of Reclamation, Office of Atmospheric Water Resources, in the Hydrology Program of the Civil Engineering Department at Colorado State University, for the period July 1, 1967 to June 30, 1968, and

2. To focus attention on the major results that may help the Bureau in planning future programs.

This report only summarizes the activities of the program. More complete information is available in already published papers or reports, or will be available in future publications. These publications are listed at the end of the report.

Section B of the report states the two major objectives of the program and the two functions it serves.

In order to meet the objectives it was necessary and convenient to divide the overall project into several main categories. Section C describes briefly the major divisions of the project. The reasons for these divisions and their relation to the objectives of the program are discussed.

Each of the following four sections correspond to one major division of the research effort. Within each of these Sections (D through G) the problems are formulated, the difficulties are assessed, and the solution that was applied is briefly described. The results are very succinctly mentioned in a descriptive manner, technical formalism and mathematical symbolism being avoided. By juxtaposition of the formulation of the problem and of the answers given to date for each division of effort, the extent of the additional effort needed to meet the objectives becomes reasonably clear.

B. OVERALL PURPOSE OF PROGRAM

The Colorado State University Hydrology Program has two clearly defined objectives to serve two complementary functions. The two objectives are:

1. The development of a definite technique for evaluating the results of atmospheric water resources programs by mathematical and statistical analyses of streamflow records, and

2. The study of criteria, methods and procedures to be used in selecting drainage basins suitable for atmospheric water resources programs.

The program is to serve two functions:

1. To answer in theory the unsolved problems in order to meet the two objectives stated above, and

2. To provide the Bureau of Reclamation with an engineering capability to apply the theoretical results practically and specifically to the Bureau's programs in the Central Mountains Region.

C. WORK DIVISIONS AND RELATION TO OBJECTIVES

The first division in the project centered around the question of Statistical Evaluation of Weather Modification Attainments. Actually it is more accurate to say that this project was not so much concerned with the statistical evaluation of the attainment as with its statistical significance. In other words the effort was oriented toward the development of a test to accept or reject the null hypothesis at a given significance level. The null hypothesis is the hypothesis that the data samples, corresponding to the periods prior to seeding and during seeding, belong to one and the same population.

The difficulty in this evaluation can be traced to two main causes:

(a) The natural variability in the hydrologic cycle far exceeds the expected range of the increase induced by man, and

(b) The inaccuracy of the measurements may be of the same order of magnitude as the induced change.

It follows that a statistical technique must in some way eliminate the natural variability from the observed hydrologic data before a positive statistical inference can be made with regard to the effect of weather modification. In other words, the failure of a statistical test to detect a gain may be due either to an actual lack of effect

of the weather modification operation or to the insensitivity of the test itself.

Because observed data upon which the tests were performed are somewhat in error, there is also a possibility that the statistical inference deduced from the data is wrong, that is, shows a statistically significant change when it should not and vice-versa. Therefore, the probability that errors in the measurement of the hydrologic data may lead to the wrong statistical inference must be calculated. Naturally, the greater the error in measurement, the greater the chance for a wrong statistical inference.

For these reasons the work effort was further divided into two research areas. One was concerned with the design of a sharp statistical test. The second consisted of a study of the type and magnitude of errors potentially incurred in the measurement and assembly of hydrologic data [1,2].

Next the suitability of a basin to atmospheric water reclamation programs was considered. In the experimental or the large-scale operational stage of the program, an operational site must be selected. Simply put, the question to be answered is: What makes one basin more suitable for a weather modification operation than another?

This question must be immediately qualified. What makes a basin suitable for different purposes? From a water resources point of view a basin is suitable if it responds to the maximum extent to a precipitation increase. From an evaluation point of view a basin is suitable if an increase in runoff can be detected in a minimum length of time. (In addition meteorological suitability must also be defined. However, this criterion was beyond the objective of the program, since the research effort was confined to hydrologic suitability from the point of view of evaluation and optimal water yield.) But the criteria defining such suitability from the two points of view are not necessarily the same. Here also the research was divided into two research efforts:

(a) definition of a criterion of suitability for optimal water yield, and

(b) definition of a criterion of suitability for minimum time evaluation.

The simplest criteria were, respectively, a high specific yield [3] and a low coefficient of variation for runoff [4]. In practice these criteria have meaning only if they vary within broad limits, for otherwise the selection of basins for weather modification operations would be made solely on climatic and meteorologic considerations. Thus it was necessary to assess the range of variability of specific yield and coefficient of variation based on actual hydrologic data. This in turn led to the development of an exhaustive hydrologic data system for the Upper Colorado River Basin. The availability of this data system is desirable for many other reasons. It serves two functions: support for research, and development of a capability for systematic operational planning in that region. However, the first utilization of the data system has been the systematic computation of specific yield and coefficient of variation for the entire Upper Colorado River Basin [4].

Finally it is rather evident that the theoretical definition of a criterion is not very helpful unless it can be evaluated quantitatively. It is not sufficient to state that the criterion for suitability of a basin to weather modification is a high specific yield, that is, a high water yield per unit area of basin. One must also be able to determine this yield, even when the basin is not gaged. Thus work was done to derive, by a statistical method of prediction, equations for specific yield in terms of physiographic characteristics evaluated from maps for basins in the Upper Colorado River Basin [3,4].

In summary, the research effort was divided into several primary categories with titles as listed below:

1. Statistical Methods of Evaluation of Attainment
2. Suitability of Basins for Evaluation
3. Suitability of Basins for Optimal Water Yield
4. Hydrologic Data System

In the following sections the achievements of each work division are reviewed.

D. STATISTICAL METHODS OF EVALUATION OF ATTAINMENTS

One of the objectives of the program was to develop tests to decide whether or not seeding increased runoff in a given target area. One wants to ascertain with a small probability of error whether or not the sample of data collected under seeding operations and the sample of data collected under natural conditions belong to one and the same population. The null hypothesis is the hypothesis that the two samples belong to the same population.

Primarily because of the nature of the tested variable, e.g., yearly or seasonal runoff, these tests were developed for the purpose of evaluation of operational experiments rather than for the purpose of exploration to discover under which conditions seeding is or is not effective in increasing runoff amounts.

The tests that were investigated fall under two main categories:

1. Two-sample tests (4)
2. Target-control tests (4)

The two-sample (historical sample prior to seeding, sample during seeding) tests are distressingly inefficient for runoff. This fact had already been well demonstrated for precipitation by several authors [6,7]. However, these simple tests point to the fact that the "size" [8] of the experiment or minimum number of years or seasons to detect a given increase in runoff varies like the square of the coefficient of variation of the target basin runoff. In the Upper Colorado River Basin this coefficient varies from 10 to 100%. In the extreme case the size of the experiment would vary a hundred fold. Most likely poor choice of a target area may entail a penalty of a factor of 5-10.

The target-control tests are much more discriminating. Roughly speaking the use of a control makes the target look as though it has an effective coefficient of variation much smaller than the actual one. The larger the coefficient of correlation between the target and the control, the smaller the apparent coefficient of variation of the target. As a result the detectability of a change in the target behavior is increased.

The most valuable test is the target-control conditional Student's t-test. This test does not assume that the population regression parameters for the historical records are known, (there are only 93 stations presently operating in the Upper Colorado River Basin, out of 820, that have 30 or more years of record) and it tests the normality or abnormality of the target, given the behavior of the control, normal or otherwise.

The power (in the statistical sense, i.e., 1 - probability of error of type II) of the above test was not calculated. However, numerical experiments performed on actual data show that the test is effective in detecting an increase in runoff in a relatively few years. Table 1 summarizes the results of various calculations.

In particular Table 1 shows that the runoff data must be corrected for engineered modifications of the natural flow. This is well demonstrated by the results of lines 1 and 7. The test fails to detect a significant increase in runoff after 15 years of operation, when uncorrected seasonal runoff is used (line 1 of Table 1). The same test on the other hand shows a highly significant increase after only five years of operation, when corrected seasonal runoff is used as the test variable (line 7 of Table 1). It also shows the importance of selecting the proper variable to be tested. Seasonal (March-August) runoff is much more representative of the effect of seeding than yearly runoff. With seasonal runoff the size of the experiment is reduced from more than 15, to 5 years, as is shown by comparison of lines 4 and 6 of Table 1.

The table also gives the most likely increase in percent. It is obtained by taking the difference between the mean historical target value calculated from the historical regression line, and the mean seeded period target value calculated from the new regression line, i.e., defined over the years of seeding only. Both quantities are evaluated at the control mean value over both the historical and the seeded periods.

TABLE 1

RESULTS OF TARGET-CONTROL STUDENT's t-TEST

TARGET: South Fork San Joaquin - near Florence Lake
(GS 11-2300)

CONTROL: Merced River at Pohono Bridge
(GS 11-2665)

Line number	Used years of seeding	Runoff Variable Yearly	Runoff Variable Seasonal	Corrected for storage and diversion	t	Significance	Most likely increase in %
1	15		$\sqrt{R}$	No	1.53	No	
2	15	$\sqrt{R}$		No	1.98	No	
3	8	R		Yes	1.45	No	
4	15	R		Yes	1.87	No	
5	4		R	Yes	1.76	No	
6	5		R	Yes	2.34	95%	9.7
7	5		$\sqrt{R}$	Yes	2.60	98%	
8	8		R	Yes	3.02	99%	10.7
9	10		R	Yes	2.61	99%	8.2
10	15		R	Yes	3.53	99%	10.1
11	15		$\sqrt{R}$	Yes	3.71	99%	
12	16		R	Yes	3.74	99%	10.5
13	16		$\sqrt{R}$	Yes	3.96	99%	

Legend: $\sqrt{R}$ means that test is based on the square root of runoff data.

TABLE 1 (continued)

Calculations are based on the data as published by the U. S. Geological Survey in their water supply papers 1315A, 1735 and yearly water supply papers for the years 1961-1966. Part of the flow is diverted from the river above the gaging point through the Ward tunnel (GS 11-2295). The flow is regulated above the gaging point by the presence of the Florence Lake dam (GS 11-2296).

Station number	Old G. S. number	New G. S. number
South Fork San Joaquin	11-064	11-2300
Florence Lake	11-062	11-2296
Ward Tunnel	11-063	11-2295
Merced River	11-124	11-2665

The question is sometimes raised that the tests may not be valid because the joint bivariate distribution of the target and control populations is not normal. For runoff the distribution that best fits the observed frequencies is usually the normal one [9]. Sometimes the normal distribution more closely approximates the frequencies when the data have been first subjected to a square root transformation or a logarithmic one. Table 2 shows that in practice the outcome is hardly affected. In statistical terms one can say that the test is "robust."

E. SUITABILITY OF BASINS FOR EVALUATION

For statistical evaluation of a highly localized cloud seeding experiment probably the most important consideration in the selection of a basin is the number of years, on the average, that will be required to detect a significant change, say in runoff, at a given confidence level. The criterion depends, among other things, on the choice of the variable selected to test the hypothesis, on the type of statistical test, and on the design of the experiment. One can define some marginal criteria to determine the relative suitability of many potential basins if the type of statistical test and the design of the experiment are not known a priori or, in other words, the criterion of suitability for the selected hydrologic variable, e.g., yearly runoff, everything else

TABLE 2

INFLUENCE OF DATA TRANSFORMATION ON THE
RESULTS OF THE TARGET-CONTROL CONDITIONAL STUDENT'S t-TEST

TARGET: South Fork San Joaquin

CONTROL: Merced River at Pohono Bridge

Years of seeding: 15

Years of record prior to seeding: 29

Data: Various transformations of seasonal runoff

Target-control conditional t-test results

Type of Transformation	t-statistic	Significance
Square	3.22	99%
None	3.80	99%
Square root	4.06	99%
Fourth root	4.16	99%
Logarithmic	4.23	99%

TARGET: Mono Creek

CONTROL: Merced River at Pohono Bridge

Type of Transformation	t-statistic	Significance
Square	1.78	<95%
None	2.08	95%
Square root	2.20	95%
Fourth root	2.25	95%
Logarithmic	2.29	95%

Values of t for significance at 95% = 2.02
98% = 2.42
99% = 2.71

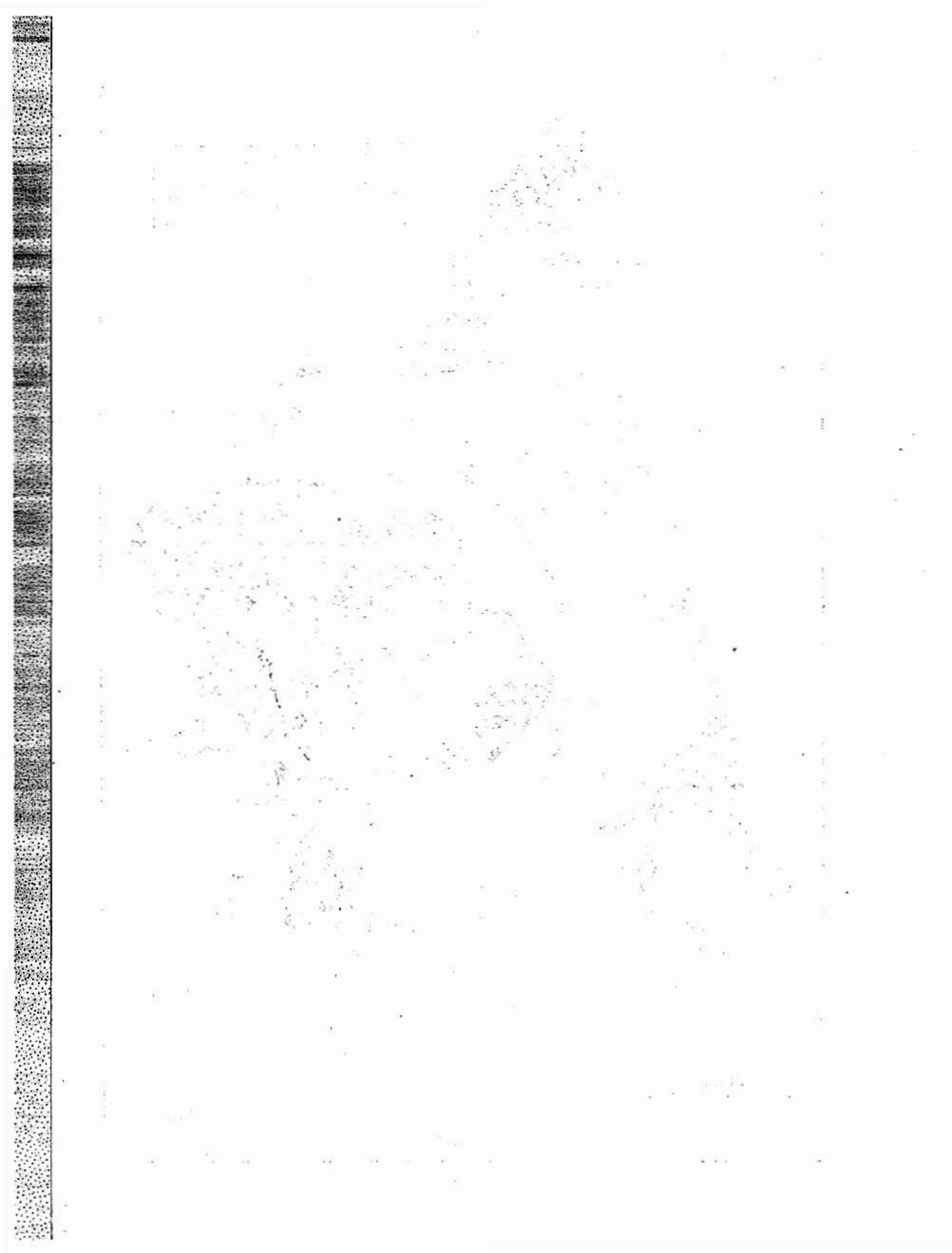
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being the same. In this particular instance the most suitable basins are the ones that have the lowest coefficient of variation.

This criterion is simple enough that it can be calculated for all gaged basins in the Upper Colorado River Basin, thereby providing the means of eliminating a great number of basins from further consideration, since the number of years increases as the square of this coefficient. Figure 1 is a map of the Upper Colorado River Basin showing the areas for which the coefficient of variation of yearly runoff does not exceed the value 30% (shaded zones).


UPPER COLORADO RIVER BASIN
Hydrology Program — COLORADO STATE UNIVERSITY
Research Sponsor — US BUREAU OF RECLAMATION
OFFICE OF
ATMOSPHERIC WATER RESOURCES RESEARCH
JUNE, 1968
LEGEND
REGIONS WITH ANNUAL COEFFICIENT OF VARIATION LESS THAN 30 %
GAGING STATION
25 0 25 50
SCALE

Fig. 1



1.0 INTRODUCTION

This annual report to the Bureau of Reclamation covers the work conducted by The Travelers Research Center, Inc. (TRC), on Bureau of Reclamation Contract No. 14-06-D-6569. This report reviews the purpose of the study, perspective, planned approach, and status of results accomplished.

The purpose of the study is to assess the potential feasibility (technical, benefit, cost) of utilizing the atmospheric water resource (AWR) in the Connecticut River Basin. This report covers only the first three months (April 1, 1968 through June 30, 1968) of the work planned for execution over a 15 month period (April 1, 1968 through June 30, 1969) and therefore the results are fragmentary. The results include:

(a) an initial qualitative identification that significant cost-benefit advantages may result from precipitation augmentation over the drainage basin of the Quabbin Reservoir, a major municipal water resource of Metropolitan Boston (see Fig. 2-1);

(b) an initial qualitative identification that precipitation augmentation may yield favorable benefit-cost considerations over the Connecticut River Basin for hydroelectric power generation, waste disposal dillution, and recreation;

(c) the formulation and programming of a simple model to estimate potential precipitation from artificial nucleation for "large" areas and times and associated identification of feasibility of surface or aircraft seedings; and

(d) an analysis of annual precipitation and the monthly height of the base of colloidally unstable clouds over the Connecticut River Basin.

It is visualized that the development of the atmospheric water resource (AWR) of a particular region is a broad-scale, multi-year program that involves field studies, laboratory studies, systems development, and economic and socio-political studies. The feasibility of utilizing the atmospheric water resource has several dimensions, including the technical or system feasibility as well as benefit, cost, political, and legal considerations. The system feasibility includes considerations of cost effectiveness, which includes the capability and reliability of the AWR system. In this context,

reliability is the probability of the AWR system performing its intended function over a specified time period and for specified environmental conditions.

This initial study is concerned only with an overview of the water resource problems in the Connecticut River Basin in relation to the impact and the potential feasibility (technical, benefit, cost) of an AWR system in this area. A study with similar objectives was reported by Hurley [4] for the Colorado River Basin. The specific goals of this preliminary study are to:

(a) assess major features of stress in supply and demand in the present and planned water resource system, users, and uses that are relevant to the atmospheric water resource;

(b) identify requirements for and estimate the potential benefits from the AWR system for preliminary assessment purposes;

(c) estimate the climatology of precipitation potential and seedable situations;

(d) assess the potential feasibility of developing the atmospheric water resource in the Connecticut River Basin.

The results of this preliminary study may be construed as an initial statement of requirements for the development of the AWR system for the Connecticut River Basin. This requirements analysis is not intended to be exhaustive. Rather, the analysis will explore those situations of potential imbalance between the present and planned water resources and water user activities that may yield benefit-cost considerations favorable to development and operation of the atmospheric water resource of the Connecticut River Basin. Depending upon the results of this study, it is visualized that the development of the atmospheric water resource in the Connecticut River Basin would follow the overall system development plan of the Bureau of Reclamation [3].

2.0 APPROACH

2.1 Background

The Connecticut River Basin is shown in Fig. 2-1. The total drainage area is approximately 11,265 square miles and includes portions of four New England states—New Hampshire, Vermont, Massachusetts, and Connecticut—as well as a small portion of Canada. The largest cities in the basin are Hartford (Connecticut) and Springfield (Massachusetts). The largest municipal water facility is the Quabbin Reservoir, which is a major part of the municipal water supply for Metropolitan Boston.

The total fall in the Connecticut River is approximately 2,200 feet over a distance of approximately 400 miles. The greatest fall, 1,200 feet, takes place in the first 40 miles, while the fall in the 70-mile reach of the river in the State of Connecticut is only approximately 40 feet. The lower 60-mile reach of the river is tidal, with the mean range during low river stages of approximately three feet at its mouth and one foot in Hartford. The river is navigable by ocean going vessels as far upstream as Hartford. Water user activities of some importance include water supplies, waste disposal, hydropower, industrial cooling and process waters, supplemental irrigation, recreation, navigation, and flood control.

The average annual precipitation over the entire basin is approximately 43 inches, with a maximum over 60 inches in the higher elevations of the White Mountains of New Hampshire and a secondary maximum in the southern Green Mountains of Vermont. The average annual snowfall in the basin varies from less than 40 inches at the lower elevations of southern portions of the basin to 14 feet or more at the higher elevations of the northern portions.

The assessment of potential feasibility of the atmospheric water resource in the Connecticut River Basin is a multi-dimensional problem that includes:

(a) water resources or supply,

(b) user activities or demand,

(c) water management policies and agreements,

(d) areas or sub-basins, and

(e) time.

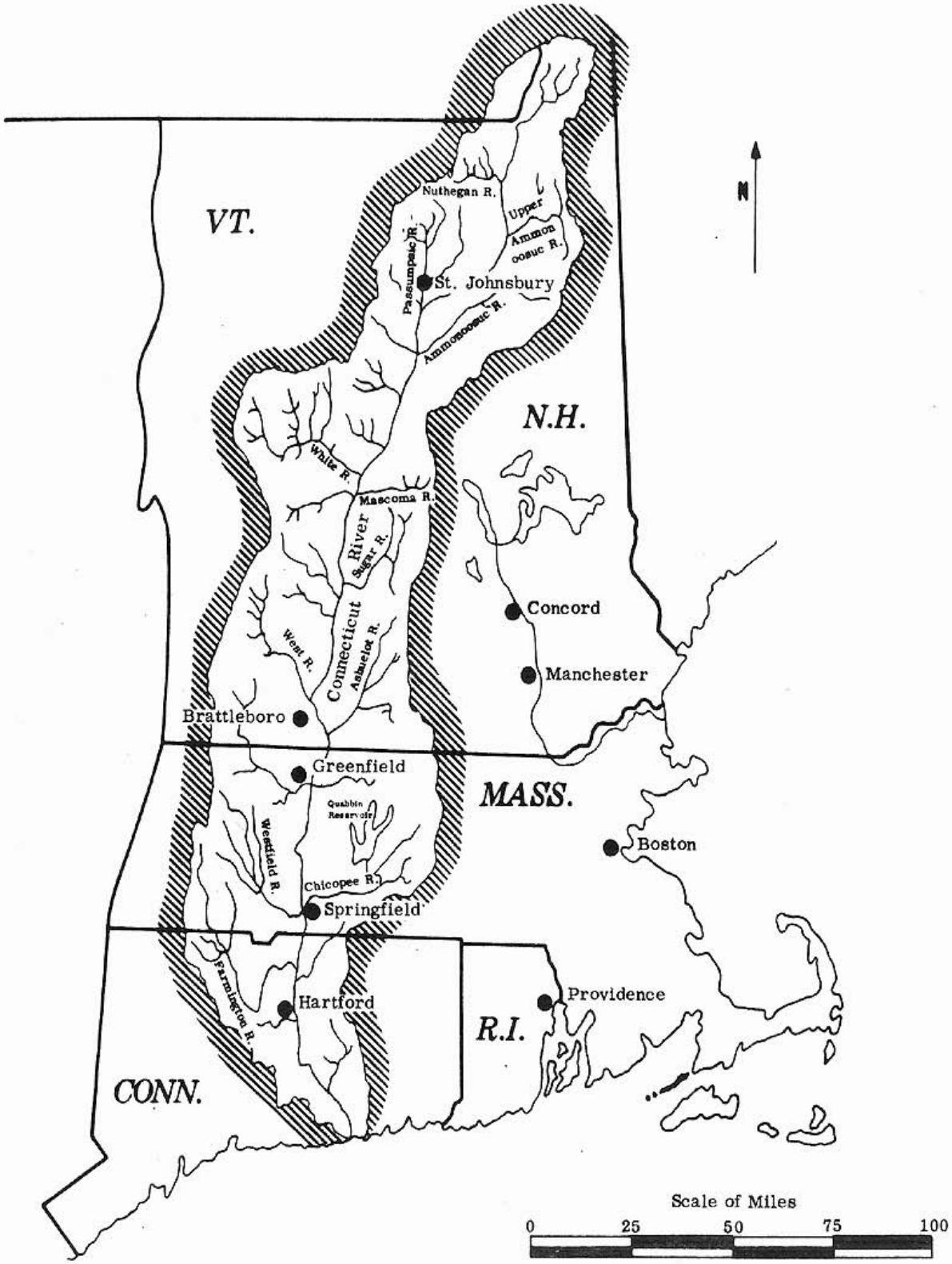


Fig. 2-1. The Connecticut River Basin

The elements of the hydrological cycle that form the major water resources in the Connecticut River Basin are listed in Table 2-1. Three major subdivisions are indicated in the table: the atmosphere, the earth's surface, and ground water. Of the various water user activities indicated in Table 2-2, those with an asterisk are presently estimated to be of major importance and will need to be addressed in this study. The overall problem is to assess the imbalances in supply and demand as a function of time and space within the Connecticut River Basin and to assess the potential benefits to be derived from enhancement and management of the atmospheric water resources. In this regard, one must estimate the potential atmospheric water resource of the Connecticut River Basin. Of importance are the volume rate and the cost of developing and operating the atmospheric water resource to benefit the present and projected water user activities of the Connecticut River Basin. A more detailed discussion of this overall approach is presented in the next section.

2.2 Technical Approach

The detailed approach to assess the potential feasibility of the atmospheric water resource in the Connecticut River Basin is described with reference to Fig. 2-2. A major activity (Activity 1) in this study is to analyze the present and future water resources and water user activities of the Connecticut River Basin. Initially, we will undertake a broad look at this problem and later analyze alternatives to augment the water resources where an imbalance is identified in the time evolution of supply and demand. An independent in-depth study of the water resources and user activities is well beyond the scope of this investigation. However, studies are underway by a variety of agencies that provide considerable background data. Maximum use is being made of the studies being undertaken by the Corps of Engineers, the Federal Water Pollution Control Agency, and the U.S. Geological Survey, and of the studies sponsored or undertaken by various state agencies, including contractors such as The Travelers Research Center, Inc. [1, 2].

Situations will be studied for which the atmospheric water resource is potentially useful. Potential target areas and times will be identified for augmenting atmospheric water (Activity 2). For selected situations, alternative schemes of augmenting the water resources of the Connecticut River Basin will be investigated. Cost and benefit estimates will be made for potential contenders according to the outline in Activity 3.

TABLE 2-1
WATER RESOURCES

Atmosphere
Earth's surface Natural flows Overland flow Stream or channel flow Storages Lakes Estuaries Reservoirs Managed snow pack Diversions Desalinization Reuse
Ground water

TABLE 2-2
WATER USER ACTIVITIES

Water supply* Municipal Industrial Private Flood control* Hydropower* Navigation	Irrigation Waste disposal* Water quality Pollution dilution Recreation* Fishing Boating Swimming Skiing

* Presently estimated to be of major importance.

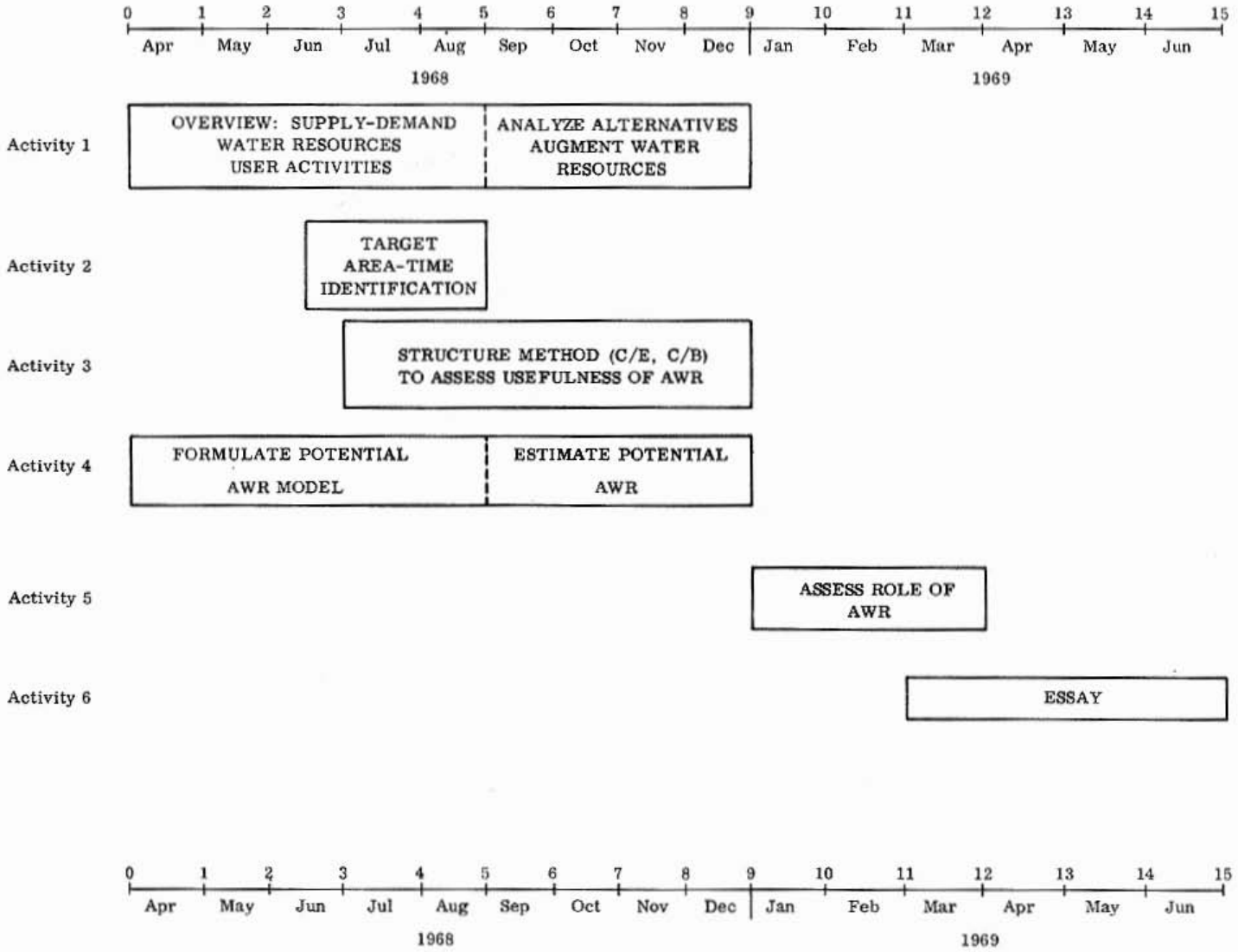


Fig. 2-2. Time-phased approach. Potential feasibility of atmospheric water resource in Connecticut River Basin.

The potential atmospheric water resource of the Connecticut River Basin is estimated in Activity 4. The approach includes the formulation of a model and the execution of this model to estimate the potential atmospheric water resource. The water resource supply and demand analysis will identify target areas and times of the year for which it is estimated that the atmospheric water resource may be of value in the water resources picture in the Connecticut River Basin. For the target areas and times identified, the potential water resource model will be used to estimate the volume rate of the AWR supply. Consideration will be given to the statistical time variation of the atmospheric water resource. A block diagram of a simple precipitation potential model is given in Fig. 2-3. The model is based essentially upon the gross statistical evidence presented by the National Academy of Sciences [6] (i.e., precipitation increases of target vs. control areas of approximately 10—20% may result from the release of colloidal instability in convectively unstable clouds artificially nucleated with silver iodide). While it is recognized that this represents a hypothesis that has not yet been tested or verified in the Connecticut River Basin, nevertheless, it does give a basis for gross estimation for "large" time and area increments to ascertain whether this increased amount of precipitation has value to the water users of the Connecticut River Basin if a delivery system were developed and operated.

For certain target areas and times, then, the usefulness of the atmospheric water resource will be evaluated in terms of a cost-benefit or cost-effectiveness model (Activity 3). This will lead to a preliminary assessment of the role of the atmospheric water resource in the Connecticut River Basin (Activity 5). It is recognized that many assumptions will have to be made in this assessment of the potential feasibility of the atmospheric water resource of the Connecticut River Basin. If the results of this study appear favorable, the next phase of research will undertake studies in greater depth with fewer assumptions, develop the atmospheric water resource, and demonstrate the several aspects of system feasibility not the least of which will be the reliability of utilizing the atmospheric water resource in the Connecticut River Basin.

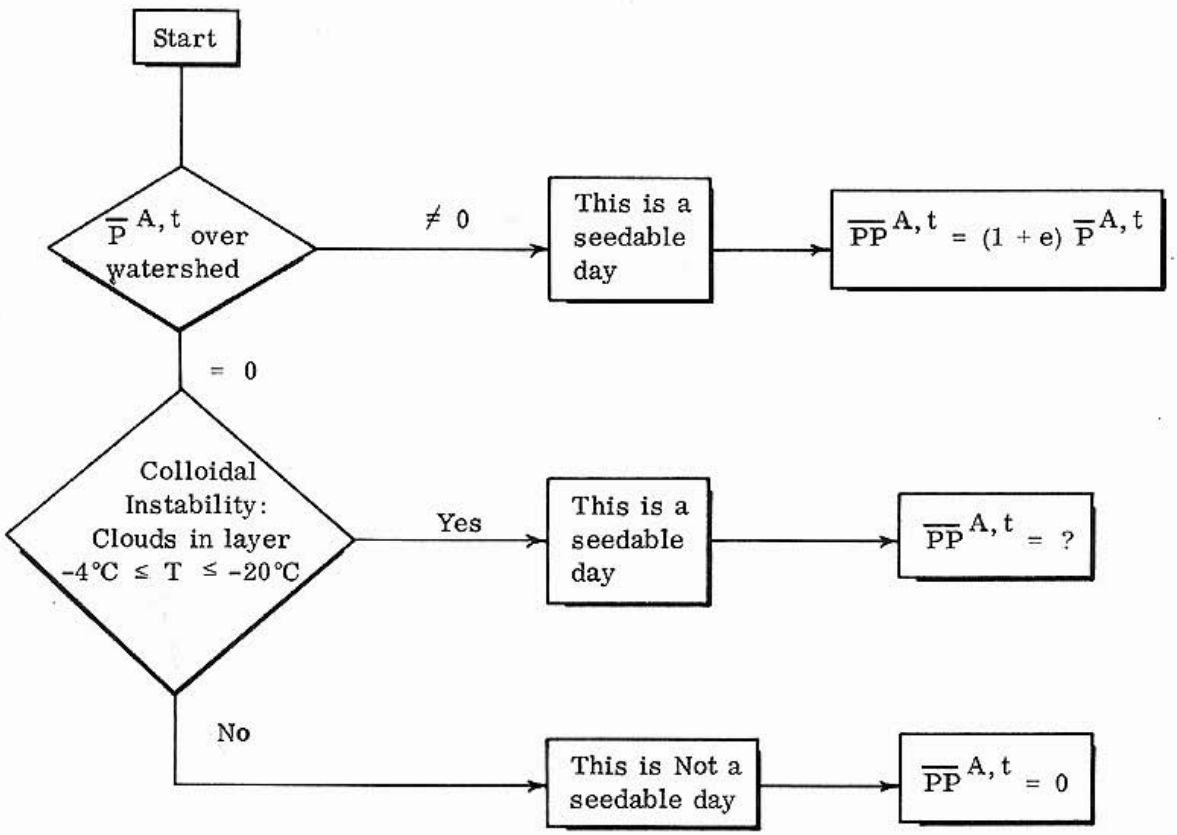


Fig. 2-3. Block diagram of possible precipitation potential model.

3.0 STATUS OF RESULTS

This report covers only the first 3 months of a planned 15-month study, and the results at this time are fragmentary and must in most cases be considered tentative.

3.1 Overview of Supply and Demand

Benefits from augmented precipitation are viewed in terms of additional storage and planned use. One may consider both existing and planned structures in relation to the additional precipitation or more efficient use of the precipitation. Present water resource structures have been designed with knowledge of the precipitation climatology. Augmented use of the atmospheric water resource will modify the precipitation climatology, which can effect the future planning of water resource structures. An overview of the relevant types of water resources and water user activities are given in Tables 2-1 and 2-2. Information in this section is organized primarily with respect to user activities.

Contact has been made with the Corps of Engineers, who are investigating the demands for surface water resources due to municipal and industrial water users of the Connecticut River Basin. Projections are being made from 1960 to the year 2020. The Corps is studying the Connecticut River Basin in terms of 6 sub-regions.

The Quabbin Reservoir, the main source of water supply for Metropolitan Boston, has a total capacity of 412 billion gallons at the full reservoir elevation of 530 ft. During the past eight years, however, it has been filled only to 50% of capacity at elevation 498 ft $\pm$. With normal rainfall and no increase in the demand of water users, it will take another 15 years for Quabbin to fill to capacity at elevation of 530 ft. With the expected increase in demand from the communities served and normal rainfall, the reservoir level will increase until 1973 to an elevation of 509 $\pm$ and then the water level will fall.

In comparison to a safe yield of 330 MGD (million gallons per day) for Quabbin Reservoir, the existing demand is about 300 MGD. This demand is estimated to increase to about 400 MGD by the year 1985, 430 MGD by the year 2000, and 500 MGD by the year 2030. Clearly, precipitation augmentation could be effectively utilized along with other sources to meet the increased future demand.

The municipal water supplies for Hartford (Connecticut) and Springfield (Massachusetts) are also within the Connecticut River Basin. The storage capacity of present and projected dams is adequate for several years of normal runoff, although spills do occur from the spring streamflow caused by the short melting period of the normal winter snowpack. Management of the atmospheric water resource to augment the water in these reservoirs appears to be most beneficial for a summer season operation.

There are 94 existing hydroelectric power stations within the Connecticut River Basin. In addition, 27 potential sites for hydropower are under investigation. Quite a few of the existing plants have potential for increased capacity. Additional information will be sought on hydropower management to assist in structuring the benefits (e.g., additional firm power) that may result from augmented use of the atmospheric water resource. Projections on demand for power within the Connecticut River Basin show an increase of 26 times by the year 2020. Although only a small fraction of this increased power is likely to be hydro-generated power, the demands for cooling waters for the additional fossil-fueled and nuclear-powered plants will pose major problems for management of the complex, competitive uses of Connecticut River water.

The Connecticut River and its tributaries are used for waste disposal by both industries and municipalities. The Federal Water Pollution Control Agency has modeled the pollution problem and is in the process of estimating the streamflows required to assimilate waste effluents sufficiently to maintain satisfactory water quality. One may, with this model and several assumptions, estimate the degree of treatment required for future industrial development. The major assumptions include estimates of population and industrial growth, the associated projected effluent, the water quality standards, and streamflow. The streams of the Connecticut River Basin reach their minimum flow during the summer. The ability of the managed atmospheric water resource to augment this low streamflow is potentially significant to the ultimate solution of the waste disposal problem of the Connecticut River Basin.

The Connecticut River Basin is utilized for summer as well as winter recreation. Swimming, fishing, and boating are of importance in the summer when the streams are at their low flow and water quality is least satisfactory. The management of the atmospheric water resource to augment low streamflow during the summer would

benefit recreation. Winter sports, primarily skiing, are of importance in the Connecticut River Basin. Augmentation of snowpack in local areas would benefit this industry. It is anticipated that the estimate of values for recreation may not be accomplished with great decision.

3.2 Estimate of the Potential Atmospheric Water Resource

An investigation has been initiated of the climatology of precipitation of the Connecticut River Basin. The average annual precipitation over the basin is shown in Fig. 3-1. This average is for a 16 year period (1950—1966). Spatial variations in excess of 100% are to be noted in the annual average between the maximum at Mount Washington (77") just outside the Connecticut River Basin and the minimum ($\sim$ 30") along the main stem of the Connecticut River to the west of Mount Washington. Secondary precipitation maxima in excess of 50" are to be noted in the southern Green Mountains of Vermont and over west-central Connecticut. Note that significant precipitation variability occurs in time. At many stations, the minimum annual precipitation is less than one half the maximum annual precipitation during the 16-year period. This is, of course, consistent with the fact that droughts of several consecutive years have occurred in the Connecticut River Basin during the last decade or two. Consideration of the time variability in water resources is relevant to an estimate of probability that the precipitation or streamflow will exceed prescribed values, and the reliability of the AWR system. The influence of a managed atmospheric water resource on these probability relationships must be considered if the atmospheric water resource can be managed in conjunction with surface and ground water resources.

A precipitation potential model (PPM-I) has been formulated and coded for computer solution along the lines of Fig. 3-2, which is in some respects a simplified version of Fig. 2-3. This model does not include precipitation augmentation due to seeding of a colloidally unstable cloud system from which no precipitation occurred naturally. Consideration is being given to a different model that would estimate the potential precipitation augmentation from this situation along the lines of the Weinstein-Davis Model [7].

The precipitation potential model (PPM-I) tests the height of the base of the colloidally unstable layer (-4°C to -20°C) that is most applicable to seeding with silver iodide. The Albany raob is utilized for this purpose. This information will be used in

The coefficient of variation ranks the various basins as to their quality of being naturally well or poorly regulated. If nothing else is known this criterion should be considered in the selection of a target. On the other hand if the design of the experiment calls for a target and a control, a likely case, since the need for predictor variables is well recognized, the criterion must reflect the favorable hydrologic characteristics of the pair rather than the target alone. The favorable pairs of basins are the ones for which the quantity $(1-\rho^2)\ C^2_{v,T}$ is lowest, where ρ is the historical sample coefficient of correlation, and $C_{v,T}$ is the target coefficient of correlation. At the 95% confidence level this gives:

$$N = 4(1-\rho^2)\ \frac{C^2_{v,T}}{k^2} \qquad (1)$$

For ranking of pairs of basins the coefficient 4 is irrelevant and similarly the denominator. However, the formula is useful to obtain an estimate of N. Sample calculations have indicated that under actual seeding conditions equation (1) provides a good estimate of the number of years needed for significance. Figure 2 illustrates the variations of N with the coefficient of correlation and the coefficient of variation for an assumed 10% increase due to seeding. Calculations were performed for a few stations in the Upper Colorado River Basin to have an idea of what could be expected if seeding operations were conducted in the area. In particular the expected number of years to detect a 10% increase at the 95% level of significance was calculated. The results are shown in Table 3.

F. SUITABILITY OF BASINS FOR OPTIMAL WATER YIELD

Whether in the experimental or the large-scale operational stage of the program, a site for operation must be selected. Again, simply put, the question to be answered at the time of decision is: What makes one basin more suitable for a weather modification operation than another?

The present criterion [3,4] for suitability of a basin to weather modification is a high specific yield, that is, a high water yield per unit area of basin.

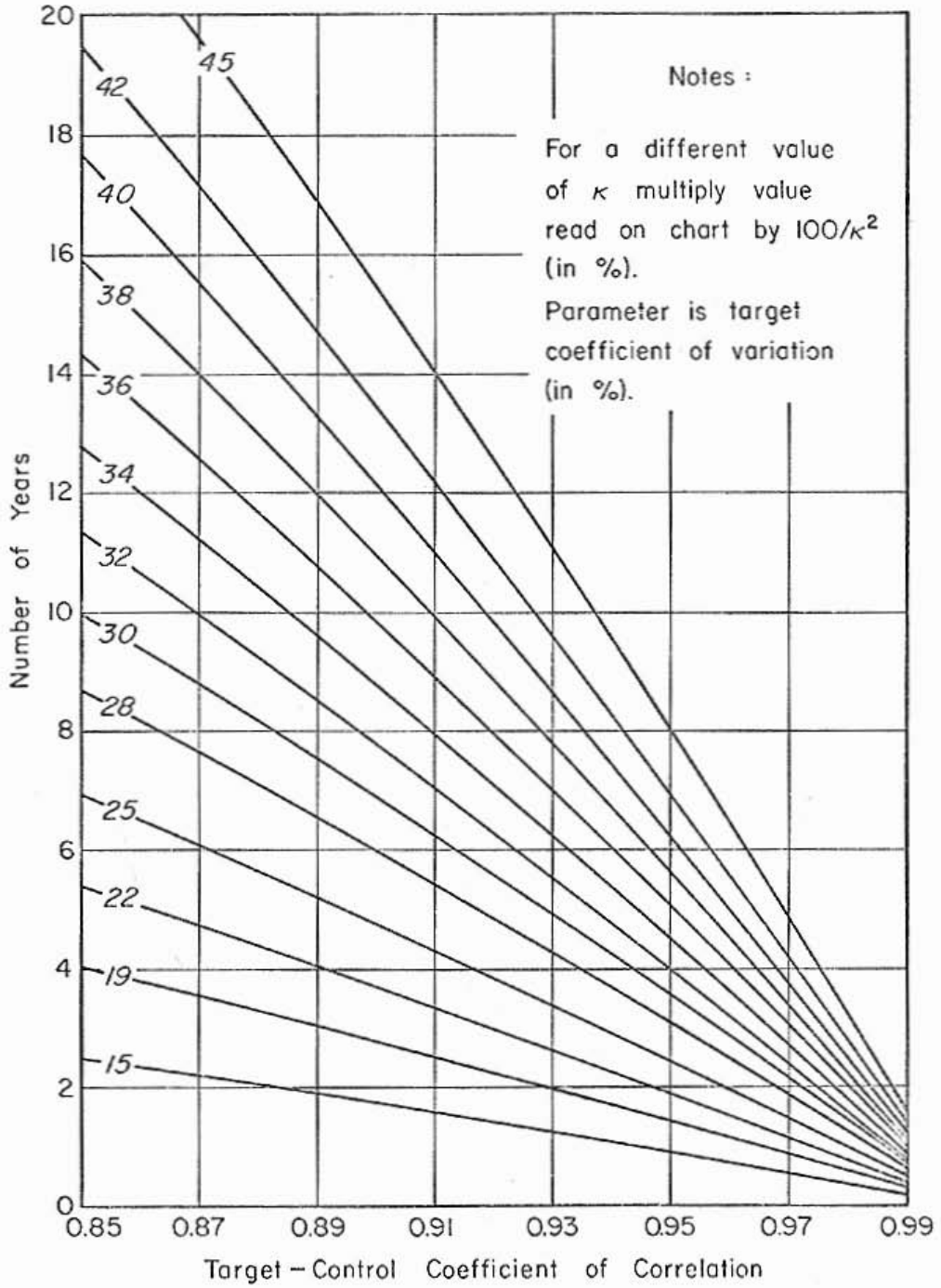


Fig. 2 Number of years (or seasons) to detect a 10 % increase.

TABLE 3

EXPECTED NUMBER OF YEARS TO DETECT A 10% INCREASE AT THE 95% LEVEL OF SIGNIFICANCE FOR A FEW PAIRS OF TARGET-CONTROL STATIONS IN THE UPPER COLORADO RIVER BASIN

TARGET				CONTROL		TARGET-CONTROL PAIR		
USGS Station Name	Drainage (sq mi)	Elevation (ft)	Coef-ficient of Varia-tion (%)	Station Name	Drainage	Years of Common Record	Coef-ficient of Corre-lation (%)	Years needed for Signifi-cance at 95% Confidence Level
Junction Creek near Durango, Colorado	26	7045	36	Hermosa Creek near Hermosa, Colorado	172	5	85	14
Animas River at Howards-ville, Colorado	56	9617	27	Hermosa Creek near Hermosa, Colorado	172	25	90	6
Dolores River below Rico, Colorado	105	8422	45	Hermosa Creek near Hermosa, Colorado	172	13	98	4
Roaring Fork at Glenwood Springs, Colorado	1460	5720	33	Colorado River at Glenwood Springs, Colorado	4560	58	89	9
North Fork Frying-pan near Norrie, Colorado	41	8400	30	Fryingpan River at Norrie, Colorado	90	23	91	7

Again the discussion would be academic if specific yield was essentially uniform throughout the basin. However, this is far from being the case. Specific yield varies from practically zero to a maximum around 40 inches.

Specific yield (in inches) has been calculated for all gages in the Upper Colorado River Basin. Figure 3 is a map of the Basin showing the areas for which the annual specific yield exceeds 10 inches (shaded zones).

By overlay of the contour lines of specific yield and coefficient of variation of a given hydrologic test variable one can delineate regions that are optimally suited for evaluation and yield augmentation. Figure 4 shows such regions (shaded zones), optimality being defined in this instance as the combination of an annual specific yield in excess of 10 inches and a coefficient of variation less than 30%.

G. HYDROLOGIC DATA SYSTEM

To achieve the objectives of the program, the development of an efficient hydrologic data system is imperative. It is essential to the engineering applications following the findings of research and it is essential to research itself since the availability of large quantities of actual observations is a prerequisite to the reliable application of the methods of statistics.

The hydrologic data are of two kinds:

1. Streamflow, and
2. Precipitation.

The development of a hydrologic data system does not consist merely of collecting data from books and transferring them onto magnetic tapes. It also involves the transfer of additional information relevant for the purpose of analysis such as a measure of some sort of the quality of the data. It involves a proper organization of the data on the tapes to permit an efficient retrieval and utilization of the data, as a whole or in part.

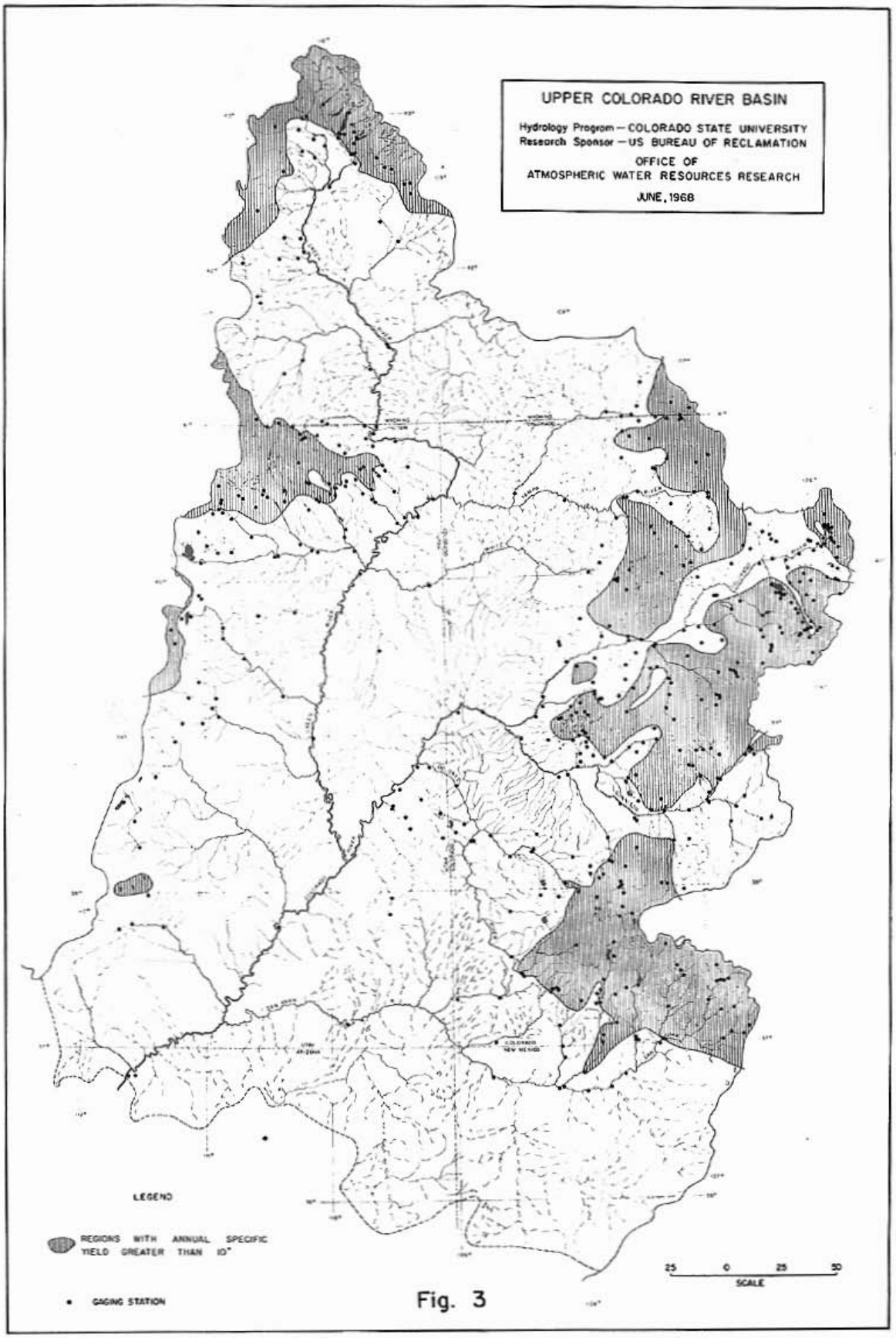

UPPER COLORADO RIVER BASIN
Hydrology Program — COLORADO STATE UNIVERSITY
Research Sponsor — US BUREAU OF RECLAMATION
OFFICE OF
ATMOSPHERIC WATER RESOURCES RESEARCH
JUNE, 1968
LEGEND
REGIONS WITH ANNUAL SPECIFIC YIELD GREATER THAN 10"
GAGING STATION
25 0 25 50
SCALE

Fig. 3



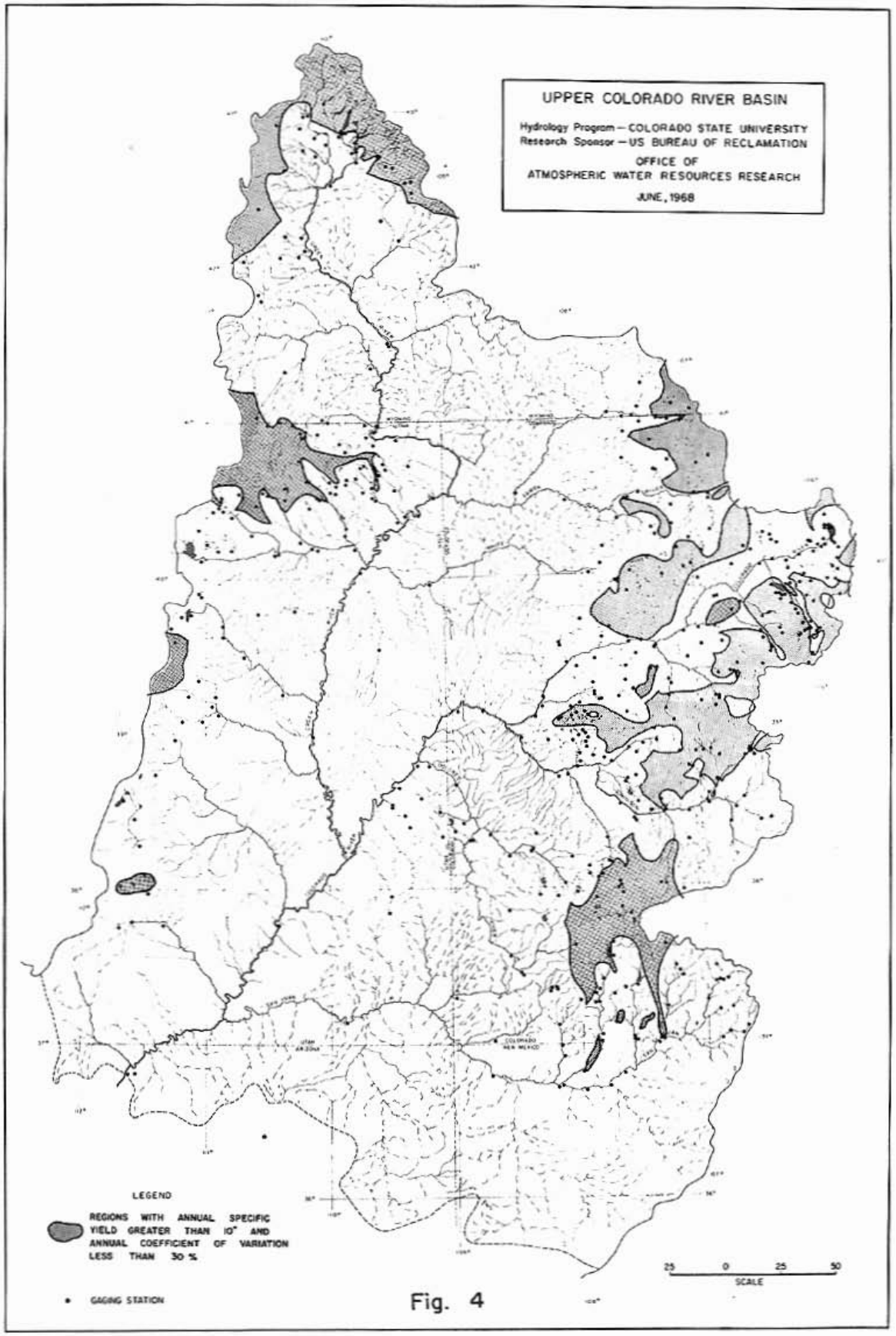

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GAGING STATION
25 0 25 50
SCALE

Fig. 4

Principles of Development of the System

The long-range goal for the system is to provide in a convenient form on magnetic tapes:

1. monthly discharges
2. daily discharges

for every streamgage in the Upper Colorado River Basin, and

3. monthly precipitation
4. daily precipitations
5. hourly precipitations,

for every precipitation gage in the same region.

Such an exhaustive system may not be desirable in the end, but if it is actually wanted it is good strategy to lay down a general program of development that is comprehensive and minimizes the work requirements.

The corner stones of the development of the complete system are the development of:

1. A monthly discharge tape for all stations, but without additional information pertaining to accuracy of data or extent of man's activities through diversion, reservoir storage, etc. (i.e. without the so-called "quality indices"),

2. A monthly precipitation tape for all stations,

3. A daily discharge tape for all stations and with the quality indices,

4. A new monthly discharge tape obtained from the daily flows tape and therefore with quality indices for all stations, and

5. An hourly precipitation tape for all stations.

Present Stage of Development

A monthly discharge tape for all stations in the Upper Colorado River Basin is now available. A check of the proper organization of the tape and of the correctness of the information was carried by selective printing of monthly flows for several stations located throughout the tape. Figures 1, 3 and 4 were drawn on the basis of statistics computed from the monthly flow tape.

The data collection for the monthly precipitation tape is almost complete [4]. The other items are in an embryonic stage [4].

H. CONCLUSIONS AND RECOMMENDATIONS

Statistical tests were developed to detect significance in attainment of increased runoff. One test, the target control conditional Student's t-test, seems particularly valuable. It appears rather insensitive to even large deviations from normality. It is a "robust" test. Though its power was not theoretically calculated, it was verified using actual data.

Additional effort should be directed toward the development of better tests. The target control conditional Student's t-test is good enough for the contemplated duration of pilot programs in the Upper Colorado River Basin (about 5 years) when coupled with a judicious choice of basin pairs. Nevertheless it was not proved optimal and this question should be investigated.

It seems that more attention should be given to proper choice of the variable to be tested in order to maintain proper balance with further refinements in the tests. Also attention should refocus from the early insistence in proving significance to the problem of estimation of the increase and its confidence limits.

Suitability criteria for both large water gain and rapid evaluation have been developed. Their application to the Upper Colorado River Basin point to three optimal zones of approximately 30 miles radius, centered around Red Mountain (half way between Silverton and Ouray), Marble (or more precisely half way between Marble and Crested Butte) and Vail.

The location of these areas should be further supported by repeating the procedures on streamflow data, thoroughly corrected back to the natural values that would have prevailed without man's intervention. They should also be supported by studies involving more refined criteria.

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Atmospheric Simulation Laboratory

Department of Mechanical Engineering

COLORADO STATE UNIVERSITY

INTERIM REPORT

For Period: July 1, 1967 to June 30, 1968

Atmospheric Water Resources Research

Bureau of Reclamation

Contract No. 14-06-D-6170

September 1968

GENERAL

This report covers the period of July 1, 1967 to June 30, 1968 and summarizes work described in greater detail in progress reports. As listed in the work plan, the main objectives of the contract are: A. Field Coagulation Study, B. Low and Medium Output Generators, and C. Design of Aircraft Generators.

PROGRESS FOR THE REPORT PERIOD

A. Field Coagulation Study

An important facet of any cloud modification experiment is to transport the ice nuclei from the source into the cloud in the most effective manner. The interaction of the nuclei with the atmosphere in general must be known. However, the objective of this portion of the contract is focused on how the particles interact among themselves over short distances. Coagulation in a source proceeds rapidly as long as concentration is above about 10^5 nuclei cm^{-3}. Such high concentrations (and much higher ones) occur in the vicinity of the nuclei generators. Therefore, the nuclei concentration in the first few hundred meters of the plume has to be studied in order to determine to what extent the coagulation reduces the nuclei number and provide experimental data for analysis so that the coagulation effect can be minimized in generator design.

The first method developed for this purpose was lapsed time sequential plume sampling: An aircraft would carry a number of bottles to be filled with air samples at various points along the traverse. The contents of the bottles would have to be analyzed for coagulation effects after landing by counting the active ice nuclei in a cloud chamber. Associated with this sample principle were the following problems:

1. Due to the short time in which the aircraft crosses the plume, the filling of the bottles has to be extremely rapid and precisely timed. This perhaps can be accomplished by using fast response solenoid valves associated with special circuitry. The sampling bottles are evacuated and lined with a rubber balloon, which makes transfer of the contents to the cloud chamber positive.

2. During the time between taking the sample and processing it the number of nuclei decreases due to coagulation and deposition to the walls of the container. Obviously it is mandatory to know these two processes in order to meaningfully interpret the nuclei counts from the point of view of in situ coagulation. (The solution to this problem will be described at the end of this section.)

At the time the above sampling technique was at the stage of prototype operation on the ground the possibility of employment of Atomic Absorption Spectrometry in the plume studies was recognized. This developed in connection with an NSF sponsored project under the direction of Dr. H. W. Edwards in collaboration with Dr. M. L. Corrin aiming at the spectroscopic measurement of silver iodide amounts in air. A feasibility study demonstrated that the crucial problem is the sensitivity of the method. To date, this is just below needs (2 PPB silver), but further development by Drs. Edwards and Corrin is expected, and the tremendous advantage over the first method - namely the real time measurement of the concentration - requires that any advances of this technique be closely watched and evaluated.

In the meantime, the availability of the high volume test stand (vertical wind tunnel) permitted an alternate method which is more tractable and economical than lapsed time sequential plume sampling whose stage of routine operation has been postponed. The alternate method is discussed below.

The alternate plume coagulation study technique utilizes the vertical wind tunnel which confines the plume and makes it easily accessible for sampling along its first 25 meters.* The samples can immediately be processed in the cloud chamber - eliminating storage effects on the aerosol. The flow characteristics of the tunnel have only recently been established, whereas aerosol concentration gradients are currently being measured.

The skyhook plume concentration study is a continuation of the above study beyond the reach of the tunnel. Instead of following the plume by aircraft, a tethered balloon is used which carries a sampling device. The latter was developed in two versions, one for high concentration - consisting of a bottle which is partially evacuated prior to sampling to provide the desired sample dilution so that coagulation is controlled. The second type is a 2-liter can whose top and bottom are open to the ambient air until, at sampling time, their sudden closing traps the sample. At this time the dilution bottle is operational. The trap sampler is under construction, and the ballooning procedure is being checked out. Since only one sample at a time can be taken by the balloon, a standard reference sample has to be taken simultaneously in an identical container located at the tunnel exit.

With the exception of the Atomic Absorption Spectrometry, all sampling methods mentioned require the use of some container, and therefore, as mentioned earlier, a decay of particles occurs due to coagulation

*Data to date demonstrate that this distance is critical due to extremely rapid coagulation rates.

and to loss to the walls. A time consuming study of these two effects combined was carried out (partly funded by another agency). Main parameters were: Initial particle concentration, container size and shape. After filling the container with AgI smoke, small samples were withdrawn periodically and the nuclei counted in a small cloud chamber. The principal conclusions for present purposes are that decay curves for a given container are reasonably well reproducible, and that below initial concentrations of 10^5 cm^{-3} log concentration vs. time resulted in a linear relationship, at least within times of the order of 100 minutes. Therefore our previously described sampling procedures are acceptable as long as we dilute down to below about 10^5/cc when taking the sample.

All plume studies require a reliable plume source. The generator developed according to Paragraph 2.c. of the contract is suitable for these investigations. Its description and performance will therefore be found in the following Section B.

B. Low and Medium Output Generators

The main effort here centered on the development of the USBR generator, a prototype designed to study various combustion parameters (fuel type included), and their influence on the nuclei characteristics.

At first, nozzle plugging and buildup of unburnt material on the walls was a problem with this medium output (~500 g AgI/h) generator. After modification, mainly addition of axial air to the original tangential supply, the generator performed reliably and well as characterized by the mass effectiveness versus temperature relationship. In connection with this, a considerable number of tests were run to investigate the influence of burn rate and solution concentration of AgI in Isopropylamine (IPA). The results, in comparison with other AgI smoke producing devices, leads to the conclusion that for lower temperatures (around -20° C) the effectiveness is high (comparable to other generators, e.g. the Lohse type) for low burn rates, but decreases with increasing burn rates whereas for higher temperatures (around -10° C) the mass effectiveness is relatively high even for high burn rates. It should be noted that the burn rate can be varied by changing the fuel flow or by changing the AgI concentration in the fuel, and that future tests will separate these two effects. A different, and for cloud engineering purposes more important, way to evaluate the performance is to consider the number of nuclei produced per unit time instead of per gram AgI: The maximum number of nuclei/min was produced at a medium burn rate in contrast to the maximum effectiveness (nuclei/gram) derived at lowest burn rate.

The effect of varying the axial-to-tangential combustion airflow ratio has been studied for one set of conditions. Only at the low axial-to-tangential airflow ratios there is a considerable effect;

however, a large number of tests in this area is necessary to understand the complex combustion and AgI recombination process because it is not plausible that the best performance occurs without tangential air.

As expected from previous generator tests the USBR generator showed maximum effectiveness for the theoretical air-fuel ratio, but it is remarkable that at least for the temperature of -15° C there is no sharp dropoff in effectiveness for deviations from the stoichiometric ratio as is observed with other devices. Previous findings (with other nuclei sources) of a favorable influence of quenching air on the effectiveness could surprisingly not be confirmed at -20° C by the USBR generator.

One more unusual feature of the USBR generator can be reported: Using a 3 percent AgI-IPA/IPA Toluene solution the resulting nuclei change their color from normal yellow to orange to red if, at a solution flow rate of under 3 gph, the combustion airflow is raised above the stoichiometric value to about 1.5. On the other hand, no red material could be produced with an AgI-NaI-Acetone. When exposed to sunlight the red or orange effluent quickly turns to yellow, but in the dark the original colors can be preserved.

The red species is by a factor of 2 to 3 less effective than the regular yellow one. A previous test at -12° C, with a .3 percent AgI-IPA solution showed the contrary. (LWC not measured - see discussion below.)

Electron diffraction work by E. F. Fullam indicated that both colors AgI basically are of the same structure, but that the red variety may contain a trace of some phosphorus compound. Since light destroys the red color it is, of course, questionable that the electron beam would not do the same, and therefore some other method has to be found for further investigation of the interesting phenomenon which indicates unexplored potentialities in altering nuclei behavior.

The program specified in the work plan, i.e. varying the parameters discussed above, was interrupted by the important discovery that the liquid water content of the cloud has a marked influence upon the effectiveness. Therefore, before pursuing the generator work, it was necessary to clarify this new aspect. This will render future investigations more meaningful and reliable with respect to natural conditions in the atmosphere where the liquid water content is a major variable.

The results obtained to date on liquid water effects indicate that at cold temperatures (-20° C) the effectiveness does not depend on the liquid water content (LWC) but does so strongly at around -10° C, e.g. increasing the LWC from .8 g/m^3 to 6 g/m^3 raises the effectiveness by almost three orders of magnitude with the major increase

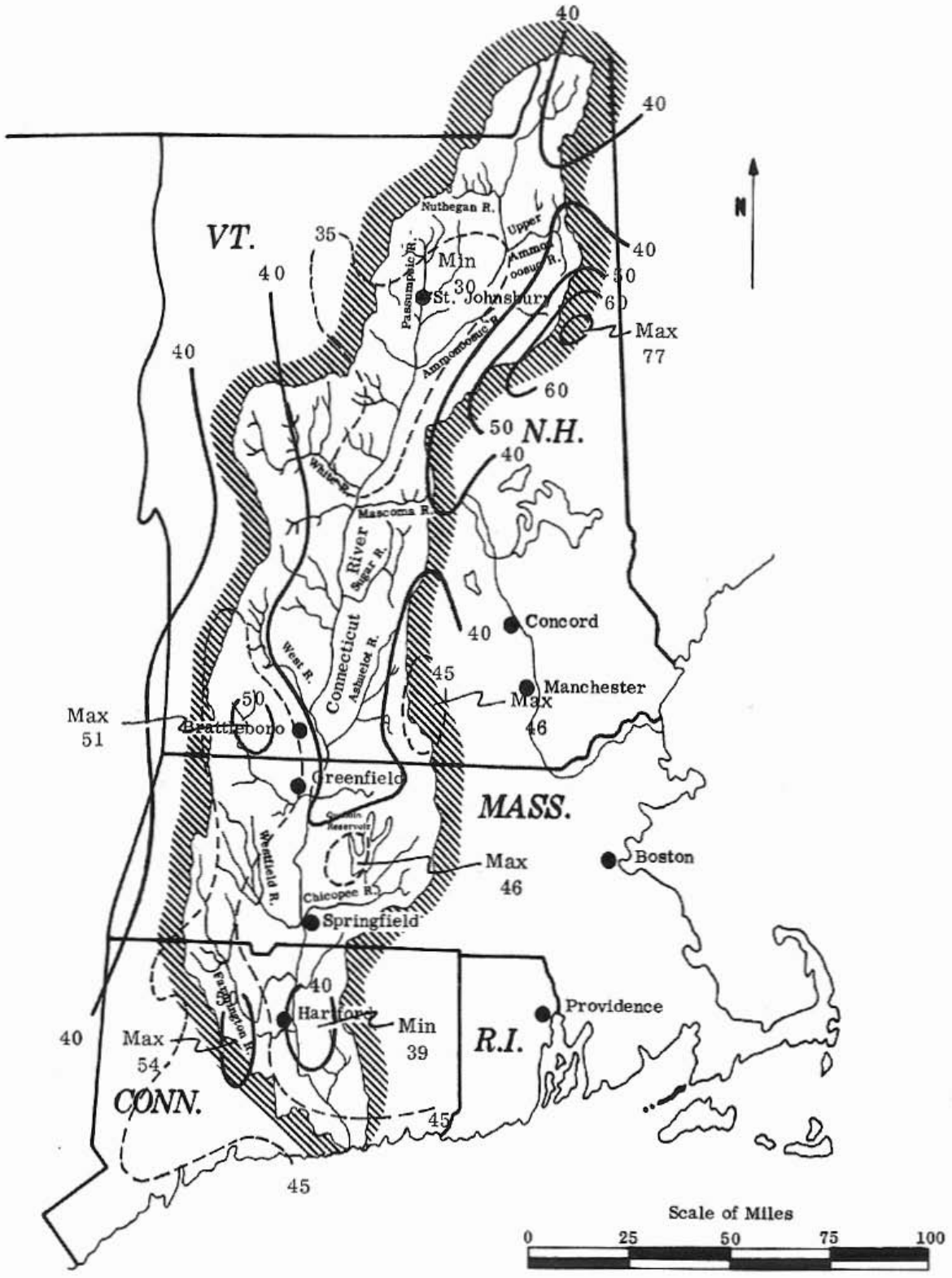


Fig. 3-1. Sixteen year average annual precipitation over the Connecticut River Basin.

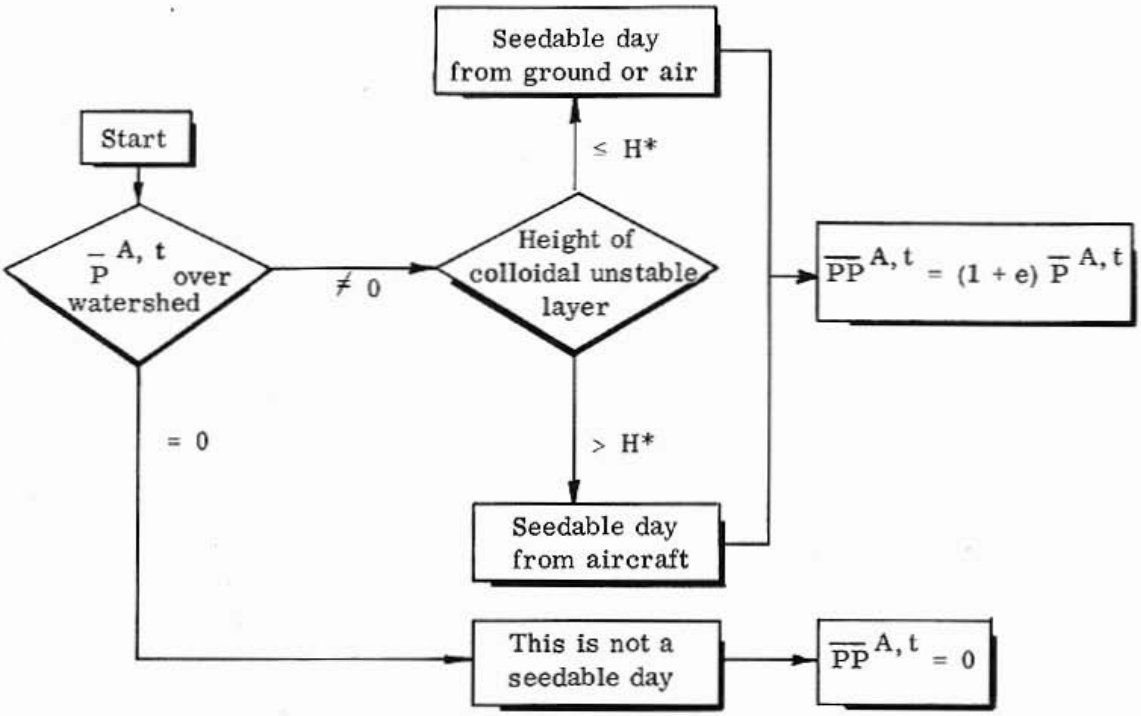


Fig. 3-2. Block diagram of precipitation potential model PPM-I.

the calculation of cost to achieve the precipitation augmentation with ground or aircraft released seeding operations, whichever is appropriate.

The output of PPM-I is an area-time integrated precipitation. It is anticipated that a target area will be a sub-basin of the Connecticut River Basin (e.g., the drainage basin of the Quabbin Reservoir). The areal precipitation is obtained by approximating the integral by a summation of precipitation stations weighted by their respective representative area elements. The Thiessen polygon method [5] is suggested as one method of estimating the representative area elements. The Thiessen polygon method approximates the area elements by a simple geometrical approach. The validity of this approximation is being tested in a pilot study for the Quabbin sub-basin utilizing the equation for the hydrologic cycle in which we utilize observations of station precipitation, streamflow, and storage to estimate the representative area elements.

The climatology of the probable height of the base of the colloidally unstable layer (-4°C to -20°C) has been computed for Albany for the 1200Z soundings. These results are shown in Fig. 3-3 based on a 5-year data sample (1958—1963). The curves represent the probability that the height of the -4°C isotherm is higher than the level indicated for each of the 12 months of the year. It is estimated that diffusive transports of nuclei from ground-based generators would have little likelihood of intersecting target volumes with a base in excess of 3 km. It would appear that airborne nucleation would be preferred in the summer, while ground-based nucleation is feasible during the winter over the Connecticut River Basin.

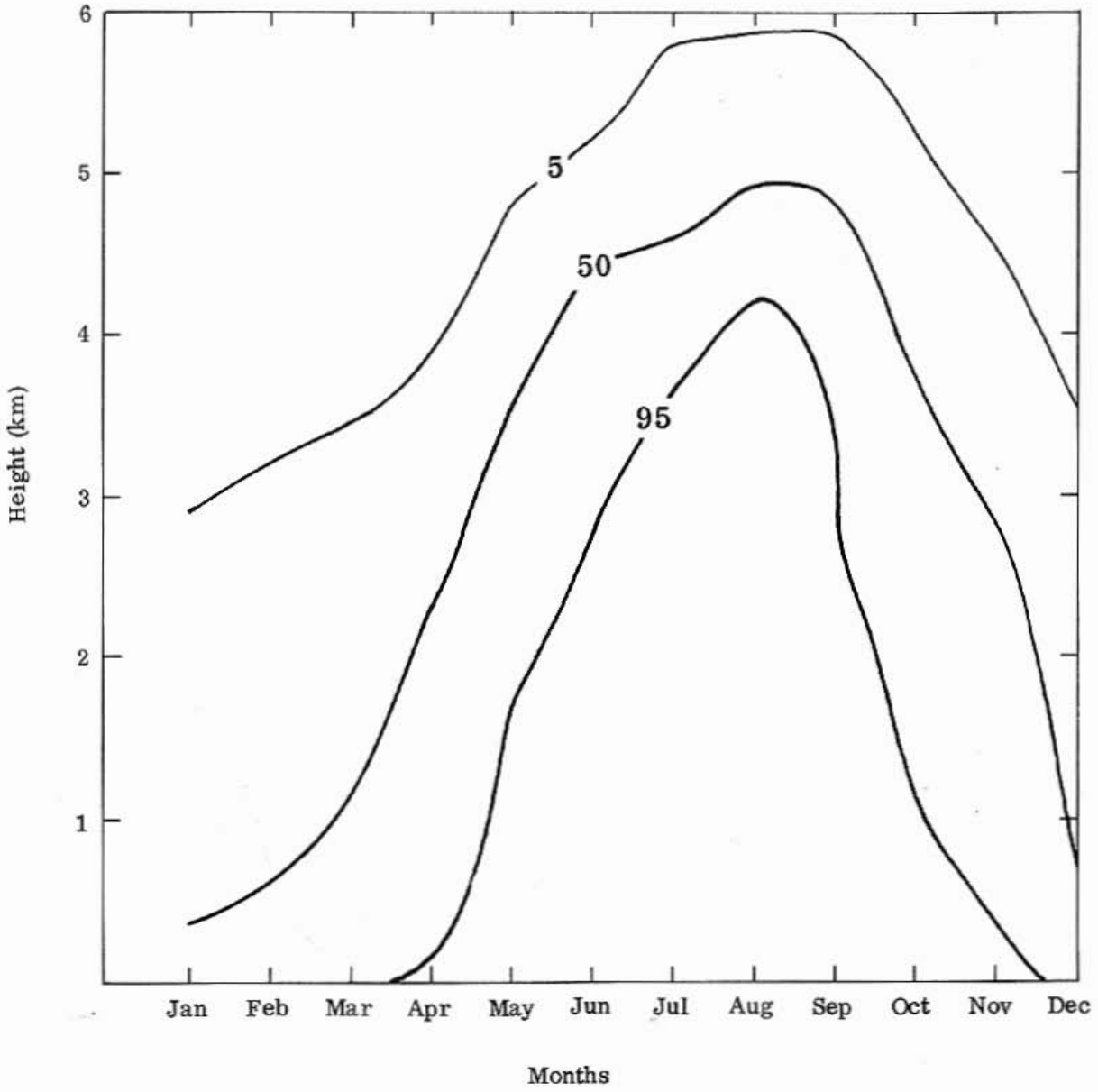


Fig. 3-3. Probability that height of base of colloidal unstable layer exceeds indicated height for Albany [P ($H_{269°}$>H].

4.0 FUTURE PLANS

The time-phased development plan indicated in Fig. 2-2 will be followed. The role of the atmospheric water resource in the Connecticut River Basin (Activity 5) will be assessed. This will in essence indicate a requirements statement for the development and operation of an AWR system for the Connecticut River Basin. The potential feasibility of the atmospheric water resource in the Connecticut River Basin will be written as an essay, so designated because the estimated precipitation potential cannot be verified (since the approach followed in this phase of work is designed to cover only selected aspects of the Connecticut River Basin) and this study is intended as a preliminary planning study.

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Illinois State Water Survey
at the
University of Illinois
Urbana, Illinois

EVALUATION OF PRECIPITATION MODIFICATION EXPERIMENTS FROM PRECIPITATION RATE MEASUREMENTS

Annual Report
Contract Number 14-060D-6575
May 1, 1968 through June 30, 1968

Sponsored by

U. S. Department of Interior
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Denver, Colorado 80225

Prepared by

Floyd A. Huff
Research Meteorologist

Glenn E. Stout
Principal Investigator

INTRODUCTION

One of the key problems encountered in precipitation modification projects has been the evaluation of the results. A logical expectation in cloud seeding undertaken to stimulate the production of surface rainfall is substantial modification of the natural rainfall rate, that is, the rate that would have occurred in the given meteorological situation in the absence of artificial stimulation. Thus, the utilization of rainfall rate measurements in the verification of seeding effects is highly desirable. However, this cannot be done until a much better understanding of the space and time distribution characteristics of rainfall rate under natural conditions is achieved, and various rate parameters evaluated with respect to their applicability in weather modification verification.

PURPOSE OF PROGRAM

It is the purpose of this research to undertake a study (1) to define both the applicability and limitations of rainfall rate measurements for the verification and quantitative evaluation of cloud seeding effects on surface rainfall and (2) to determine the type and density of sampling required to apply such knowledge. This involves extensive analyses of the space and time characteristics of natural rainfall provided by 1-minute rainfall amounts obtained from a special network of recording raingages operated in central Illinois during the 1951-1954 period.

WORK PERFORMED DURING PERIOD

During the first two months of this contract, primary emphasis has been placed upon (1) design and preparation of computer programs to accomplish data analyses needed in the achievement of the research objectives, and (2) initiation of computer processing of the 1-minute rainfall data.

The computer program for performing the first step in the analyses of area-depth and time distribution characteristics was completed, checked, modified slightly, and placed in operation. This program has been designed to provide in a convenient form (1) time distributions of 1-minute rainfall rates at individual sampling points and for areas of 25, 50, and 100 mi^2, (2) ranking of the time distribution data, and (3) spatial distributions in the form of area-depth relations of 1-minute rainfall on the above areas. At the end of June 1968, approximately 25% of the 47-storm sample of rainfall rate data had been computer processed. Advanced analyses involving various data stratifications and statistical treatments were initiated.

Preparation of a second computer program was started during June to perform analyses of the variation of point rainfall rates with distance in the storms being investigated. Information obtained will be used in (1) evaluating raingage sampling requirements in weather modification experiments involving rainfall rate determinations, and (2) supplementing area-depth analyses of the spatial characteristics of rainfall rate.

occurring between 0.8 and 3 g/m^3. This measurement was made with the USBR generator and 3 percent AgI-IPA solution burned in the generator, but a similar pattern developed with the use of the insecticide fogger (mentioned later) with 3 percent AgI-Acetone. One could assume that at low temperatures the sublimation process is dominant, whereas at higher temperature a nuclei-droplet collision process could be more efficient and therefore would depend on more factors than just the cloud temperature. This problem demands thorough investigation.

In order to carry this out, a number of modifications of the isothermal cloud chamber became necessary. A lithium chloride dew point meter was installed which measures the total water content of chamber cloud continuously.

Nuclei generator work not impeded by the LWC effect was the development of the remote control equipment for the USBR generator, e.g. a cam-operated timing device and the replacement of pressurized fuel tanks by a variable stroke, positive displacement pump. Also, a commercially available, inexpensive insecticide fogger was adapted (corrosive solutions) for nuclei generator use. A small pulse jet pressurizes the tanks, and the exhaust ejects the small solution droplets sprayed into same. The effectiveness curves are remarkably steep, and again, the dependence on the LWC is evident.

C. Design of Aircraft Generators

Due to the fact that the design of aircraft generators has to base largely upon the findings of the work with ground generators, especially plume coagulation effects, no construction has started.

A careful study of existing steady state aircraft generators was carried out and used as groundwork for a thorough consideration of the various parameters and operation requirements. Especially power and weight limitation and aerodynamic properties have to be considered. More important than for a ground generator would be an easy in-flight output variability.

Further development of air-to-air pyrotechnic seeding devices seems necessary, and a respective study was initiated. In particular, it is felt that a large number of pyrotechnic AgI pellets can be distributed over a large area by incorporating them into a multistage detonating device. Development of this device is being held up pending approval of the contract office, since this represents a departure from the work plan.

CONCLUSION

In terms of contract objectives, it has been found that coagulation is a dominant variable in generator design and must be minimized to optimize a given cloud treatment system. While much work remains, it can be stated that this problem is tractable.

The medium output ground based generator developed for these studies is competitive with other systems at -20° C and is superior than most at -10° C provided adequate dilution equipment is provided. This latter statement also applies to equipment presently in use in the field. Provision for remote operation in the field, another aspect of the generator development program, has progressed to the point of installation of remote system components.

Turning to aircraft generators, little was reported since this work is dependent upon the coagulation study and the ground generator program.

Denver Research Institute
University of Denver
Denver, Colorado

Interim Progress Report No. 2

1 September 1968

Period

1 July 1967 to 30 June 1968

Bureau of Reclamation

Atmospheric Water Resources Research

Contract No. 14-06-D-6151

Dated 1 April 1967

TABLE OF CONTENTS

		Page
I.	INTRODUCTION	1
II.	OVERALL OBJECTIVES OF THE PROGRAM	2
III.	ACCOMPLISHMENTS ON TASKS DESCRIBED IN WORK PLAN	3
	A. Critical evaluation of past weather modification experiments	3
	B. Analyses conducted	5
	C. Development of design criteria	8
	D. Development of analytical techniques and statistical computer programs	11
IV.	TECHNICAL REPORTS AND PAPERS PRESENTED AT PROFESSIONAL MEETINGS	14

I. INTRODUCTION

One of the stated goals of Project Skywater is to determine optimal methods for significantly increasing, controlling, and redistributing precipitation so that it falls in places where it can be used most efficiently. This involves unique and complex experimental design and statistical evaluation problems. New statistical theory and operational research techniques must be developed in order to handle the data generated by the growing number of experiments in this relatively new research field. The traditional analytical methods of problem solving are no longer adequate to deal with the complex optimization problems facing the precipitation management scientist. The system is a very complex one and there are many complex problems yet to be solved; however, neither the complexity of the system nor the impurity of available mathematics relieves the precipitation management scientist of the necessity of the obligation of dealing with it. The Project Skywater program at the Denver Research Institute has made some progress in this area and proposes more contributions in the future.

II. OVERALL OBJECTIVES OF THE PROGRAM

The overall objective and proposed efforts of the research program are to develop experimental design criteria and statistical methods to aid in the evaluation of atmospheric water resources programs. More specific objectives are:

(1) to critically evaluate past weather modification experiments with emphasis on the research methodology, statistical techniques, and interpretation of findings to determine their suitability for a particular experiment or for general application,

(2) to conduct analyses to determine the effect of individual parameters such as treatment techniques, terrain factors, and weather conditions on the reliability and validity of the results of weather modification experiments,

(3) to develop design criteria for field experiments with special consideration of the parameters referred to above, and

(4) to develop computer programs and analytical techniques for evaluating and comparing a wide variety of weather modification experiments.

The overall approach is directed toward developing operations research techniques for the purpose of optimizing precipitation management systems.

III. ACCOMPLISHMENTS ON TASKS DESCRIBED IN WORK PLAN

A. Critical evaluation of past weather modification experiments

1. The following pertinent journal and miscellaneous articles were reviewed, for which critical evaluations were reported in monthly progress reports to the Bureau of Reclamation:

Aerometric Research Inc. Design of a Southern Sierra seeding test program, 1967.

Anderson, E. A. Development and testing of snow pack energy balance equations. Water Resources Research, Vol. 4, No. 1, 1968, p. 19-37.

Biswas, K. R., Kapoor, R. K., Kanuga, K. K., and Bh. V. Ramana Murty. Cloud seeding experiment using common salt. Journal of Applied Meteorology, Vol. 6, Oct., 1967, p. 914-923.

Bowen, E. G. Cloud seeding. Science Journal, August 1967, Vol. 3, No. 8, p. 68-73.

Brelsford, Wm. M. and Richard H. Jones. Estimating probabilities. Monthly Weather Review, Vol., 95, No. 8, p. 570-576.

Dennis, A. S., Schock, M. R., Koscielshi, Alexander, and P. M. Mielke. Evaluation of cloud seeding experiments in South Dakota during 1965 and 1966. Report 67-1, Institute of Atmospheric Sciences, South Dakota School of Mines and Technology, Rapid City, South Dakota.

Dye, J. E. and P. V. Hobbs. The influence of environmental parameters on the freezing and fragmentation of suspended water drops. Journal of Atmospheric Sciences, Vol. 25, Jan. 1968, p. 82-96.

EBA optical snow-rate sensor. Technical report submitted to the Bureau of Reclamation by E. Bollay Associates, Inc., Santa Barbara, Cal., March 1968.

EG&G, Inc., W. E. Howell Associates. A test of certain evaluation designs for cloud seeding experiments. Technical Report No. B-3662, Sept. 1967.

Henderson, Thomas J. Cloud seeding in the county of Tulare, California. Final report, 1963-64 season, Atmospherics Incorporated, March 1965.

Huff, F. A. The effect of natural rainfall variability in verification of rain modification experiments. Water Resources Research, Vol. 2, No. 4 (1966), p. 791-801.

Lopez, Manuel E. Cloud seeding trials in the rainy belt of western Columbia. Water Resources Research, Vol. 2, No. 4, 1966, p. 811-823.

Neyman, Jerzy and E. L. Scott. "Asymptotically optimal tests of composite hypotheses for randomized experiments with non-controlled predictor variables. J. Amer. Statist. Assoc., Vol. 60, 1965, p. 699-721.

Neyman, Jerzy, and E. L. Scott. Rationale of statistical design of a rain stimulation experiment. Statistical Laboratory, University of California, Berkeley. Proceedings of the Design and Evaluation Conference, Bureau of Reclamation, Denver Federal Center, Oct. 1967.

Neyman, Jerzy and E. L. Scott. "Some outstanding problems relating to rain modification". Proceedings of the Fifth Berkeley Symposium on Math. Stat. and Prob., Berkeley and Los Angeles, University of Calif. Press, 1966, Vol. 5.

Prikhot ko, G. F. Experimental development of an approximate criterion possibility of inducing artificial clouds in the Ukraine Socialistic Republic. Translation No. 612, Office of Engineering Reference. U. S. Dept. of Interior, Bureau of Reclamation, Denver, Colorado, 1966.

Rodda, John C. Development of rain gauges by Asit K. Biswas (Sept., 1967), discussion. Journal of the Irrigation and Drainage Div. (ASCE) Vol. 94, No. 1R1, March 1968.

Schleusener, Richard A. A perspective on weather control. Journal of the Irrigation and Drainage Div. (ASCE), Vol. 94, No. 1R1, March 1968, p. 73-78.

Schmid, P. and J. C. Thams. Results of a large-scale rain stimulation experiment on the southern slopes of the Alps. Archiv fur Meteorologic Geophysik und Bioklimatologie, Series A: Meteorologic und Geophysik, Band 16, Heft 2-3, 1967.

Scott, William T. Poisson statistics in distributions of coalescing droplets. Journal of the Atmospheric Sciences, 24, No. 2, March 1967, p. 221-225.

Simon, W. E. and L. A. Walter. A new technique for determination of cross-power spectral density with damped oscillators. To be published.

Thompson, John W. Similar problems in meteorology and psychology. General Systems, Vol. 10, 1965, p. 49-60.

Weinstein, A. I., P. B. MacCready, and L. G. Davis. Numerical modeling of cumulus clouds. Meteorology Research, Inc., Report No. MR 167-M-642, August 1967.

2. Several documents and interim reports from the Park Range Atmospheric Water Resources Program and other Skywater programs were also reviewed.

B. Analyses conducted

1. A re-analysis of the Kings River streamflow data. The results of the analysis are presented in Technical Report No. 3 prepared by DRI for the Bureau of Reclamation. Three reports relevant to the program are reviewed. They are:

(1) Henderson, T. J. Cloud seeding on the Kings River watershed.

(2) Markovic, R. D. Statistical evaluation of weather modification: target two sample run method.

(3) Markovic, R. D. A method for statistical evaluation of weather modification at the River flow control level.

Several statistical analyses are made using several statistical techniques, each of which tests a different hypothesis or solves a different problem. Some recommendations for future research involving streamflow analysis are presented.

2. The EBA optical snow sensor evaluation. Only preliminary results of this study were accomplished during this reporting period (FY 1968). The procedure and preliminary results can only be summarized here. Data for the Rabbit Ears Pass station (Park Range) for eight analysis periods from November 1966 to February 1967 were obtained for six variables. Data were collected for five minute intervals during

the analysis periods for (1) snow sensor measurements (.001 inches of precipitation), (2) plastic sheet measurements (.001 inches of precipitation), (3) temperature (nearest whole degree Fehrenheit), (4) wind speed (miles per hour), (5) wind direction (0-360), and (6) nuclei count (counts per liter). Preliminary results based upon the total sample of observations are shown in Tables 1 and 2. These preliminary results are based upon the total sample of observations. Some comments about the results in the two tables are as follows:

(1) One notes (and, of course, this was not unexpected) the extreme variability, especially in nuclei count, in each of the measures with the possible exception of temperature.

(2) The mean amount of precipitation for the plastic sheet is slightly higher than for the snow sensor (this can be tested for statistical significance).

(3) The wind direction is primarily from the WSW and at average rate of 22.92 miles per hour.

(4) The coefficient of correlation between the snow sensor and the plastic sheet is a respectible .80 (this too can be tested for significance and confidence limits established).

(5) As the temperature rises there is a slight tendency for precipitation to increase as measured by both the sensor and the plastic sheet.

(6) As the wind speed increases there is a very slight tendency for the precipitation to decrease as measured by both the sensor and the plastic sheet.

RESULTS TO DATE

It is much too early in the investigation to present results of any phase of the research. Any statements made now with respect to behavior trends observed in the time and space distributions would be premature and subject to later rejection.

PROBLEM AREAS

In the early stages of the research, no problem areas have developed that need further work before contract objectives can be achieved. However, such problems could develop in the future analyses progress.

REPORTS

Appropriate technical reports will be prepared as soon as the analyses are completed.

Cascades Atmospheric Water Resources Program

Department of Water Resources
State of Washington

July 1967 - June 1968

This report is a summary prepared by the Bureau of Reclamation of the reports of three subcontractors to the State of Washington.

Report of E. Bollay Associates, Inc.

INTRODUCTION

The Cascade Atmospheric Water Resources Program is investigating weather modification techniques for redistributing surplus winter precipitation from the west side to the east slopes of the Cascade Mountains.

The program was directed in Phase I (February 2, 1966 - June 30, 1966) and Phase II-A (July 1, 1966 - June 30, 1967) by the State of Washington, Weather Modification Board, and in Phase II-B (July 1, 1967 - June 30, 1968) by the Department of Water Resources, State of Washington. Field operations, research and physical studies were subcontracted to E. Bollay Associates, Inc., Battelle Northwest Laboratories, University of Washington, and Washington State University.

Phase I results were reported in the Weather Modification Board Report No. 1, August 1966, and Phase II-A results were reported in the Board Report No. 2, September 1967. This final report describes E. Bollay Associates, Inc. activities for the total contract period February 2, 1966 through June 30, 1968, and includes principal results described in the Interim Progress Report (period January 1, 1968 through June 30, 1968) submitted to the Department of Water Resources by E. Bollay Associates on June 30, 1968.

Field operations were centered at Snoqualmie Pass throughout the contract period. Radar, radiosonde and rawin data were collected at Enumclaw during Phase II-A. In Phase II-B, radiosondes were also collected at Enumclaw, but radar observations were made at Snoqualmie Pass.

PHASE II-B (July 1, 1967 - June 30, 1968)

The ground precipitation network was expanded with an additional 12 weighing-type precipitation gages. Nine of these gages were installed at the ridge sites, and two along Highway 10 between Cle Elum and Ellensburg. One gage was scheduled for Amabilis Mt., but because of insufficient landing area for the helicopter, the instrument was installed at the project office.

Data from the weighing-bucket gages was tabulated on an hourly basis for analysis periods. Inspection of the records from the weighing bucket gages installed on the ridge sites, revealed that daily and monthly totals were generally less than nearby valley stations in the network. Further analysis between records of the weighing bucket precipitation gages and storage gages with a large orifice indicated that there was, on the average, 24 percent less precipitation

measured by the weighing buckets than the storage gage at the ridge sites. A similar analysis performed for the valley stations reveal 13 percent more precipitation in the storage gages than the 8-inch orifice weighing gages. Extreme differences were as high as 46 and 37 percent for Salmon La Sac and Elk Highway stations. These examples indicate the importance of wind in the catch of the gage. As stated earlier, wind shields were not installed, to avoid capping by snow; however, from these data it is recommended that the valley stations be equipped with wind shields. With the ridge stations, wind shields would increase the catch, but would increase capping. The limitations on moving the instruments to a more sheltered site, because of the helicopter requirement, does not give any relief to the problem.

An alternative would be complimentary sensors, such as snow pillows, which would give an accurate measurement of total precipitation as snow only. Wind shields could then be installed on the precipitation gages, because capping would not be a problem when rain occurred, and during snowfall the snow pillow would assure a usable record.

Radar tracings were plotted against optical snow rate sensor data from the project office station. Five minute average precipitation thickness was plotted against similar precipitation rate data, in time sequence. From these data, one concludes that periods of precipitation are preceded by an increase in radar precipitation thickness - as would be expected. To obtain more detailed data of this type, it is recommended that a recorder be connected to the AGC voltage of the radar and the range gate automatically swept in altitude. A continuous recording of the echo intensity versus height and time could be obtained and related to precipitation profiles for comparison with data from seeded clouds.

Background counts of ice nuclei were made at Snoqualmie Pass and Stampede Pass; these measurements were coordinated with a study that Dr. P. Hobbs was making at the University of Washington. For comparison of data collected by U.S.W.B. personnel at Stampede Pass with that collected by the University of Washington, the digital printer and microphone from the University of Washington unit was connected by a "Y" to the sensor of the Snoqualimie Pass ice nuclei counter. Threshold levels of the two printers were then adjusted until identical counts were received over several sampling periods.

Units were generally operated at three temperatures, -10° C, -15° C, and -21° C, during each observation period. Sampling rate was 10 liters/minute. During observation periods, background counts were around 0.1/liter at -21° C.

Three diffusion tests were performed using the ice nuclei counters to detect artificial ice nuclei plumes; two releases were from

Crystal Mt. and one near Stampede Pass. A description of these tests follows.

On April 4, 1968 a AgI generator was operated from Crystal Mt.. Approximately 1 liter per hour of a 4 percent acetone solution of AgI was burned in a Washington State generator. Ice nuclei counters were operated at Snoqualmie Pass and Stampede Pass; sampling rate was 10 liter/minutes, and chamber temperature -21° C.

During the seeding time and for two hours thereafter, only background count, i.e., less than 0.1 nuclei/liter was observed at the ice nuclei counters, indicating that the plume was not intercepted. Analysis of the surface winds at Crystal Mt. and North Bend indicate the plume may have been carried westerly and was restricted to the west side. No upper-air wind data is available in the Snoqualmie Pass or Stampede Pass area, so it is difficult to estimate the plume path from Crystal Mt.

The second diffusion test was also conducted on April 4, 1968 from Crystal Mt., 0930 to 1500 PST. Ice nuclei counters for this test were at Cle Elum, Stampede Pass, and the University of Washington mobile unit operated at three locations - South end of Lake Keechelus, Easton, and 5 miles west of Cle Elum. Again the sampling rate of the counters was 10 liter/minute at -21° C. Nuclei counts at all counters were less than 0.1 nuclei/liter.

On this test, an attempt was made to obtain some upper-air wind data with the radiosonde equipment at Enumclaw. A temporary azimuth and elevation indicator were attached to the GMD-1 antenna; while the radiosonde was tracked, an additional person read and recorded azimuth, elevation and time. Wind vectors were then plotted for one minute intervals. Unfortunately, due to the faulty oscillator in the radiosonde receiver, the highest the sounding reached was only the -6° C level at 11,481 feet MSL. Analysis of the sounding does indicate an inversion from about 3280 to 4900 feet MSL, but this is well below the top of Crystal Mt. at 6800 feet MSL. Surface wind direction at Crystal and around Snoqualmie Pass and Stampede Pass was favorable for the plume to be directed over the area of the ice nuclei counters, as were the lower level, upper-wind directions, as indicated from tracking the Enumclaw radiosonde. Even the short sounding shows that for the AgI to be an effective freezing nuclei on this date, it would have had to reach in excess of 12,000 feet MSL. Using measured upper-air winds below 10,000 feet MSL as representative, and diffusion and fall velocities of 1 meter/second, Crystal Mt. should have been a fairly good seeding location, 30 to 36 miles from the target area for these conditions.

The third diffusion test was conducted from about 1 mile east of Stampede Pass on April 25, 1968. Ice Nuclei counters were operated at Snoqualmie Pass and Stampede Pass, and the University of Washington mobile unit was on the east shore of Lake Kachess. Sampling rate was 10 liter/minute at -21° C. During this test, and attempt

was made to generate the plume close enough to one ice nuclei counter to assure a reasonable opportunity of finding some of the plume. The seeding generator was operated from 1315 to 1515 PST with a four percent AgI acetone solution and a rate of 1 liter/hour. Surface winds at the generating site and hourly wind data for Snoqualmie Pass and Stampede Pass were recorded. The ice nuclei counters at Snoqualmie Pass and Stampede Pass did not record above background count of 0.1 nuclei/liter. The mobile unit also recorded less than 0.1 nuclei/liter, with the exception of a period from 1536 to 1541 PST when the count went to about 5 nuclei/liter. This is good evidence that the mobile genrator did sense part of the plume. The AgI generator was located on the lee side of Stampede Pass, and the University of Washington mobile unit was only 6 miles directly downwind from the generating site. It is likely that, close to the surface, west to northwest flow carried the plume to the south earlier and later than 1545 PST.

These limited diffusion tests demonstrated (1) the questionable nature of any analysis without adequate upper-air wind and radiosonde data and (2) the need for airborne ice nuclei count data to determine the vertical distribution of surface-released freezing nuclei. Future diffusion tests should be accompanied by hourly upper-air wind soundings, periodic radiosonde ascents, and several airborne traverses, west to east at 10,000 to 14,000 feet MSL, to determine if the vertical displacement of the plume is sufficient to place it in a favorable environment for accelerated crystal growth. It is recognized that these steps would require considerable resources and effort, but unless such an effort is made, it is not possible to obtain meaningful diffusion/activation estimates.

Report of Battelle-Northwest

INTRODUCTION

The objective and scope of performance prescribed in the contract between Battelle-Northwest and the State of Washington involves research in the development of the atmospheric water resources. Specifically, this research is directed toward the design of engineering techniques for augmenting and redistributing wintertime precipitation in and across the Cascade Mountains of Washington. These accomplishments would increase the snowpack and the consequent runoff from mountain watersheds, particularly those draining into the arid, eastern portion of the State of Washington.

The total research program embraces two major objectives: (1) to enhance the understanding and detailed knowledge of precipitation mechanisms relative to their frequency and contribution to the total water supply in the area of interest by a program of comprehensive data analysis; and (2) to develop and provide plans and specifications for the conduct and evaluation of a field experiment to test the feasibility of a trans-sky diversion of water across the Cascade Mountains of Washington.

Summaries of six Research Reports are included. They are separated into two major categories that represent the primary element of program-objective attainment.

1. Data Analysis Program. Research Reports I through IV emphasize the analysis techniques and results related to the physical measurements segment of this research.

2. Experimental Design Program. Research Repots V and VI describe the research leading to development of experimental design specifications.

DATA ANALYSIS PROGRAM

RESEARCH REPORT I
RIVER RUNOFF ANALYSIS

SUMMARY

This report treats the statistical analysis of historical streamflow data relative to the penetration of precipitation to the eastern side of the Cascade Divide. A considerable body of data has been accumulated regarding watersheds, rivers, and corresponding sensors encompassing the area from the Olympic Peninsula in Washington

to the Bitterroot Range in northern Idaho. All streamflow series were examined for significant correlations and common factors, using the BMD-03M Factor Analysis computer program. On the basis of these considerations, six major streamflow series in the Cascade area were selected for further analysis - three on the west and three on the eastern side of the Cascade Divide. Various regression lines were constructed and fairly high correlation coefficients were found between east and west streamflows. Residuals or deviations about these lines were of interest because they are conceivably influenced by several factors such as measurement error, variations in seasonal temperatures, and precipitation variations. It was determined that these residuals directly reflect increased or decreased precipitation on the eastern (lee) side of the Cascade Range. A principal component analysis was carried out on both the three western streamflow series and the three eastern streamflow series. In each case, thy first eigenvector and the corresponding eigenvalue indicated that a simple average of the three streamflow series would account for 98 percent of the total variability.

RESEARCH REPORT II
PRECIPITATION ANALYSIS

SUMMARY

This report describes the research relating to precipitation distribution patterns from west to east across the Cascade Range. It was considered important to determine whether precipitation data reflected the same kind of lee side precipitation anomalies detected in the streamflow data. Through the use of correlation analyses and factor analyses, groups of stations were segregated into individual precipitation regimes and the seasonal effects on the distribution patterns were observed. Other correlation analyses to investigate relationships between selected precipitation regimes and streamflows clearly indicate that both streamflow and precipitation regression residuals contain structure over and above random observational error. This emphasizes the importance of precipitation in the size of streamflow regression residuals and also the relatively high quality of both streamflow and precipitation data.

RESEARCH REPORT III
SYNOPTIC ANALYSES OF INDIVIDUAL PRECIPITATION EVENTS

SUMMARY

The research effort described in this report provides a basis for developing a descriptive classification of synoptic meteorological conditions and the corresponding precipitation patterns. Restrictive factors that limit the effectiveness of this approach are discussed.

Analyses of several years of precipitation data have been completed, and specific years have been classified as either excess (above normal) or deficient (considerably less than normal). Computer programs have been written to relate precipitation events to windflow, moisture content, stability, vertical velocities, etc.

Precipitation events during the past winter season were examined by constructing three-dimensional cross section and long-section analyses. These analyses were integrated with the ESSA 6 weather satellite photographs and with the various U.S. Weather Bureau chart analyses received via the national weather facsimile network. These studies indicate that the predominant feature of the eastern slope of the Cascade Range is large scale subsidence and a consequent decrease in cloudiness and precipitation in the lee of the mountains.

It was observed that areas of high moisture content moved rapidly through the area of interest in relatively small tongues or cells. However, the sparseness of the present U.S. Weather Bureau radiosonde network made detection of sufficient numbers of these moisture cells unlikely and thus prohibited moisture flux studies on an individual storm basis. Supplemental observations strongly suggest that a measurements program in the lee side of the mountains could provide data that would lead to a determination of the magnitude of the subsidence and thus facilitate identification of seedable periods.

RESEARCH REPORT IV
ONGOING ANALYSIS OF CURRENT DATA

SUMMARY

The objective of this research is to process current data with emphasis on development of new techniques for evaluating various experimental designs for weather modification projects. Initial efforts were directed toward establishing the presence or absence of a specific precipitation gradient distribution pattern along the established line of precipitation recording stations. A distinct distribution was observed; however, the variability of the distribution was so large that it would be difficult to observe a change in precipitation gradient of less than 20 percent under experimental conditions.

A comparison of the recently established "mountain" and "valley" precipitation stations was accomplished. There was a striking similarity in the precipitation records obtained for both groups with the exception that the valley stations record greater precipitation amounts than the mountain stations. From these studies, it was determined that a number of stations contributed redundant data and should thus be discontinued or relocated to establish a more favorable benefit/cost ratio for their operation.

EXPERIMENTAL DESIGN PROGRAM

RESEARCH REPORT V
EXPERIMENTAL DESIGN PLANS AND SPECIFICATIONS

SUMMARY

The objective of this reserach segment is to develop plans and specifications for a field measurement network, a data collection and analysis scheme, and an associated cloud treatment technique for evaluating the feasibility of modifying natural areal precipitation distributions. The entire historical (1929-1966) hourly precipitation records for each station were analyzed to determine specifications for defining which precipitation events may be regarded as "seedable" units. Three-dimensional analyses relating precipitation and synoptic data were made to determine appropriate target and control areas, and hourly and monthly precipitation data were analyzed to determine the location and type of sensor system to be established in the field network. Precipitation variability studies were made for selected hourly precipitation recording stations and for selected groups of stations. A new evaluation technique based on precipitation gradient information was developed and is presented for discussion.

This portion of the research program is directed toward development of plans and specifications for a field measurement network, a data collection and analysis scheme, and an associated cloud treatment technique for evaluating the feasibility of modifying natural areal precipitation distributions; i.e., outlining the design execution, and evaluation of a weather modification experiment.

The design and evaluation of weather modification experiments has been given considerable attention by leading statisticans and meteorologists and was the topic of a recent symposium* held in Denver, Colorado. Even though significant contributions have been made by these acknowledged leaders, there is still general disagreement as to the effects of seeding supercooled clouds to produce precipitation. The rapidly changing natural events make it difficult to interpret statistically the processes necessary for successful weather modification.

The design of any experiment will in general consist of three parts:

(1) A statement of the objectives
(2) A description of the experiment, covering such matters as the experimental units, the experimental treatments, the size

*Bureau of Reclamation Planning Conference (Project Skywater), Design and Evaluation of Weather Modification Experiments, October 11-13, 1967, Denver, Colorado.

Table 1

Means, standard deviations, and sample sizes

Variable	Sample size	Mean	Standard deviation
1. Snow sensor	416	3.59	3.20
2. Plastic sheet	423	4.25	4.10
3. Temperature	431	20.26	8.25
4. Wind speed	368	22.92	15.53
5. Wind direction	355	234.02	22.35
6. Nuclei count	308	678.22	2221.42

Table 2

Intercorrelation matrix for the six variables*

	1	2	3	4	5	6
1	1.00	.80	.33	-.15	-.10	.02
2	408	1.00	.38	-.16	.09	-.13
3	416	423	1.00	-.51	.19	-.30
4	355	362	368	1.00	-.46	.26
5	355	349	355	355	1.00	.09
6	293	300	308	254	241	1.00

*The top half of the matrix shows the correlation and the bottom half shows the sample size.

(7) The correlation between temperature and wind speed is -.51 which means that there is a fairly substantial tendency for the wind speed to decrease as the temperature increases.

(8) There is a very slight hint that an increase in snow sensor measurements is associated with more southerly winds; whereas, higher plastic sheet measures are associated with westerly to northerly winds.

(9) Higher wind speeds tend to be associated with a WNW direction.

(10) The nuclei count measure is so unstable that the results are not reliable. The highest correlation is -.30 with temperature. This suggests that higher temperatures are associated with lower nuclei counts.

These results were obtained using a missing data intercorrelation computer program.

C. Development of design criteria

1. Technical Report No. 1, "Fundamental concepts of experimental design and statistical analysis in weather modification programs" was prepared to provide background information relative to this task. It is stated in the report that, "It is because many researchers in the field of weather modification have expressed such a need that this report has been prepared. It is hoped that it will be of practical use and will provide the impetus and technical assistance for better designed field and laboratory experiments in precipitation management with more appropriate statistical evaluations." The five basic types of research

designs or logical devices, for conducting an experiment are discussed as to their advantages and disadvantages. The author summarizes the experimental design section of the report in the following manner:

> Everything we know as a fact resulting from observation and experiment, whether true or false, was discovered by the use of one or another of these methods. The use of correct statistical tools in addition to the use of correct method of experimental inquiry is a must for satisfactory research. If an investigator is aware of the fallacies, he can interpret his results accordingly. To be forewarned is to be forearmed.

2. In Technical Report No. 5, "Optimization techniques in weather modification," the problem of design criteria is dealt with to some extent in the following manner:

> The technique of optimization in weather modification involves a sequence of individual optimizations and the optimization of the various components in an integrated fashion.
>
> Precipitation targeting requires the consideration of the whole system. The process starts at the place where the precipitation is desired to fall, then it must be determined where it would have to fall from, where the cloud processes which produced it would have to begin, and finally the nucleation source required to treat the clouds in the desired manner. The sequence problem needs to be solved in both time and space coordinates.
>
> Large scale systems can be optimized through partial optimization of one stage at a time. Dynamic programming, a mathematical technique often found useful for making a sequence of interrelated decisions, would seem to be an appropriate optimization technique for precipitation management systems. It provides a systematic procedure for determining the combination of decisions which maximizes overall effectiveness. It is a general type of approach to problem composition strategy which is the technique of breaking a structured system down in order to suboptimize the components.

3. We are currently evaluating previous and current work on the development of mathematical models for measuring the economic consequences of weather modification programs. Precipitation, runoff, storage and water utilization models are being investigated.

Evaluations of beneficial or detrimental effects of weather modification programs generally have included and often have been restricted to an analysis of precipitation runoff some distance downstream from the actual modification efforts. Such an approach, while providing needed documentation of research effects, does not yeild sufficient information on the interaction of the variables that cause the resulting runoff.

Long range programs of weather modification, especially precipitation augmentation, must be concerned with the overall economic gains to:

1. The initial water users
   (a) hydro-electric power
   (b) municipal and industrial consumption
   (c) irrigation
2. The net productivity of an economic region as measured by some type of input-output analysis.

In order to provide adequate measurements for an input-output analysis, the direct benefits to the initial users must be reasonably well established. To date the work in this area has been very limited. What is needed is a model form that will allow testing of precipitation sensitive variables within a basin or water shed. At this time, three sequential model forms are being suggested as necessary:

1. precipitation - runoff
2. runoff - storage
3. storage - utilization

These models would include streamflow synthesis, ground water storage,

multi-reservoir storage, and time-dependent demands of the primary users.

Streamflow synthesis has been studied for a number of years. Fiering (1967) describes a number of approaches that have been proposed. Linsley is currently working on simulation models that will evaluate the hydrological effects of rainfall augmentation.

Ground water management has been evaluated with a systematic approach by Dracup (1966). Mathematical models that permit sensitivity tests of system variables are now at least a partial reality.

The office of Water Resources Research is currently funding several studies in the area of economic evaluation under risk and uncertainty as it applies to water resource allocations.

Each of these individual research efforts provides a basic element in the model forms described above. What is needed is a total system sensitivity test to determine which of the precipitation variables are most likely to affect a significant economic gain to the primary users.

Once the models described above are at least operational it will then be possible to begin to explore the side-effects of precipitation augmentation as they modify regional economic stimulators such as agriculture, electrical power dependent industries, or the rapidly growing ski industry located in the center of the proposed modification areas.

D. Development of analytical techniques and statistical computer programs.

One of the goals of the program is to develop and maintain a library of modern statistical programs. The following two programs are now a part of this library of statistical programs:

1. Incomplete data intercorrelation program. The primary purpose of this program is to compute product moment intercorrelations among up to 80 variables, any number of which may have missing data. Means and standard deviations based on all non-missing values are computed separately for each variable. The correlation coefficients are computed and rounded to six places. The program was originally written in FORTRAN, using single-precision floating-point arithmetic. The basic formulas involved are:

a. Mean: $$X = \frac{\sum_{i=1}^{N} X_i}{N}$$

b. Standard deviation: $$s = \sqrt{\frac{\sum_{i=1}^{N} X_i^2 - \frac{\sum_{i=1}^{N} (X_i)^2}{N}}{N - 1}}$$

c. Correlation: $$R_m = \frac{\sum_{i=1}^{N_m} X_i Y_i - \frac{\sum_{i=1}^{N_m} X_i \sum_{i=1}^{N_m} Y_i}{N_m}}{\sqrt{\left(\sum_{i=1}^{N_m} X_i^2 - \frac{\left(\sum_{i=1}^{N_m} X_i\right)^2}{N_m}\right)\left(\sum_{i=1}^{N_m} Y_i^2 - \frac{\left(\sum_{i=1}^{N_m} Y_i\right)^2}{N_m}\right)}}.$$

where N is always the sample size for complete data, and N_m is the sample size for nonmissing values of pairs of variables.

2. Simulation, analysis and modeling (SAAM). This computer program, recorded on magnetic tape, was received from the National Institute of Health during September 1967. The program is a tool to aid in the mathematical analysis of experimental data by simulation, data fitting, and model building. Included in the program is the methodology for the solution of a wide variety of model types. The SAAM computer program, consisting of six chained main programs governed by a master program, and more than 150 subroutines, is recorded in FORTRAN IV and FORTRAN II card images. It is stored on a "blocked" tape and each of the several hundred blocks has its own internal control statements. Unfortunately the program is not yet in operation on the DRI system (Burroughs B5500). Another attempt will be made to use a FORTRAN Compile program that will convert the FORTRAN card deck directly into a machine language program comprehensible to the Burroughs computer, thereby obviating the problems anticipated in translating. A syntax-generated Compile program has been obtained by the DRI Computer Section. Unfortunately it doesn't work on large programs at present, but hopefully the program will be in operation in the not too distant future.

3. Analysis of variance and other statistical computer programs. These programs are in the process of being developed for the DRI Computer System.

IV. TECHNICAL REPORTS AND PAPERS PRESENTED AT PROFESSIONAL MEETINGS

A. Technical report No. 1. Fundamental concepts of experimental design and statistical analysis in weather modification programs. Dec., 1967.

B. Technical report No. 2. The role of simulation in precipitation management research. April, 1968.

C. Technical report No. 3. Some comments on the statistical evaluation of the Kings River streamflow data. June, 1968.

D. Operations research in weather modification programs. Operations Research Around the World Meetings, Madrid, New Delhi, Tokyo.

E. Project Skywater: Research design and statistical evaluation. Prepared for presentation at the Bureau of Reclamation's Design and Evaluation Conference, Denver Federal Center, 11-13 Oct., 1967.

F. The application of operations research techniques to civil engineering problems. Prepared for presentation at the ASCE, Colorado Chapter Meeting, February, 1968.

G. Design and evaluation in Project Skywater. Prepared for presentation at the First National Conference on Weather Modification of the American Meteorological Society, 28 April - 1 May 1968, Albany, N. Y.

H. Optimization techniques in weather modification. Prepared for presentation at the National Symposium on the Analysis of Water-Resource Systems, sponsored by the American Water Resources Association at the University of Denver on 1 July 1968.

Fresno State College Foundation

ATMOSPHERIC WATER RESOURCES RESEARCH

SUPPLEMENTAL FINAL REPORT

United States Department of the Interior
Bureau of Reclamation
Contract No. 14-06-D-5819 dated
1 December 1965
Amended 10 January 1968

This report summarizes the research activities conducted by the Atmospheric Water Resources Research under a contract with the Bureau of Reclamation for the period 1 July 1967 to 30 June 1968.

BUREAU OF RECLAMATION SUMMARY

INTRODUCTION

Increases in water supply resulting from weather modification activities in distinctly orographic areas have been known for a number of years. Recognition of this fact has led to the conduct of commercial weather modification activities in the Sierra Nevada mountains of California for the past 18 years. The water resources in this area are characterized by storage of runoff resulting from predominantly winter precipitation for subsequent use during dry portions of the year. Successful development of these resources has taken the form of irrigation systems which have resulted in an agricultural economy that is unsurpassed in the nation. This type of resources development has also resulted in an increasing demand for water supplies. Part of this demand has been satisfied in the past by use of weather modification, but the economic importance of water to the area indicates a desirability to produce greater amounts and more stable increases.

The weather modification activities conducted over the past 18 years have been able to show increases in annual streamflow from seeded areas of 5 to 10 percent. Thus, a program to investigate ways to increase runoff through weather modification which included proof of the ability to obtain increases by this means was not needed. Rather, a program was developed that used the results obtained by the long-term commercial projects as a basis for efforts to improve the existing techniques (1). The goal of the program has become the improvement and expansion of weather modification efforts in the Southern Sierra to provide for the greatest possible increases in water supply at the least cost.

PROGRESS

The basic approach to the problem involved consideration of the potential for water supply increase to be derived from storm systems on a year-around basis. The program was designed to provide operational research toward achievement of the goals (2), and was organized to utilize existing technology and equipment as represented by various commercial organizations on a contract basis. The program design was based on the following five interrelated projects which contribute to the overall goal:

1. Sierra Cumulus
2. Sierra Planning
3. Sierra Sensor/Seed
4. Sierra Silver
5. Hydrologic Studies

Provision for the addition of projects as desirable to accomplish the goal was written into the program design. A brief summary of the activities and results achieved in each project is given below.

A. Sierra Cumulus

Goal: The ultimate goals of Sierra Cumulus are:

1. To provide a census of meteorological characteristics and airmass properties prevalent in the Southern Sierra region from spring through early autumn. Comparisons are being made between high potential days and "no Go" days.

2. To develop a method which will aid in determining those periods and conditions of high potential for increased usable water resulting from seeding.

3. To make the above studies and results available within a 3-year period to any qualified person who may desire to undertake a commercial project in this area.

The second summer of operations on Project Sierra Cumulus was completed in 1967. This project was initially designed to be completed within 3 years, and conducted in two phases. Phase I - Pair Seeding was completed during 1967. The report Sierra Cumulus Project I - Summer 1966 (3) discussed the first season's activities. Seeding Summer Orographic Cumuli Over the Southern Sierra Range in California (4) presented preliminary results from both years to the scientific community attending the 48th Annual Meeting of the American Meteorological Society.

Phase I - Pair Seeding

This phase was designed to investigate the potential supplemental water supplies which could be obtained from initially nonprecipitating orographic cumuli developing over the Southern Sierra. The 2 summers of operation resulted in a total of 43 documented test cases conducted on pairs of developing cumuli. One cumulus turret was randomly chosen from each pair of cells and seeded with either dry ice or silver iodide. Details of these operations may be found in (3) and (4).

Several types of analyses were conducted using the 1966 and 1967 pair data. Applying the Chi square test to various categories of test cases gave high levels of significance in each category, showing almost beyond doubt that precipitation was initiated by the seeding activities.

A series of correlative diagrams was drawn to show the relationships between various meteorologic parameters, aircraft data and cloud activity. Results from these diagrams indicate that the optimum

depth for a prospective seeded cloud lies between 5,000 and 12,000 feet, and also that both types of nucleant produce good results from such clouds. More detailed discussions can be found in (4).

Time and space vertical sections, hourly surface maps with streamline analyses and upper level charts were drawn to depict meteorologic patterns occurring on test case days. It was found that on good seeding potential days, the upper level winds were southeasterly in the lower layers, shifting to southerly above and accompanied by a moist layer between 700 and 500 mb. Additional information on the meteorologic analyses can be obtained from (4).

Phase II - Area Seeding

As a result of the summer 1966 Sierra Cumulus project, several high-elevation Sierra subbasins showed indications of having a high potential for producing sizeable amounts of runoff from summer storms (5). At the end of that season, it was determined that two more seasons should complete the work necessary to show with a high level of significance the amounts possible from the area type of seeding effort.

Considerable effort was devoted to a statistical design for evaluation of amounts and determination of a suitable summer test basin. The first step in deciding which subbasins would be seeded and which would act as controls was to analyze historical runoff records for the high potential basins. The production potentials and the storm runoff relations between the high elevation basins investigated showed that Bear Creek, in the upper San Joaquin River Basin, would be a good seeding prospect. Four other basins separated by at least 15 miles to the north or south would act as controls. Once determination of the basins suitable for use was made, simulated analyses were conducted using sample data in order to further check the feasibility of such operations.

It was determined that in order for each occurrence having an average increase of 2 acre-feet per square mile to be verified in the Bear Creek Basin it would take about 2 years of operation to be significant at the .99 level. The actual number of years necessary for verification depends on the frequency of runoff occurrences after the end of snowmelt for an individual year. End of snowmelt did not take place until September 1, 1967 so the number of test cases now available after one season is severely restricted.

B. Sierra Planning

Goal: To design a research program which will provide for the development of a systematic weather modification program capable of exploiting the knowledge gained in a beneficial manner.

A project to design and plan the observing and associated data analysis systems required to determine the changes in the regional water budget resulting from applying different modes of seeding was initiated in October 1966. This project utilized subcontract assistance to provide a detailed study in the form of an idealized test program which would encompass a 5-year period. In this manner, it was possible to make use of the experience and knowledge accumulated by individuals who have been active in this general area for a number of years.

The plan is considered to be idealized in the sense that it provides an outline and the background information for a study that can be accomplished in the time period only if sufficient funding is available as required for each phase. The plan deals with specific aspects of the overall problem of water supply in the Southern Sierra Nevada, and necessarily must be fit into the overall program which considers the problem on an annual rather than seasonal basis.

The design consists of eight "working models" which are utilized to describe the various mechanisms or processes involved in the natural rain-producing processes or in the modification of such processes by artificial means. The eight models have been designated as follows:

1. Frontal
2. Convection Bands
3. Convection
4. XZ Plane Mass Flow
5. XY Plane Mass Flow
6. Mountain Quantitative Precipitation Forecast
7. Evaluation Statistics
8. Seeding Model

The conceptual and theoretical basis for each of these models is described in detail in a report (6) covering this work and will not be repeated. It should be noted, however, that the models are not complete and ready for testing at this point. Testing and refinement of the various models will be required to fully develop them to the point where description of the pertinent mechanisms and seeding effects will be possible. In addition, the success of the plan depends heavily on the establishment of observing networks both on the surface and aloft. Delay of such instrumentation will seriously hamper efforts toward observational operations required for verification of the models; and, hence, prolong the achievement of the goals.

In summary, it can be stated that an excellent beginning has been made toward the development of a complete plan for research operations in the Southern Sierra Nevada. Obviously, changes and refinements will be required in the plan. However, since a sound basis for development is available, work should progress as rapidly as possible

toward utilizing the plan in its entirety. Work is currently under way to provide for re-evaluation and refinement of the models on a subcontract basis during the summer 1968.

C. Sierra Sensor/Seed

Goal: To provide the measurements and operations required to describe and evaluate the changes in storm mechanisms resulting from artificial manipulation.

During the initial planning phases of the overall research program, it was recognized that a developmental phase would be required for any project designed to measure the parameters involved in winter storms in the Southern Sierra Nevada. New techniques and equipment for research measurements held a great deal of promise for providing the information required to completely describe the mechanisms involved in winter storms. However, these new techniques and equipment, as well as some of the older, more standard methods, were largely untried under the conditions experienced with these storms. Thus, the first phase of operations was designed to test the feasibility of various operational techniques under actual operating conditions. This phase of the project was designated Sierra Sensor I.

Testing of five observing systems was proposed for this first year. These five systems were described in a report (1) and are as follows:

1. Instrumented aircraft capable of in-flight balloon launches
2. Radar including tracking capability
3. Radiosonde
4. Forecast/Analysis facility
5. Ground-sensing network

Specifically, an attempt was made to describe flow patterns over and near the Sierra barrier by means of multiple rabals, radiosondes, neutrally buoyant balloon profiles, aircraft observations and standard Weather Bureau sources. Supplemental airmass information was obtained from Weather Bureau radiosondes, the surface-sensing network and the instrumented aircraft.

Following selection of the observing systems to be used, an idealized observing cycle was developed to permit utilization of all five systems as effectively as possible. Revision and further development of this cycle became part of the goal of this initial project. The idealized cycle is discussed and presented in detail in the report which covers Sierra Planning (6).

Numerous operational analyses of each system's performance were conducted both during the course of the project and following its completion. The first and most significant result of this project was that the most important single research tool in the operational

program was an operational tracking and surveillance radar. Neither surface nor aerial measuring profiles could be successful without it.

Aircraft operations during the project provided a great deal of design information for future operations. Icing layers during prefrontal conditions restrict aircraft penetrations of the clouds involving sustained flight in these situations. These same icing conditions also made the use of superpressure balloons designed to be launched from aircraft and fly at constant altitude levels infeasible.

It was further shown that proper design of the observing cycle which provided for the use of suitable alternate airports and which allowed climb-out ahead of restrictive conditions would permit effective aircraft operations above icing layers. In this manner, the aircraft could be used as a practical tool for collecting sounding and cloud top information. Additionally, it was found that data collection requirements during icing conditions could be partially achieved by the use of previously established remote, ground, balloon launching sites. This technique provided only limited coverage of the total project area, however.

Aircraft operations during this initial effort also proved that cumulus bands associated with postfrontal weather conditions could be penetrated without undue hazard to aircraft or crew members. Thus, it appeared possible to collect almost unlimited data in a variety of aircraft attitudes during these weather sequences. It was further determined during these flights that high-altitude profiles (25,000 to 30,000 feet) did not show sufficient parametric variations to warrant continued data collection activity at these levels. It was found that climb and descent and several shorter vertical maneuvers would provide more significant information in the form of sounding than level flight at a constant altitude.

Radar-aircraft wind circles were found useful in establishing wind velocities at selected altitudes. However, a more standardized and less complicated procedure such as a dropsonde, tracked by radar, was felt to be much less costly and somewhat more accurate. Such a technique would also release the aircraft for more diversified activities such as those described above.

Results from the use of the NCAR-Bollay ice-nucleus counter indicated that concentrations decrease rapidly with distance from industrial sites in the X-Y plane and also with altitude (7). Except near the tops of surface radiational inversions where the change in concentration was abrupt, the decreases in both the X-Y and X-Z planes are geometric. Use of this equipment in aircraft operations was found to be marginal because of its size and complexity.

The data collected and analyses made were largely concerned with airmass characteristics. Two case studies were made of storm systems occurring during the month of March 1967. These studies utilized aircraft and radiosonde data to prepare both time and space vertical section analyses during the two periods. Particular parameters employed in these cross-sectional analyses were:

1. Temperature;
2. Mixing ratio;
3. Winds;
4. Equivalent potential temperature; and
5. Pressure.

The vertical sections were supplemented with standard surface and constant pressure analyses for 3-hour intervals using Weather Bureau data. In addition, detailed analyses of hourly precipitation rates were conducted to investigate convective band characteristics for these storms. The major conclusions drawn from these studies involved the requirements for the type, amount, coverage and frequency of observations necessary to adequately describe the storm mechanisms. Accuracy of the data also was considered in the analyses.

The second season of activity on Sierra Sensor continued toward the initial goal with additional provision for actual testing of the concepts provided by the overall program design. Data collected during this project was analyzed in various ways including testing of the models (6) used to describe the storm mechanisms.

The observing systems utilized during the 1967-1968 season were as follows:

1. Tracking radar system composed of:

   a. M-33 tracker equipped with transponder receiver, analog recording system, and photographic recording of surveillance radar presentation;
   b. T-33 tracker with track capability only; and
   c. Surveillance radar with I.F.F. capability.

2. Airborne meteorological system with sensors for:

   a. Position
   b. Temperature
   c. Wet-bulb temperature
   d. Indicated airspeed
   e. Liquid water content
   f. Rain rate
   g. Time
   h. Buoyancy.

In addition, this system is equipped with cloud seeding devices, a digital data system, and dropsonde capability.

3. Radiosonde units located at Fresno and Castle Air Force Base

4. Surface sensing network, described in a separate section

5. Forecast/Analysis facility with no major changes from those during the first year

6. Support equipment including vehicles, two-way communications, warehouse/shop facilities and radar crew quarters.

Operations during the 1967-1968 season can best be summarized by use of the observing cycles developed for the project. Two basic cycles were employed to provide for data collection and operations under different conditions. Cycle A was designed to provide for data collection only, during prefrontal conditions. This cycle had a 6-hour duration, and could be repeated as many times as was deemed necessary to provide a continuous picture of these conditions. Cycle B was designed to provide for both data collection and seeding operations during postfrontal situations when aircraft operations in and around convective bands could be accomplished. Cycle B also included provision for data handling which consisted of card punching, analog chart reduction and digital data record handling. Field operations and data handling were combined AWRR - subcontractor activities. A report summarizing the activities of the subcontractor and detailing the data collected has been prepared in the form of three volumes (8) (9) (10). Volume I which contains a summary of activities is available for general distribution. Volumes II and III pertaining to computer programs and data tabulation are available on request.

Both the development of equipment and techniques and actual portrayal of the parameters involved in storm mechanisms was attempted. The analyses conducted utilizing data from Sierra Sensor II was directed toward verification of the descriptive models proposed under Sierra Planning. The analyses anticipated to contribute to the verification of the proposed models will be discussed separately below. However, in most cases only preliminary verification was possible since all observing systems were not complete enough, and could not provide all of the input necessary to permit total description by the models.

The description of fronts as proposed was primarily a synoptic model, and has not been developed to the point of numerical modelling. The analyses currently under way will be used to provide background information and indicate requirements for additional types of analyses for this model. Specific types of analyses that contribute to an understanding of this model are:

1. Time and space vertical sections as derived from radiosonde, and aircraft sondes

of the experiment, the experimental material, and the total operation of the experiment

(3) An outline of the method of analysis of the results.

RESEARCH REPORT VI

INVESTIGATION OF SPECTRAL ANALYSIS EVALUATION TECHNIQUES

SUMMARY

Snow-sensor data taken from the Cascade Project during 1966-67 were analyzed to investigate the power of evaluation methods based on spectral analysis techniques. The basic data for each collection station consists of a series of total precipitation figures on a 2-1/2 min. sampling interval. Such a time series of data will naturally contain certain frequencies or periodicities. On the low end of the spectrum will be a dominant frequency which represents the average time lag between storms as they sequentially pass over the sampling location. Peak precipitation rates will occur during the center of such storms with minimal rates in the period between such storms. On the opposite end of the frequency spectrum will be a high frequency due to the microturbulence in the atmosphere immediately in the vicinity of the collection instrument. In general, any such series of data will contain a gamut of frequencies ranging between these two extremes. One representation of the series is a linear combination of sinusoidal wave functions of varying amplitudes, each accounting for a frequency present in the time series of raw data. If a set of such series are available for a given collection station, certain frequencies will tend to repeat in several of the series. The mean square value of the amplitude (calculated over all the series in the set) for a fixed frequency measures the average contribution of that frequency in all the series of the set. The spectrum of the time series is just this mean square amplitude function versus frequency.

With this trigonometric model for the precipitation data the spectrum tells us what frequencies are most likely to appear in any given time series of observed precipitation data. With a mathematical assumption ("stationarity") that guarantees the persistence of distributional properties of data collected at the station of interest, a single series of precipitation data can be used to estimate the spectrum for all such series. The estimate is necessarily quite crude, being in the form of a histogram of broad bands of frequencies as opposed to estimation of the relative weight of each frequency. The longer the time series, the better the estimate in the sense that height of the histogram is more precisely determined and the widths of the frequency bands are diminished.

The Spectral Approach of the Verification of Increased Precipitation as a Result of Cloud Seeding

Suppose that the spectral distribution is known at a given sampling location. Suppose further, that there is a frequency range which is not very pronounced in this spectrum. If it is possible to cloud seed at a frequency in this range, and if the cloud seeding frequency persists through the process leading to precipitation at the sampling location, then comparison of pre- and post-seeding spectral estimates at this sampling location may determine whether or not the precipitation was enhanced by the seeding. It is important to realize that the spectral approach only has a chance of success if the seeding frequency persists through the complex nucleation, transport, and precipitation collection phenomena.

Simulation Studies to Determine the Feasibility of Verification of Cloud Seeding Using Spectral Analysis Techniques

The literature indicates that simulation studies show that if cloud seeding induces a 5 percent increase in the average precipitation level, then a spectral analysis approach to the design and evaluation of cloud seeding experiments will detect this effect in the precipitation data. The following reasoning gives rise to this conclusion. A spectral estimate is calculated from precipitation time series data at a given station. Now a frequency not dominant in the estimated spectrum is induced into the time series raw data. The induced signal is a deterministic square wave. Now the sample spectrum is recalculated. When the induced square wave has an amplitude of approximately 5 percent of the precipitation average, a blip appears in the estimated spectrum which, it is felt, is significant enough to be detected.

It is felt that this is not a realistic way to evaluate the feasibility of the spectral analysis approach. This conclusion is based on similar simulation work. It is concluded that the level of the induced precipitation must be about 30 percent of the average precipitation rate in order for this induced frequency to be detectable in the estimated spectrum. The primary reason for the difference in these two calculations is the assumption surrounding the model for the induced signal; i.e., (1) assuming that the induced precipitation signal is identical to the on-off square wave which represents the seeding signal, or (2) assuming that this square wave undergoes modification during nucleation, transport, and precipitation prior to the collection time of the precipitation sample. Without going into the details of the mathematical modeling, the effect is that the square wave signal develops a random amplitude distributed about the cloud seeding rate, and that the time interval between seeding and arrival of the induced precipitation at the sampling site randomly varies about some average quantity. This is an attempt to model the fact that there will be a variable transport time between seeding and arrival at the sampling station due to variation

in wind direction and speed, and that there will be a variation in the total fraction of the induced precipitation which eventually arrives in the neighborhood of the sampling station. With this type of model a 5 percent influx is not detectable in the sampling spectrum. A 30 percent influx is the smallest which causes a significant blip in the estimated spectrum.

REPORT OF THE UNIVERSITY OF WASHINGTON

The Automatic Cloud Condensation Nuclei Counter

As described in the monthly reports the automatic CCN counter developed by Radke and Hobbs was transported by helicopter to the Atmospheric Sciences Research Station on Mt. Olympus, Washington. The instrument was operated at this location from January 30 to March 30, 1968, during which time a wide variety of meteorological conditions were experienced. The sampling site was sufficiently good that we now have a good base line measurement for the concentration of CCN active at 1 percent supersaturation winter maritime air. Counts of 40 cm^{-3} were typical for stormy weather with westerly flow. Modified maritime air had an average of 80 cm^{-3} CCN, and air modified by flow through the Puget Sound Basin averaged 140 to 180 cm^{-3}. Probably the most interesting observations that were made were those which linked the CCN count with upwind convective activity. The CCN count decreased when cumulus clouds were developing upwind, and increased again when the clouds dissipated.

In addition to the standard data reduction, a computer cross-correlation study has been made of all the parameters that were measured in the Olympics. On some occasions the CCN concentration showed a good correlation with the light scattering coefficient of the air and the condensation nuclei measurement. The degree of correlation seems to depend on meteorological conditions; heavy clouds or precipitation reduce the cross-correlations considerably.

Following the field program in the Olympics, considerable effort has been expended in modifying and improving the automatic CCN counter.

In June and early July we participated in the University of Washington's forest fire studies at Pack Forest in the Rainier National Forest. The Cloud Physics Laboratory Mobile Lab was stationed downwind and 1000 feet above the level of the fire. The measurements showed that burning wood products produce copious CCN effective at 1 percent supersaturation, but that the particles produced are relatively ineffective at 0.2 percent.

The Sodium Particle Counter

The probable importance of sea salt particles in precipitation from warm clouds has long been recognized. The Cloud Physics Laboratory built a flame spectrometer to count these chemically distinct CCN. The counter was used during the latter part of the Mt. Olympus field program and gave excellent results. The concentrations of particles containing sodium could be clearly linked to wind direction and cloud and precipitation events. In the last few months some effort has been expended in making this device more simple to operate, calibrating it, and improving the data format.

Nephelometer

A nephelometer for measuring the light scattering of the air is being built in the Cloud Physics Laboratory. The machine work has been completed but the electronic work is not scheduled for completion until the end of July 1968.

Laboratory and Field Research Program

Our experimental program during 1968-69 will continue to emphasize the measurement of cloud condensation nuclei, although a number of additional parameters will also be measured. We plan to build a smaller version of our automatic cloud condensation nucleu counter which will be suitable for use in an aircraft. We will also carry our some developmental work on a superior version of the counter which uses a monochromatic nephelometer to measure the extinction coefficient of a cloud of droplets. During the past few months we have built a sensitive device for measuring the concentrations of sodium particles (presumably NaCl) in the air; we hope to develop this instrument to the point where it can give a continuous read-out in real time of the sizes and concentrations of salt particles in the air. Finally, we will attempt to develop an automatic cloud droplet spectrometer suitable for use from an aircraft.

Using the instruments described above, and others which are available commercially, we plan to make simultaneous measurements from aircraft of the concentrations of cloud condensation nuclei, sodium particles, cloud droplet spectra, and liquid water contents. These measurements will be made in various synoptic situations over the Pacific Ocean, along the Pacific Northwest coast, in the Puget Sound region, and in eastern Washington. We will also investigate the contributions which forest fires and local paper mills make to the number of condensation nuclei in the atmosphere, and the effects that these sources have on the microstructures of adjacent clouds. This program should yield valuable information concerning the influence of cloud condensation nuclei on the development of cloud droplets in different types of air masses.

Theoretical Program

In order for significant progress to be made in cloud modification it is essential that much more effort be devoted to the development of theoretical models in which the effects on precipitation of changing the microphysical characteristics of clouds (e.g. concentrations of cloud condensation nuclei and ice nuclei) can be investigated by numerical methods and then compared with field observations. We believe that the time is opportune for the development of such a model for the clouds that form over the Olympic and Cascade Mountains.

Interim Report

Environmental Science Services
Administration

This report, prepared by the Bureau of Reclamation, summarizes a number of papers submitted by ESSA personnel from the Weather Bureau's Techniques Development Laboratory and the Special Studies Branch of the Office of Hydrology.

STORM PRECIPITATION AND ASSOCIATED METEOROLOGICAL FACTORS OVER THE SNAKE RIVER BASIN ABOVE ANATONE, WASHINGTON

ABSTRACT

The 31 most intense storms over the Snake River Basin above Anatone, Washington, have been studied in relation to the circulation in the atmosphere below the 500-mb level and sources and magnitude of moisture. This report presents the results of that investigation and a brief summary of the results. An attempt has been made to determine the relative importance of orography and the convergence mechanism within each storm in producing precipitation.

SUMMARY OF RESULTS

Introduction

The number of storms studied do not comprise a complete sample of the major storms over the Snake River Basin. In addition, time did not permit the attempt to compile typical or characteristic storm patterns which are responsible for moderate to heavy precipiation over the Snake River Basin above Anatone, Washington. Some tentative conclusions, however, can be made from a limited examination of this storm sample.

Seasonal Variation

The majority of the storms occur during the months from November to February (Table 1). The month of greatest frequency of storm occurrence, however, was June with slightly over 20 percent of the total storm sample. All but one of the June storms occurred within the first half of the month, and three of the four May storms occurred in the second half of the month. The early spring and the summer months do not contribute to this series of storms. All storms with a basin average precipiation greater than 1.0 inch occurred during the winter.

Table 1. Months of occurrence of storms producing moderate to heavy precipitation over the Snake River Basin above Anatone, Washington

J	F	M	A	M	J	J	A	S	O	N	D
5	2			4	7			4	2	2	5

Importance of Convergence Mechanism

An attempt was made in each of the storms to ascertain whether the precipitation was primarily the result of atmospheric processes,

convergence, or primarily a result of orographic lifting. Our techniques for making this distinction are subjective and are not exact, but they provide some useful insight into the relative importance of the two mechanisms. It must be remembered, of course, that the precipiation in every storm in a mountainous region such as the Snake River Basin results from a combination of the two processes. Table 2 shows the predominant mechanism for each storm, grouped by the number of standard deviations of the peak observed moisture above the mean daily value for the storm date. Because the distribution of moisture values is not normal, having a lower but not an upper bound, the use of standard deviations based upon a normal distribution will give values which show greater departures above the mean than is numerically realistic. The use here is merely to provide an easily computed relative scale to compare the various storms. One conclusion that can be drawn from the data presented in Table 2 is the importance of a relatively strong convergence mechanism when the moisture values are only slightly above the mean values. As the exceedence of the moisture over the mean increases it becomes less necessary to have a strong weather system to produce moderate to heavy precipiation in this region.

Table 2. Predominant cause of precipitation grouped by exceedence of the mean daily observed moisture value (3 storms without moisture values)

<2.0			2.0-3.0			>3.0		
O	C	E	O	C	E	O	C	E
1	7		3	6	3	4	3	1

The convergent mechanism is more important in the warm season than in the winter. This is shown by the fact that the 15 storms studied during the period May through September, 13 were considered convergent and only 2 orographic. On the other hand, the December through February storms were considered convergent in only 2 cases with 6 listed as orographic and 4 where orography and convergence played essentially equal parts.

Moisture Source

There appears to be a trend for a seasonal shift in the moisture source for these storms. For the late fall and winter storms the primary moisture source is the northern Pacific Ocean from approximately the latitude of California northward. In the early summer or late spring storms the moisture source is more varied and tends to shift farther southward and is primarily off the southern California coast. Occasionally, the moisture source is even farther south. Moisture from the Gulf of Mexico was present in some spring,

early summer and fall storms, but was not found in any of the winter storms studied.

SYNOPTIC CLIMATOLOGY OF THE INTERMOUNTAIN REGION OF THE WEST

INTRODUCTION

Development of the synoptic climatology of the intermountain region of the West continued during the past fiscal year, but at a reduced level of effort. Investigations carried out and completed earlier have been described briefly in the Interim Reports for the years 1965, 1966, and 1967. A more complete discussion of these results appears in the following publications:

1. "A Synoptic Climatology of Winter Precipation from 700-mb. Lows for Intermountain Areas of the West," by D. L. Jorgensen, W. H. Klein, and A. F. Korte. Washington, D.C., U.S. Department of Commerce, ESSA, Weather Bureau, Technical Note 45-TDL-4, May 1966, 25 pp.

2. "A Synoptic Climatology of Winter Precipitation from 700-mb. Lows for Intermountain Areas of the West," by D. L. Jorgensen, W. H. Klein, and A. F. Korte. Journal of Applied Meteorology, Vol. 6, No. 5, October 1967, pp. 782-790. (Condensation of Technical Note 45-TDL-4 listed above.)

3. "Charts Giving Station Precipitation in the Plateau States from 700-mb. Lows during Winter," by D. L. Jorgensen, A. F. Korte, and J. A. Bunce, Jr. Weather Bureau Technical Memorandum WBTM-12, October 1967, 15 pp. and 102 charts.

4. "Relation between Upper Air Lows and Winter Precipitation in the Western Plateau States," by W. H. Klein, D. L. Jorgensen, and A. F. Korte. Monthly Weather Review, Vol. 96, No. 3, March 1968, pp. 162-168.

5. "Climatological Probabilities of Precipitation for the Conterminous United States," by D. L. Jorgensen. Weather Bureau Technical Report WB-5, March 1968, 60 pp.

The studies mentioned in the above list bring out the complexities of the storm systems responsible for weather in the western part of the country. The complex storm characteristics result from many factors, the two most important of which appear to be, first, the natural variability of the storm systems themselves (no two storms are alike), and, second, the added complications contributed

by the tremendously varied terrain of the intermountain region. These factors are reflected in relationships giving the distribution of weather and precipitation associated with the storm systems.

An additional factor influencing the development of a synoptic climatology for the area is possible variation of storm characteristics with season. It is known, and this is supported by the accumulated data for the spring season, that upper lows form more frequently over the western United States in spring than in winter. Whether or not the greater activity of the atmospheric circulation over the area during the spring months is accompanied by a different relationship between circulation and precipitation, when compared with winter, can be determined only by a separate investigation of the data for the spring season. If significant differences do not appear, the data for the two seasons can be combined, thus giving a larger and therefore more representative sample.

In order to investigate possible seasonal differences in the occurrence and structure of storms, the study is being extended to include the spring and fall seasons, with summer to be considered at a later date. These and additional studies which are being undertaken are described in the remainder of this report.

Completed Tasks

During the past year the main emphasis has been on completion of the investigation for the winter season. The paper published in the Monthly Weather Review entitled "Relation between Upper Air Lows and Winter Precipitation in the Western Plateau States" gives the general relationships between upper lows at the 850-, 700-, 500-, and 300-mb levels and the associated precipitation for all stations in the Plateau region for the winter season. As has been pointed out in previous reports, this approach tends to average out the orographic effects, leaving, in the main, the precipitation pattern reflected by the dynamic effects of the storm. When a satisfactory precipitation record of sufficient length is available for a particular station, a somewhat more useful product can be obtained by dealing with each individual station separately. This approach results in maintaining both the orographic and dynamic components which are operating to produce precipitation at the station. The phase of the investigation dealing with precipitation distributions about individual stations was completed last year for the 700-mb level, and a selection of stations was analyzed and published under the title "Charts giving Station Precipitation in the Plateau States from 700-mb Lows during Winter." Similar charts for the 850- and 500-mb levels are described in the following subsections. With the addition of these two levels, no further work along these lines is contemplated for the winter season.

1. Winter Precipitation at Individual Stations from 850-mb Lows.

This portion of the investigation was presented at the 49th Annual Joint Meeting of the American Geophysical Union and the American Meteorological Society held April 8-11, 1968, at Washington, D.C.

Earlier studies indicated that greater specification of precipitation from tropospheric lows was obtained from the lower levels of the atmosphere than from higher levels. For the intermountain region, the 850-mb level most nearly coincides with the average surface elevation and therefore could be expected to yield the best relationship between atmospheric circulation and precipitation. For this reason, and to add to our overall knowledge of the structure of storms with closed circulations, the 850-mb level was investigated in a manner similar to that already carried out for the 700-mb level. As in the earlier study, the winter months of December, January, and February from 1951 through 1964 were used as dependent data.

The precipitation distribution about each of the 280 stations in the Plateau area was obtained for the 1,110 lows occurring during the period of record. This was accomplished by reversing the computer program so that the station, rather than the upper low, was placed at the origin of the grid system. The computer then printed out for each of the 280 stations the number of precipitation and nonprecipitation cases and the average precipitation amount which occurred in each cell of the grid for each of the three intensity classes. A selection of 35 stations was made on the basis of the importance of the station and the completeness of the precipitation record for which analyses of the computer data were carried out. The resulting 105 charts are designed for operational use.

2. Winter Precipitation at Individual Stations from 500-mb Lows.

Although precipitation, on the average, appears to be generated in the lower levels of a system characterized by closed circulation, it does not necessarily follow that the lowest levels are the most useful from a forecasting standpoint. This problem results from the greater difficulty experienced in prediction of low level flow. In the long run, that level will be the most effective operationally which contains the optimum combination of predictability of the flow with a high degree of specification. This optimum combination may very well depend on the station elevation, the geographic location of the station, and other factors.

Current numerical prediction methods appear to be most successful in the middle troposphere, i.e., near the 500-mb level, with the highest degree of accuracy attained at this level. Whether or not

this greater accuracy is sufficient to overcome the loss in specification at this level (as compared to the 850-mb level, for example) can be determined only from examination of the combination of prediction and specification for all levels. If prediction is not involved, then the problem does not arise.

As a first step toward solution of this problem, it is necessary to determine how well each level specifies the precipitation. Therefore, the investigation has been extended to include study of upper lows at the 500-mb level. The precipitation distribution about each of the 280 stations in the area of interest was obtained for the 875 lows occurring during the period of record. This was accomplished in the same manner as for the 850- and 700-mb levels, and results were printed out by computer. The data have been plotted and analyzed for the same selection of 35 stations used for the other 2 levels, thus allowing a direct comparison between levels.

Upon completion of individual station charts for the 850- and 500-mb levels, it is planned to issue them in published form as a Technical Memorandum.

Continuing Investigations

Development of a synoptic climatology for the intermountain region is continuing along several lines. These include extension of the studies already completed to additional seasons of the year, as well as several new approaches. The investigations currently underway are as follows:

1. Extension to the spring season of procedures completed for winter
2. Development of monthly normal charts for the 1,000-, 850-, 700-, 500-, and 300-mb levels
3. Development of regression equations by means of a screening technique to predict winter precipitation
4. Investigation of conditional probabilities of precipitation for short time periods
5. Accumulation of upper-air data on magnetic tape.

These projects are in various stages of planning and development, but all are being actively pursued. They are described in more detail in the following subsections.

1. Extension of Synoptic Climatological Study to Spring Season

In order to extend this investigation to the spring season, upper-air charts have been examined for the months of March, April, and May for each year from 1952 through 1964. The positions and intensities of closed lows appearing at the 850-, 700-, and 500-mb levels have

been tabulated for this period of record. Precipitation occurring during the spring months for this same period has been recovered by the National Weather Records Center from their files at Asheville, North Carolina, for 157 stations in the intermountain area. This number of stations represents a considerable decrease from the 280 stations used in the earlier studies. This decrease was made as a means of reducing the effort and expense of recovering and processing precipitation data. The greater number of cases involving upper lows during the spring season should help in maintaining the representatives of the data.

As a first step, tabulations involving the 700-mb level have been forwarded to NWRC for processing. The computer will give the general precipitation pattern associated with low centers, as well as the patterns for individual stations, each for the three intensity classes. When this processing has been completed, analyses will be made of the resulting printouts, and the results will be compared with similar analyses for the winter season.

2. Development of Monthly Normal Charts for Five Atmospheric Levels

Recently acquired upper-air data are being used to generate normal charts for the 1,000-, 850-, 700-, 500-, and 300-mb levels. These data are being obtained on magnetic tape by contract from Litton Systems, Inc. (see Subsection 5.), through partial support from the Bureau of Reclamation.

The period of record involved is from November 1961 through October 1968, with the normals being derived upon receipt of data for the succeeding months of the current year. Normals are being derived separately for each of the two observation times per day, 00Z and 12Z, as well as for the two time periods combined, to give eight normal charts per month. If diurnal changes are found negligible, only the combined periods will be used. These charts are required in carrying out the synoptic climatological studies described in Subsection 1. above.

Upon completion of the normal charts for each of the 12 months, it is planned to issue them in published form as a Weather Bureau Technical Report. These charts would fill a pressing need in the field of meteorology for charts of this nature.

3. Development of Prediction Equations for Winter Precipitation

This investigation involves use of a statistical screening program on the CDC 6600 computer in Suitland, Maryland, to derive multiple regression equations for specifying and predicting precipitation each day at selected stations. This project was mentioned under

"Future Plans" carried in Interm Report No. 3, July 1967, and is now being initiated.

Screening of daily precipitation at 108 stations in the conterminous United States for the months of December, January, and February for the period of record from 1964 through 1968 will be made against 31 meteorologically significant variables. These will include height, vorticity, and temperature fields at 5 atmospheric levels, dew point depression fields at 3 levels, and advection of each element at various levels. The predictors will have values at the beginning and end of the 12-hour precipitation period. They will be taken from twice-daily data at 181 grid points obtained from Litton Systems, Inc. The predictands (precipitation occurrence) will be divided into 4 groups of 27 cities each making up the northeast, southeast, northwest, and southwest portions of the country. The winter of 1968-69 will be used for testing on independent, prognostic data.

4. Investigation of Conditional Probabilities of Precipitation for Short Time Periods

This investigation is a sequel to the study recently published as Weather Bureau Technical Report No. 5 giving the climatological probability of occurrence of precipitation by months for 6-, 12-, and 24-hour periods for 108 stations in the United States. The same data used in this earlier study are being processed again to give additional information on the occurrence of precipitation based on recent or existing weather conditions. The study will investigate the quantitative and qualitative aspects of the occurrence of precipitation for various time periods depending on the condition that precipitation did or did not occur during a specified prior period.

The occurrence of precipitation during a given period of time is an indication of the precipitation producing potential of the existing atmospheric circulation. Since atmospheric conditions tend to persist, precipitation is more likely to occur and perhaps be heavier following a wet period, and similarly, is less likely with lighter amounts following a dry period. Forecasters have found that persistence relationships are a substantial aid in making short period forecasts, and this study will make such country-wide information readily available to the forecasters.

The results of this investigation will be the conditional probability of precipitation as a function of location, season, time of day, and prior weather. They are expected to be published either as part of a forecaster's manual or separately as a Technical Memorandum.

5. Accumulation of Upper-Air Data on Magnetic Tape

This project involves the extraction of various data fields from the Fleet Numerical Weather Facility files. These fields include pressure surfaces at 1,000-, 850-, 700-, 500-, and 300-mb levels, and selected temperature and dewpoint fields. The period of record includes November 1961 through January 1968 for which the data extraction has been completed, and in addition the current year which is being completed on a month-to-month basis.

The project is being carried out under contract with Litton Systems, Inc.

A SYNOPTIC CLIMATOLOGY OF WINTER PRECIPITATION FROM 700-MB LOWS FOR INTERMOUNTAIN AREAS OF THE WEST[1/]

Donald L. Jorgensen, William H. Klein, and August F. Korte

ABSTRACT

A synoptic climatology of precipitation resulting from upper closed lows is developed for the intermountain area of the West for the winter months of December, January, and February. Precipitation amounts at about 280 stations for 12-hour periods, centered at upper-air observation times and expressed as percentages of 7-day normal station amounts, are related to the positions of low centers at the 700-mb level through the use of a moving grid system. The upper lows are classified into three intensity categories according to the departure from normal of the central height. For each category, the average precipitation amount, extent, and frequency of occurrence over the area of the grid system are presented. The area of maximum precipitation is found just southeast of the centers of intense 700-mb lows. As the intensity of the low center decreases, not only does the frequency of precipitation diminish, but the area of maximum frequency also progressively shifts to positions south and west of the center.

CHARTS GIVING STATION PRECIPITATION IN THE PLATEAU STATES FROM 700-MB LOWS DURING WINTER*

by

Donald L. Jorgensen, August F. Korte, and James A. Bunce, Jr.

ABSTRACT

Precipitation resulting from 700-mb low systems during the winter months has been examined for individual stations in the Plateau region. Marked differences are noted in the frequency with which precipitation occurs, depending upon the storm intensity and the relative positions of the upper low systems. Locations of the cyclonic centers with the heaviest amounts of precipitation and the highest frequencies of occurrence vary from positions directly over the observing station to positions several hundred miles to the east, north, and west. Lowest frequencies of occurrence and lightest amounts are generally observed when the center passes

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1/This paper is a condensation of an earlier technical report (Jorgensen et al., 1966).

*A condensation of this paper was presented at the annual joint meeting of the American Meteorological Society and the American Geophysical Union, Washington, D.C., April 17-20, 1967.

well to the south of the station. These differences between stations are explained in terms of geographic location and the local and broadscale surrounding topography. Use of the derived results as a forecast aid is illustrated.

RELATION BETWEEN UPPER AIR LOWS AND WINTER PRECIPITATION IN THE WESTERN PLATEAU STATES

William H. Klein, Donald L. Jorgensen, and August F. Korte

ABSTRACT

A comparison is made of the relative effectiveness of the cyclonic circulation pattern at four different tropospheric levels in specifying winter precipitation over the intermountain area of the western United States. This is accomplished by developing the synoptic climatology of precipitation resulting from lows at the 850-, 700-, 500-, and 300-mb levels. Twelve-hour precipitation amounts (expressed as a percent of the 7-day normal) at 280 stations in the Plateau States for 13 years are related to the positions of nearby low centers through a computer system of moving coordinates. For each level, the upper lows are classified into three intensity categories according to the departure from normal of their central heights. Average precipitation amount, distribution, and frequency of occurrence are then calculated for the area of the grid system. The dependence of these precipitation characteristics upon the level, intensity, and location of the upper low is described and illustrated. The geographical distribution of lows at the four upper levels and a schematic model of their associated precipitation are also presented. It is concluded that the effectiveness of upper lows in producing precipitation generally varies directly with their intensity and inversely with elevation.

CLIMATOLOGICAL PROBABILITIES OF PRECIPITATION FOR THE CONTERMINOUS UNITED STATES

Donald L. Jorgensen

ABSTRACT

Climatological probabilities, as represented by observed frequencies, have been generated for 6-, 12-, and 24-hour periods for 108 stations distributed over the conterminous states. A 15-year period of record was used which included the years 1949 to 1964. The results are presented in the form of plotted data with smoothed topographically dependent analyses giving 7 charts for each month, for a total of 84 charts.

Seasonal and diurnal trends in the observed data are discussed briefly in terms of the synoptic and topographical influences for various regions of the country. Frequencies of precipitation occurrence are strongly influenced in a unique manner by topographic and synoptic influences, with extreme variability observed in the western states. Smooth patterns are observed in the Great Plains with the pattern further distorted by the mountains in the East. Seasonal trends in precipitation occurrence are influenced by the shifting tracks of cyclonic systems in the fall-winter-spring period, with a transition to thunderstorm precipitation during the summer months.

PROBABILITIES OF STATION PRECIPITATION IN THE WESTERN PLATEAU STATES FROM 850-MB LOWS DURING WINTER*

ABSTRACT

An earlier study of precipitation from 700-mb lows for selected stations in the Western Plateau has been extended to include lows at the 850-mb level. As in the earlier study, precipitation at individual stations is shown to vary with the intensity and position of the low and with the surrounding topography. The specification of the frequency and amount of precipitation is compared for the two levels. At lower latitudes, the effectiveness of the two levels is similar, but the 850-mb level is considerably more effective at the higher latitudes. This increase in effectiveness appears to result from a greater frequency of closed centers at lower levels which are associated with open troughs aloft. Use of the derived charts as forecast aids is described.

METEOROLOGY OF MAJOR STORMS IN WESTERN COLORADO EASTERN UTAH

R. L. Weaver

ABSTRACT

The 42 most intense general storms in eastern Utah and western Colorado since 1899 are studied in relation to the observed or estimated broadscale upper air circulation patterns and sources of moisture. The report summarizes individual analyses of the storms. Storms are typed by reference to the behavior of the 500-mb patterns. The role of upper lows in transporting moisture is emphasized. Indices are developed which evaluate storm moisture, temperature, and

*Paper presented at the 49th Annual Joint Meeting of the American Geophysical Union and American Meteorological Society, April 8-11, 1968, at Washington, D.C. Conference details are in the Transactions, AGU, Vol. 49, No. 1, March 1968.

influence of topography. The relative importance to the precipitation sequence of peak moisture versus proximity of upper lows or troughs is compared. Moisture source regions are related to storm type and season. Local topographic effects are summarized by upper wind direction. Other relationships between various factors are discussed.

2. Surface synoptic and constant level charts as derived from standard Weather Bureau data and supplemented by project observations

3. Precipitation patterns as portrayed by time-lapse photographs of the surveillance radar

4. Surface precipitation rates as determined from the telemetered gage network and standard Weather Bureau cooperative stations.

Essentially, the acitivites on this aspect of the project are concentrated on the development of preliminary model descriptions.

The initiation of a climatology of convective bands was one goal of the analysis of data during the current year. The analyses which provides for classification and characterization of the convective bands are:

1. Time and space vertical sections
2. Surface synoptic and constant level charts
3. Precipitation patterns
4. Precipitation rates and total amounts
5. Portrayals of aircraft penetrations of the bands
6. Vertical profiles of radar returns from the bands

The contribution to the convection model which has recently been computerized is again largely preliminary. The verification of this model requires accurate measurement of vertical winds in addition to the other parameters. Attempts were made during the 1967-1968 season operations to measure as many of the required parameters in and around convective cells associated with bands as was possible with one aircraft. The types of analyses which provide background information for future activities designed to compare predicted versus measured systems are:

1. Profiles of aircraft penetrations made in and around convective cells

2. Vertical profiles as obtained from radiosondes and dropsondes

3. Vertical time and space sections

4. Surface hourly precipitation rates

The one model scheduled for actual testing during the 1967-1968 project was the X-Z plane mass flow. This model has been computerized and project activities were designed to provide the necessary data. Essentially, testing consisted of prediction of an outflow sounding over the crest of the mountains on the basis of radiosonde inflow data observed in the valley on the upwind side.

Descriptions of the X-Y plane mass flow are also being attempted. Analyses of the changes in pressure along a constant potential temperature surface and changes in potential temperature on a constant pressure surface are used as a basis for description of the flow. The particular data sources used for these studies will be:

1. Flow patterns derived from rabal information
2. Vertical and horizontal sections obtained from radiosonde and dropsonde data
3. Constant level portrayals

D. Sierra Silver

Goal: To provide information regarding diffusion patterns through silver occurrences in precipitation samples which may be related to seeding activities up-wind of the observation sites.

Questions of the dispersion of silver iodide seeding material are basic to any of the studies envisioned. Relative amounts and areas affected by seeding materials from various dispensing systems are required to provide insight into the effectiveness of seeding techniques used. The problem of evaluation of effectiveness of seeding does not only revolve around the ability to determine how to provide seeding materials to the storm systems, but also how to determine which areas have been affected by comparable concentrations. It is further recognized that the detection of silver in precipitation does not provide conclusive proof of the amounts of silver iodide which entered into the precipitation process. However, the amounts of silver in the sample can provide an index of the effectiveness of dispensing techniques and the amounts of dispersion experienced in various areas.

Operations during the first year were conducted primarily for the purpose of:

1. Obtaining representative samples from a variety of locations and subject to varying meteorological conditions with which comparisons between seeded and unseeded areas could be made.

2. Developing the sample collection and handling techniques required to provide uncontaminated samples for analysis by the neutron activation method.

Under this project, the complicated chemical processing involving ion exchange operations and the actual neutron activation of the concentrated sample were conducted by the staff of the Desert Research Institute. Analyses of the results have been conducted on various phases of the work by the staffs of both AWRR and the Desert Research Institute.

A total of 45 samples was collected during the first winter season. In general, the samples were collected immediately following storms. It appears that single storm samples, collected as soon after the storm period as possible, provide better information than integrated samples. Since the movement of silver through the snowpack as the snow melts is not adequately known, the snow in the integrated sample may have lost some of its silver content to the ground or snow layers beneath the sample zone. Thus, even samples composed of snow from all layers may be subject to silver loss. The importance of this loss requires that care be taken in obtaining only new snow or snow from identifiable single layers and in making accurate notes.

The maximum concentration of silver found in a Southern Sierra snow sample was 5.2×10^{-10} grams per milliliter. Absolute minimum concentrations are more difficult to obtain but the smallest amount measured in the Fresno area did not exceed 7.9×10^{-12} grams per milliliter. The median concentration was 318×10^{-11}. Each sample was accompanied by an error factor which was a combination of transfer efficiency, contamination from chemicals used and background noise during activation. The errors varied from 83 percent to 5.2 percent. In most cases the high possible errors occurred with low sample concentrations of the magnitude 10^{-12}, which were near the minimum detection level of the analysis system.

Preliminary results from analysis of single sample concentrations indicates that the storm unit of measurement is most usable. There were three storm periods after which samples were obtained from both the suspected seeded area and the control basin. From these cases it appears that the effects of seeding can indeed be detected in the treated area indicated by the larger absolute values of silver found and also the larger values when compared to the untreated area.

E. Hydrologic Studies

Goal: To conduct hydrologic investigations for the purpose of evaluating the effects of artificially induced precipitation and to provide information required for the design of an effective program.

A twofold purpose has been established for the hydrologic studies conducted during the initial 2-year period of operations. These can be broadly categorized as:

1. Individual studies with objectives directed toward meeting the general goal of the program.

2. Support studies with objectives directed toward meeting the specific objectives of other projects.

Hydrologic studies during FY 1968 involved three individual studies and three support studies. The individual studies were:

1. Summer hydrology of the high Sierra
2. Regional hydrologic analysis of historical water year data
3. Delta precipitation study

Support studies were:

1. Study basin location
2. Sierra cumulus evaulation
3. Central Sierra project

Summer hydrology of the high Sierra was a project designed to study the effect of thundershower activity upon runoff in California's Sierra Nevada. The time period of analysis was from the end of snowmelt through the end of the summer period. Quantity and timing of runoff were estimated with respect to basin physical characteristics which contribute to production of summer runoff. Findings of this study were published in a paper given at the Western Snow Conference, Boise, Idaho in April 1967 (6).

The activities during FY 1968 were primarily concerned with the expansion and refinement of these earlier studies. Their goal is to provide information regarding the potential for runoff from the basins in order to design cloud seeding operations which provide the maximum return. Specifically, this study involves the investigation of runoff as related to physical characteristics and includes all of the basins on both sides of the Southern Sierra Nevada barrier. Factors considered in this study include elevation, vegetative cover, slope and aspect, rate of water use by basin, direction of barrier, basin size and pertinent meteorological characteristics. Analyses include:

1. Summer runoff per occurrence in terms of physical basin characteristics
2. Number of runoff occurrences in terms of physical basin characteristics
3. Size distribution of occurrences within specified time periods during summer.

The regional hydrologic analysis of historical water-year data had the goal of delineating areas of apparent runoff increase or decrease in the Sierra Nevada resulting from weather modification. This study was designed to investigate the relative trends in runoff on a regional basis, and develop a better understanding of the areal extent and magnitude of the effects of historical weather modification activities. The investigation included analysis of Sierra East Side basins to identify additional control basins, the effect of West Side seeding on East Side basins and the effect of previous seeding operations. The work required computer operations involving streamflow records for all watersheds from the American River

basin south through the Kern River basin for the period from 1925 through 1964. The results of these analyses were combined with the results obtained from the previous year, and were summarized in the form of a map showing areas of effect. A paper describing this work was presented at the American Meteorological Society's National Conference on Weather Modification in Albany, New York, and the Western Snow Conference, Tahoe, Nevada, April 1968 (13).

The delta precipitation study is intended to analyze Sierra Nevada's winter precipitation on a storm-by-storm basis to establish the relationship between the effects of historical seeding projects and the meteorological characteristics of the storms. The approach to this study involves the use of the computer, and requires the development of a basic data library in card form. Specifically, a program has been developed which selects storm periods and precipitation amounts from the historical record based upon:

1. Days with little or no precipitation recorded
2. Time of year
3. Meteorological parameters

In addition, the study considers the storm type for each period selected, whether it was seeded or not and the seeding technique used. The analysis requires the development of correlations between precipitation amounts at the target stations, storm characteristics, seeding and precipitation amounts at a single or group of control stations. This portion of the study is currently under way.

Consideration of the portion of this study involving snowpack data is virtually the same as consideration of precipitation gage data in concept. However, the concentration of snow courses in the high Sierra is much greater than that of daily precipitation gages. Unfortunately, the frequency of measurement on snow courses does not permit inspection of individual storms, but only groups of storms by months. The approach to this study necessititates the tabulation of differences in monthly snowpack measurements for the historical period 1930 - 1967. The next step in the project is the development of a program to compute the precipitation occurring at control stations during the period between the snow measurements. It is also necessary to develop predominant storm characteristics for each such period. Included in the analysis is consideration of periods of unusual melt based on the temperature records. With this data it will be possible to develop correlations between increase in snowpack at the target, increase in precipitation at control course, predominant storm type, seeding and snowpack at the control courses. This portion of the study is currently under way, also.

The support study which considered study basin location was directed toward selection of a study basin for proposed field testing programs. This study involved the following analyses:

1. Precipitation analysis. This analysis considered precipitation on a monthly basis in an effort to develop measures of monthly variability from north to south along the range. The objective was to establish areas which typified the southern Sierra on the basis of the number of storms and storm precipitation quantities. Investigations of data along several transects of the Sierra were also made.

2. Runoff analysis. In connection with the regional hydrologic studies, an analysis similar to the precipitation analysis was conducted to identify basins with similar seasonal distrihution and quantities of runoff. Results of the study were used not only to assist in the selection of a study area, but provide information for the design of the evaluation model used in the regional hydrologic study.

Hydrologic studies were also conducted in direct support of the Sierra Cumulus Project. Phase II operations of Sierra Cumulus were designed to determine the amounts of increase in runoff resulting from cloud seeding efforts. Briefly, the hydrologic studies involved the comparison of runoff amounts from a high elevation target basin with the runoff from four other high elevation control basins. Differences between predicted and observed daily hydrographs from the target basin were correlated with seeding activities and meteorological conditions. The use of daily hydrographs as a basis for evaluation required positive identification of the source of runoff which in turn caused operations to be restricted to the portion of the water-year occurring after the end of snowmelt in the high Sierra. Thus, the overall evaluation was designed to be conducted during the latter parts of the 1967 and 1968 summer seasons. Evaluation of the results for the 1967 season has been completed; however, definite conclusions of the effectiveness of the program cannot be made until a sufficient number of observations are made, as previously discussed.

A series of computerized studies were also conducted to assist with the evaluation of Phase I activities of Sierra Cumulus. These studies involved use of the data collected regarding the effects of pair seeding, and resulted in identification of trends and effects requiring more detailed study. In addition, a brief analysis of Weather Bureau radar records from Sacramento was made to determine if thundershower activity could be identified and located geographically in the San Joaquin basin. Results of this study indicated that only exceptionally large buildups could be identified at that distance, and operator interpretation could negate any statistical conclusions of significance to the Sierra Cumulus Project.

A study has been conducted to gain background on the hydrology and meteorology of the proposed test-seeding area in the Stanislaus-Mokelumne watersheds. All suitable available records of runoff,

precipitation and temperature from the project and surrounding area are currently being developed in computer input form for further analysis. Precipitation data is being analyzed to establish variability and predictability within the proposed target area on a storm-by-storm basis. Runoff is being analyzed on a longer time period.

F. Instrumentation

The development of the AWRR program is contingent on the ability to provide satisfactory instrumentation. Results of the overall program are expected to be in the form of designs for field operations to produce additional water supply within the time schedule given. However, basic to each of the projects designed to provide the results is the assumption that measurement equipment is or will be made available when needed by the program. To date, instrument acquisition and installation has lagged behind the other aspects of the program.

Some progress has been made in the establishment of the necessary instrumentation during the past 2 years. Radiosonde-receiving capability and two rehabilitated M-33 tracking radars provide adequate coverage of radiosonde and wind information. However, obtaining the spare parts for these surplus units is becoming a problem of major proportions. No major changes have been made in these radar units; however, a major capability has been added in the form of the 403 MHz transponder interrogation and tracking system. This system which is portrayed schematically in Figure 10 not only provides for tracking of balloon or aircraft-carried transponders, but receives and records temperature and humidity data from dropsonde units.

Progress in surface instrumentation has taken the form of the establishment of two sensing profiles which extend across the upwind side of the Southern Sierra. Of particular interest are the telemetered instrument networks in the "MET" and "HYDROMET" categories. Specifically, the SUMOP network is designed to provide surface information along a profile extending from Morro Bay on the Pacific Coast to the Sierra Crest at the headwaters of the Kings River. This network consists of a series of seven hygrothermographs supplemented by standard Weather Bureau sites in the San Joaquin Valley and the Kings telemetry system in the higher portions of the Sierra Nevada.

It should be noted that the Kings system is a cooperative effort involving AWRR and the Corps of Engineers. Instrumentation to measure the parameters required for weather modification purposes has been added to snow measuring equipment at three different sites. This is an example of the basic concept of the instrumentation program which requires that new installations complement rather than duplicate existing instruments.

The SCOBAN network which consists of six telemetered precipitation measuring sites is designed to determine the characteristics of convective bands by means of precipitation amounts and rates. This network extends from the Sierra Nevada foothills east of Fresno west-northwestward to the Coast Range near Pacheco Pass. The information obtained from this network is again supplemented by the Kings' system including the Wishon experimental site.

Supplemental information to these two profiles is provided by a third transect which has been located across the higher portions of the Merced-Tuolumne watersheds. Instrumentation in these basins, which serve as control areas for evaluation of seeding effects in the Southern Sierra, presently consists of storage precipitation gages. Additional sites will be located and installed in these areas which will extend the transect in both elevation and horizontal range.

Two instrumentation sites that are operated on a cooperative basis are located at remote, manned sites. A site at Florence Lake in the San Joaquin basin provides temperature, wind and snow crystal data on a continuous basis, and is operated by employees of the North American Weather Consultants. The second site is located at Mineral King in the Kaweah watershed, and provides temperature, wind, humidity and snow crystal data. This site is operated by employees of the Disney Corporation.

CONCLUSIONS

The conclusions drawn from each of the projects can be summarized as follows:

1. It is quite clear that precipitation can be initiated from previously nonprecipitating, summer-time, orographic cumuli located over the high Sierra by seeding based on selected, desirable parameters. This factor, combined with activities on an expanded testing scale during the summer of 1968, should provide the desired information regarding the amounts of precipitation increase to be expected from such seeding efforts in the near future.

2. A basic design for a seeding test program to serve as a guide for the experimental program is complete. Revision and expansion of the design on a continuous basis as new information becomes available will be required throughout the program.

3. Testing of techniques and equipment with which to measure and evaluate winter storm mechanisms has shown sufficiently good results to warrant planning for concentrated observing activities of this nature.

4. Detection of silver in precipitation by neutron activation has been developed to the point where it can be used as an operational tool in the study of diffusion patterns of seeding material.

5. Hydrologic studies of streamflow data have been shown to be an effective tool as a means of detecting weather modification effects in the Sierra Nevada and providing design criteria for research activities.

6. While significant advances have been made in instrumentation of all types in the past 5 years, the number of required instruments is inadequate. Remotely operated surface sensing equipment provides satisfactory performance but adequate coverage of the area of interest is not provided. Radar equipment is minimally adequate. Airborne equipment is satisfactory both from the standpoint of performance and number of units.

In summary, the overall program in the Sierra Nevada has reached a stage of development that permits the initiation of field experimentation on an operational basis to provide for optimization of weather modification technology.

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Hannaford, Williams	Summer Hydrology of the High Sierra
Hannaford, Williams	Regional Hydrologic Area Study as an Analysis Tool in Weather Modification
Henderson, Williams, Vyverberg	Seeding Summer Orographic Cumuli Over the Southern Sierra Range in California
Vyverberg, Williams	Summary of Recent Research in Nucleation
Williams	Weather Modification as a Watershed Management Tool

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Author	Title
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ATMOSPHERIC WATER RESOURCES PROGRAM

BUREAU OF RECLAMATION

ANNUAL REPORT

Dated: September 1, 1968

by

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BUREAU OF RECLAMATION SUMMARY

INTRODUCTION

The Overall Purpose

The overall purpose of the project is to conduct studies to develop the technology for the management of atmospheric water resources in Montana.

The immediate procedures to be pursued include (a) determining the natural characteristics of precipitation over and downwind of the Bridger Range, (b) determining the storm characteristics of the area, (c) determining weather modification techniques and operational criteria applicable to the area, (d) determining the downwind effects of winter artificial nucleation over the Bridger Range, and (e) to install and operate a radar on the Bangtail Ridge in the Bridger Range to be used as a quantitative tool in cloud analysis.

In implementing these objectives we are proceeding as follows:

1. In the area of the Bridger Range and immediately to the east we:

   (a) Have determined many of the natural characteristics of storms and precipitation.

   (b) Are in the process of determining the most feasible method for seeding and will apply the method in the winter of 1968-69.

   (c) Will determine and compare the characteristics of seeded and unseeded storms, and the resulting precipitation patterns to determine whether significant differences exist for various stratifications based on meteorologic parameters.

2. Statistical techniques are being utilized in the study of both natural and modified precipitation patterns, and seeding will be randomized to provide a sound basis for statistical work. The long-time period required to collect date for statistical evaluation of seeding effects is considered a disadvantage of the method and other more direct methods of evaluating effects are being sought.

3. The existing "natural laboratory" consisting of Bridger Range as a site from which the atmosphere can be modified, and Bangtail Ridge as a site at which the modification effects can be observed, will be utilized. Efforts will be made to determine methods of evaluating the effects of cloud seeding which are directly observable; e.g. by radar.

The Experimental Area

Terrain in that portion of the experimental area presently being intensely studied varies from the rocky crags of the Bridger Range (average elevation 8500 feet ASL) to the semiarid ranch lands of the Shield's Valley in the east (average elevation 4600 feet ASL). The mountainous Bangtail Ridge (average elevation 7600 feet ASL) lies in between.

The lower slopes of the Bridger Range and most of Bangtail Ridge are timbered, with frequent clearings and meadows. The eastern slopes of Bangtail Ridge are an area of dry pasture and grain farming with a limited area of choice, irrigated bottomland along the Shield's River.

The entire area, including the most distant gate is within 30 miles of the campus.

The most frequent storm situation is the passage of Pacific Frontal systems which move into the area on prevailing westerlies and rise over the Bridger Range. These storms bring frequent moderate amounts of winter snow, especially to the higher elevations.

Occasional severe storms which form in the area bring very cold air from the northeast upslope against the eastern slopes of the Rockies and specifically up the eastern slopes of Bangtail Ridge and Bozeman Pass. While storms of this type are less common, they appear to bring more snow per storm than Pacific Frontal Storms, especially to valley locations.

The area is an excellent one in which to study natural storm and precipitation regimes, as well as changes which may occur as a result of attempts to modify the precipitation. Logistic problems are less than would be the case for the majority of mountain ranges in Southwest Montana. Also, the Bridger Range offers a relatively "simple case" for study because of its long, rather uniform ridgeline which lies across the typical west-to-east airflow, and its relative isolation from upwind and downwind ranges. Travel in the region in summer is by truck and trailcycle over roads which vary from Interstate 90 to little more than game trails. Winter travel is by pickup truck and 4-wheel drive vehicle on the main and secondary roads, and by Ski-Doo, skis, and snowshoes when off the roads.

Instrumentation

A network of 21 high resolution weighing gages was operated during the period November 1, 1967 through March 31, 1968 (Figure 1).

Standard USWB type weighing gages were modified with a 20-inch-diameter orifice, large catch pans, and large shells. The modification made possible a resolution of 0.002-inch water equivalent. Time could be resolved to plus or minus 5 minutes with the 24-hour chart rotations used.

A 403-mc radiosonde on loan from USWB was used to obtain a total of 42 soundings. Data were taken to 400 mbs and included temperatures, moistures, pressures, and computed heights of standard pressure surfaces.

An attempt was made during March to collect radiation data through and above storm clouds by attaching a Suomi-type net radiometer to the sounding ballon and using the radiosonde transmitter to send radiation data. The equipment functioned satisfactorily on a test run, but wet March snows which would stick to the radiometer polyetheleine shields prevented any flights.

A thermograph in a USWB-type shelter was operated at 8500 feet (ASL) atop the Bridger Range during the 1967-68 winter season.

An M-33 radar was obtained on loan from NCAR for the winter. A total of 42 wind runs was made and data were reduced to speed and direction with a computer program prepared for the Sigma Seven Computer on campus.

A total of 200 PPI scope photographs was taken using a Polaroid camera. However, lack of an automatic timing device and the performance of duties of higher priority caused the time spacing to be irregular and often too large for use in detailed analytical work.

Difficulties involved in returning the set to a configuration suitable for tracking precluded the collection of any information prior to February 1968.

The Analysis Procedures

Climatological Data

Daily precipitation totals for 68 stations in Southwestern Montana and extreme Northwestern Wyoming were extracted from USWB Climatological Publications for November through March of 1960-61 and 1961-62. The data were placed on punch cards, and a computer program was used to sort the data. Surface and upper air charts from the USWB Forecasting Center at Great Falls were used to provide daily information on upper winds and surface pressure gradients for the same period of time. From the combined information an objective procedure is derived for classifying winter storms.

RESULTS AND CONCLUSIONS

Storm Classification in Southwestern Montana

The Area

The area of concern is that portion of the headwaters of the Missouri River upstream from Helena, Montana, and the Yellowstone River upstream from Billings, Montana. It is rugged, mountainous terrain of Southwestern Montana, and extreme Northwestern Wyoming. Its geographical boundaries can be roughly specified as the area from Billings west to the continental divide and from a Butte-Billings line south to the continental divide.

The 68 precipitation stations selected for study were those which (a) lay in the Upper Missouri Drainage as specified above and, (b) had complete records for the two winter periods used. Each station is either a first order USWB station, and FAA observing station, or an official USWB climatological station. All gages were the nonrecording type with 8-inch-diameter orifices.

The Classification Parameters

The 700-mb flow was selected because it is the lowest level at which the large scale features of the hemispheric flow begin to emerge. Both speed and direction were considered, but no success was achieved in relating speed to precipitation. Since most precipitation occurs with westerly flow aloft, neither the 700- nor the 500-mb flow provided an adequate basis for classification alone, although a secondary maximum of precipitation with 700-mb wind directions from 030 to 059 degrees was apparent.

The maximum surface pressure gradient vector was selected because it provides an objective method of estimating low level flow direction over rugged terrain. The value of any measured surface wind as an indicator of low level flow direction in this region is severely limited. Both the magnitude and direction of this vector were originally considered; however, the magnitude was not found to be useful as a classifying factor for precipitation.

Maximum surface pressure gradient direction is defined as the direction from high to low pressure in which the maximum pressure difference can be found over a fixed distance. When considered in the light of the gradient wind relationship (or simply Buys-Ballot's law), with a rather severe allowance for friction over the rough terrain, a flow direction can be approximated.

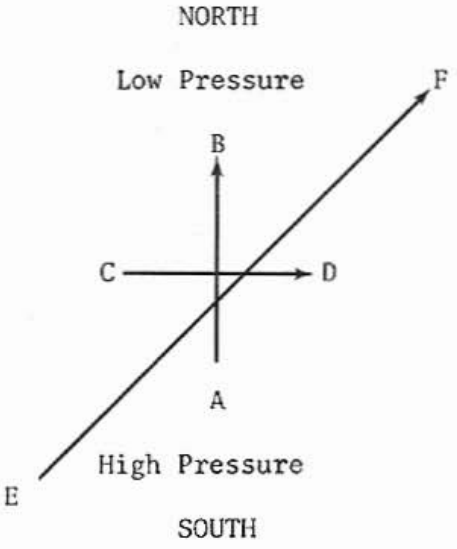


Figure 1

If, as shown in Figure 1, the maximum surface pressure gradient vector is AB, then the Maximum Surface Pressure Gradient Direction (hereafter abbreviated MSPGD) would be 180 degrees. The gradient wind direction could be approximated by CD and a severe allowance for friction would give an actual flow direction between the direction of the pressure gradient and the direction of the gradient wind. As an approximation, 40 degrees might be added to the MSPGD to approximate the low level flow direction. EF could then represent a reasonable low level flow direction over rugged terrain.

It is not, of course, to be implied that the precipitation process is explained by these simple parameters. The importance of nucleation processes, moisture, advection, stability, etc., is recognized.

The Data and Processing

500 mb, 700 mb, and surface sectional charts for the months November through March for the two winters 1960-61 and 1961-62 were selected from the chart files of the USWB Forecast Center, Great Falls, Montana. These two winters were selected because complete chart records existed whereas gaps were present for other recent winter seasons.

Precipitation measurements for the stations selected were extracted from the USWB Climatological Data.

Since precipitation measurements are made at most stations for the 24-hour period ending at 1700 MST (0000Z), 0500 MST (1200Z) was selected

as the midtime or representative time for the period. Use of this single midtime permitted the completely objective extraction of data from charts. Although this procedure resulted in a few non-representative situations (precipitation occurred before or after 0500 MST and the data did not represent the situation when precipitation was occurring), it was felt that the value of having the procedure completely objective outweighed this disadvantage. Besides, if the classification depended upon a judgement factor, it would probably be of minimal value.

700-mb wind direction was extracted for Great Falls, Montana, from each 1200Z (0500 MST) upper air chart for the period and tabulated by date.

MSPGD was extracted from each 1200Z (0500 MST) surface sectional chart over a 240 nautical mile distance centered on 45°00' N, 111°30' W. A circular overlay with radius of 120 nautical miles was divided into 10° increments. It was placed on each chart and the magnitude and direction of the maximum surface pressure gradient vector were recorded by date. In most cases the direction and magnitude were immediately apparent from the isobars and the circular overlay. In a few cases rather careful consideration was required to determine the direction of a maximum. Whenever the magnitude of the vector fell at or below 2 millibars, the case was classified by reference to the surrounding area as simply "high" or "low" pressure and placed in one of these categories.

Only precipitation totals of over a trace were extracted for each date and station and placed on punch cards. A sorting program was used to obtain summations of all stations for each day.

Storm or Precipitation Regime Classification

There is a marked grouping of precipitation and precipitation days with 700-mb wind direction between 240° and 329°, and MSPGD between 180° and 260°. Interpretation of MSPGD in terms of low level flow direction establishes this as what will be termed of the westerly flow case. The low level flow and the 700-mb flow are generally in the same direction. As the two tabulations indicate, roughly one-third of the total precipitation falls on the one-third of the total precipitation days which are in this category.

There is also a grouping with wider distribution of 700-mb wind direction, and MSPGD between 300° and 059°. Interpretation of the MSPGD in terms of low level flow direction establishes this as what will be termed the northeasterly flow case. It is interesting that in this classification roughly one-third of the total precipitation falls with 700-mb wind direction outside the 240° to 329° zone used to establish the westerly flow case. As the tabulations indicate,

42 percent of the total precipitation falls on one-quarter of the total precipitation days.

Further, there is a grouping favoring a westerly to southwesterly 700-mb flow and MSPGD in the category "low." Interpretation of this in terms of low level flow indicates really no flow direction and simply lower surface pressure in the study area, relative to the surrounding region. This is termed the low pressure case. As indicated, roughly 12 percent of the total precipitation falls on 9 percent of the total precipitation days.

Precipitation in the three categories termed westerly case, northeasterly case, and low case account for 87 percent of the total precipitation falling on the area during the two winters studied.

Synoptic Types Associated with Classification

With the westerly flow case the surface (low level) flow and the 700-mb flow are approximately from the same direction. Frequently a Pacific cold front or occlusion will be in the flow, although this is not a necessity. An upper trough, or simply the flow of moist, unstable air from the Pacific, will often provide the opportunity for precipitation. It is not uncommon for this situation to change to the northeasterly case if (a) the front is moderately intense and becomes stationary south of Montana or (b) a low forms in the area or in eastern Montana and a continental polar or artic airmass moves southward behind the low and becomes stationary in Montana.

In the northeasterly flow case easterly, northeasterly, or northerly surface flow results either from a marked high pressure to the north or a low pressure to the south (really the same thing but often one feature is more conspicuous than the other). The air flows upslope into and against the eastern slope of the Rockies. While 700-mb flow (and higher) may be from the west, it is frequently from the north or even northeast. There will often be a frontal boundary through Idaho and Wyoming which may add to the intensity and duration of the precipitation, but the front is not essential to the classification. During the deep winter months of December, January, and February the frontal system may represent an extreme contrast between artic air and the more moderate airmasses to the south or west.

In the low case a trough of low pressure lies oriented from southeast to northeast. There will usually be a frontal system in the vicinity of the continental divide. Seven hundred-mb flow will generally be westerly or slightly south of west and the relation between frontal orientation and upper flow is quite significant

in the production of precipitation. Frequently the front will develop waves which may either remain stable or deepen into major storms. When there are waves on the front it is quite common for the situation to oscillate between the low case and the northeasterly case as the waves ripple along the front and modify the local pressure gradients in passing.

Conclusions and Recommendations

During the two winters studied the 700-mb flow and MSPGD provide an effective and objective method of relating precipitation to synoptic regimes.

The classification method should be tested on a larger sample of data over a longer period of time.

The classification method should be tested at individual stations to determine whether or not it will isolate various components of precipitation at individual stations effectively.

The amounts of precipitation related to each storm type should be further investigated to determine the contribution of each type to the total over a longer period of time.

Isohyetal Analysis

An isohyetal analysis of the water equivalent of precipitation from each of the 29 storms was accomplished. In addition, isolines diagramming the percentage deviation of each station from the normal for each storm were drawn. These analyses of storm totals and departures from normal were quite useful in drawing conclusions concerning factor analysis.

The westerly storm type generally produces substantial snow in the mountainous regions but relatively little in the Gallatin and Shield's Valley. It is also apparent that, on the average, northeasterly type storms produce more snow per storm at all stations and substantially more snow at the valley stations. However, the large snowfall associated with Storm No. 29 makes it questionable whether this would hold for a long-term mean.

It seems possible that the vigorous, localized orographic mechanism of westerly wind flow over the Bridger Range is important in the westerly case while a more gentle, widespread upslope lifting resulting from easterly flow is significant with the northeasterly case.

Isohyetal plots of snowfall totals for 15-minute intervals were prepared for selected storms in an attempt to isolate sub-storm

features. Our Monthly Progress Report No. 11, dated December 1, 1967, discussed a storm which had distinctly different precipitation patterns before and after a frontal passage. However, we have been generally unsuccessful in attempting to define any substorm features based on precipitation data.

The ability to objectively define substorm features would have substantial importance in evaluation of seeding effects. Therefore, it is intended to continue searching for such features using information in addition to precipitation data; e.g. radar PPI data.

Precipitation Gage Network Evaluation

In order to evaluate the effects of artificial nucleation on precipitation, it is obviously necessary to measure the precipitation with adequate accuracy.

The difficulties of accomplishing this at even a single point are considerable. Probably the best measure of point snowfall can be obtained with a snowboard set flush with the snowpack surface. Even here substantial errors are possible if redistribution of the snow by wind action occurs.

The MSU program uses chiefly shielded weighing gages to measure snowfall. Such gages are generally subject to greater catch errors than snowboards, largely due to wind action. However, the difficulties of oversnow travel in mountainous terrain preclude per-storm sampling of more than a few snowboards. Hence, gages which can be serviced as infrequently as once per several days are a necessity. The time distribution of snowfall obtained by weighing gages is, of course, a point in their favor.

We have attempted to locate each of our gages in a position where wind effects would be minimal while still maintaining an approximate constant areal spacing and reasonable accessibility. Obviously, some compromising was necessary.

The Factor Analysis of Storm Precipitation Totals

Factor analysis was applied to 29 storms, using the total precipitation measured at each of the 21 gages for each 29 storms as input data, and considering the storms to be the independent variables. The computer programs used in the analysis were similar to those described by Cooley and Lohnes (1962).

This type of analysis extracts several mutually independent factors from the input data in a completely objective manner. The "loading" of each factor for each storm is calculated. The loading is

an indication of the relative importance of the factor in accounting for the observed precipitation distribution of a particular storm. Of course, the factors can be considered in terms of precipitation distribution only because of the nature of the data herein considered. The analysis is concerned only with a matrix of numbers, in this case formed by total storm precipitation measurements at 21 points for 29 particular storms. The factors are extracted from the matrix in such a manner as to be orthogonal.

It should be noted that the magnitude of the loading indicates the importance of a factor, rather than the sign which results from the mathematical procedure or rotation. However, a change of sign within the loadings for a particular factor does mean an opposite effect; e.g. if a positive loading is associated with increased precipitation, a negative loading for the same factor at another station indicates decreased precipitation. The decision as to whether a given sign is associated with an increasing or decreasing effect must be part of the physical interpretation of a factor.

After factors are derived, physical explanations can be searched for. It should be noted that a particular factor (distribution) may be caused by complex interactions of many physical mechanisms. Nevertheless, factor analysis provides an objective exploratory tool which we believe has substantial potential in the study of storm characteristics. Moreover, it offers a means of objective storm classification, based on observed precipitation distributions. If this means of classification can be related to physical parameters we (a) can increase our knowledge of storm characteristics and mechanisms, and (b) can possibly use the method to study seeding effects. For example, let us assume that a particular set of physical parameters is closely associated with a particular factor. A storm with this set of parameters which is seeded may have high loading with a different factor (distribution) giving an indication of the effect of seeding on precipitation distribution.

Factors 1 and 6 have high loadings (value without sign greater than .7) for several storms while no other factor has for more than three storms. We, therefore, examined the physical characteristics of these two storm groups in an attempt to isolate physical parameters associated with these factors. It appears that factors 1 and 6 together generally represent the precipitation distributions associated with westerly type storms.

Factor 1

a. Significant snowfall in the Gallatin Valley.

b. Snowfall amounts at gages 1 and 19 on the south end of the Bridger Range similar to remainder of Bridger-Bangtail area.

c. Snowfall amounts at gage 3 are at least two times and often several times greater than that at neighboring gages.

d. Snowfall amounts in the Shield's Valley ranging from zero to significant.

Factor 6

a. Little or no snowfall in the Gallatin Valley.

b. Snowfall amounts at gages No. 1 and 19 on the south end of the Bridger Range relatively low for the Bridger-Bangtail area.

c. Snowfall amounts in the Shield's Valley range from zero to significant.

It was attempted to relate factors 1 and 6 with available synoptic upper air data such as stability, wind velocity, 500 mb (approximately cloud top) temperature and moisture but consistent relationships could not be found.

The Gage as the Independent Variable

The total precipitation at each of the 21 gages in our network for each of 29 storms has also been subjected to factor analysis considering the gages to be the independent variables. Precipitation totals were considered for each of three groupings:

a. Eight northeasterly case storms;

b. Twelve westerly case storms; and

c. All 29 storms.

The following information was calculated:

a. The number of factors necessary to explain 96 percent of the variance* in the input data matrix.

b. The amount of the variance explained by each factor.

c. The loadings for each factor at each gage.

*Note that variance is not herein used in the conventional sense, but represents the mean-square reduction as pointed out by Stidd (1967).

It is to be emphasized that relating physical mechanisms to the purely statistical results of factor analysis is an uncertain process and it is quite possible that more than one interpretation can exist * * * or that no interpretation can exist. It is also possible that no physical mechanism can be identified with a specific factor or that the factor is a composite effect of several physical mechanisms and can not be identified. However, if the factors can consistently be identified, the technique provides a powerful tool for the analysis and study of storm mechanisms and the variations of areal precipitation patterns.

Empirical Eigenvectors of Precipitation Rates During the March 17-18, 1968 Storms

In recent years eigenvectors have become used more and more in describing patterns or arrays of data in the meteorological field. Stidd (1967) and Kutzbach (1967) mentioned the wide diversity of application of eigenvectors in meteorology as used by different investigators. In this study eigenvectors are used in exploring the patterns of precipitation rates during the passage of a winter storm in the Bridger Range area. The ultimate purpose is to determine the possibility of applying the method in detecting changes in the precipitation patterns which might be caused by cloud seeding.

The storm which passed the Bridger Range from March 17 to 18, 1968, was used in this study. The characteristics and other pertinent information of this storm are described elsewhere in Appendices 5 and 6 of our Interim Report dated June 30, 1968. The 15-minute precipitation rates from 1400H March 17 to 1400H March 18, were arbitrarily subdivided into four 6-hourly periods. Thus, periods I, II, III, and IV are, respectively, 1400H-2000H March 17; 2000H-0200H March 17-18; 0200H-0800H March 18; and 0800H-1400H March 18.

For each period, computations were carried out to obtain the eigenvalues and eigenvectors. The computer program subroutine used was described in Cooley and Lohnes (1962). The individual and cumulative percent of variance accounted for by the eigenvectors associated with the largest eigenvalues were also determined. In this manner, it was determined that only the first few eigenvectors were needed to approximate the original observations. The eigenvector multipliers were then computed from the reduced number of eigenvectors. For a detailed description of the computation, the reader is referred to Stidd (1967).

The time variation of the first five eigenvectors for each period was plotted. An examination of the graphs reveals that there is a considerable variation of each eigenvector within a 6-hour period when considered at 15-minute intervals. The patterns for the various eigenvectors also show considerable differences. However,

there seems to an indication that the pattern of one eigenvector for one period could be analogous to a pattern of an eigenvector in another period. To test the analogy objectively and numerically, the method and criterion due to Grimmer (1963) was used in this study.

In the computation of the eigenvectors, the orthogonality of the transformation matrix was implied. Thus, any pair of eigenvectors for any one period are orthogonal and orthonommal. The inner product, therefore, of an eigenvector multiplied with itself or with another eigenvector would be unity and zero respectively, for a given period. But for pairs which do not belong to the same period no such property must hold. The inner product of any two pairs of eigenvectors from different periods may be an index of analogy. According to Grimmer (1963), such pairs having an inner product of 0.9 or more are identical whereas a value of 0.7 indicates a similarity of a high order. The first five eigenvectors of Period I were systematically compared with the first five eigenvectors of the other periods.

From the analysis, two things become apparent. First, the degree of resemblance of the eigenvector patterns between Period I and the other three periods differ. But there is no indication that the farther removed a period is from Period I the lesser the degree of resemblance of an eigenvector to said period. Secondly, it can be seen that a physical factor may have a dominant effect in one period but may be overshadowed by another factor in a different period.

An implication of the analysis suggests a very important approach in detecting the effect of seeding on the precipitation pattern. If seeding is an important factor, it might be identified as an eigenvector pattern. This pattern should persist during storm periods when seeding is effective. Thus, its importance during the different periods could be assessed by determining the variance explained by that physical factor for individual periods.

Harmonic Analysis

Precipitation rates at each gage for two storms were subjected to harmonic analysis using a standard computer program. First harmonics were plotted in terms of the time of the occurrence of the maximum amplitude of the harmonic at each station. Harmonics other than the first were not considered because they were never found to be significant at more than a few gage sites.

The first harmonic suggests a generally east-to-west movement of the occurrence of highest precipitation intensity, with possibly

higher speeds in the valleys and slower speeds over the more rugged terrian of the Bridger-Bangtail area. However, this is based on limited data and must be considered as conjecture.

The apparent motions of the first harmonics on the meso-scale represented by the precipitation network leads to some interesting speculations. It might be expected that the mechanism causing the period of generally highest precipitation rates would be carried along and/or partially caused by the airflow at some levels. Such mechanisms could include upslope motion, convergence due to flow into narrowing mountain valleys, orographic lifting, frontal lifting, and the movement of convective calls or bands. In the March 17-18 case, the movement of the first harmonic seems to be in general agreement with the airflow. However, in the November 22-23 storm, winds at 700 mb and above were from west to north as measured at Great Falls, 130 miles north of our network. We would not expect the winds over our networks to be markedly different in direction.

Surface winds at the Belgrade airport were westerly to northwesterly during the period.

Time of passage of the first harmonic did closely coincide with the frontal passage (about 2100 MST) as determined by surface barograph traces in the area. However, the apparent direction of motion was opposite or perpendicular to the direction of airflow at all levels. We can only state that this case points out the complexities of winter storms in mountainous terrain.

It is intended that harmonic analysis be applied to other storms to determine if it can be a useful tool to track the main "pulse" of a storm. If so, it may aid in understanding the complex precipitation mechanisms involved. Also, it might lead to a means of stratifying storms for evaluation of seeding effects.

Reports and Papers Produced Under Contract No. 14-06-D-6144

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LABORATORY OF ATMOSPHERIC PHYSICS

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FINAL REPORT

on

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BUREAU OF RECLAMATION SUMMARY

CLOUD PHYSICS AND WEATHER MODIFICATION TECHNIQUES

Wave Cloud Experiments

A. Purpose and Design

A lenticular cloud forms generally from air which is closely following streamline flow; the cloud itself is often nonturbulent and the fluctuations of cloud parameters are lower by one or two orders of magnitude than in most other types of clouds. The lenticular cloud, therefore, can serve as a laboratory where the cloud properties are near adiabatic and depend only on position within the cloud. The following experiments with wave clouds appear especially attractive:

1. To relate the condensation nucleus spectrum to the cloud droplet spectrum measured by the formvar replicator.

2. To relate the natural ice crystal concentration to measurements of the freezing nucleus spectrum upwind of the cloud.

3. To measure the change of cloud droplet spectra by condensation following a streamline within the cloud.

4. To measure ice crystal growth rate following a streamline in nonseeded and (where appropriate) seeded clouds.

5. To observe crystal habit and rate of mass increase at different temperatures in nature.

These are fundamental problems in our understanding of precipitation mechanisms. Their solution could lead to new or better techniques for cloud modification. Answers to these apparently simple questions have not yet been obtained which are adequate for engineering planning.

Other basic problems are concerned with the transition of ice crystals growing from the vapor to graupel particles growing by accretion of supercooled water drops. These events begin to happen in nature as drops and ice crystals grow in the deeper clouds which occur, for example, with the close approach of a frontal system. These clouds are usually rather turbulent, but in any case, the phenomena of particle formation and early growth discussed above would strongly influence later developments. This second stage of growth where accretion becomes important does not occur in lenticular clouds, but fortunately it is amenable to laboratory simulation. Work which relates to this stage is described later.

B. Results

The attractive opportunities presented by the wave clouds have proved, for the present, too difficult to utlize. The major reasons for this are: first, no aircraft has been available which could operate flexibly at wave cloud levels; and second, there are still very serious problems connected with the formvar particle sampler. The Beechcraft C-45 has a service ceiling of 16,000 feet; wave clouds typically occur in the region from 25,000 to 30,000 feet; and the few that do occur at lower levels are usually turbulent; and so, useless for the proposed experiment. Despite the inadequate ceiling of the C-45, it has penetrated wave clouds many times at altitudes up to 32,000 feet, using the lift of the wave. At such heights it has practically no operational flexibility, so that very few results have been obtained regarding the physical processes occurring in these clouds. It has, however, been possible to make use of such flights to test and develop instrumentation.

The formvar replicator has been found to present a number of problems; yet, for the study of the ice phase, no alternative is as yet available. Work directed at the solution of these problems will be described later.

Aside from these two aspects, progress has been made in developing approaches to making some of the kinds of measurements which would be needed to attack the basic cloud physics problems (1. to 5. listed in A. above). As previously mentioned, any utilization of the wave clouds for these purposes would demand good knowledge of the three dimensional windflow through and around the cloud.

Two methods to determine the wind field have been devised. One method involves radar tracking of chaff. Allowance has been made for the known fall speed of the chaff, and the radar outputs were so arranged that the path of an air particle which was originally at the drop point was traced on a vertical plane parallel to the horizontal wind vector. A brief description of the technique was given by the Desert Research Institute (1967). By this method, one is able to track air motions inside as well as outside the wave cloud. Theory and observation both indicate that riming of the chaff in the cloud were so slight as to have no appreciable influence on its fall speed.

Another method of measuring the motion of the air uses a smoke marker. The development and use of this technique has been described by Nielsen and Berry (1968). While this method cannot be used to trace in-cloud air motions, it does make it possible to estimate the turbulence of the air, which would be important to observe in some investigations. For example, if seeding agents were to be dispersed upwind of the cloud and allowed to flow into

it in order to measure their efficiency under natural cloud conditions, it would be necessary to know how rapidly the seeding agent would spread out. If it disperses rapidly because of a high level of general turbulence, the output of the generator would need to be increased above that which would be necessary when the plume spreads slowly. Conversely, if, on a day when the flow is quite laminar, too much seeding material were used, the result would be that the cloud would be overseeded within the narrow plume. The saturation ratio of the air in the plume would then fall below unity (with respect to water) and it would not be possible to interpret reliably the observed behavior of the seeding agent. A brief exploration into another interesting area of application of the smoke technique - low level convection - has been described by Berry (1968a).

Theoretical Studies of Droplet Collection

A. Purpose and Design

In the absence of ice, precipitation can form a result of the differing sizes and fall speeds of cloud droplets. The process is somehwat affected by Brownian motion, but is basically gravitational. Until Telford (1955) pointed out the importance of the stochastic element in such collection processes, however, it was impossible to reconcile observations of the time taken for rain to form in tropical shower clouds (order 20 min.) with theory, which, with realistic assumptions about the rain-forming clouds, predicted 1 to 2 hours formation time.

Berry (1967) has carried out the most extensive calculations so far made of the consequences of stochastic collection and, as a part of Project Skywater, has used this general body of computations to attack two problems of immediate practical importance - the implications of stochastic theory with regard to the possibility of modifying warm cloud processes, and with regard to the rate at which the radar reflectivity of a warm cloud grows. The latter is important because radar echo intensity is by far the most easily and commonly measured property of precipitating clouds, so that opportunities could be found to test the validity of the collection theory quantitatively, and thus improve it.

B. Results

Just as the modification of cold clouds depends on influencing a sensitive nucleation process (the formation of ice), so the possibility of modifying warm clouds would appear to hinge on our being able to influence a nucleation process (the initial formation of the cloud droplets from the vapor). It seems that it may be practicable to modify this process by introducing additional condensation nuclei into the air, for example.

Berry (1968b) has used the stochastic collection calculations carried out earlier to examine the rate at which the liquid water which is present in the form of cloud droplets is converted over into the liquid water in the form of incipient rain drops by coalescence. He found that this rate is very sensitive to the concentration of droplets per unit volume and to the dispersion of the droplet sizes resulting from the initial condensation process. In fact, the rate of conversion can vary by orders of magnitude. This indicates that, given an adequate understanding of the condensation process and a suitable technology, there is great potential for modifying warm clouds by changing the nature and number of condensation nuclei.

The same general body of calculations has been applied to study how the radar reflectivity of a warm cloud would increase as a result of coalescence processes. The result found was that the rate of increase of the mean mass of the droplets present in a cloud depends only on the liquid water content, and that the radar reflectivity is proportional to the product of this means mass and the liquid water content (Berry, 1968c). If, therefore, the latter is known or can be estimated, as is often the case, observation of the radar reflectivity would make it possible to follow in time and increase of the mean droplet mass, and so check the existing collection theory.

The basic calculations leading to the results described above had been made possible by the cooperation of the National Center for Atmospheric Research, which kindly made its powerful C.D.C. 6600 computer available. As is always very desirable with complex numerical calculations, they had been guided and checked at several points by analytical investigations. So far, analytical solutions have been possible only for special cases of the general problem, but this sufficed to serve the purpose of checking the numerical calculations. This work has been reported by Scott (1967a, b, c, d).

Multiplication and Accretion Growth of Particles

A. Purpose and Design

These recently begun studies have been aimed at gaining a better knowledge of certain phenomena which have been observed to occur in the laboratory and which seem certain to influence the course of events in deep clouds where coalescence growth becomes important. These phenomena can hardly fail to influence precipitation efficiency in either natural or seeded clouds. It is not possible to observe these microscale events in the field and the only way to proceed is to examine them in the laboratory so that we can understand them well enough to be able to predict the physical conditions under which they can be expected to become important in

clouds. Because of the higher probability that they may strongly influence precipitation efficiency in suitable circumstances, the following phenomena were selected for study:

1. Droplet multiplication due to impact of a drop on a liquid surface, and

2. Ice crystal multiplication caused by the bursting of air rejected from solution during drop-freezing.

B. Results

1. Droplet Multiplication

Up to now, the major effort in this area has been in building apparatus which can produce, at accurately timed intervals, single water drops ranging in size from raindrops down to very large cloud drops. This apparatus has been used in the study of the impaction of drops on liquid layers of different thicknesses as a prelude to a study of their interaction with falling graupel and hailstones. It is to be used also to study drop behavior on striking sampling surfaces.

Considerable effort has been expended to construct a modified version of Lane's (1947) apparatus to produce uniform drops in the range of diameter 600 μ to 2,000 μ at intervals from a few seconds to some tens of seconds. The air flow was made intermittent in order to reduce its influence on the drop after it was released. The water was carefully filtered and its flow rate accurately regulated. The air pulses were produced by opening a solenoid valve for a hundredth of a second. The drops produced in this way were collected in a silicone fluid and measured; their diameters had standard deviations of about 1 percent. The apparatus is adequate for the intended use in respect not only to droplet uniformity but also in respect to accuracy of timing and ability to consistently hit a small target. The final design of this device is fully described by Riel and Hallett (1969).

2. Ice Crystal Multiplication

It has been known for some years that the concentrations of crystals observed in clouds are too high to be readily explained in terms of atmospheric ice nuclei. One possible cause of this discrepancy is the multiplication of ice crystals in various ways. One of the likeliest causes of ice crystal multiplication is the bursting of the bubbles which are always formed as drops freeze.

Only a few exploratory experiments have been made so far. Ice crystals were grown in a pyrex glass tube which was slowly lowered over a period of 8 to 30 hours into a brine bath at -20° C. Bubble

formation was examined either by subsequent sectioning of the ice or by time lapse photography in situ. An appropriate optical system submerged in the cooling fluid enables photographs to be taken from outside the system.

Studies were made using: (a) distilled water in equilibrium with air at 20° C (at Reno where the ambient pressure is about 850 mb), containing 20 ml of air with N.T.P. per ml of water; (b) distilled water degassed to a content of 8 ml at N.T.P. per ml of water by boiling.

It was found that, at the ice water interface growth rates so far examined, the bubbles were in the form of long threads, the length decreasing and the diameter increasing as the growth rate increases; there is also a tendency for the concentration of threads to decrease. These results contrast with the observations made by Carte (1961) of the nucleation of nearly spherical bubbles at high growth velocities. He found also that the bubble concentration increased with increase of interface growth velocity.

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Particle Sampling

A. Purpose and Design

Among the difficulties encountered in the attempts to make use of the wave clouds for physical investigations are those associated with the formvar continuous replicator. These investigations cannot be undertaken unless the collection efficiency of the sampler is known, and the replication process is sufficiently reproducible and well understood.

B. Results

1. Collection Efficiency

The cloud sampler of Squires and Gillespie (1952) was available for comparison with the replicator. This device made possible a very direct approach to the problem. However, the many problems associated with the simultaneous use of two samplers (accurate synchronization, personnel-carrying, and ceiling limitations of the aircraft) had the result that only three apparently satisfactory comparisons were achieved. Of these, two gave results which seem plausible, and one gave results which seem obviously incorrect. A careful reinvestigation of this case has failed to reveal the cause of the apparent problem and, in view of the operational difficulties mentioned above, no further attempts have been made along these lines.

The second "wave cloud" method relies on the apparently plausible assumption that the droplet concentration per gram of air in a laminar lenticular cloud is constant along the wind. In the absence of turbulent mixing, no droplets would be evaporated as a result of the entrainment of dry air; since the droplets in these clouds are quite small, the effects of fallout in moving the droplet population relative to the air is negligible (total relative displacement of the order 2m), and the effect of coalescence in reducing the droplet concentration is likely to be small also. Thus, provided a cloud is laminar and there is no ice present, the very simple model of a constant concentration population of droplets growing as they move along a streamline from the forming edge to the apex to the wave, and then becoming smaller, is probably close to the truth. This approach to the problem, due to Berry, has been described in detailed by Reinhardt (1968).

The experimentally deduced values do not resemble very closely those for any simple geometric shape. The likeliest cause of

inaccuracy in the values found is that, even if droplet number is conserved along a streamline, it may well vary from one streamline to another due to the vertical gradients of the parameters which influence initial drop formation at the leading edge, and hence the droplet concentration.

In the third, surface approach the required relative velocity was achieved by using a high-speed car with a skilled racing driver. The instrument being studied is carried on a boom extending sideways. A cloud of droplets of measured size and concentration is enclosed in the box and the car driven so that the aluminum foil is broken and the instruments exposed momentarily to the known cloud.

These devices have been built and tested. Preliminary indications have been obtained from measurements of spheres that the measured collection efficiencies are comparable with the theoretical values found by Langmuir and Blodgett (1946).

2. Replication

The process of replication obviously depends on layer depth, and also on the degree to which the surface has begun to harden at the moment of replication, and this itself must depend on the temperature and ventilation of the film surface, neither of which are easy to control in a reproducible manner. Both pump and nozzle have been redesigned and a visually uniform layer can now be deposited under flight conditions.

By means of interferometric photography, details of the structure of the replicas of both drops and crystals have been studied. While some of the particles have been completely enclosed and, after evaporating, have left behind a hollow shell, others were not fully enclosed by the formvar and the only imprint left is an indentation in the surface.

The investigation of impact and replication of drops and crystals is clearly a difficult problem. The droplet-producing apparatus has so far been used for only a few experiments. They are, however, of some interest, being elementary prototypes of experimentation which will help to resolve impact and replication problems. Since there is so great a range of possible conditions - kinds of sampling surfaces, velocity of impact, and size of impacting particle, for example - an extensive series of well-planned experiments will be needed.

The following observations have been made so far:

Drops of diameter 2000 μ were allowed to fall from a tower, reaching about 60 percent of terminal velocity, to impact on a

water layer of depth between 2.0 and 10.0 mm. The resulting interaction was studied by high-speed photography. It was found, for example, that with shallow layers the crown only was present. With increasing depth, the central jet became more dominant. When the liquid was about 6 mm deep, the central jet formed a separate drop which was thrown to a height of 26 cm, while with a deep layer, the height reached was only 3.5 cm. At cloud drop sizes, the behavior is completely different from that described above. In another experiment it was found that, when 200u diameter droplets impacted on a water surface at terminal velocity, they often bounced several times before coalescing; on the other hand, 60u diameter drops consistently penetrated the surface uneventfully, despite their much lower terminal velocity.

Development of a Smoke Marker Technique

A. Purpose and Design

In connection with the wave cloud experiments, a visual method was desirable in order to check the results of radar chaff drops for wind measurements and also to give a direct indication of the level of turbulence of the air in which the wave clouds form.

B. Results

The U.S. Forest Service smoke marker technique was adapted to the C-45 aircraft as described by Nielsen and Berry (1968). Figure 2 shows how this smoke trail behaved as it approached a wave cloud, tilting upwards towards the cloud, but spreading very slightly (if at all) beyond the extent to which it was dispersed by the turbulence of the aircraft wake.

Another very simple experiment was undertaken with the aim of finding out whether this technique could be applied to the study of convective flow patterns near the ground in the hope that this technique could prove useful in studying the dispersion of the aerosol from a seeding generator. The results were encouraging, and have been described by Berry (1968).

Data Processing

A. Purpose and Design

Data processing techniques were developed during the preceding contract period for use in the South Dakota and Flagstaff Projects of summer, 1966. The same techniques were intended to facilitate the conduct of the wave cloud experiments.

B. Results

At Flagstaff, in July and August 1966, parameters measured on the C-45 aircraft were telemetered to the ground and were displayed as meter readings and recorded as a digital output. By means of a small data processing type computer (PDP 8), the vector velocity of the aircraft through the air was subtracted from its vector velocity with respect to the ground to give instantaneous wind velocities along the path of the aircraft. These were displayed directly in graphical form. In this manner, the scientists in charge had available, in real time, data in a form which could be used for making operational decisions for the conduct of the flight. The techniques used have been described by Chisholm (1966a, 1966b, 1967).

Unfortunately, the operational and instrumental difficulties which were encountered in the attempt to carry out physical experiments in the wave clouds prevented the application and further development of the very promising data processing techniques described above.

Comparison of Snow Gages

A. Purpose and Design

The observational network installed for the observation of precipitation profiles in the lee of the Sierra Nevada (see included a variety of types of gages and presented an opportunity to compare their performance.

B. Results

An analysis of their behavior (Klieforth and Rogers, 1968) has shown that, in strong winds, gages near the ground collect much drifting snow and so overestimate precipitation, while those mounted some feet above the ground underestimate precipitation as a result of losses due to wind-caused swirl. As is well known, heated tipping bucket-type gages suffer serious evaporation losses in light precipitation and their overall efficiency appears to vary from 95 percent at the best down to 20 percent in strong winds.

Obvervations before and after the installation of Nipher screens indicates that while these devices slightly increase the catch, serious swirl losses still occur in strong winds.

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The Elko Project

A. Purpose and Design

This project was designed in 1962 as a long-term statistical experiment in the use of ground seeding to increase winter snowpack on the mountains near Elko. The design of the experiment has been described by North American Weather Consultants (1963), and synoptic situations leading to precipitation have been discussed by Strojie (1968). Some 20 ground generators were placed in two north-south lines, the westernmost being about 30 miles upwind of the two target areas. One target lay well to the north, the other to the south of Elko. The effect of seeding was to be detected and measured by seeding randomly either the north or the south area through a particular storm period, the unseeded area being to gage the natural snowfall in the area due to the storm. The experiment was originally planned to run until 75 test storms had been seeded and no statistical analysis was to be undertaken until the experiment had been completed. So far, 58 tests have been made. However, in view of serious doubts which have arisen about the efficiency of the experimental design, it was decided to begin an interim statistical analysis based on the existing 58 tests.

B. Preliminary Results

The final results of this analysis are not yet available, but preliminary results indicate:

1. Prima facie, there has been a slight increase in precipitation in the target areas as a result of seeding.

2. The prima facie result is not statistically significant and could well be due to chance influences.

3. The originally planned 75 tests would not be enough to achieve acceptable levels of statistical significance.

With the cooperation of the National Center for Atmospheric Research, Boulder, Colorado, two flights were made to measure ice nucleus concentrations with the object of finding out whether the expectations with regard to the transport of the aerosol were grossly in error. For operational reasons, these flights had to be made in generally fine (VFR) weather with scattered snow showers, instead of in storm conditions. The first flight in the vicinity of the close-in line of generators indicated that the aerosol moved toward the target as expected from synoptic considerations,

but passed over the target snow gages at a level below that of the cloud base in a typical storm. In such a case, the aerosol could have no effect on precipitation until it passed beyond the gages. For the second flight, AgI generators at a greater distance (the more westerly line) behind an orographic carrier were turned on. Nuclei counts indicated that the aerosol moved north up the valley near the surface without crossing the intervening barrier until it had passed far beyond the point where higher level southwest flow could possibly carry the aerosol into the target area. These two flights were, of course, too few to give a good idea of the average result. Furthermore, the results might have been quite different in a period of stormy weather.

Warburton's technique for analyzing snow samples for the presence of minute quantities of silver consistently found that the silver content of snow falling in a seeded area is much higher than elsewhere. In most cases, however, samples of snow obtained from the target areas near Elko in various ways contained concentrations of silver (of about 10^{-11} g ml^{-1}) which were typical of an unseeded rather than a seeded area. In only 7 cases out of 59 was there any indication of an influence due to seeding.

It seems clear that the "targetting" efficiency of this experiment is quite low, and if this is so, it can hardly be expected to produce clear evidence of significant increases in precipitation in a reasonable number of years.

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PRECIPITATION AND STREAMFLOW ANALYSIS

Analysis of Precipitation for Silver

A. Purpose and Design

Effective methods have long been sought for the identification of trace amounts of seeding materials in precipitation. The value of such a technique is obvious; it can give independent evidence of the degree of success achieved in the "targetting" of seeding

plumes. In any cloud seeding field experiment, this is a crucial problem which sometimes in the past has been given little attention because no economically feasible method of studying it had been developed.

Silver iodide is by far the most frequently used seeding material, and a technique to detect (or, preferably, measure) trace concentrations of silver would be a long step towards solving the problem discussed above. By the beginning of the contract period, techniques for the determination of traces of silver by neutron activation analysis had been developed and were ready for field use (Warburton and Young, 1968a).

B. Results

With the perfection of the technique, a wide range of applications opened up. Work carried out in the contract period (July 1966 to June 1968) included the following:

1. Analysis of snow and rain samples for silver

    a. Background silver concentration
    b. The Elko Project
    c. Cooperative experiments
    d. Seeding projects of other groups

2. Comparisons between the neutron activtation method and two other trace analysis techniques which have high sensitivity for silver.

3. Laboratory tracer studies on the design of a sequential precipitation sampler.

4. Improvement and monitoring of silver analysis methods.

The results obtained in these areas of work are discussed in turn below:

1. Analysis of Rain and Snow Samples for Silver

Table I summarizes the results and conclusions from analyses of precipitation samples from three different areas. For more detailed information see Warburton and Young (1968c).

Table I

Silver Concentrations in Snow (gm ml^{-1})

Reno-Mt. Rose	Elko Project	Co-op I Exp (Colorado)
1967-68 concentration range	Background not yet well known	Background not yet well known
1.9×10^{-12} to 1.9×10^{-11}	Unseeded concentrations Range 4×10^{-12} to 1.3×10^{-11}	Range of concentration 7×10^{-12} to 1.1×10^{-9} (130 samples with measured values)
90 percent of samples 2.5×10^{-12} to 7×10^{-12}	Seeded samples range 5×10^{-12} to 1.46×10^{-10}	Without subtracting out the unseeded samples from this group of 130
	4/13 seeded samples contained	65 percent of all samples contained
	Ag > background (Reno)	Ag > background (Reno)
	2/4 were outside target areas	
Hence:	Hence:	Hence;
Background average is about 4×10^{-12}	25 percent success with targeting	At least 65-percent success with targeting

2. Comparison of Analysis Methods

In cooperation with the laboratory of E. Bollay Associates at Boulder, Colorado, comparisons have been made between the results found from the neutron activation technique and those obtained at Boulder by atomic absorption methods, using a set of snow samples collected during the Co-op I Experiment which were divided into two halves, one for analysis in Boulder and one for Reno. The results confirmed the result found earlier in connection with a National Science Foundation research project aimed at the use of trace analysis methods in the study of fundamental cloud processes; namely, atomic absorption spectrophotometry is a reliable technique for trace silver determinations in snow. The results were in good agreement with those

obtained by neutron activation analysis. Ion-exchange enrichment was used for the NAA and solvent extraction enrichment for atomic absorption. The methods in use at Boulder are somewhat less sensitive by a factor of about 10, so that atomic absorption, as used at present. does not measure background concentrations of a few times 10^{-11} gm ml^{-1}. When the samples were from a seeded area and contained higher concentrations of silver (10^{-10} g to 10^{-9} gm ml^{-1}) the results from the two laboratories were in very good agreement. Out of 26 such samples which were compared, 85 percent of the results agreed within a factor of better than 3 to 1. In 4 samples, one order of magnitude differences were found. In 3 of these, AA gave the higher value; in the other, NAA was higher. At these extremely low concentrations, the differences may have been real, as such differences could easily have been caused by contamination of one or other of the samples in the handling procedures. The sensitivity of these techniques is such that it is imperative that all possible sources of silver contamination be scrupulously avoided (see Warburton and Young, 1968e).

3. Trace Studies Related to Design of a Sequential Precipitation Sampler

At the request of the Office of Atmospheric Water Resources of the Bureau of Reclamation, some earlier studies of plastic films were extended. Various films were evaluated for their absorptions properties as well as their trace chemical content and sensitivity in capturing and handling precipitation samples. This work was undertaken for the purpose of assisting Meteorology Research, Inc., in the design of a sequential precipitation sampler which could automatically obtain successive samples of precipitation and store them in polyethylene containers for later analysis for trace constituents.

More than six plastic films were tested for their tendency to contaminate a precipitation sample with elements which would confuse or invalidate later analysis for silver. It was found that contamination with aluminum was a difficulty with some films. However, either parafilm or polyethyelene is satisfactory for the purpose, the former being somewhat preferable.

Testing was also carried out on a prototype sequential sampler. Recommendations were made to eliminate the cross-contamination of successive samples which was occurring in the prototype due both to the takeup of silver and carryover of silver-containing water on the various plastic surfaces and in tubing through which the sample passed to the polyethylene containers.

4. Improvement and Monitoring of Silver Analysis Methods

During the contract period, several laboratory studies were performed and modifications and improvements made in the silver analysis procedures.

a. Effects of Change in Concentration of NH_4CNS.

b. pH Effects on Ion-Exchange Efficiencies.

c. Water Purification Studies.

d. Computer Analysis Procedures.

e. Reproducibility Studies.

f. Studies on Apparent Changes in Standards.

Tracing of Ice Nuclei in Snow

A. Purpose and Design

The silver analysis technique described earlier has proved very useful in understanding more about field cloud seeding experiments as, for example, in the Elko Experiment described later. However, the presence of silver in snow sample does not prove that the seeding caused or helped to cause the snowfall. A more refined analysis of events would be possible if the artificial nucleus could be located in the snow crystal. A study of the structure of the crystal will then reveal what role, if any, it played in the nucleation of the ice crystal.

Two procedures designed to locate the nucleus have been examined:

1. Autoradiography
2. Fluorescent tracers

B. Results

1. Autoradiography

Exploratory work was undertaken to determine whether it was possible to detect one or several silver iodide particles in a snowflake, with the object of refining the kinds of diagnosis which could be useful in the design and improvement of seeding experiments. Such a method, which would in effect detect the presence of 10^{-14} g of silver iodide would be vastly more sensitive than the bulk analysis of samples, which can detect silver only if the total mass present exceeds 10^{-9} gm. Clearly, improvement by a factor of 10^5

in ultimate sensitivity could be extremely useful in an appropriately designed cloud seeding experiment. A description of this work has been given by Warburton (1966).

2. Fluorescent Tracers

In order to be able to detect a nucleus in a crystal by its fluorescence, it must be large enough to be detectable. The first part of the task was to build a generator capable of producing such nuclei.

A small generator has been built in which a 10-percent solution of phloroglucinol in methanol is atomized by a jet of compressed air to form droplets of average diameter around 4 microns; on evaporation of the solvent, a particle of diameter about 2 microns is produced (Hoffer and Perthel, 1968). These are found to be effective nuclei at temperatures colder than -6° C. If the particles are rendered fluorescent by the incorporation of a suitable dye, they are easy to observe by means of a microscope. Attempts to achieve this by incorporating fluorescein in the sprayed solution were not encouraging because the fluorescein strongly decreased the nucleating ability of the particles.

Measurements of Precipitation Profiles

A. Purpose and Design

Studies were initiated in 1966 in order to obtain background information which would permit a more penetrating analysis of an area-type cloud seeding experiment in the Sierra. The observational network consisted of 26 cans and boards, and 5 recording gages in July 1966; it had increased to 45 cans and boards and 13 recording gages by June 1968. No such project is now planned, the whole effort in field weather modification experiments being concentrated on the Elko Project.

B. Results

The synoptic-scale setting of the storms which gave rise to these precipitation profiles has been considered. The analysis of the relationships between profile and synoptic types has only just begun.

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A STUDY OF THE FEASIBILITY OF SOCIAL SCIENCE RESEARCH DESIGNED TO IDENTIFY AND ANALYZE SOCIAL RESPONSES TO PRECIPITATION MANAGEMENT OPERATIONS IN NEW ENGLAND

Prepared for the Bureau of Reclamation

By

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Bureau of Reclamation Summary

Generally, New England can be accurately viewed as a "water rich" area. Natural water sources have been on the whole adequate for a full range of users. Even at this time in the 20th century, when the population of the area is at all-time high and the profusion of water-using equipment both in the home and in industry is steadily increasing, the region's water supply sources are available in sufficient quality and quantity. Perhaps there is no better indication of this situation than the continued reliance on a legal system based on riparian rights and the common law governing the use and abuse of water resources.

In some "water-poor" states, particularly in the weatern and southwestern parts of the United States, the riparian system was never adopted and in others it was quickly replaced by the more efficient and less tolerant appropriation system of water law and water use allocation. However, New England's water supply is apparently large enough, despite dramatic increases in demand, to allow the continuation of the riparian system.

However, valid an assessment this may be of the New England water supply situation, there is some question that it will remain valid in the future. As Edward A. Ackerman has pointed out:

> The size of the expected population growth of the United States in the next 20 years and the expected location of the Nation's people by 1975 are such that water problems of major proportion may be forecast.1/

It is safe to assume that New England will share in the nation's growth and the region's growth will be accompanied by an increase in the demand for water. Whether these increases in population and demand will be of such magnitude to require a regular program of precipitation augmentation, however, is not clear. The New England River Basins Commission has just recently started a comprehensive study to determine the region's probable water supply needs into the next century. Certainly the results of this effort will be of considerable interest to all concerned with water resources use and development.

However, even in the absence of long-range water demand forecasts, water resource officials in the region view precipitation management to be of only minor significance in any program to increase the region's water supply. Inadequate precipitation is not usually a major problem. The problems are related to how man stores, distributes, and uses precipitation after it falls. More than one official contacted during this study stated that New England's natural supply of water was more than adequate for the probable needs of the future. Those water supply shortages that do occur

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1/Edward A. Ackerman, "Design Study for Economic Analysis of Weather Modification," Final Report, Advisory Committee on Weather Control, Vol. II (Washington: Government Printing Office, 1957), p. 236.

can be traced to the absence of suitable storage facilities, inefficient distribution facilities, an archaic and unrealistic legal system and/or pollution. Until these problems and inadequacies are removed or corrected, there is little reason for increasing precipitation in the area.

The region's natural supply of water is depleted in some areas by man-caused pollution. Over the past few years, concerted efforts have been made to clean-up polluted streams and to prohibit the creation of new sources of pollution. These programs include not only interstate streams and rivers, but also interior lakes and ponds. However, the job is truly a massive one and the response of public agencies is often limited by inadequate funding. Nevertheless, expanded programs of pollution control and prevention are viewed as essential to the success of any effort to increase the supply of useable water in the region.

On the other hand, precipitation management or rainmaking, as most of those contacted prefer to call it, is viewed with little interest and even some skepticism. Of the six New England states, three have had some experience with cloud seeding within their boundaries. In each case, the operations were carried out to alleviate drought conditions, particularly harmful to agricultural and forestry interests. In each case, the appropriate state government took some part either in initiating the operation or in providing some degree of supervision or regulation.

Sewell and Day, interviewing a larger sample composed of nonfarmers as well as farmers in Canada as well as the United States found that residents of humid areas expressed more doubt concerning the utility of cloud seeding than those residing in more arid areas. A similar relationship was reported in response to the question of governmental involvment in such activities. Those who expressed less confidence in the utility of cloud seeding were also less convinced that Government should be involved in such activities.

However, there was general agreement no matter where the respondent resided or what his occupation was that improvements in weather forecasting would be of greater use than advances in cloud seeding technology.2/ People in New England, historically a "wet" region, quite probably hold attitudes similar to those found by Sewell and Day in the more humid areas included in their study. Certainly the small number of cases where cloud seeding was carried out and the even smaller number of state statutes relating in any way to cloud seeding support this assessment.

2/W. R. Derrick Sewell and J. C. Day, "Precipitation of Possibilities of Weather Modification and Attitudes Towards Government Involvement," Human Dimensions of Weather Modification, pp. 336 ff.

Nevertheless, these contacted in the course of this study raised some questions related to precipitation management which might indicate possible uses for the technology in the region. For example, the need for improved, long-range weather forecasting was indicated. If "dry" years could be forecast far enough in advance, then attempts to increase precipitation from winter and spring storms might well be made. Questions much like the following were raised:

> Why in 1959 did western Europe experience one of the finest summers of the century, in 1960 one of the worst and in 1962-1963 break all records for persistent winter cold since observations began?3/

With improvements in the accuracy of long-range forecasting, periods of less than normal precipitation might be predicted and selected cloud seeding operations conducted under favorable rather than crisis conditions. Under such conditions, cloud seeding might well prove its usefulness as a successful tool in forestalling the effects of unusually low precipitation levels.

It was also stated that while officials in the New England region might not be involved in precipitation management operations, they would be interested in the results of similar efforts in other parts of the nation and they would be concerned about the effects of such efforts on New England's economy and climate.

These are some of the thoughts and questions which are expressed on the topic of cloud seeding in New England. They indicate some skepticism, a mild curiousity and some possible ideas about cloud seeding in the region - its possible applications, its utility, and perhaps some clue to the degree of public support such operations might receive. The reactions to cloud seeding appear to be limited by the belief that cloud seeding technology is still in its rudimentary stages of development and that the region's water needs can be met more efficiently by other methods. The chief concerns of resource officials can be stated as two questions:

> 1. How can we better store, distribute, and use the region's natural water supplies?
>
> 2. How can we better understand and predict the forces which influence weather systems, including precipitation levels, active in the region over a significant period of time?

Cloud seeding is a last resort, a technique to use when everything else has been tried and failed. It will quite likely remain as

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3/R. C. Sutcliffe, Weather and Climate (New York: W. W. Norton and Co., Inc., 1966), p. 155.

such until other improvements - in facilities and in institutions - are carried out.

A program of social science research in New England, therefore, should focus to a great extent on the larger questions of man and environment, on the influence of weather in shaping the attitudes and institutions of society. It should focus on questions which are already very real, not those which are predicated on technological advances yet to be fully defined.

However, a program for social science research should also recognize that field experimentation is an important asset if a new technology is to be improved and tested. Since precipitation management may in fact have some beneficial applications within a "water-rich" region such as New England, an effort should be made to provide the proper social environment for meaningful cloud seeding experiments. Also, since cloud seeding has been carried out under the sponsorship of Government in three states and since cloud seeding may quite probably be tried again, under crisis conditions, efforts should be initiated to deal effectively with those problems which marred previous cloud seeding operations in order to avoid their repitition in the future.

NEW MEXICO STATE UNIVERSITY

Las Cruces, New Mexico

Atmospheric Water Resources Research in the State of New Mexico

Prepared for:

Atmospheric Water Resources Research

U.S. Department of Interior

Bureau of Reclamation

Denver, Colorado

Annual Report

Covering Period: July 1, 1967 to June 30, 1968

Contract No. 14-06-D-6146

BUREAU OF RECLAMATION SUMMARY

Ever increasing demands on our water resources have resulted from the growing and varied use of water. The need for water to support our expanding progress is magnified when we look closely at the vital role water has played in the development of our industrial, agricultural, and domestic complex. If the United States is to maintain its way of life and satisfy the ambitions of her people in this changing world, then it is imperative that the nation so control its water resources that these values can be enhanced and protected.

Runoff in the Rio Grande for the past several years has been so low that the water shortage now seems almost normal. The average flow for the Rio Grande for the 10-year period, 1945 to 1954, was about two-thirds that of the previous 10 years. This condition has not materially changed during the period 1955 through 1965. If it is to be assumed that streamflow is going to be average, it also can be assumed that it will be short. Several years of below normal precipitation, along with rapid increases in water requirements, are responsible for the current shortage.

The importance of water resources augmentation for our survival is self-evident. Foremost among the methods of water resources augmentation is the modification of weather for increased precipitation and, therefore, runoff. In fact, a successful project of this sort in the Rio Grande basin would be a blessing when viewed in the light of previous droughts. Further, the results obtained in this field program will be applicable to similar areas in the arid southwest.

This report summarizes the research activities and results for the period July 1, 1967, through June 30, 1968. The New Mexico project is physically situated within the Jemez and Sierra Nacimiento Mountain ranges near Cuba, New Mexico.

The primary purpose of the New Mexico engineering research program is to develop and use precipitation augmentation and management procedures to increase the quantity of celestial waters that can be contained and used for beneficial purposes within the Rio Grande basin. In addition, the technology developed in this specific basin can be integrated with the technologies developed from other research projects within "Project Skywater" to allow the creation of a national program to enhance the nation's total water resources. The region offers the opportunity to develop techniques for precipitation augmentation where water supplies are very critical and where the physical constraints enhance the probability of a successful program. The drainage basin is very well defined and contains approximately 350 square miles. The climate, hydrology, geography, and logistics are very unique in the New Mexico program.

A research and experimental program to objectively manage precipitation augmentation from winter orographic snow storms must include the following components:

a. A statistical design that will determine the experimental units, and procedures for data collection and analysis.

b. A scientific study of the meteorological parameters to determine treatibility of natural storm systems.

c. An adequate treatment delivery and measurement system.

d. An adequate terrestrial precipitation measurement system.

e. Adequate support facilities, such as transportation, communications, radar, radiosonde releasing and tracking, and emergency shelters.

f. Cooperative work agreements with other state and governmental agencies (U.S. Forest Service, U.S. Soil Conservation Service, U.S. Atomic Energy Corporation, U.S. Geological Survey, New Mexico Engineers Office, New Mexico Fish and Game Department).

g. A good public relationship with the citizens of the experimental area and its environs.

h. A comprehensive analysis system to evaluate data within a reasonable time.

i. Sufficient funds and personnel to adequately complete the experimental program within a reasonable time.

The New Mexico Project has been involved in the development and implementation of each of these components. The amount of effort expanded has been limited by a lack of scientific personnel (meteorologists), transportation facilities, precipitation and ice nuclei measuring equipment, and finances.

The specific area of field experimentation is located within the Jemez and Sierra Naciemiento Mountain Ranges in the Rio Grande River basin. The activities of the personnel and the research results are summarized as follows:

Finances

Field year 1968 was used to plan and initiate the field research program. The initial Work Plans were based upon a contract funding of $110,000 and a hope that both personnel and equipment could be obtained. The funds were cut to $90,000 early in 1968 and then

restored in mid-May to the original amount. As a result, the purchase of a communication system and a radiosonde receiver system was delayed until after the winter measurement season was over.

Personnel

All administrative and field employees were obtained except a meteorologist. Several applicants for the position were evaluated, however, none were found suitable for a field research program. The project needed the services of one or more meteorologists to assist in planning the field operations, evaluating the atmospheric data and making the weather forecasts.

Statistical Design

The statistical design requires the use of precipitation data from both a target area and a control area. The Mt. Taylor target area was not instrumented during the FY 1968. Insufficient funds were available for telemetered precipitation stations. An alternative of using a field technician and a ski-doo to service the three stations every 10 days has been under study.

Storm System Classification

Detailed analysis of historical storm systems passing through the experimental area has been completed. Surface Weather Maps and 500 and 700 mb information from the U. S. Weather Bureau's "Daily Weather Maps" have been used with Daily Weather Forecasts from the Forecast Branch of the White Sands Missile Range Facilities in the analysis.

The types of frontal systems have been discussed with respect to both the frequency of occurrence and their importance to the Jemez experimental area. Frontal systems that advect moisture into the experimental area from the Gulf have produced the major precipitation storms.

Vertical time cross-sections for the weather of FY 1968 were prepared. Temperatures, pressures, freezing levels, precipitable water, and 500-700 mb heights and winds were presented for each storm.

Personal observations of weather during storms were very valuable in the analysis of data.

Meteorological Parameters

Storms are very complex and have proven difficult to categorize. They are made up of a series of components which interact and make

weather forecasting very difficult. The science of forecasting has grown considerably in recent years. The important variables and their ranges have been well defined. The variables utilized by the New Mexico personnel for the experimental research project are:

a. Direction of storm movement

b. Amount of precipitable water available

c. Temperature, wind field, pressure and heights at 400, 500, and 700 mb levels

d. Freezing level relative to ground level

e. Bottom and top elevations of storm system

f. General 500-mb synoptic map of the entire United States.

Treatment and Delivery System

Five nuclei generators were designed, fabricated, and successfully used in the target area. The units use a 2 percent AgI-Acetone solution in conjunction with a pressurized propane system. Special care had to be exercised with the syringe injection component. Purging followed by routine cleansing was required. A unit was taken to Prof. Steele's laboratory at Colorado State University for calibration. A calibration curve was obtained; however, its precision was not as good as desired. Actual field "seeding" was limited to a series of short-time diffusion studies.

Nuclei Counter - Diffusion Study

An NCAR-Type acoustical nuclei counter was delivered to the project office in Las Cruces, New Mexico in January 1968. Insufficient directions for assembly, missing parts and no directions for operation of the counter delayed its actual use for three weeks. A separate portable power supply was purchased so the unit could be used for diffusion studies within the target area.

The counter was used in a "Special Diffusion Study" on February 27-28, 1968. Satisfactory results were obtained from the study. Concentration levels of AgI nuclei in the target area at three points were measured. The response of the counter to a pulsing of the generators was excellent. A complete plume analysis was not performed due to the lack of an over-snow vehicle.

The Ice Crystal Replicator was received and used in February 1968. Roads that were not passable without over-snow vehicles prevented

the crew from reaching areas within the target areas where the temperatures were -8° C. The results of the replicas were unsatisfactory.

Terrestrial Measurement System

The Soil Conservation Service has measured 9 of 12 snow courses in the target area and its environs. Road 103 (additional three snow courses) is impassable in midwinter without the use of an over-snow vehicle. A snow cat was purchased after the winter season was over.

Project personnel installed and serviced 15 precipitation stations within the experimental area. The sites were selected to present a grid system at variable elevations. Precipitation stations were not installed in the Mt. Taylor control area. Precipitation data for the period of measurement (January 4 to March 20, 1968) can be summarized as follows:

a. Precipitation of 6.53 inches fell at Blue Bird Mesa, a low of 2.22 inches fell at Telephone Canyon No. 3, with an average of 4.32 inches for the experimental area.

b. Nine storms passed over the experimental area.

c. Twenty-two days had a recorded precipitation greater than 0.01 inches.

d. Forty-nine "seedable units" were identified.

e. The maximum intensity of precipitation was 0.48 inches per hour at Clear Creek and was recorded on February 14, 1968.

f. The storms were generally spread over the entire area, but were not of uniform intensity nor duration.

Project personnel installed and serviced two MRI Mechanical Weather Stations at Blue Bird Mesa and Rock Creek Mesa. The predominant wind direction for the areas measured was west to southwest and the range in temperature was from -20° F to 57° F for the period November 17, 1967, to April 8, 1968.

Support Facilities

The project used two 4-wheel drive and one 2-wheel drive vehicles for transportation into the experimental area. This arrangement was unsatisfactory because an over-snow vehicle was needed for the period of January 1 - March 15 in the deep interior of the target area. An agreement was made to utilize a SCS snow-cat. However,

the vehicle was delivered after the winter season had ended. The vehicles rented from the Physical Science Laboratory had frequent breakdowns that interrupted field activities.

A radio communication system was approved by the Federal Communications Commission and the New Mexico Department of Radio Communications for use in the experimental area. Specifications were submitted to commercial suppliers, bids were opened, however, the purchase was delayed until June 1968.

A field office was located at Cuba, New Mexico to provide a centralized control for field activities. House trailers were located in Cuba, La Cueva and on Forest Service Road 103 for routine use. Emergency shelters and supplies have been located on Blue Bird Mesa, Fenton Lake, Red Top Mountain and Cerro Pelado Peak.

A Wilcox 890 Series Radar and van was located on Cuba Mesa. It is a manual tracking unit with a relatively short range for snow storm systems. The unit was modified to utilize a camera for pictures of the PPI scope. The unit with its attendant camera, the two MRI weather stations and the daily weather log has proven very valuable in conjunction with the forecasts from the U.S. Weather Bureau in Albuquerque in establishing and recognizing "seedable units."

Personnel from the following organizations were cooperative an helpful in the establishment of the research program:

a. Office of Atmospheric Water Resources, Bureau of Reclamation, Denver, Colorado.

b. U.S. Forest Service, Rangers in the experimental area and Administrators in Santa Fe, New Mexico.

c. U.S. Soil Conservation Service, Snow Survey Supervisor at Colorado State University and Administrators at Albuquerque, New Mexico.

d. The Physical Science Laboratory Administrators, Engineers and Technicians, New Mexico State University, Las Cruces, New Mexico.

e. U.S. Geological Survey, Surface Water Branch, Santa Fe, New Mexico.

f. U.S. Weather Bureau Office, Albuquerque, New Mexico.

g. White Sands Missile Range, Weather Forecast Branch, White Sands Missile Range, New Mexico.

ANNUAL REPORT

February 1 through June 30, 1968

to

Bureau of Reclamation
Department of Interior

Richard M. Schotland
New York University
Geophysical Sciences Laboratory

I. Purpose of the Program

The spatial distribution of atmospheric water vapor is a basic parameter in weather modification studies. Normally this information is obtained by means of instrumented aircraft or radiosondes. Both of these techniques are of limited value when as is often the case it is necessary to monitor on a continuous basis a specific region of the atmosphere. For this reason it would be desirable to develop a ground based system which could perform such studies. Theoretical and experimental investigations carried out at New York University over the past years have indicated that spectroscopic measurements utilizing a ruby laser system could be used in this application. One of the objects of this program is to develop an optical radar suitable for field studies of atmospheric water vapor.

A second objective of the program is to develop a method to differentiate between cloud particles in the liquid and ices phases using a ground based laser radar system. In this application a comparison will be made of depolarization ratios in the back scattered laser return as a function of the shape and size of the cloud elements. The back scattered radiation from spherically symmetrical and uniform elements such as cloud droplets retain the polarization of the incident energy while the energy returned from non symmetrical ice crystals will be partially depolarized.

II. Discussion of Work Undertaken During the Reporting Period

2a Introduction

In the conventional spectroscopic method for determining a water vapor profile one essentially studies the attenuation of a nearly monochromatic beam of light whose wavelength corresponds to an absorption line of water vapor. The distribution of the gas along the optical path is determined by observing the differential absorption which occurs as the distance between the source and the detector is varied. The spectroscopic method can be applied to the atmosphere via optical radar by utilizing as an energy source the molecular and particulate back scatter which occurs when a pulse of light is projected into the atmosphere.

If a receiver is located adjacent to the source of the light pulse, then the time history of the detected energy can be interpreted in terms of the spatial distribution of the water vapor and other attenuating constituents. A schematic diagram of such a system is shown in Figure 1.

The rapid development of the pulsed ruby laser has provided an energy source suitable for the study of water vapor. This laser oscillates at approximately 6943 A° at a temperature of 300K and can be thermally tuned through the range 6934 to 6950 A° (Abella and Cummins, 1961). This spectral region includes several moderately intense lines of the 6981 A° band of water vapor. The output

of the laser when operated in the 'Q switched' mode is of the order of 20 nanoseconds in time or 3 effective meters in space. The beam divergence of the laser is approximately 5 milliradians and this value may be reduced by suitable optics.

An analysis has been performed of the operation of the Lidar (laser radar) spectrometer. A transfer equation was developed and evaluated which related the received power to that which was transmitted as a function of altitude of the Lidar pulse. The results of this calculation have been used in a signal to noise study of the system as a function of the system parameters. The results of this work indicate that it is probable that a transportable lidar spectrometer can be constructed which will measure the spatial distribution of water vapor in the first four kilometers of the atmosphere.

2b Lidar System Design

The basic concept followed in the design of the Lidar (laser radar) spectrometer is that the system be a portable package which will yield in a real time the spatial distribution of water vapor. Real time means in this context that the computing functions will be performed during the time interval between the pulsing of the ruby laser. Portable means that the system will be mounted in a van and require no external sources of power.

A block diagram of the system is given in Figure 2. The major elements are as follows:

1. Ruby Laser Pockel cell 'Q switch'.
2. Etalon control unit.
3. Optical collector (mirror and predetection filter).
4. Detector.
5. Data handling system (computer).

III Problem Areas Remaining

1. Optimization of the lidar detector system.
2. Servo control of the frequency stabilizing etalon.
3. Design of data recording system.
4. Experimental analysis of ice crystal depolarization properties.

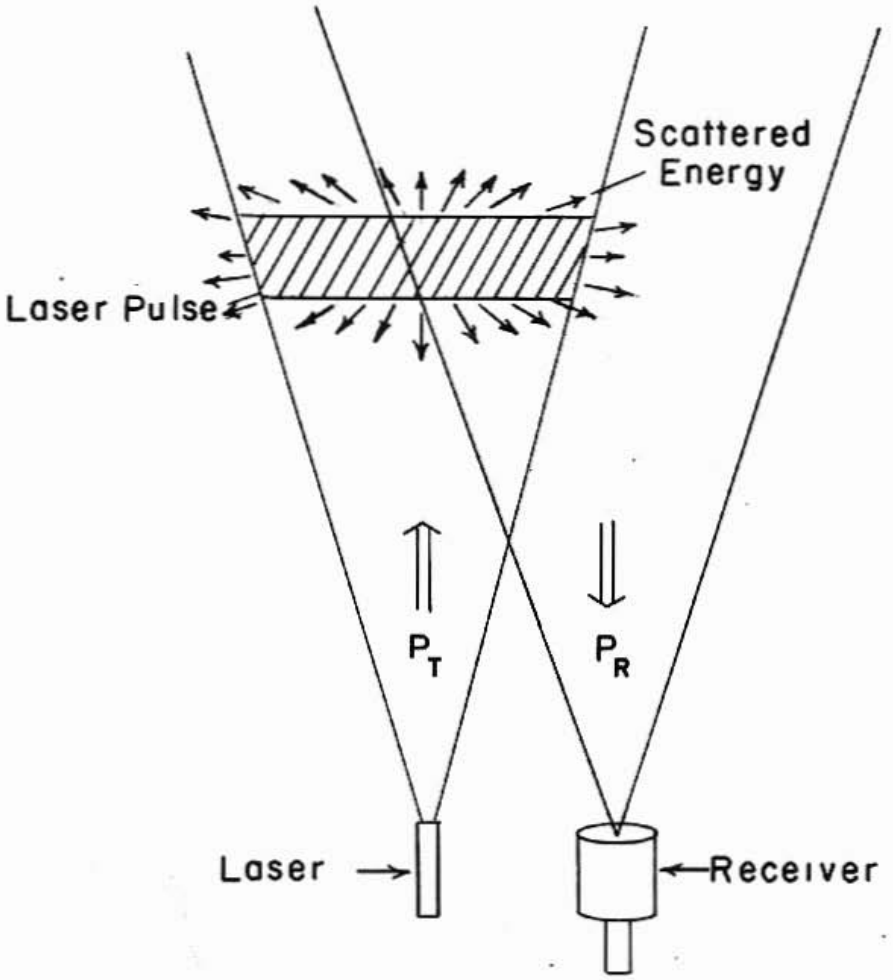


Figure 1. Schematic of Lidar Spectrometer
(Beam divergence exaggerated)

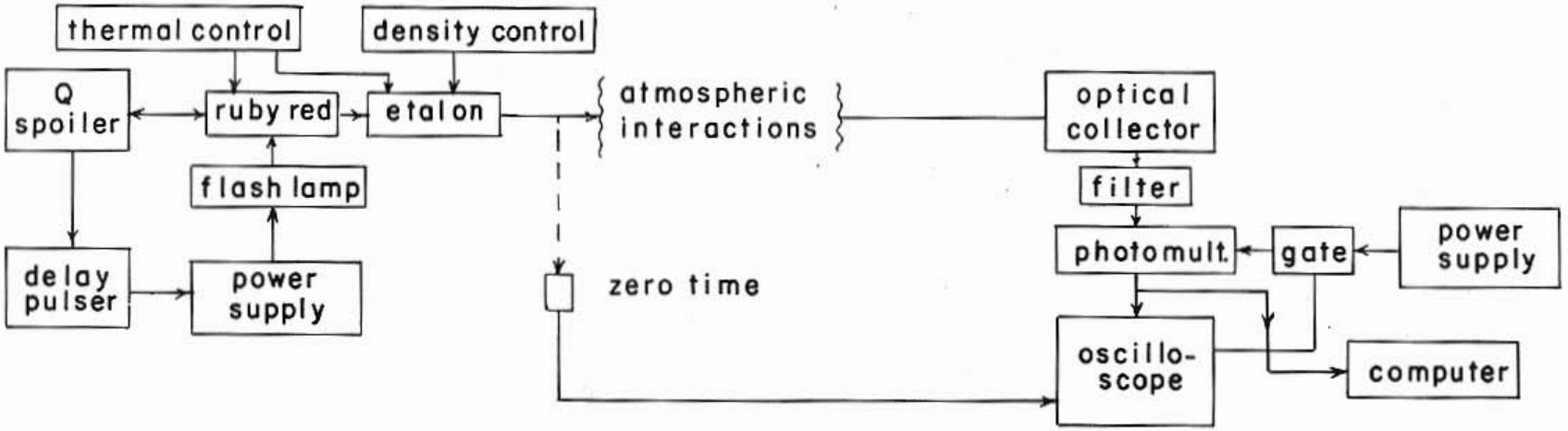


Figure 2. Block Diagram Lidar Spectrometer

The Pennsylvania State University
Institute for Research on Land and Water Resources
University Park, Pennsylvania

Annual Report
April 1, 1968 to June 30, 1968

Atmospheric Water Resources Research
Bureau of Reclamation
Contract No. 14-06-D-6571, Dated April 1, 1968

HYDROLOGIC BEHAVIOR OF SELECTED WATERSHEDS IN THE NORTHERN APPALACHIAN REGION

HYDROLOGIC BEHAVIOR OF SELECTED WATERSHEDS IN THE NORTHERN APPALACHIAN REGION

I. OBJECTIVES

The objectives of this project are to conduct research in, and to develop a definite procedure for predicting hydrologic behavior of watersheds in the northern appalachian regions including the impact of the application of precipitation modification techniques.

II. SUMMARY OF METHODS AND PROCEDURES

A. Select several watersheds that as a group are generally representative of watersheds in the ridge and valley region of the northern half of the Appalachian Mountains. Collect and analyze hydrologic, climatic, physiographic and other pertinent data for the selected watersheds.

B. Utilize and modify certain existing mathematical watershed models suitable for simulating a wide range of hydro-meteorological conditions and effects for the selected watersheds; prepare the necessary computer programs and process input data; and subject the models to sensitivity analysis to determine the degree of accuracy needed on inputs to achieve accurate model output.

C. Utilize model to simulate watershed behavior for a wide range of historic and synthesized precipitation events using both natural and estimated modified precipitation data.

D. Make generalized preliminary planning estimates on water supply augmentation in selected river basins of the northern Appalachian Regions, with estimates for augmentation possibilities during low flow periods.

III. WORK PLAN

A. Selection of Watersheds for Study

Streamflow data collected and published by the U. S. Geological Survey for watersheds in the upper Appalachian Mountain region and streamflow data for experimental watersheds operated by the U. S. Forest Service will be used to search out possible suitable watersheds for use in this study.

Initial criteria established for suitable watersheds are as follows:

1. Watersheds under 100 sq. mi. in area,
2. Streamflow monitored by a water-level recorder,
3. A stable stage-discharge relationship for the entire period of record,
4. Minimum or no effect of ice on winter months' record,
5. Published record should be rated "excellent" which indicates that, in general, the error in the daily records is less than 5 percent,
6. No regulation or diversion of runoff on the watershed,

7. Minimum length of record of 15 years and preferably longer,
8. Relatively stable land-use on the watershed for the period of record,
9. Good to excellent precipitation records for the watershed.

After a site inspection of the potential watersheds is completed, final selection of the watersheds to be used in the study will be made. All necessary hydrologic, climatic, and physiographic data will then be collected.

Streamflow records from the selected watersheds will be compared with regional streamflow characteristics to determine representativeness.

B. Models to be Utilized

1. The Hiemstra Model

In this model (Fig. 1) the watershed is divided in 5 storages which form a cascade, that is the outflow out of one storage becomes inflow or supply for the next. The storages are spaced according to the slope on the catchment and each storage is a lumped representation of catchment properties like soil textural class, vegetation, land use, etc. which can be associated with the slope of the storage. The output of the model is a hydrograph with ordinates at appropriate time intervals.

Outputs such as floods can be generated by using real time data. For example, a series of floods can be obtained by means of random sampling through frequency distribution functions for the magnitudes of the major changing factors of the storm producing system, like time distribution of rainfall intensities, storm durations, soil moisture content, etc. If a suitable rainfall amount is used on a problem catchment it is also possible to assign a probability to the model value of the generated flood series. Therefore the model has the capacity to show peak rates and hydrographs for a variety of inputs.

2. The Raphael-Markov Chain Model

The main concern of this model (Fig. 2) is the relationship between precipitation and the resultant runoff from a system of watersheds. By "runoff" only that portion of the total flow is considered which appears as the surface runoff due to excess precipitation.

Various methods have been proposed and developed in hydrograph analysis, including the unit hydrograph analysis, the synthetic unit hydrograph method, the dimensionless hydrograph method, etc. Here, the problem of predicting the resultant runoff due to a rain storm or a series of rain storms passing over an interconnected system of watersheds was dealt with using a probability theory methodology. In addition, the developed model gives the final proportions or the percentages of water going into the categories of evapotranspiration, deep ground seepage, and surface flow.

It was assumed that all the precipitation water was lost from the system

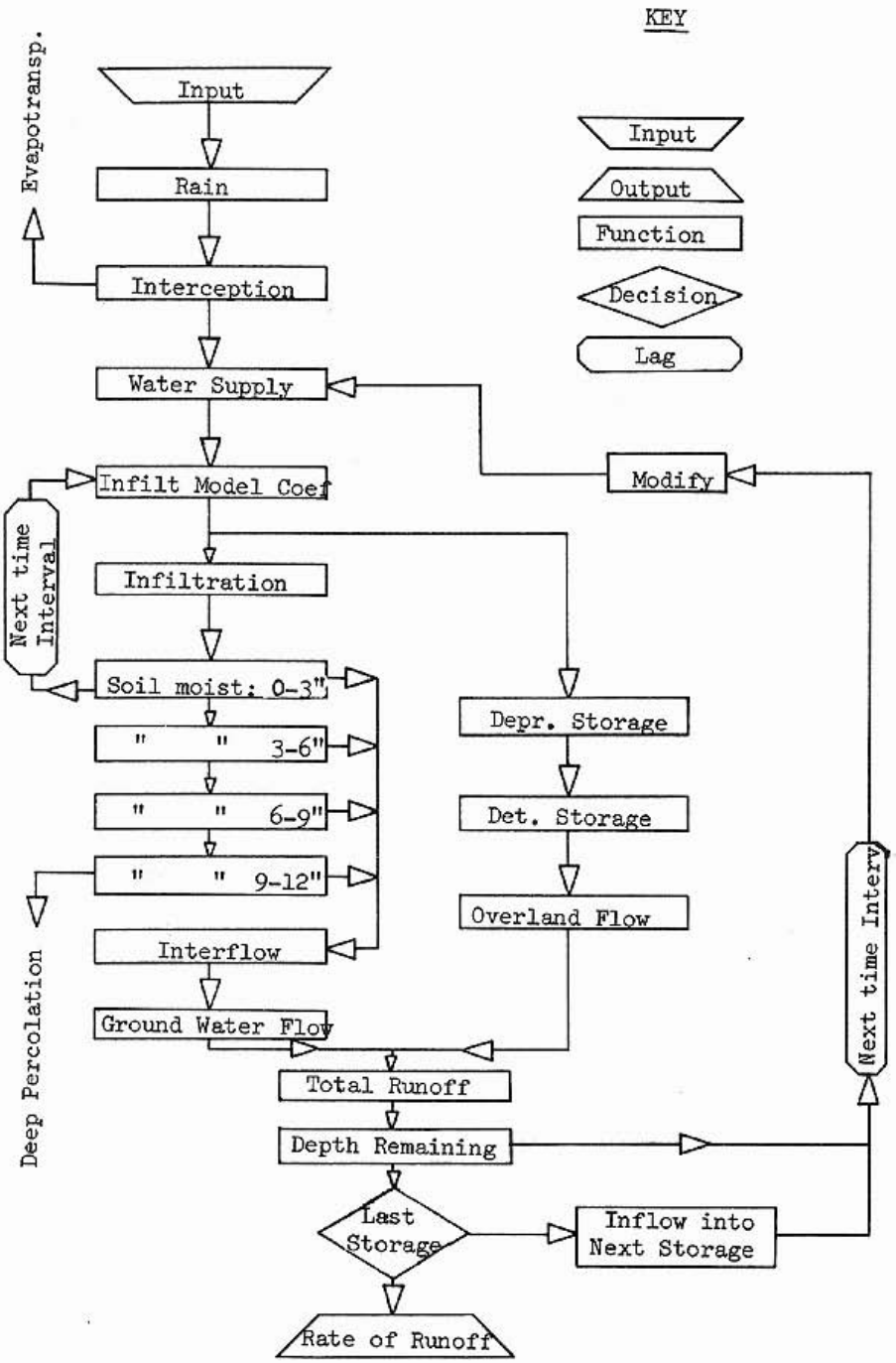


Fig. 1. Flow-chart for the Hiemstra conceptual model

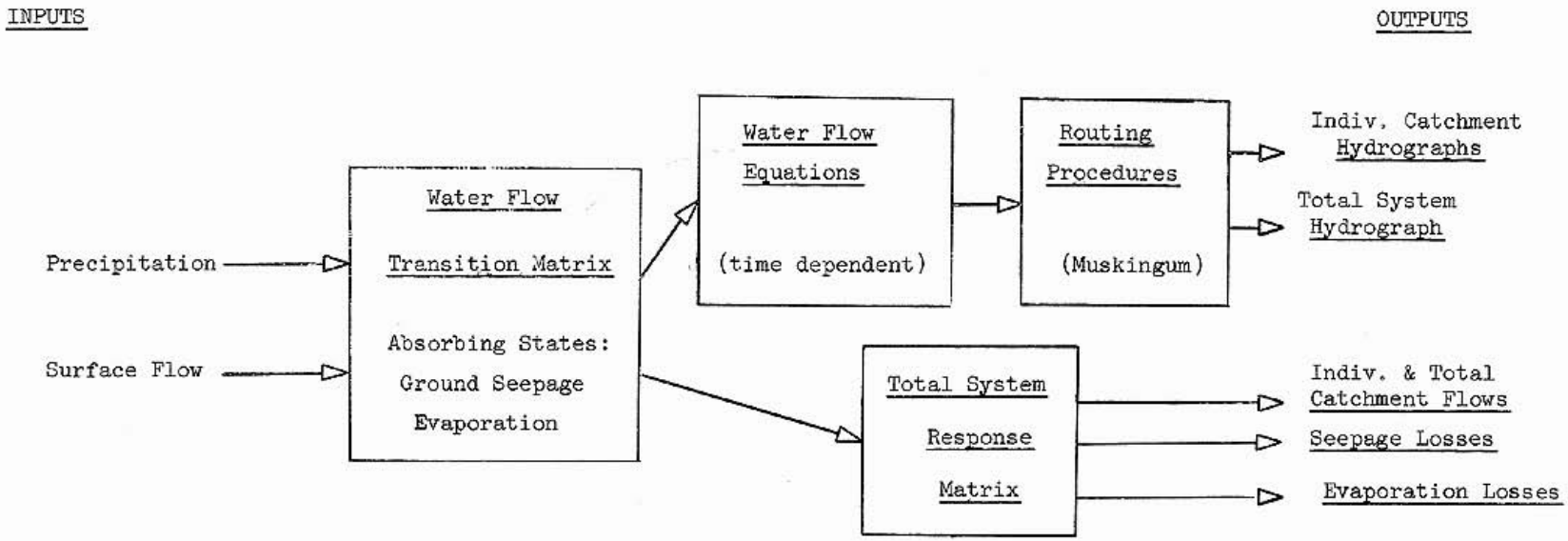


Fig. 2. The Raphael-Markov Chain Model

Flow Diagram

through one of three ways: evapotranspiration, seepage to ground, and surface flow. It was also assumed that prior knowledge of the evapotranspiration coefficient or some function of it, seepage coefficient or its function and the surface flow coefficient or some function of it exists or can be estimated on a regional basis. These coefficients determine the amount of water that evaporates, the amount which seeps into the ground, and that which is available as surface flow. They are the transfer coefficients which govern the flow of water through a watershed or through the whole system of watersheds.

The model treated these initial or direct coefficients as transition probabilities. They were set up in the form of a square matrix. Given the three ways through which all the water was lost, that is, given evapotranspiration, seepage and the surface flow, if the interconnected system of watersheds had m watersheds, then the matrix would be a $(m + 3) \times (m + 3)$ square matrix consisting of these various transfer coefficients.

The model is a discrete time parameter absorbing Markov chain with evaporation, seepage and surface flow as the three absorbing states. This meant that the volume of water which entered the system was eventually absorbed into one of these three states.

The $(m + 3) \times (m + 3)$ matrix was raised to various powers until all the entries in a portion of it approach zero. These powers represent a transition from one time period to another. A mathematical manipulation of these powers and their entries gives a model which can conveniently be used to generate the resultant outputs given the input functions. In this way, output hydrographs for the system can be generated. The model can also be used to give the total response behavior of the system.

Thus, it was assumed that, theoretically, the hydrologic phenomenon of surface flow due to rainfall would approach that of an absorbing Markov chain with certain absorbing states in the body of the chain. The prerequisites for a prediction with a Markov chain are (1) a given starting state and (2) the probabilities of transferring the process from one state to another in a given time period. Similarly, for a surface flow estimation in hydrology, the various transfer coefficients or probabilities could be estimated and a starting state could be specified. The only difficulty that arises here is due to the fact that these transfer coefficients may not remain constant for the entire time interval in a hydrologic cycle under study. This may be due to the varying soil moisture conditions, varying precipitations and varying climate.

To make some provision for this, the transfer coefficients will be estimated as an average of various proportions for the total time period considered for the study. The total rainfall and the total surface flow attributed to this rainfall will be estimated from regional data. A sophisticated equation showing the relationship between the rainfall and the surface flow could be worked out to give consideration to soil conditions and the other physical characteristics of the basin. This would have required an immense amount of time. Hence, an engineering approach to the problem of estimating will be followed in carrying out this pilot study.

Figure 3 shows how a river basin's hydrologic behavior would be simulated by the model.

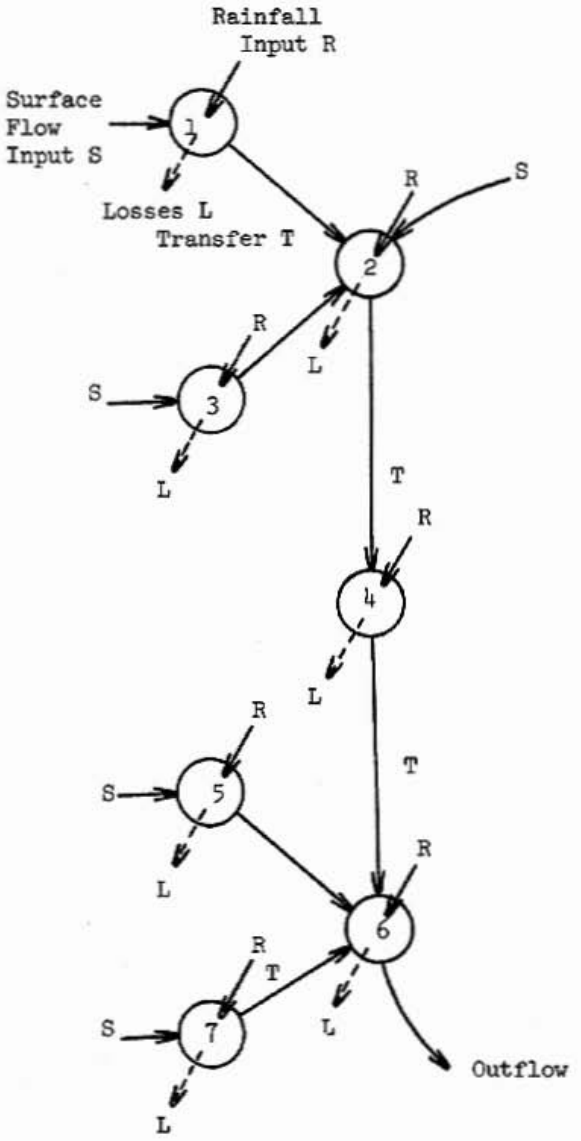


Fig. 3. Interconnected System of the Susquehanna River Basin.

3. Stanford Watershed Model

The Stanford Watershed Model is a mathematical representation of the hydrologic cycle developed to simulate watershed behavior. It was designed to produce a continuous runoff hydrograph from inputs of climatological data and watershed parameters such as surface characteristics, soil moisture storage and retention properties, groundwater storage and discharge characteristics, and channel configuration.

The major input data are precipitation and potential evapotranspiration. Calculations begin from a known or assumed soil moisture condition and continue until all input data is exhausted. Precipitation is stored in three zones. These are the upper and lower soil moisture storage zones and groundwater storage. The upper and lower soil moisture zones control overland flow, infiltration, interflow, and inflow to groundwater storage. The upper zone simulates the initial watershed response to rainfall, particularly small storms. The lower zone controls watershed response to large major storms by controlling longer term infiltration rates. Groundwater storage supplies controls the base flow to stream channels. Evaporation and transporation may occur from all three storage zones.

The total channel inflow from overland flow, interflow, and groundwater enters the channel system simulation and emerges as a synthesized continuous hydrograph of outflow from the watershed.

C. Sensitivity Analysis

When the three models have been adapted to an Appalachian watershed, sensitivity studies will then be made. The purpose of these studies will be to evaluate the response sensitivity of each of these models to the various required hydrologic inputs, particularly the precipitation parameter.

The aim of these investigations is to determine the accuracy and efficiency of each of the models in terms of their ability to predict the downstream hydrograph resulting from the various precipitation inputs. The studies will simulate high flow and low flow conditions in the watershed systems. It is hoped that an evaluation can be made as to the best model for prediction for a given set of watershed conditions.

The possibility of a combination and a synthesis of the models will be considered. As it is highly possible that each model will have strengths that the others do not have, an attempt to combine the strengths of each into a single effective Appalachian model will be made. However, developing a new model goes beyond the scope of this initial project.

The basic bench mark for evaluation will be the actual streamflow data for the watershed system. Each model will be tested to see how accurately it can respond to the recorded hydrologic input over time. An evaluation will then be made as to the efficiency of each model, with respect to time and money, in producing its response. With this type of information, the search for an optimal modeling technique can be started. Studies will then be made using an assortment of synthesized possible inputs to the modeled system.

D. Application of Watershed Model to Other Larger Regional Watersheds

Based on the information gained from the sensitivity analysis one of the models will be selected for use in making some preliminary planning estimates on water supply augmentation in the study watersheds and also on other regional watersheds. Initially only the study watersheds will be utilized. However, within the limits of time and funding this will be expanded to larger watersheds and river basins in the northern Appalachian region.

Some rather naive assumptions will be applied to weather modification potentials since there is not a suitable seedability analysis for this region. At this time it is anticipated that the approach will be to assume varying precipitation increases of 5, 10, 15 and 20 percent, etc. These increases will be distributed in different areal patterns over the watershed. These increases will be applied to historic situations that would initially appear to have some seeding potential. The number of such historic situations covered and the areas involved would again depend on the time and funding available. It is currently anticipated that the "Cumulus Model" (Davis and Weinstein) or some modification thereof will be used to select events with some seeding potential. However, before any firm decisions are made on the use of this model, the watersheds must first be analyzed.

These studies will not consider the cases when snow is present on the ground.

IV. WORK ACCOMPLISHED DURING THE PERIOD APRIL 1 TO JUNE 30, 1968

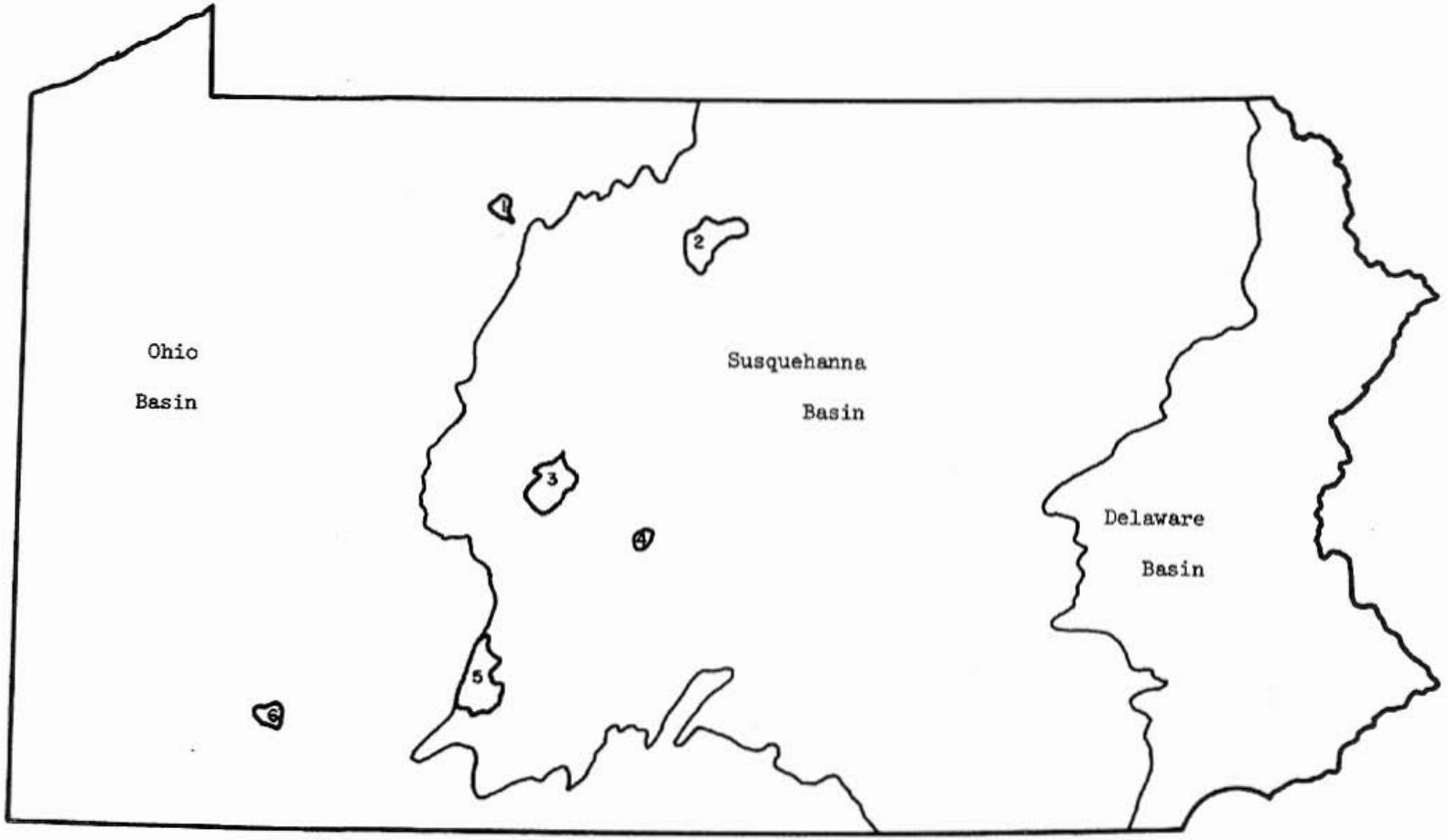
A. Watershed Selection

Six watersheds were selected in the Appalachian Mountain region of Central Pennsylvania. (Fig 4). Hydrologic, climatic, physiographic, and land-use data were collected for each watershed from published U.S.G.S. streamflow records, topographic maps, and field inspection. These data are summarized in Tables 1 to 5. Table 1 lists the six potential study watersheds. Table 2 gives pertinent data available on the surrounding larger basins of which the study areas are sub-watersheds. Table 3 presents the physical characteristics of the study watersheds. To determine the representativeness of the selected watersheds, streamflow characteristics of the six study watersheds were compared with average regional streamflow characteristics (Tables 4 and 5).

B. Watershed Model Modification and Adaption

The Hiemstra Model has been modified to improve the infiltration portion of the model and to adopt it to the Northern Appalachian region. The program is now ready to operate on the University IBM Model 67 computer. The Leading Ridge experimental watershed has been selected for initial hydrograph simulation because the watershed has been under intensive study during the past nine years and hydrologic and climatic records are readily available

The Raphael-Markov Chain Model originally developed at the Pennsylvania State University has also been modified and adapted to the new IBM 360 Model 67 computer and is now in operation. This model will be used later in the



1. Sevenmile Run
2. Kettle Creek
3. Moshannon Creek
4. Leading Ridge
5. Dunning Creek
6. Green Lick Run

Fig. 4. Location of study watersheds by major drainage basins.

Table 1. List of Potential Study Watersheds

	Study Watersheds	U.S.G.S. Gaging Station No.	Years of Record	Area Sq. Mi.	Type of Record	Accuracy of Record
1.	Kettle Creek	1-5445	26	136	ADR	Good
2.	Moshannon Creek	1-5420	26	68.8	ADR	Good
3.	Dunning Creek	1-5600	27	172	ADR	Good
4.	Sevenmile Run	3-265	15	7.84	ADR	Good
5.	Green Lick Run	3-0830	25	3.07	ADR (V-notch weir)	Good
6.	Leading Ridge Experimental Watershed		10	0.47	Water level recorder V-notch weir	Excellent

Table 2. List of Potential Application Watersheds

Possible Study Watershed	Application Watershed	Area Sq. Mi.	Record	Remarks
1. Moshannon Creek	W. Br. Susquehanna (1-5425)	1462	ADR (Good)	Some reg. by reservoir and lake, 26 years.
2. Sevenmile Run	Clarion River (3-0295)	807	ADR (Good)	Some reg. by reservoir and industrial plants at low-flow, 28 years.
3. Kettle Creek	W. B. Susquehanna (1-5455)	2975	ADR (Good)	Flow reg. by lakes and reservoirs, 59 years.
4. Dunning Creek	Raystown Branch Juniata R. (1-5620)	756	ADR (Good)	Some reg. by mills, 55 years.
5. Green Lick Run	Youghiogheny River (3-0835)	1715	ADR (Good)	Reg. by several reservoirs, 46 years.

Table 3. Physical Characteristics of Study Watersheds

	Study Watersheds	Land-Use (percent cover) Forest	Open	Urban	Water	Swamp	Relief	Relief Ratio	Mean Channel Slope	Circ. Ratio (Shape)	Gage Sta. Elev.	Lat.	Mean Max. Jan. Temp.	Mean Max. July Temp.
		%	%	%	%	%			ft/mi		feet	deg.	°F.	°F.
1.	Kettle Creek	90	9.8	--	0.2	(.04)	1459	.014	38.6	0.49	1027	41.47	28.3	79.2
2.	Moshannon Creek	76	23	1	--	--	1175	.024	34.6	0.50	1447	40.83	31.6	80.8
3.	Dunning Creek	57	43	--	--	--	2071	.018	42.6	0.45	1051	40.07	36.7	84.2
4.	Sevenmile Run	99.7	0.3	--	--	--	560	.022	199.7	0.49	1691	41.62	30.5	79.5
5.	Green Lick Run	71	29	--	--	--	960	.071	346.8	0.69	1254	40.10	39.2	83.5

Table 4. Comparison of Annual and Seasonal Water Yields of Selected Study Watersheds and Regional Watersheds

Region	Season				
	Winter	Spring	Summer	Fall	Annual
Upper Susquehanna Basin (7)	inches	inches	inches	inches	inches
Region Ave.	4.85	10.34	1.85	2.78	19.86
Kettle Creek	4.77	11.99	1.68	21.5	20.70
Moshannon	4.51	11.58	2.87	1.91	21.35
Lower Susquehanna Basin (3)					
Region Ave.	4.29	8.70	1.53	1.26	15.79
Dunning Creek	4.70	9.11	1.39	1.16	16.51
Leading Ridge	4.66	9.47	1.52	0.81	16.46
Ohio Basin (8)					
Region Ave.	6.19	9.12	2.49	2.21	19.89
Sevenmile Run	6.00	11.41	2.39	2.52	22.16
Green Lick Run	8.04	9.31	2.27	2.14	21.75

Note: 1. Comparison of Streamflow Characteristics for 12-year period 1954 - 65.

2. Regional watersheds are all those in the basin under 200 sq. mi. in area with good to excellent records.

3. Winter (Dec., Jan., Feb.); Spring (March, Apr., May); Summer (June, July, Aug.); Fall (Sept., Oct., Nov.)

Table 5. Comparison of Peak Discharges, Seasonal Water Yields, and Streamflow Timing Indices

Region	Peak Daily Discharges Above 10 csm		Seasonal Water Yield		Streamflow Concentration Index	Streamflow Dispersion Index
	No./yr.	Size	Dormant Season	Growing Season	Shortest 1/2-Flow Interval[1/]	Longest 5 percent Interval[2/]
Upper Susquehanna Basin (7)		csm	inches	inches	days	days
Region Ave.	5.2	16.5	14.45	5.25	68	100
Kettle Creek	8.8	16.9	15.56	5.18	54	110
Moshannon	3.5	14.8	14.29	7.06	68	86
Lower Susquehanna Basin (3)						
Region Ave.	4.4	15.3	11.91	3.82	68	103
Dunning Creek	4.2	14.3	12.86	3.60	64	103
Leading Ridge	4.0	14.0	12.41	4.05	38	-
Ohio Basin (8)						
Region Ave.	4.9	16.5	14.22	5.13	72	102
Sevenmile Run	6.4	19.1	17.07	5.93	73	105
Green Lick Run	8.1	16.2	17.13	5.51	75	100

1/ Shortest 1/2-flow interval is the shortest number of consecutive days which yield one-half of the total annual flow.

2/ Longest 5-percent interval is the longest number of consecutive days which yield five percent of the total annual flow.

study to synthesize hydrographs for the watershed system on the West Branch of the Susquehanna River.

The Hiemstra-Raphael Hybrid Model. From research to date, a combination of the above two models appears possible and potentially useful. On the basis of preliminary results the Hiemstra model appears to satisfactorily portray the hydrologic behavior of small watersheds and provides reasonably accurate hydrologic output parameters. These outputs, in turn, can be used as inputs to the Raphael model which was developed originally to deal with larger basins and complex watershed systems.

V. GENERAL COMMENTS

Since this report covers only the first three months of the contract period only the very preliminary work has been accomplished. Due to this there are neither positive or negative results as of June 30, 1968.

One potential problem area has recently been noted. This is the conversion of the Stanford Watershed Model to the Penn State Computer. A detailed study of this is currently underway.

No reports or published papers have been issued on this research, other than required by the contract.

VI. Personnel Working Project

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Institute for Research on Land and
Water Resources,
Asst. Professor of Meteorology

Principal Investigators

William E. Sopper, Professor
Forest Hydrology

David L. Raphael, Assoc. Professor
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Research Aide

Robert Creese, Instructor
Industrial Engineering

Report 68-10 September 1968

ANNUAL REPORT ON RESEARCH UNDER PROJECT SKYWATER FROM 1 JULY 1967 TO 30 JUNE 1968

By: A. S. Dennis, J. H. Boardman, B. L. Davis, and H. D. Orville

Prepared for:

U. S. Department of the Interior
Bureau of Reclamation Contract No. 14-06-D-5979

Institute of Atmospheric Sciences

South Dakota School of Mines and Technology

Rapid City, South Dakota 57701

TABLE OF CONTENTS

	Page
Table of Contents	i
List of Figures	ii
1. INTRODUCTION	1
2. THE YEAR'S WORK	1
2.1 Organization	1
2.2 Cumulus Dynamics	1
2.3 Cloud Physics Laboratory	3
2.4 Meteorological Analysis	6
2.5 Radar Instrumentation	9
3. PROBLEM AREAS	11
APPENDIX: LIST OF REPORTS AND PAPERS	14

LIST OF FIGURES

Number	Title	Page
1	Map showing locations of field projects	2
2	Fields of motion, temperature, and moisture in and around numerical clouds	2
3	Interior of cold chamber facility	4
4	Technician Janet Wood operating air preparation system in nucleation studies facility	4
5	Distribution of Wilcoxon rank test statistics for SW flow cases, 1966 - 1967	8
6	Research engineer James Boardman with PDP-8 computer at radar facility	10

1. INTRODUCTION

The purpose of this report is to summarize progress achieved by the Institute of Atmospheric Sciences under Project Skywater during the period 1 July 1967 to 30 June 1968. Results to 30 June 1967 were summarized in the Institute's Report 67-4, which was incorporated in Volume 2 of the Project Skywater 1967 annual report.

The work under Project Skywater during fiscal year 1968 was directed again toward the development of means to increase rainfall from the cumuliform clouds characteristic of the northern Great Plains during the summer months.

The work performed during the period and the results obtained are outlined briefly in the following section. Problem areas that need further work before the contract objectives can be achieved are discussed in Section 3.

The reports published and papers presented by Institute staff members during the year are given in the Appendix.

2. THE YEAR'S WORK

2.1 Organization

The year's work was carried out under the overall direction of Dr. Richard A. Schleusener, director of the Institute, with the assistance of James N. Simmons, administrative officer.

The scientific and technical staff members were organized in four groups for their research work. Dr. Harold Orville, with the assistance of several graduate students, pursued his research on cumulus dynamics using computer models. A cloud physics laboratory was operated by Dr. Briant L. Davis and John A. Donnan. A meteorological analysis group headed by Dr. Arnett S. Dennis undertook an analysis of all cloud seeding experiments and cloud penetration data obtained by the Institute up to the fall of 1967. Members of this group also handled the day-to-day conduct of the various field experiments (Fig. 1). The radar and instrumentation group, headed by Dr. Paul L. Smith, maintained all radar and aircraft instrumentation and assumed responsibility for incorporating new equipment, including a PDP-8 computer, into the Institute's research program.

2.2 Cumulus Dynamics

The two-dimensional numerical model of a cumulus cloud developing over a ridge was improved further during the year. The most notable

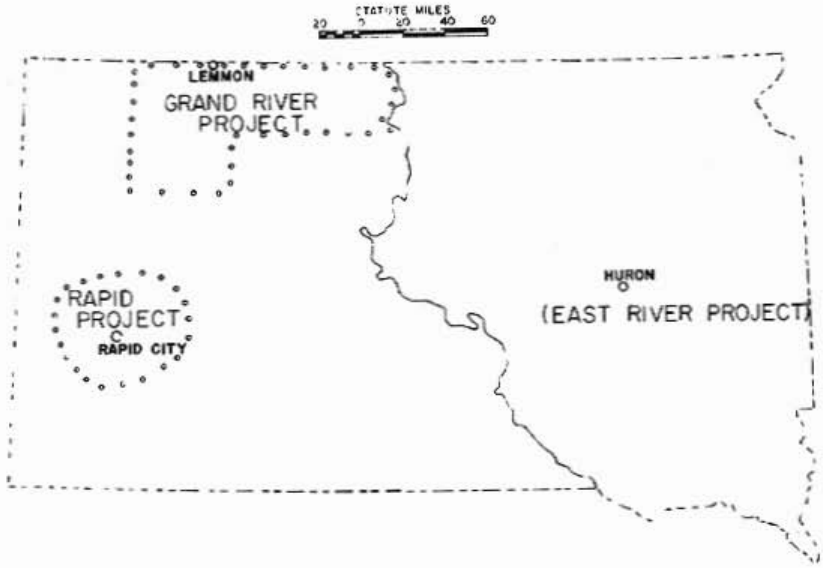


Figure 1. Map showing locations of field projects.

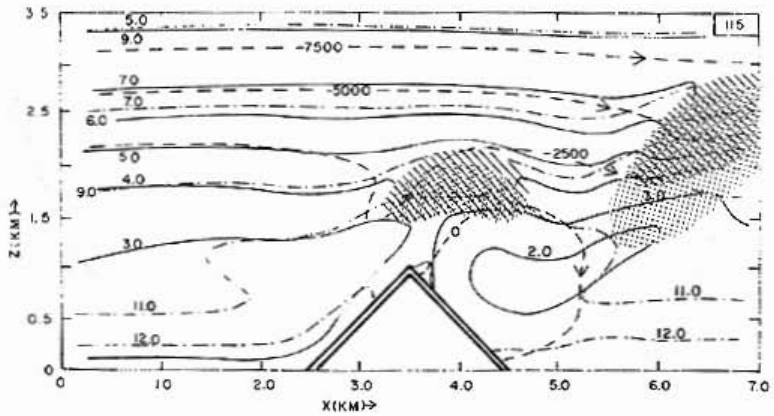


Figure 2. Fields of motion, temperature, and moisture in and around numerical clouds. Dashed lines show stream function in m^2 sec^{-1}; solid lines show temperature deviation from a base state in °C; dash-dot lines are isohumes in gm kg^{-1}. The slanted lines depict the cloud (100% relative humidity) and the dots depict all rainwater content equal to or greater than 2.5×10^{-5}. Total time of heating and evaporation in minutes is shown in the upper right-hand corner.

change was the incorporation of a precipitation process. This was done using parameterized conversion factors to account for the coalescence of cloud droplets into raindrops and the accretion of cloud water to existing raindrops. The results confirm that the formation of precipitation in cumulus clouds affects their growth and dissipation. The principal effects are the formation of a downdraft in the unsaturated rainfilled air beneath and to the side of the cloud, and the creation of rainfall at the ground if the evaporation of raindrops is slow enough.

Other features added to the model allow the mountain slopes to be heated at different rates, simulating shady and sunny slopes. Also, any clouds formed may cast shadows which affect the resulting motion, particularly if the shadows fall on the mountain slopes. The interaction of cloud with the underlying terrain through shadow and rainfall processes is perhaps more important to further cloud development than the internal effects of precipitation.

The computations are carried out on the CDC-6600 computer at the National Center for Atmospheric Research. A CRT display of the outline of clouds and precipitation areas provides time-lapse pictures of the growth of the numerical clouds (Fig. 2). Subsequent viewing of the display is proving useful in clarifying the behavior of cumulus clouds under varying environmental conditions.

In addition to the meteorological studies, a number of investigations have been made into possible sources of error in the numerical model. The problem of implicit diffusion, which is inherent in many numerical cloud models, is the subject of a note recently accepted for publication in the Journal of the Atmospheric Sciences.

2.3 Cloud Physics Laboratory

Activities in the cloud physics laboratory centered around a wind tunnel/cloud chambers facility and a nucleation studies facility.

The cold chambers and associated fog and aerosol production assemblies for the wind tunnel/cloud chambers facility were constructed and placed in operation during the year (Fig. 3).

In the original design, the optical/photographic system for the facility was to consist of an MP-3 Polaroid Land Camera mounted on a lens-prism arrangement. Although some pictures were obtained to magnifications of 150 power, the insertion of the film pack threw the crystal image out of focus and resulted in low quality photographs. Further research resulted in the adoption of the Nikon AFM system, which permits focusing and viewing of the crystals in a through-the-lens system. Five such Nikon systems have been purchased and satisfactory photographs have been obtained. Some problems which occurred in the film-advance system have been resolved by replacing the original film tracks with Teflon tracks.

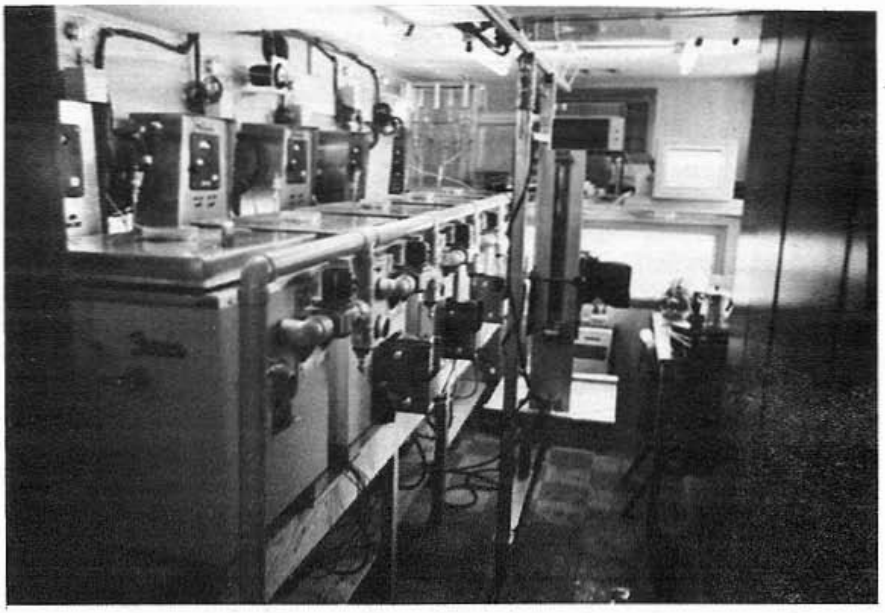


Figure 3. Interior of cold chamber facility.

Upper center: Clear plastic fog generator and fog injection manifold.
Left: Five cold chambers, with fog injection and film advance systems.
Center: Movable photographic system.



Figure 4. Technician Janet Wood operating air preparation system in nucleation studies facility.

The original testing of the optical system was carried out in conjunction with testing of the pyrotechnic devices. We have found that the flow pattern is as expected, the sampling tubes are operational, and the filters seem to be as effective as specified by the manufacturer. However, there are minor problems involving rapid clogging of the filter and consequent reduction of the flow rate. A pressure gauge has been mounted in the filter chamber to determine when the filter should be replaced.

Six basic research studies were carried on using the nucleation studies facility (Fig. 4). These will now be described separately.

(1) The effect of deformation on the nucleating ability of silver iodide, covellite, and kaolinite.

A considerable amount of time was put into a study of deformed-undeformed pairs of the above nucleants in an optical cold chamber, at constant saturation ratio and temperature. It was observed for all three compounds that the time-dependent nucleating ability for the deformed material was much higher than for the undeformed material. We feel that the effect here is due to the stored strain energy from the crushing process, which introduces dislocations and an elastic homogeneous strain into the sample. A comprehensive report describing this process and the sources of energy involved is being prepared at the present time.

(2) Additional data on the freezing and sublimation thresholds as determined at high initial supersaturations in the x-ray cloud chamber.

By successive injection of clean moist air and moist air containing condensation nuclei at 5° intervals from -20C to -80C, we were able to observe changes in cloud density, cloud dissipation rates, and ice formation that depict the position of both the homogeneous freezing and (we believe) homogeneous sublimation thresholds.

(3) The effect of silver iodide nuclei on the freezing of pure water and of dilute NaCl solutions.

This study was carried out using the optical system in a manner similar to the deformation experiments, the freezing of solutions and pure water being carried out by pairs under identical conditions. We have observed that the presence of dilute (.007 molal) solutions, such as would be expected by salt seeding in cumulus clouds, have little effect upon the supercooling and subsequent freezing. The results of this study are being published in the Proceedings of the South Dakota Academy of Science.

(4) An analysis of the cubic and hexagonal phases in silver iodide aggregates.

A short study involving the determination of a calibration curve to calculate the ratio of cubic to hexagonal phases in silver iodide mixtures was carried out during this year. We encountered some unique problems because of the softness of silver iodide, and the formation of the cubic phase during grinding. A relatively simple technique was devised, however, to provide a relatively accurate and reproducible method for the analysis. The results have been submitted to the Journal of Applied Crystallography for possible publication.

(5) Research carried out at the Yellowstone Field Expedition (YFRE-8).

During the one-week stay at Yellowstone, one of the members of the Cloud Physics Laboratory suspended small ice pellets on a tripod downwind from supercooled vapors of some of the geysers in the Yellowstone Park. The ice particles were suspended in a manner to permit rotation by the wind, and ice growth was recorded by sectioning and Formvar replication. A number of interesting structures were formed during growth of the ice pellets, which are believed to have formed in a manner similar to those observed in hailstones.

(6) A small amount of time was taken during the year to revise the compressibility and elastic constant analysis of silver iodide.

Large uncertainties discovered in the initial data precluded publication of the compliance data so that only the compressibility data have been submitted for publication. The manuscript has been accepted by the Journal of Geophysical Research and will appear late this year.

2.4 Meteorological Analysis

Personnel of this group were involved with the completion of the 1967 seeding experiments, the analysis of the resultant data during the winter months, and the resumption of seeding experiments for the summer of 1968. Preparation of short-range weather forecasts, the organization of information for debriefing sessions, and the compilation of rainfall data on punch cards were involved in addition to the actual field operations.

Much activity centered about the Rapid Project, a randomized crossover experiment near Rapid City involving silver iodide seeding of cumulus clouds by aircraft operating below cloud base (Fig. 1). Alexander Koscielski acted as project meteorologist. A total of thirty test cases were logged on the Rapid Project during 1967, bringing the total number of test cases to sixty-seven. The rainfall observations for the two

years were analyzed on the School's computer using covariance analysis, multilinear regression, and rank tests. The various tests yielded compatible results. The findings, which were presented to the 1968 annual meeting of the American Meteorological Society and published in the Institute's Report 68-5, were as follows:

1. Cloud seeding tends to increase average rainfall in the seeded target on days with southwesterly-flow aloft, with the results being more clear-cut on days with isolated showers than on days with widespread storms.

2. Results are inconclusive for days with northwesterly-flow aloft.

3. Seeding effects are not uniform throughout the target areas.

4. There is some evidence of a dynamic seeding effect, possibly due to release seeding of latent heat, in the lee of the Black Hills.

Figure 5 shows the results of the Wilcoxon test applied to north-south rainfall differences on days with southwesterly flow during the two seasons. Positive test statistics are indicative of regions where rainfall tended to be heavier on north-seed days. It is seen that there is a general tendency for rainfall to be heavier in the north target area on north-seed days and in the south area on south-seed days, but a reverse effect is noted in the southwestern ends of the target areas, which extend into the Black Hills.

Precipitation data from 1966 and 1967 were subjected to factor analysis for insights into rainfall distributions in the Rapid City area, but the data sample is too small to give stable factors when the data are stratified according to wind direction and other meteorological parameters.

The Rapid Project was resumed on 15 May 1968. The Baron seeding aircraft again was used with a Lohse generator and a rack carrying fourteen pyrotechnic flares mounted on each wing. The Rapid City area experienced a cool late spring, and only eight test cases had been declared up to 30 June. Many of these were dry days (with less than 0.70 inches precipitable water) and therefore not favorable to significant shower development. Results for the 1968 test cases have not yet been incorporated into the analysis.

During 1967 a randomized salt-seeding experiment was carried out on isolated cumulus clouds. Twenty-two test clouds were observed, of which thirteen were actually seeded. Seeding was carried out by dispensing finely ground sodium chloride in the updraft below cloud base. An instrumented aircraft made penetrations of the test cloud at the -5C level at roughly five-minute intervals from five minutes before seeding to 30

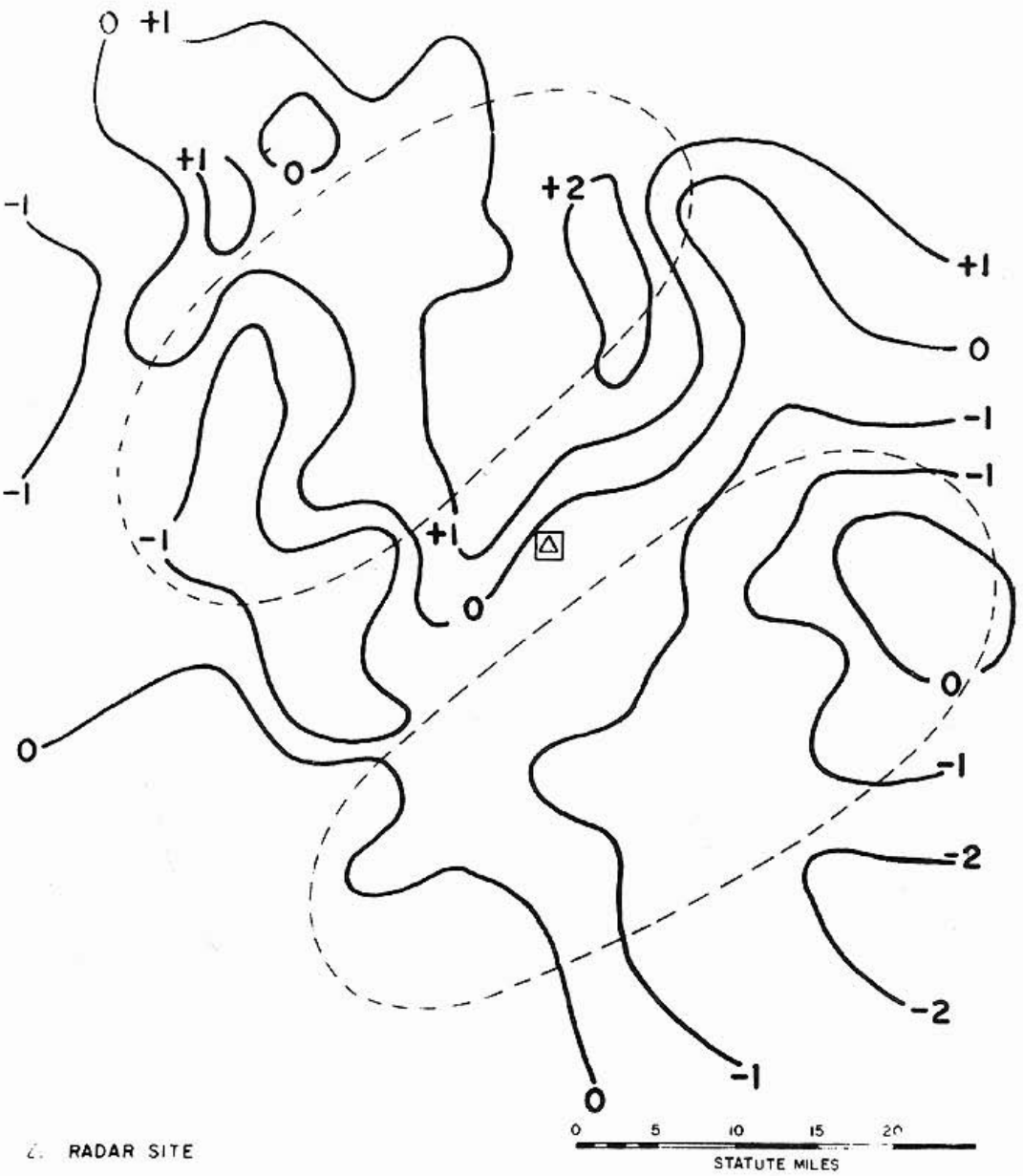


Figure 5. Distribution of Wilcoxon rank test statistics for SW flow cases, 1966 - 1967.

minutes afterward. The seeding aircraft remained below cloud base to estimate precipitation intensity. The results were analyzed by Martin R. Schock as a thesis topic. The limited sample did not provid conclusive evidence that salt-seeding had an effect on precipitation processes. The search for predictors of precipitation development and of other aspects of cloud behavior led to the use of regression techniques to screen various cloud parameters recorded on the first pass at -5C for their prediction value. It was found that positive correlations among updraft speed, temperature excess and liquid water content within a cloud are among the strongest indicators of continued cloud growth and precipitation development. Earlier, John H. Hirsch and Carol Lundy Schock, in a study of cloud penetration data obtained in 1965 and 1966, had found such positive correlations to be characteristic of young cumulus clouds. Their results will appear shortly in the Journal of Applied Meteorology.

The results of a summer of field observations at Huron, South Dakota in 1967 (the East River Project) were submitted in a report by Edwin I. Boyd. The diurnal rainfall regime at Huron shows a double maximum, the more pronounced in the early morning and a secondary one in the afternoon. Warm, non-precipitating cumulus clouds are common in that area during the afternoon hours, suggesting that salt-seeding experiments might prove fruitful.

On 15 May 1968 the Grand River Project was activated at Lemmon, South Dakota, covering Perkins and Corson Counties (Fig. 1). This is a cooperative project, sponsored only in part by Project Skywater. Edwin I. Boyd is acting as manager of the project and Martin R. Schock as project meteorologist. The project is designed to study the effects of heavy seeding using pyrotechnic devices upon precipitation patterns. Up to 30 June, operations had been conducted on 22 days and 84 hours of flight time logged. Data were being collected from a network of approximately 100 raingauges and 300 hailpads.

All rainfall data from the Rapid and Grand River Projects were edited and added to our punch card decks as received.

2.5 Radar and Instrumentation

Most of the work carried out by this group centered around the Institute's radar facility east of Rapid City. Two complete Nike-Ajax systems, including two S-band and four X-band sets, were operated during the summers of 1967 and 1968 in support of the Rapid Project and other programs being carried on in the area. The application of each of the six sets was described in the last annual report. An M-33 radar system was also installed at the radar site. The M-33 3-cm tracking radar will be used with a modified receiver to track balloons equipped with 403-Mc transponders. We planned to use the M-33 10-cm radar in conjunction with an FPS-6 antenna to gather quantitative precipitation echo intensity data. However, attempts to mate the M-33 to the FPS-6 antenna

have been unsuccessful so far. The profiler device, first used for logging radar data in 1967, was modified during the winter to drive a PDP-8 computer as well as the oscillograph. This required the addition of circuits to the profiler to provide a larger output signal. A complete calibration procedure for the profiler radar system was developed, so that absolute values of radar reflectivity can now be determined from the profiler data. The receiver calibration was carried out daily during the 1968 field program, and the other radar parameters were measured frequently.

Perhaps the most notable achievement of the group during the year was the acquisition of a PDP-8 computer and its incorporation into the radar system (Fig. 6). The purpose of this addition is to increase our ability to record and analyze profiler data. Before the computer could be used, many "system" programs and subroutines had to be written. The effort required for this preliminary programming significantly reduced the time available for developing real-time analysis programs. However, some of these programs are near completion and will be ready for use on future occasions.

Approximately 80 percent of the profiler data for the 1968 Rapid Project has been stored, via the computer, on magnetic tape. The analysis of this data should proceed much more rapidly than in previous years when the data had to be manually digitized from oscillograph chart paper.



Figure 6. Research engineer James Boardman with PDP-8 computer at radar facility.

The computer system, in general, appears to be quite flexible in the sense that it is capable of performing several types of analysis of the data and also in that it has already proved to be useful for other tasks not directly involved with the data. An example is the role it played in speeding up the procedure for calibrating the profiler. We expect that the PDP-8 will play an increasingly significant role in our field operations as time goes by.

Other improvements made at the radar facility during the year included the installation of a time-code generator, a new intercom system, and a burglar alarm, and the construction of a storage building. The time code generator and associated remote display units enabled us to synchronize all operations and more accurately correlate time-lapse PPI pictures with other data taken at the same time.

During the winter of 1967-1968, the AMS-3 instrument package used in the leased Piper Apache aircraft was completely rebuilt. This permitted a considerable reduction in the space requirements for the AMS-3 in the aircraft cabin.

An APS-3 X-band radar mounted in a house trailer was operated as part of the East River Project at Huron, South Dakota in the summer of 1967. Considerable overhaul work was done on this system during the winter. It was used on the Grand River Project at Lemmon during the summer of 1968. An additional indicator was provided so that time-lapse photographs could be obtained without interfering with the use of the radar as an operational tool.

Miscellaneous activities carried out during the year included the development of a failure-reporting system, and a survey of U. S. Bureau of Reclamation contractors regarding their spare-parts problem.

3. PROBLEM AREAS

There are a number of problem areas that need further study before the objective of increased rainfall in the northern Great Plains can be achieved on a routine basis. Only four of them, but four which we consider of major importance, will be touched on here.

(1) Clarification of the role of precipitation in the dynamics of cumulus clouds.

The idea that accumulating precipitation inside a cumulus cloud could act as a brake on the updraft received widespread acceptance following its publication in The Thunderstorm in 1949. One numerical cloud model developed recently at the University of Chicago pulsates in direct response to the precipitation brake.

Preliminary results obtained here during the past year suggest that the precipitation brake is not the dominant factor in the timing of the development of new cells, although it has some effect. This problem can only be solved with further use of computer models.

(2) Increased understanding of mesoscale systems.

Our work during the past three summers has shown us that precipitation patterns near the Black Hills are strongly influenced by mesoscale circulations. These circulations are typically considerably larger than the Rapid Project target areas of 700 square miles each, so that we are sometimes trying to modify one part of a mesosystem and leave another part (expected to pass over the control area) unaffected. We probably are not succeeding in the latter objective; this may account for the reverse seeding effect near the edge of the Black Hills which was referred to in Subsection 2.4 above. It appears that understanding of the mesoscale systems will require computer modeling of the circulation over the Black Hills. A start in this direction is being made by one of our graduate students.

(3) Standardization and quality control of seeding devices and monitoring of their output.

Results from our cloud physics laboratory and elsewhere show that the effectiveness of seeding agents varies considerably with degree of contamination and with ambient conditions. The quenching rate is of major importance in determining the output of silver iodide generators.

The monitoring of the output of seeding devices is unusually difficult when they are mounted on aircraft. This problem is being considered in our cloud physics laboratory but no hardware has been developed so far.

(4) Development of a method to monitor rainfall over large areas in real time.

Despite the uncertainties in the Z-R relationship (between reflectivity and rainfall rate), we consider radar to be the most promising tool for this purpose. It will be necessary to use S-band equipment rather than X-band to avoid attenuation. Because radar sets generate much information, it is essential that efficient means be devised to compress and store the data. We have selected the profiler followed by a PDP-8 as the most efficient system to achieve this end. Much work remains to be done in converting to S-band radars, standardizing calibration procedures for the radar sets and profiler, and developing software (programs) to enable the PDP-8 to analyze the data collected and present meaningful output to the project meteorologist.

It appears that the establishment of a randomized pilot project would provide a focus which would help toward solutions of problem areas (2), (3), and (4). Such projects are called for in Project Skywater planning documents as an immediate step between experimental and operational projects. A pilot project would involve a target area of roughly 2,500 mi^2, and thus be more suited than the Rapid Project to determine effects of seeding on mesosystems. It would also function as an outdoor laboratory in which further engineering work could be done on seeding devices, weather radars, and data processing systems.

APPENDIX

LIST OF REPORTS AND PAPERS PREPARED UNDER PROJECT SKYWATER

1 July 1967 to 30 June 1968

Submitted to Bureau of Reclamation

1. Dennis, A. S., 1967: Interim Report on Research Activities and Results Under Project Skywater from 1 July 1966 to 30 June 1967. R 67-4

2. Dennis, A. S., A. Koscielski, and C. L. Hartzell, 1968: Rapid Project Report for 1967. R 68-5

3. Boyd, E. I., 1968: Analysis of 1967 East River Project Data. R 68-8

Papers Presented at Meetings or Published

4. Davis, B. L., 1968: Ice crystal sizes and settling velocities determined with an x-ray diffraction cloud chamber. The Norelco Reporter, XV, 17-21.

5. Dennis, A. S., 1967: Outline of design principles and data requirements for field programs in weather modification. Presented at Conference on Design and Evaluation of Weather Modification Experiments, Denver Federal Center, Denver, Colorado, 11-13 October 1967.

6. Dennis, A. S., 1967: Evidence of singularities in radiosonde data for Rapid City, South Dakota. Quart. J. Roy. Meteor. Soc., 93, 522-527.

7. Dennis, A. S., and A. Koscielski, 1968: Evidence of rainfall increases in randomized seeding of convective clouds. Presented at 48th Annual Meeting of the AMS, San Francisco, 29 January - 1 February 1968.

8. Hirsch, J. H., and C. A. Lundy, 1968: Cumulus cloud characteristics over western South Dakota. Presented at the 48th Annual Meeting of the AMS, San Francisco, 29 January - 1 February 1968.

9. Koscielski, A., and A. S. Dennis, 1968: A randomized seeding experiment in South Dakota. Presented at First National Conference on Weather Modification, Albany, New York, 28 April - 1 May 1968 [pp. 47-54 of Conference Proceedings].

10. Koscielski, A., 1967: The Black Hills tornado of 23 July 1966. Presented at Conference on Severe Local Storms, St. Louis, Missouri, 19-20 October 1967 [pp. 226-228 of Conference Proceedings].

11. Koscielski, A., 1967: The Black Hills tornado on 23 July 1966 in South Dakota. Weatherwise, 20, 272-275.

12. Orville, H. D., 1967: Computer modeling and experimental design. Presented at Conference on Design and Evaluation of Weather Modification Experiments, Denver Federal Center, Denver, Colorado, 11-13 October 1967.

13. Orville, H. D., 1967: The effects of shady slopes on the initiation of cumulus clouds - A numerical experiment. Presented at the Conference on Numerical Prediction, Monterey, California, 31 October - 3 November 1967.

14. Orville, H. D., 1968: Recovery of the pressure field in mesoscale numerical models. Presented at the 48th Annual Meeting of the AMS, San Francisco, 29 January - 1 February 1968.

15. Orville, H. D., 1968: Ambient wind effects on the initiation and development of cumulus clouds over mountains. J. Atmos. Sci., 25, 385-403.

16. Simmons, J. N., and J. H. Hirsch, 1967: Rapid recall of data from field experiments in weather modification. Presented at Conference on Severe Local Storms, St. Louis, Missouri, 19-20 October 1967 [pp. 65-68 of Conference Proceedings].

17. Schleusener, R. A., 1967: Evolution of uses of cloud-seeding technology. Proc. Amer. Soc. Civil Eng., 93, (IR3) 187-197.

18. Schleusener, R. A., 1968: A perspective on weather control. Proc. Amer. Soc. Civil Eng., 94, (IR1) 73-78.

19. Schleusener, R. A., 1968: Hailfall damage suppression by cloud seeding - A review of recent experience. Presented at the first National Conference on Weather Modification, Albany, New York, 29 April - 1 May 1968 [pp. 484-493 of Conference Proceedings].

20. Wood, J. M., and D. N. Blair, 1968: Supercooling of droplets of water and dilute NaCl solutions with and without AgI nuclei. Presented to South Dakota Academy of Sciences, Huron, South Dakota, 26-28 April 1968.

As of 30 June 1968, approximately ten papers were in press or undergoing review.

TEXAS A&M UNIVERSITY

Department of Meteorology

Interim Progress Report No. 1

(April 15 through June 30, 1968)

Research on

Feasibility of Warm-Cloud Management

Contract No. 14-06-D-6469

Dated April 15, 1968

U.S. Department of the Interior
Bureau of Reclamation
Atmospheric Water Resources Research

Texas A&M Research Foundation
Contractor

Horace R. Byers
Principal Investigator

College Station, Texas
July 10, 1968

BUREAU OF RECLAMATION SUMMARY

A. Activities Carried Out or In Progress

Activities of the research are in the following categories: (1) Flight Program; (2) Analysis of Data; (3) Theoretical Models; (4) Cloud Modifying Substances; (5) Logistics of Seeding. Progress on each of these is described in the following paragraphs.

1. Flight Program

The Beech Queen Air airplane of the National Center for Atmospheric Research was assigned to Texas A&M for meteorological flights during the month of May 1968. The airplane, flown by NCAR pilots and with all flight, instrumentation, and preliminary data reduction costs paid by NCAR, was used for measurements related to other research projects at Texas A&M University as well as for penetrations through warm clouds for the Bureau of Reclamation project. However, no opportunity was missed to penetrate warm clouds when they existed, especially when near the rain-initiation stage. A total of 25 flights were made over southeast and south-central Texas with a total data acquisition time of approximately 56 hours. Clouds were penetrated on 13 of the flights.

The NCAR instrumentation performed as expected and with a marked improvement over similar flights the previous year. Recorded on magnetic tape for digital processing at NCAR were temperature, dew point, static pressure, true air speed, liquid-water content, aircraft heading, time counts, on-off times of ancillary equipment, etc. Precipitation particles were collected for counting and sizing by the Brown foil sampler. Direct radio communication was maintained between the aircraft and the base station at the Department of Meteorology radar control. By means of a transponder beacon supplied by Texas A&M, the aircraft was displayed on the radarscope at all times. Meteorological observations by the scientist on board, flight data, instrument checks, remarks, and narrative were recorded on an audiotape recorder. The aircraft also was equipped with VOR-DME for position checks. Two cameras, one looking forward and the other to the side, took time-lapse pictures throughout each flight.

The Texas A&M dual-frequency radars (10 cm and 3 cm) functioned without interruption during the flights, obtaining precise data on the location and development of echoes. Characteristically the warm clouds produced radar returns in those cases where even the smallest precipitation droplets appeared on the windscreen of the aircraft. Scope photography was obtained for all radar coverage.

Upon completion of the flights, the month of June has been spent in assembling flight records as rapidly as they come off the computer at NCAR, making enlargements of the microfilm of data plots for ease

of analysis, transcribing the voice records, examining for errors, and arranging the material for evaluation and analysis.

2. Analysis of Data

During the period of this report the data from the flights were barely becoming available for analysis, so there is practically nothing to report as yet. About 66 individual clouds were penetrated, with multiple traverses (up to six) successfully completed through about 75 percent of them. Other penetrations through stratocumulus cloud areas, one more aspect of cloud convection, provide supplementary data for the cumulus cloud studies.

The flight program was highly successful in that it has provided many well documented cases of warm clouds. The flight meteorologists often observed that incipient raindrops, and even larger water particles, were plentiful in the upper portions of clouds with tops 1000 ft or more below the freezing level. The collections from the foil sampler support the tentative conclusion that such clouds may produce precipitation. Moreover these clouds, reaching only to 12,000 ft or so, appear to have considerable structure and circulation.

3. Theoretical Models

Dr. Das has been working on the completion of two papers on models of precipitating convective clouds, papers started before this project began. When dealing with a population of droplets it is found that larger supersaturations than previously supposed can exist in the updraft while the downdraft is characterized by undersaturated conditions. New computations on collision-coalescence of drops by Davis and Sartor, Berry, Shafrir, Walshaw, and others indicate that these processes proceed much more easily than formerly thought. Hocking's 19-micron lower limit has been pushed to smaller sizes and although their collection efficiencies are low, the smaller drops play an important role because they are so numerous. Calculations based on the new data will more easily explain warm-cloud rain and give us a new model to work on.

4. Cloud Modifying Substances

Only preliminary thinking on this subject has been carried out, the main thrust in this area being considered for a later phase of the research.

5. Logistics of Seeding

Activity in this area will come in a later phase of the project.

METEOROLOGICAL ANALYSIS OF THE PRECIPITATION EFFECTS OF THE SWISS HAIL SUPPRESSION EXPERIMENT, II

Final Report

to the

United States Department of Interior

Bureau of Reclamation

Contract No. 14-06-D-6159

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University of California, Los Angeles

Department of Meteorology

October 31, 1968

I. INTRODUCTION

The Swiss weather modification experiment "Grossversuch III" covers seven summer seasons from 1957 to 1963. Its purpose was to test the feasibility of suppressing hail by cloud seeding with silver iodide released from ground generators. The experimental procedure together with delineation of target area and location of generators and rain gages is described and displayed in Appendix I and its Figure 1. Evaluation of hail frequency indicated that for the entire target area hail occurred on 38 days out of 145 seeded days and on 23 days out of 147 unseeded days, while duration, areal extent and intensity were not significantly changed by seeding (Schmid, 1967). Precipitation amounts were also recorded at a number of rain gauges in the target area, so that this experiment also yields a wealth of data suitable for studying the precipitation effects of seeding because the method of seeding was basically the same as is generally used in the attempt to modify the amount of precipitation. Evaluation of the precipitation effects has been carried out by Schmid in Switzerland and by Neyman and Scott at the University of California Statistical Laboratory in Berkeley.

In their analysis of the results of this experiment Neyman and Scott (1967) stratified the data according to the forecaster who made the prediction each day that the following day was suitable for inclusion in the experiment. They found that on experimental days selected by forecaster Ambrosetti a large positive seeding effect, highly significant, was indicated while on days chosen by Zenone the apparent effect was negative, though at less significance. Neyman suggested that these two meteorologists had correctly although unconsciously

distinguished, at least in part, the conditions under which seeding increases (decreases) rain, and that analysis of the meteorological factors associated with the situations selected by each would enable identification of these conditions. At his request we undertook to ascertain whether there was any difference in meteorological conditions to which these marked differences in effects of seeding could be due. More generally, our attempt has been to identify conditions under which seeding produced increases (decreases) in precipitation in this particular experiment.

A trip to Switzerland to gain background information regarding conduct of the experiments and to arrange for the loan of weather maps and other meteorological data pertaining to the period of the experiments was made by the principal investigator in the summer of 1966. The maps and other data arrived at UCLA in September 1966. The trip and initial research work was carried out under the previous contract, number 14-06-D-5986, which covers the period June 1966 to January 1967. A new agreement, covering the period February 1967 to September 1968 provided for the continuation of the research. The important findings of our investigation are contained in two papers. One, which is titled "The Meteorological Factors Associated with the Precipitation Effects of the Swiss Hail Suppression Project," was presented at the First National Conference on Weather Modification of the American Meteorological Society in Albany, New York, April 28 - May 1, 1968 and has been accepted for publication in the Journal of Applied Meteorology. It is reproduced here in Appendix I of this report. The other, titled "Influence of Atmospheric Stability Layers on the Effect of Ground-Based Cloud Seeding, II. Hypothesis in Explanation" was

presented at the meeting of the National Academy of Sciences in April 1968 and published in its Proceedings in June 1968. It constitutes Appendix II of this report.

II. SUMMARY OF PROCEDURES AND RESULTS

The principal results of our investigation are presented in detail in the two appendices. In this section the methods used will be reviewed and a brief summary of some other results will be presented. Some references to upper air data will be made; unless otherwise identified the data are those for Milan, Italy, the station nearest the target area, for noon GCT of the experimental day.

Initially we were concerned about the use of post-facto analysis. Suppose the data are examined from ten standpoints, and a positive relationship is found in one of them with a significance level of one in ten that it could occur by chance. Does this relationship have any expectation of validity, or should it be rejected as just the chance occurrence which is to be anticipated? To avoid this dilemma and provide an independent sample with which to check any finding we initially divided the experimental days into two separate groups by random selection, with the intention of reserving one of them and carrying out the analysis with the other. It was found, however, that stratifying the data using just one-half the total population led to very small numbers and very low significance levels, so that the process of dividing the population appeared to be self-defeating and was abandoned.

In approaching the problem of identifying the conditions under which seeding appeared to produce increases in amounts of rain and

those in which it appeared to produce decreases, we were guided by the ways in which seeding with silver iodide from ground generators might be expected to work.

First of all, the question of the transport of the nucleant to the cloud, and the effect of the concentrations resulting from various rates of transfer and various conditions must be considered. To be effective in any way over the target area the silver iodide smoke must be transported into the clouds forming there. This involved firstly the horizontal transport from the generators to the target, and secondly the upward transport into the cloud. The target area was over the southern Alps, and the generators largely in the southern part and to the south of it. Southerly winds generally tended to carry the silver iodide toward the target and to blow upslope, carrying the nucleant aloft to levels where it could be effective, whereas northerly winds tended to do the opposite. Thus the effects of seeding should be most prominent on days with southerly flow.

It should be noted that the southerly wind days, for which seeding effects might be expected to occur from the standpoint of transport of AgI reaching suitable locations in high enough concentrations, are also the days on which precipitation amounts should be expected to be large, both because of the lifting of air by the mountains and because southerly winds occur generally in advance of approaching cyclonic systems or fronts, whereas days with northerly flow would tend to have little or no precipitation. Seeding would have no effect if clouds did not develop or extend sufficiently high to be supercooled. We defined a set of days adverse to seeding as characterized by the following:

1. Days with $\bar{V}_5$ over the target area having a direction between NW and E sector, where $\bar{V}_5$ is the weighted mean wind at 500 mb for Milan, Payerne, and Munich.

2. Days of fair weather, i.e., with at most scattered clouds.

3. Days with top of significant cloud layer over southern Alps slope lower than the 0°C isotherm. Significant cloud layer is cloud layer covering one-half or more of the sky.

4. Days with highest cloud top (including isolated Cb or Cs) over Alps below 6,000 m.

Days with one or more of these characteristics are also days most unfavorable to natural precipitation development. The mean rainfall over the entire target area of 57 such days was only 1.54 mm as compared to 13.61 mm for all other experimental days.

Representing by A_S, A_N the days forecast by Ambrosetti on which seeding did and did not take place, and similarly Z_S, Z_N for Zenone and T_S, T_N for all other forecasters, the distribution of days with at least one of these four characteristics among the forecasters was as follows:

A_S	A_N	Z_S	Z_N	T_S	T_N
8	8	13	4	14	10

Note that 13 out of a total of 17 such days picked by Zenone were chosen by the random selection process to be seeded. Thus it is to be expected that Zenone's seeded days would be deficient in precipitation. With this group of days removed, the apparent negative seeding effect associated with Zenone loses any significance.

Of course the question may be raised, could the great excess of seeded days with conditions unfavorable to precipitation among the days forecast by Zenone be the result of the seeding? While this possibility cannot be demonstrably excluded, the tremendous scale of the atmospheric systems governing the flow patterns aloft over Central Europe, as represented by $\bar{V}_{5}$, suggests that it is most unlikely that these patterns were materially influenced by the introduction of relatively small amounts of silver iodide over a small area. With respect to the fair days and days with clouds at warm temperatures, the fact that the way silver iodide is expected to have an influence is by action in pre-existing cold clouds speaks against its being responsible for the absence of such clouds.

The question of relative concentrations is considered to some extent in Appendix II. The interpretation is made there that the rate of emission of silver iodide from the ground generators was inadequate to produce an effect on days with unlimited upward mixing, but on days with inversions at Milan the silver iodide was kept concentrated below the inversion and transported upward in adequate concentrations at the slopes of the Alps into the clouds forming there. The data showed a large, highly significant, apparent increase attributable to seeding on days with inversions and a smaller decrease at a level of significance below the usual acceptable margin on days with small vertical stability.

Neyman and his colleagues in a recent paper indicate that in spite of the low significance level the decrease on days of "uninhibited updrafts" may be real because similar statistics were found for rainfall at stations at large distances downwind of the target. If

the decrease is real the above explanation, that dilution under conditions of unlimited vertical mixing was too great for any effect, must be replaced by some mechanism which leads to a decrease for small concentrations and an increase for large concentrations of ice nuclei. No plausible explanation has occurred to us.

In addition to the direct effect the silver iodide might have in initiating precipitation by the three-phase process in supercooled clouds earlier than would take place naturally, the release of latent heat by the freezing of the liquid drops could affect the buoyancy of the cloud and thereby enhance the vertical development of the cloud. As an indication of the magnitude of the effect, consider a cloud in which the liquid water content is 1 gm/m^3 and the subcooled layer is at 500 mb with a temperature of -5°C. The phase change of droplets into ice would release 320 $joules/m^3$, enough to raise the temperature of the cloudy air 0.5°C.

We considered that if the temperature structure was already unstable the added buoyancy would have little effect; if it was sufficiently stable the release of heat would be insufficient to produce instability and vertical motions; but for an intermediate range of lapse rates the seeding would produce an effect which might be reflected in the amount of precipitation resulting from the convection. The measures of stability used are described in Appendix I. To decrease the "noise" due to the influence of other factors the stability effect was examined for experimental days with southerly 500 mb winds on which rain actually fell. Table 7 of Appendix I shows the results, indicating that the hypothesis put forward is partially verified.

A destabilization index was computed in the attempt to allow for the variation of stability with time due to advection at various levels. It did not result in improvement of the stability relationships.

The dependence of precipitation on moisture variables such as dew point depression at 850 mb and total precipitable water was investigated. It was found that any influence of available moisture or initial closeness to saturation on the seeding effect was completely overshadowed by the effect of atmospheric motions, particularly in the upper air. For example the mean total precipitable water (in gm cm^{-2}) for 77 days with $\underset{\sim}{V}_5$ northerly was 2.4 and for 54 days with $\underset{\sim}{V}_5$ southerly and $\geq$ 40 kts was 2.7, only slightly more, yet the mean rainfall over the entire target area for the former group was 1.97 mm but for the strong southerly wind group was 22.11 mm, more than 11 times the former. This also is in agreement with synoptic experience. It is the prevailing dynamic process rather than the amount of water substance currently available that controls the amount of precipitation. As long as a strong southerly wind exists, moisture will be continuously brought in from the Mediterranean Sea, lifted along the slopes of the Alps, producing condensation and precipitation.

III. CONCLUSIONS

The conclusions indicated by the data are presented in Appendix I and Appendix II. In the present section some views resulting from the experience of attempting to analyze the meteorological conditions which produced certain statistical results will be presented.

At best post-facto analysis of this kind will give rise to hypotheses which should be the subject of new experiments. In order

that these hypotheses be sufficiently explicit, data concerning the various parameters such as natural and artificial nuclei concentrations and temperature structure over the target are required. Thus the mechanisms postulated in Appendix II in explanation of the effect of stable layers on the apparent effect of seeding remain speculative without measurements of these quantities.

Furthermore, it would be desirable that the explanations or hypotheses offered for testing be quantitative, in order to provide a guide for the procedures used in further experiments. However, until now no one has established a coordinated theory of precipitation which would enable estimation of the number and sizes of condensation nuclei and of ice nuclei effective at various temperatures which would lead to maximum precipitation for a given distribution of temperature, humidity and vertical velocity. There have been some attempts in this direction, among them that of Chao and Tin (1963), who found that for some fairly general conditions an ice nucleus concentration of $1.25 \times 10^5/m^3$ would be necessary for maximum precipitation efficiency. This is about 10^3 times the usual measured values of the natural ice nucleus effective even at -20°C. To supply the optimum concentration estimated necessary with a moderate rising motion, a rate of about 115 AgI nuclei/m^3 sec reaching the subcooled cloud layer is required to obtain maximum precipitation efficiency. Unless the meteorological conditions are most favorable for the upward transport of AgI nuclei, such an optimum rate would not be achieved with the generator capacity used in Grossversuch III. If these estimates are correct, for this type of cloud seeding experiments using 20 ground AgI generators for covering a target area of about 10^3 km^2, underseeding is much more likely to

occur than overseeding. Unless the meteorological conditions are extremely favorable the concentrations of silver iodide crystals in the supercooled cloud would be less than the optimum value, especially in consideration of the attrition due to photolysis. In favorable conditions this would lead to an increase in precipitation, in usual conditions to no effect, but under conditions in which the earlier initiation of the ice phase would prevent the cloud from developing to as great depth and intensity of circulation as would occur naturally, a decrease might result.

For weather modifications which depend specifically on overseeding, such as hail suppression, it would appear that seeding with ground generators is impractical, and it is desirable to use methods of introducing the nucleating agent directly into the cloud with little opportunity for dilution and photolytic attrition. Use of aircraft or, as applied by the Soviet hail suppression activities, artillery shells directed by radar, appears indispensible.

Precipitation decrease likewise seems favored by overseeding such as can be obtained by seeding from aircraft. Thus, Neyman and Scott (1967) classified known rain stimulation experiments according to the indicated effect of seeding given in the original report. Among 10 cloud seeding experiments unambiguously indicating decrease in rainfall with seeding, 9 employed airborne AgI generators (SCUD also used ground generators). It seems reasonable to infer that overseeding is best achieved by aircraft dispensing AgI nuclei while flying directly into the subcooled portion of the cloud or a short distance upwind.

If one had an explicit quantitative theory for the effect of particular dosages of seeding agent administered in particular ways under

particular conditions one could render specific the above very general and highly speculative inferences.

Similarly if one could make definite quantitative forecasts of the amount of natural precipitation which would occur under given meteorological conditions the effect of introduction of artificial nucleants could be readily evaluated.

The predominant feature of the distribution of daily precipitation in mid-latitudes is its high variability. For example, the mean rainfall on experimental days in Zone 3 of the target are was 12.63 mm but the variance was 547 mm^2. This great natural variability in the precipitation process is largely controlled by the dynamic processes determining the motions of air currents which give rise to the general conditions for the formation of clouds and precipitation. The large scale motion field exerts control not only over rainfall over wide areas associated with frontal passages and cyclonic circulations but also on cumulus scale processes by creating conditions favorable or unfavorable for the development of convection. The fact that we found rainfall amount in the target area and the effect of seeding was greatly dependent on the 500 mb wind field at Milan as shown in Tables 3 and 4 of Appendix I, demonstrates clearly the control exerted by the synoptic scale motion together with the effect of terrain on the precipitation formation. By using large scale meteorological conditions as predictors the variability of the precipitation could be reduced and the evaluation of a cloud seeding experiment made less uncertain.

However, within the framework of the large scale control, the growth of an ensemble of precipitation elements including individual cloud circulations and the phase change of water substance and

collision coalescence of droplets depends on the variability of updrafts and the in-cloud local distributions of supersaturation, droplet concentrations, etc. These in turn are subject to the influence of small scale turbulence elements both of cloud scale and within the clouds. Under apparent identical meteorological conditions as represented by measurements of wind, pressure, temperature, etc. at grid points spaced of the order of 200 km apart and at significant and mandatory levels in the vertical it is entirely possible that on one day any ten square kilometer area within the larger grid might experience heavy rain while on another day no rainfall would occur there. Only average precipitation over large areas could be expected to be sufficiently well determined by large scale weather conditions, and this only to the extent that some account could be taken of the effect of smaller scale fluctuations.

Improvement of meteorological predictions are required for optimum evaluation of weather modification experiments. However, full use of present prediction techniques would lead to more effective experimentation than has been carried out until now.

For future experiments it is urged that the seeding operations be accompanied by extensive measurements, including natural ice nuclei concentrations at various levels before and upwind of the seeding operation, concentrations of artificial nucleants at various levels and positions over the target and downwind of it during the operations, vertical temperature and wind structure over the target before, during, and after the operations, positions and liquid and ice content of clouds over the target before and during the operations, etc. With such measurements and with predictions based on them and on the large

scale meteorological situations much more can be learned regarding the processes at work and the results of the artificial treatment.

ACKNOWLEDGMENTS

The initial impetus to undertake this study came from discussions with Professor J. Neyman and the results of the studies by Neyman and Scott (1967).

We are grateful to Mr. J. Thams, Director of Research of the Swiss Meteorological Service, and Dr. M. Schuepp of that organization for furnishing us with weather maps and data for this study. Mr. Jerome Namias of the Extended Forecast Division, U.S. Weather Bureau, ESSA, supplied Northern Hemisphere tapes for 1000 mb and 700 mb levels.

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APPENDIX I

THE METEOROLOGICAL FACTORS ASSOCIATED WITH THE PRECIPITATION EFFECTS OF THE SWISS HAIL SUPPRESSION PROJECT

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Abstract

During 1957-63 a randomized experiment to test the efficacy of cloud seeding to suppress hail in the southern Alps was conducted using ground-based silver iodide generators. While the results from the standpoint of hail suppression were negative, there appears to have been a definite overall effect in increased precipitation on days with seeding. Further, Neyman and Scott discovered that the precipitation effect was strongly positive on days selected for the experiment by one forecaster, and somewhat negative on those selected by another. This paper is an attempt to identify the factors responsible for this difference.

An analysis of the meteorological conditions associated with the experiment showed that in general the conditions favoring convective precipitation, namely, southerly flow and upper-level instability, were also associated with positive seeding effects. To some extent the difference between forecasters referred to above was due to accidental differences in the random selection of seeding opportunities among cases of southerly and northerly flow. Not all the difference was explained in this way.

The conditions favoring large amounts of precipitation and large seeding effects were studied. For instance, the experimental days were typed according to surface pressure pattern, and in two of the weather types strong positive seeding effects were present.

The necessity of caution in attributing to seeding differences which might be due to other factors is discussed in the light of the possibility of the process of random selection producing unequal samples from meteorological types having widely different physical characteristics.

APPENDIX II

INFLUENCE OF ATMOSPHERIC STABILITY LAYERS ON THE EFFECT OF GROUND-BASED CLOUD SEEDING, II HYPOTHESES IN EXPLANATION

By Morris Neiburger and Ho-Chih Chin

Abstract

This paper examines some questions raised by the relationship between stable layers and seeding effects disclosed in an analysis of data from the Swiss hail-suppression experiment. Among these are the following: (1) Can AgI reach levels where the temperature is lower than -4° C on days with low-lying warm stable layers? (2) Why is there a large increase due to seeding on such days and no significant change on days with no stable layer?

Theoretical considerations and available observations in mountain terrain indicate that surface heating over the plain may destabilize only that layer below the inversion. On the mountain slope the heating will eliminate the inversion along the slope, creating a channel through which convection will carry air from below the inversion. The increase in precipitation on these days seems to be due to increased concentrations of AgI reaching the clouds, due to the channeling. On days without the stable layer, the AgI is diffused and the clouds are greatly underseeded.

Wasatch

Weather Modification

Project

UTAH STATE UNIVERSITY

Logan, Utah

July 1967 - June 1968

BUREAU OF RECLAMATION SUMMARY

FINAL TECHNICAL REPORT
Period: July 1967 - June 15, 1968

The Project Objective

The objective of the Wasatch Weather Modification Project is to assess the relative effectiveness and the practicability of selected procedures for increasing the water supply, from precipitation over the Wasatch Mountains, by cloud seeding. All Project activities have been directed toward the fulfillment of this ultimate goal.

The accomplishment of this objective requires:

a. The development and subsequent application of knowledge of the natural precipitation processes, patterns, and characteristics of the experimental area.

b. The evaluation of cloud seeding activities through comparisons between natural and seeded precipitation patterns and characteristics, both from the time and space viewpoints.

c. The assessment of the availability, usability, and importance of artificially induced increases in precipitation to communities, who are or will become dependent upon Wasatch Mountain precipitation for their water supplies and/or hydroelectric power.

Introduction

There are several reasons why the Wasatch Mountains offer high potential for the practical increase of precipitation through cloud seeding.

a. The abrupt rise of the nearly north-south oriented, almost continuous Wasatch Range results in significant and recognizable orographic increases in the precipitation from winter storms crossing the Wasatch Mountains. The result of this topographic influence, accompanied by the fact that most precipitation productive "storms" approach from a westerly direction is that:

(1) The amount of natural precipitation is sufficient so that relatively small, artificially induced increases would be significant and measurable.

(2) It is physically reasonable to expect that it may be possible to get nucleating materials into the effective portions of clouds from ground-based generators.

b. Additional water supply is of growing importance to the relevant water and power dependent communities.

c. The experimental area includes important headwater regions.

d. A large fraction of artificially induced increases in snowpack would be stored naturally for summer use.

The Experimental Plan

In summary, the assessment of the "relative effectiveness" is to be based primarily upon: differences in the precipitation amounts recorded at: target and control stations; each of selected stations during seeded and unseeded storms. However, evidence of differences between space and time precipitation patterns and characteristics of seeded and unseeded storms, which is not amenable to statistical testing is also to be examined and interpreted.

Current plans call for the simultaneous operation of two generators, at moderately high altitudes. The general idea is that a target area which is limited to the region estimated to be occupied by the plumes of both generators is a more reliable assumption than a target area assumed for a single generator. The desirable horizontal distance between generators, and the required generator output are both under consideration. The site selection is, of course, somewhat controlled by the spacing of favorable natural conditions and site authorization problems. However, it is also necessary to consider the resulting particle densities at different distances downwind as a function of generator outputs and spacing.

In an effort to provide additional information for the decisions concerning generator output and spacing, a small study is in progress which relates horizontal and vertical dispersion rates, wind speed, the horizontal and vertical diffusion angle, generator output and spacing, and particle density, plume width, and height at given distances downwind.

A computer program has been written and debugged that allows for vertical as well as horizontal diffusion, and it calculates particle densities, plume widths, and heights at selected distances downwind, under the assumed conditions. The calculations assume an elliptical half-cone, bounded on the bottom by a flat plane. The axes of the ellipse are determined by the rate of horizontal and vertical diffusion. The computed volume, at a given distance downwind, assumes a thickness equal to the distance traveled by the wind in one second.

The Statistical Design

The statistical analysis will be applied to comparisons between the precipitation amounts at target and control stations and to comparisons between precipitation amounts from seeded and unseeded storms, each of several stations. Thus the following quantitive comparisons have been planned:

a. $(A_T - B_C)$ vs $(A_U - B_U)$

b. A_T vs A_U

c. A_C vs A_U

where A refers to any specific station, B refers to any other specific station, T indicates that the station is within the target area, C indicates that the station is in the control area during the same period that the compared station was in the target area, and U indicates a measurement for a period when there was no seeding.

The comparison $(A_T - B_C)$ vs $(A_U - B_U)$ is to be made for each reasonable pair of stations. The purpose of the comparison $(A_C - A_U)$ is to test the assumption that the A_C values have been properly designated as "control" measurements.

The statistical plan is still under consideration. It may be necessary to incorporate a normalizing procedure, although the first comparison $(A_T - B_C)$ vs $(A_U - B_U)$ effectively does the same thing.

Significance tests are to be applied. In general, there will be more unseeded storms than seeded storms for each comparison. It is doubtful if a Gaussian assumption for these differences can be justified. Consequently, the selected tests probably will be nonparametric. Since the final selection of the test is not urgent, the project has arranged for the one-fifth time services of an applied statistician (Dr. David White) during FY69. He will assist in the selection of the specific test, or tests, to be applied. No matter which test is to be applied, it is certain that the experiments must be stratified on the basis of concurrent synoptic-thermodynamic stability - vertical temperature structure - humidity-trajectory conditions.

The Tentative Seeding Data Collection Plan

Storms are to be classified as seedable or unseedable. Work on the details of the definition of a "seedable" storm is in progress. Although this definition is not yet completed, it is highly probable that the following criteria will be included.

a. Temperatures within those portions of the clouds in which seeding from the project's generators is considered to be a reasonable possibility will be between -5° and -24° C, inclusively.

b. Precipitation is forecast to occur naturally, at least at higher elevations.

c. The forecast effective wind speed is no greater than 15 mps. The method of determining the effective wind speed has not yet been selected. This wind speed limitation has been selected because of the loss efficiency of the can-type precipitation collection device, especially in snow, even with an Alter shield. It is recognized that high wind speeds may present the most favorable circumstances for seeding from ground-based generators. However, from the experimental viewpoint, there is no reason for seeding if you can't get reliable measurements of the results.

d. The forecast trajectory will be such that at least three stations are expected to be within the target area.

Once a seedable storm is forecast, the decision to seed or not seed will be made on a random, totally objective basis. Climatological studies suggest that it is not unreasonable to expect 30 seedable storms in even a dry season. A single storm was arbitrarily defined as a period of precipitation during which there were no precipitationless periods of more than 4 continuous hours.

The selection of the proper experimental unit is a perplexing problem. A storm itself is not always, if ever, really a single experimental unit, insofar as this project's approach is concerned. Frontal storms are obvious examples. However, this premise is equally true for storms with changing trajectories within an air mass, since orographic effects must be influenced by the direction of flow relative to mountain orientation. Days are obviously arbitrary units of convenience, which rarely exactly coincide with periods of the desired quasi-homogeneity in the dynamics of a storm.

In brief, the statistical plan is to mathematically examine the differences between two series of values, each series of which was collected under given control circumstances, which are under test, such as at a seeded station, an unseeded station on a seeding day, or an unseeded station on a day without seeding activities. In order for these tests to be valid with a realistic number of replications, other controls, which are not being tested, must also be exerted. Thus, grouping by natural precipitation periods is highly desirable.

The Precipitation Measurement System

The heart of the project's cloud seeding evaluation program is the network of telemetering precipitation gages that has been developed under the direction of Utah State University. The entire telemetering system (the transducer, the receiving transmitting unit, the translator, and the Automatic Readout Console (ARC) were designed by project personnel. The fabrication of the translator and the Automatic Readout Console* and the field installations of the Translator, the Cable, and

*In previous documents this unit has been called the Terminal Readout Station (TRS).

the Remote Stations all have been accomplished by project personnel. In the installation of the Remote Stations, the project had the benefit of the active cooperation of the U.S. Soil Conservation Service, with the U.S. Forest Service cooperation in site authorization.

The bulk of the project's effort thus far has gone toward the development of this network. FY 1967 and FY 1968 were primarily fabrication, installation, check-out, debugging periods. The status of the system is now such that we expect a significant portion of the 1968-69 winter to be devoted to storm case studies, with the telemetering network providing data for determining time and space precipitation patterns, both for seeded and unseeded storms.

The Telemetering System

The Telemetering Precipitation Network System is made up of the following four major components:

a. The Automatic Readout Console (ARC) at the Utah Water Research Laboratory. This is also called the Terminal Readout Station (TRS). A separate report providing the technical details of this component is in preparation.

b. The Cable carries the messages between the Automatic Readout Console and the Mt. Logan Translator. There are 27 quarter-mile sections in each of two, four-wire cables. The second cable is to be used for backup in the event of failure. Provisions have also been made for an electronic backup, for the unlikely event that both cables fail.

c. The Mt. Logan Translator. This translator relays the information from the Automatic Readout Console to the Remote Telemetering Stations and vice versa. One additional relay is tentatively planned for FY69.

d. The Remote (sensing-reporting) Telemetering Stations. Since a separate report is in preparation, the discussion of the details of this unit will be brief and somewhat general. These stations are essentially all the same except that 70-inch capacity cans are used at some sites and 36-inch capacity cans at others. Each installation includes:

(1) The Support Assembly on which the precipitation collection-weighing system is mounted. This may be either a tower or a 2-1/2-inch (diameter) galvanized iron pipe.

(2) A Standard Can-type Precipitation Collector, either 70- or 36-inch capacity with an 8-inch orifice. These cans are Alter shielded.

(3) The Weighing Transducer. The collecting can is supported by three springs. As precipitation is added the springs are compressed causing an iron bar to be further inserted into an inductance coil. This change is reflected in a change in audio frequency, which is telemetered to the Translator. Modifications of the transducers design, as a step toward elimating response to temperature changes, is under active consideration.

(4) The Electronics Housing. This is a cylindrical can, which is sunk into the ground. It reduces the variability of the temperature environment of the electronics, and protects the unit from rain, snow, animals (including humans), etc.

(5) The Electronics Unit, which is capable of both receiving and sending signals.

(6) An Antenna.

Although some of the components of the telemetering system are extremely complicated, the general principle of operation is quite simple. The Terminal Readout Station interrogates a Remote Station. The query is carried by the Cable to the Mt. Logan Translator, which electronically transmits the message. The appropriate Remote Station responds, if it is able to do so, with an electromagnetic frequency which is received by the Translator. This signal is then converted and sent via the Cable to the Automatic Readout Console, where it is printed out on adding machine tape.

The station interrogation order is quasi-permanently programmed into the Automatic Readout Console. However, stations can be omitted from this order at the discretion of the operator. Once the stations to be queried have been selected and the switch turned on, the Automatic Readout Console will automatically interrogate the stations in turn until all have been queried. It will then return immediately to the first station, repeating the cycle over and over until the switch is turned off. If, during a cycle, a station does not respond, it is automatically queried three times. If there is still no response, the next station is automatically interrogated.

The data printout is in systems units, either electromagnetic periods or frequencies. These printed values are punched and computer converted to precipitation values. The appropriate programs have been written and debugged.

As of June 15, 1968, complete stations have been installed at 38 sites. The support assemblies, electronics housing, and antennas are installed at another three. Twenty-seven of these are 70-inch capacity stations and 14 are 36-inch capacity stations.

Seeding Operations

On April 2, 1968, a silver iodide generator was operated for 2 hours at a site near Mantua, Utah. The primary purpose of this activity was to gain experience in the field operation of silver iodide generators. The test has been scheduled for a longer period, but minor problems forced premature termination of the operation. The telemetering precipitation system was operated during this period, and 15 radar pictures were taken.

The silver iodide generator was again operated at the same site for a 24-hour period beginning at noon on April 16th. The telemetering precipitation measurement system was operated throughout this period, and radar pictures were taken at 15 minute intervals from 1:45 p. m. to midnight on the 16th.

The data from these two efforts have not yet been analyzed.

Silver in Precipitation Samples

The Utah State University group has been looking into two distinctly different approaches to the quantification of very low concentrations of silver in precipitation samples. One of these, the colorimetric approach, depends upon the relationship of the depth of the color of certain dyes to the silver concentration of the tested water. Dr. Harvey Millar has directed this effort. The other approach is through the use of the Perkin-Elmer, model 303 Atomic Absorption Spectrometer under the direction of Professor Joel E. Fletcher.

The Colorimetric Method. A literature survey indicated that the colorimetric method proposed by Palacios is probably the most sensitive of all of the reported methods for the quantification of very low concentrations of silver in water (Millar, 1968). Palacios, using p-dimethylbenzylidene-rhodanine as a dye, applied this technique to appropriately prepared spots on filter paper. This work provides the foundation for the Wasatch Weather Modification Project investigations into the potential of the colorimetric methods. Several departures, showing varying degrees of promise, have been studied.

The Tag Method

After filter paper was suitably treated with the rhodanine compound it was cut into suitable small pieces, called tags, which were 1- x 3/4-inch on a side. One was put into each of several one-liter standard silver solution samples and allowed to react for several hours. The tags were then removed and allowed to air dry, and the reflectance data were obtained on the DB spectrophotometer.

This method has proved to be the most encouraging procedure tried to date. Results were consistently obtained down to a dilution of 10^{-10}. Therefore, more sample of standard silver solutions were made up, separately using river water, snow water, and deionized tap water. Test results on these samples were all good. None of them contained impurities that would interfere with this method. A set of standard silver solutions containing sodium iodide in the amount of one part per million were made up. Tests on these samples indicated that this relative amount of sodium iodide may interfere with this technique. Then, for no obvious reasons, the rhodanine compound suddenly lost its sensitivity to changes in silver concentrations in dilutions below 10^{-6}. The solid rhodanine compound as tested in dimethylformamide or dimethylsufoxide no longer performed as it had been doing.

Some of the problems is to find a means of prolonging the shelf life of the compound. Several procedures seem promising, and should be pursued immediately. If none can be found, a simplified system will have to be generated for periodically checking the activity level of the compound. The maintenance of this system would be tedious, but not overwhelming. The important factor is that the effects of chemical aging have been recognized.

Drying the Chemically Treated Tags

It has been found that the sensitivity of the rhodanine compounds (dimethyl, diethyl and 3-propyl) is influenced by the conditions under which the tags are dried. An increase of sensitivity of from one to three orders of magnitude can be effected by drying the tags under the right conditions.

Reproducibility by the Tag Method

Attention has been directed primarily to developing those conditions which would extend the sensitivity of the method to the extreme dilutions required. Therefore, not much time has been available for specifically testing the reproductibility of results. Indeed, until a method shows sufficient promise, extensive reproducibility testing is not justified. However, many experiments have been made with only slight variations and therefore give an insight into reproducibility. With a compound whose shelf life is not expended and under a given standardized procedure, reproducibility, using the Tag Method, appears to be quite acceptable.

Using the best technique that has been developed to date, concentrations have been measured in dilutions as low as 10^{-11} gram of silver per milliliter of solution. The next step is to test for reproducibility under the specific conditions which have produced this high degree of refinement. It is also necessary to learn more about the influence of sodium iodide on this technique. Dr. Millar suspects that sodium

iodide may wash out earlier in the plume path. If so, it would not be present in the samples under inspection during silver iodide plume studies.

There are still several variations that can be studied in the attempt to extend sensitivity. Obviously, each extension of the sensitivity beyond the 10^{-11} level, will increase the reliability of the measurements at this level, since the improvement would no doubt result in a steepening of the calibration curve in the 10^{-11} region.

Advantages of the Tag Method

This method, once fully developed has several attractions:

a. Other than a suitable spectrophotometer, expensive equipment is not required.

b. The method lends itself to the procedure of running several samples at one time. Constant detailed attention is not necessary during most of the procedure. One person should be able to run 80 to 100 samples per week.

c. A person with a suitable analytical chemical background (a technician) could easily be trained to perform the tests.

d. The work could be done in the field.

The Atomic Absorption Spectrometer Technique

The emphasis in this effort has been on the development of an inexpensive and rapid technique for determining silver concentrations that can be accomplished by a technician. Among other considerations, special attention has been paid to avoiding extensive concentrating activities. Since a report on the technique (Fletcher, 1968) was previously submitted to the Bureau of Reclamation, only the subsequent studies will be included in this document.

The following quote from an internal Project Memorandum by Professor Joel E. Fletcher on "Detection of Silver in Water Solutions by Atomic Absorption" illustrates his position with respect to the USU capability for quantifying the silver content of precipitation water by this technique.

"It has been noted for some time that certain organic solvents enhance the sensitivity of an atomic absorption system to metals. Among the better of these are ethyl propionate and ethyl butyrate.

"If a water solution in an amorphous polyethylene container is acidulated to a pH of 3.2, with acetic acid, absorption of silver

becomes very small. If 500 ml of this solution is extracted with 5 ml of a 0.025 percent solution of diphenyl thio carbazone in ethyl butyrate, and aspirated into the atomic absorption spectrometer, a series of readings versus silver concentration, similar to the attached, may be obtained.

"Most waters can be measured satisfactorily by merely adding the chelate solution to the acidulated water solution, shaking, allowing to stand 3-5 minutes, and dipping the aspirator tube in the dark-colored solution floating on the water sample. Certain waters cause the chelate solution to form jells. When this occurs, it is necessary to separate the chelate solution from the water and add 2 ml of acetone before aspirating the chelate.

"The extraction concentrates the silver about 30 fold and the enchancing agent about doubles that again.

"The method is rapid and simple, and the reagents are relatively inexpensive, costing less that 10 cents per sample. The rigid control needed when water alone was the solvent can be relaxed to the extent that a good technician could make the determination with normal supervision."

From Professor Fletcher's diagram it may be noted that there is a difference of nine counts between the 10^{-11} and 10^{-12} concentrations, and of six counts between the 10^{-12} and 10^{-13} concentrations. These large differences in the DCR-1 readings for successive orders of magnitude suggest a considerable resolution capability.

Background Nuclei Studies

The Wasatch Weather Modification Project faces a somewhat unique background nuclei problem. The abruptness of the west side of the nearly north-south, nearly continuous Wasatch Front, is expected to play a prominent part in the transport of cloud seeding materials into clouds, as well as in the precipitation production processes. The same transport capability probably will apply to the heavy accumulation of contaminants, artificial and natural, just to the west of this range.

There are several sources of nuclei, both ice-forming and hygroscopic, which may affect the results of the project's experimental endeavors. These sources are all within a few miles, to the west, of the Wasatch Front.

The Great Salt Lake, the salt flats, and salt processing plants are all possible sources of hygroscopic nuclei. Do these release a sufficient number of large hygroscopic nuclei to significantly affect precipitation processes? Flights in an out of the two jet-airports may also add significant hygroscopic nuclei to the area.

The largest open pit copper mine in the world and the accompanying smelters are just to the west of the Wasatch Front. Are there also significant amounts of silver and lead, and are there iodides from the salt sources with which these metals could combine?

In addition, there are the steel mills, the refineries, and the automobiles, with the major highway nearly paralleling the range and only a short distance away. Salt Lake City, Ogden, Brigham City, and several villages and towns in between, lie very close to the mountains. Will the burning of leaded gasolines contribute active nuclei, especially in cooperation with any iodides that might be released from the salt areas? What are the effects of all of these other contaminants?

There is also some question of possible effects from deliberate seeding in Nevada and California. However, surely these effects must be miniscale in comparison with probable contributions from the immediately adjacent highly contaminated areas.

To date, the only real activity on this phase has been the partial collection of a bibliography on "Inadvertent Cloud Seeding by Air Pollution." More work has been planned, but unfortunately sufficient funds have not yet become available to carry out this critically important assignment.

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BUREAU OF RECLAMATION SUMMARY

INTRODUCTION

During the past two decades, interest in the development in water resources has increased considerably by both the private sector and most governmental agencies. Many alternatives to the problem have been pursued by a variety of groups. One alternative to the problem of water resources is the exploration and development of the atmosphere which is of great interest to the Atmospheric Resources Research group of the University of Wyoming. The overall objectives of the Atmospheric Resources Research program sponsored by the Bureau of Reclamation is to develop effective and usefully beneficial precipitation management techniques; or more specifically, to develop sound snowpack augmentation procedures with special emphasis on orographic clouds. In order to fulfill this overall goal, the Natural Resources Research Institute has developed the Elk Mountain Water Resources Observatory as an outdoor natural laboratory in which the cap cloud is being used to delineate and study the important cloud processes as well as determine the potential yield by the augmentation techniques considered.

RESEARCH ACTIVITIES

A systematic approach to a precipitation management program has been developed utilizing the Elk Mountain Water Resources Observatory and the associated orographic cap cloud. This approach involves monitoring and evaluating salient parameters for the (a) environment (b) airflow (c) nucleation and growth (d) precipitation and (e) development of the not readily available instrumentation required to accomplish items (a) thru (c). The environmental studies involve determining as completely as possible the environmental factors such as temperature, humidity, background cloud and ice nuclei, thermodynamic stabilities, etc., in which the cap cloud occurs. The airflow studies are necessary to determine the mass flow characteristics in order to insure delivery of nucleating material to the cloud, determine the moisture and airflux into the cloud, and determine the cloud particle trajectories. Detailed studies of this kind are necessary to make the laboratory more effective, but will also be useful in determining to what degree the airflow for a given area must be described to be reasonably sure nucleating material of specified concentrations will be delivered to the clouds. The nucleation and growth of cloud particles within the cap cloud has been studied under both treated and natural conditions. These studies involve the determination of the droplet spectra and concentrations, liquid water content (LWC), supersaturations with respect to ice, ice crystal population and types, ratios of ice crystals to ice nuclei, snowfall rate, etc.

The evaluation of the precipitation from the cap cloud under both treated and natural conditions in very difficult at best. The use of conventional sensors such as snow pillows and snow courses has not been sufficiently sensitive to detect precipitation changes on the time scale under consideration (hours). However, some progress has been made using such methods as calculating the amount of water changing from the liquid to the ice phase and a systematic study of the ice crystals.

RESULTS

The studies conducted to date by the Atmospheric Resources Research group has produced the following results in each of the categories considered.

A. Environment

During the past 2 years, data has been obtained which define, preliminarily at least, those meteorological conditions which spawn the orographic clouds on Wyoming's higher mountains. Analysis of the available data has tentatively identified those weather systems which produce the isolated cap cloud. The formation of cap clouds generally occurs when short waves, at the 500-mb level, pass to the east of the area. These short waves may be those of the classical sense, easily distinguished by wind shear lines and/or pressure height falls. Often times, these small disturbances can be very difficult to detect when imbedded in the westerly flow. Continuously tracking these short waves and monitoring microbarograph traces often provide the only means of detection. However, keen synoptic analysis coupled with local barometric pressure changes at the surface provide acceptable operational forecasts. Cap cloud formation is generally observed when the trough line of these short waves is located at an average distance of 65 nautical miles downstream and cap cloud dissipation typically occurs when the trough line passes 265 nautical miles downstream. Rising pressure, measured by the microbarograph traces at the Elk Mountain Observatory following the passage of the short wave trough, always accompany cap cloud duration and averages 3.5 millibar through the lifetime of the cloud. A return to steady or falling pressure heralds the dissipation of the cap cloud. Occasionally, when the 500-mb short wave trough is located over the barrier, with an apparent surface front appearing slightly to the west, a cap cloud will develop which gradually merges into a general snow situation with the passing of the apparent surface frontal system. However, after the departure of the frontal zone precipitation activity, the classical cap cloud situation once again sets in to continue until such time as the upper trough moves beyond the critical distance downstream.

There is a tendency for the short wave troughs to move through the area in the early morning hours, thereby providing cap clouds by sunrise which, on the average, continue until 1700 and rarely dissipate before 1300.

B. Airflow

The characteristics of the silver iodide plume from an acetone generator have been observed and parameterized in terms of temperature lapse rate and horizontal angle of diffusion. In addition, the ratios of the traveling speed of the AgI nuclei to the mean wind speed in the transporting layer have been determined. Analysis of the available data suggests that the horizontal angle of dispersion is independent of the speed of the transporting wind. A complete description of the experiment can be found in Auer et. al. (1968). Limited measurements of the vertical diffusion of the AgI plume at Elk Mountain at distances of 10 km downwind from the generator reveal that the tops of the plume are between 300 and 450 meters above the terrain and that they are detected at the higher elevations only during conditions of superadiabatic lapse rates.

A two-dimensional numerical model for the airflow over a mountain has been developed. The model was empirically obtained by selecting functions which are physically reasonable and quantitatively predict the airflow and cloud as observed in the natural laboratory. The observed input functions are the upwind temperature, moisture and wind soundings plus cloud base height, and cloud top height. Utilizing this information, one can calculate the height from which the air must rise to form the observed cloud base and cloud top. The following assumptions were made in constructing the numerical model.

1. The air at the cloud base continues to rise to the crest of the mountain.

2. The nodal line is obtained by assuming the amplitude of the rising air decreases linearly with height.

3. The air begins rising along a function ($A \sin \theta$) which extends vertically from the base of the mountain ($\theta = 0$) upwind to the nodal line ($\theta = \pi/2$). The amplitude (A) was arbitrarily selected to be the height of the nodal line minus the height of the upwind plains. Since no cap cloud was observed to extend out over the upwind plains during the 1967-68 season, all models were run with the same amplitude. However, the amplitude could easily be doubled or tripled to predict cap clouds which do extend over the upwind plains.

4. The air ceases to rise along a function ($A/2 \sin \theta$) which extends vertically from the crest of the mountain ($\theta = 0$) upwind to the nodal line ($\theta = \pi/2$). The amplitude ($A/2$) is one-half the height of the nodal line minus the height of the upwind plains. Such an amplitude was selected since it translates the cloud peak upwind of the mountain crest and also begins cascading the air down the lee slopes, both of which are normally observed during cap cloud situations on Elk Mountain.

5. The air is assumed to flow along a function (RB sin φ) where B is the vertical distance from the cloud base source to the mountain, R is 1.0 at the cloud base source height and decreases linearly to 0.0 at the nodal line, $\varphi = \pi/2$ along the sine function (A sin θ) extending from the base of the mountain and $\varphi = \pi/2$ along the sine functions (A/2 sin θ) extending from the crest of the mountain.

6. The vertical velocity field is predicted by multiplying the slope of the airflow function $[\frac{d}{dx}$ (RB sin $\varphi)]$ times the upwind horizontal velocity at that height. The mean vertical velocity field was thus predicted for comparisons with the mean vertical velocity field as observed by the aircraft and superpressure balloon systems. Moisture was accounted for in the model using standard moist thermodynamic equations.

Results indicate that the cloud base and cloud tops are closely reproduced and the adiabatic liquid water concentration (LWC) field is in close agreement with the LWC observed at the Observatory.

The vertical airflux, as observed at various levels upwind of the mountain by the aircraft, was obtained by analyzing the vertical velocity field. The vertical airflux for the levels observed by the aircraft system were calculated utilizing the numerical airflow model by assuming that the airflux normal to the airflow was 5 km wide and by integrating the vertical velocities over the areas which the model predicted. The 5 km width was selected in order to fit the available data to the model. This 5 km width is also physically reasonable since the 9,500 feet msl contour is approximately 5 km wide. The aircraft vertical airflux and the model vertical airflux appear to be related within a factor of two. The value of the airfluxes over Elk Mountain are approximately one order of magnitude below that observed for large thunderstorms and hailstorms (Auer and Marwitz, 1968).

The airflow program is now sufficiently adequate to permit superposition of the observed snow crystals upon the airflow field and grow the snow crystals by diffusion and accretion in reverse. The ice crystal generation field will thus be determined.

C. Nucleation and Growth

The cloud's physical parameters which describe the ambient cap cloud have been identified and categorized; these parameters are monitored during seeding operations to test for the response to a given treatment.

The mean background ice nuclei spectrum ranges from about .03 per liter at -7°C to about 1.3 per liter at -25°C, for a total of 22 individual background spectra (51 hours of sampling). The values of the spectrum have been corrected for the counting deficiency of the NCAR counter rate computer discussed in the instrumentation

section. The spectrum is essentially exponential at the warmer temperatures; and the background ice nuclei concentrations increases by one order of magnitude per 6°C cooling. The average concentration of ice nuclei active at -20°C is 0.9 per liter.

Kumai (1961) reported that a solid particle was found at the center of all but one percent of the 271 snow crystals of various types in his study. Ice nuclei spectra from crushed samples of Wyoming and Alberta bentonite (Vali, 1968) bear a close resemblance to the observed background spectrum suggesting the investigation of bentonite as a possible source of background ice nuclei in the Elk Mountain area.

It is necessary when conducting seeding experiments to know the background ice nuclei spectra. A nomogram relating the concentrations of the detectable AgI nuclei (active at -20°C within the NCAR chamber at the Observatory) to the active concentrations of AgI nuclei at any given cloud temperature was prepared for the University of Wyoming silver iodide generator, which was calibrated by the Colorado State University generator testing laboratory. Unless the AgI concentrations within the plume detected (-20°C) at the Observatory exceed 20/liter, the true concentrations of AgI nuclei active at a cap cloud temperature of -10°C are only equal to or less than the average background concentration of 0.03/liter.

While conducting an experiment within the Elk Mountain Water Resources Observatory on February 1, 1968, considerable ice nuclei contamination was observed in the Saratoga valley. The general area of the contamination was mapped using the NCAR ice nucleus counter onboard the NRRI Twin Beech aircraft. Seeding activity had been conducted throughout the previous day near Steamboat Springs, Colorado. Analysis of the available data suggests that this silver iodide which was released approximately 50 miles south of Elk Mountain crossed the Park range into the Walden valley, then drained north into the Saratoga valley.

Comparison of the amount of silver iodide released with that detected near Saratoga, Wyoming, indicates that the silver iodide had deactivated about one-half order of magnitude per hour after exposure to sunlight for 6-8 hours. This is also in general agreement with the findings of St. Louis and Steele (1968).

Using average values of plume dimensions, transport speeds, and generator nuclei output; the calculated concentration of AgI nuclei within the core of the plume, assuming uniform dispersion, is near 450/liter. This corresponds quite well with the average direct measurements of 150/liter for a 30 minute nuclei travel time. This ratio of observed concentration to the calculated concentration does not seem to support the current thinking of photo deactivation rates of two order of magnitude per hour (Smith et. al., 1956, Fletcher,

1962; and MacCready, 1967) for AgI; however, our ratio does agree nicely with St. Louis and Steele (1968) who reported decay rates of 6-fold per hour in laboratory experiments.

For eight out of nine occasions during the period of 12 hours prior to the passage of the short or long wave, background ice nuclei concentrations were observed to be increased by several factors. For example, the increase in ice nuclei concentrations activated at -20°C or colder increases by a half order of magnitude or greater. Several hours after the onset of precipitation (if any), the background ice nuclei concentrations were observed to return to their previous values. Further study is being planned to determine if the increase in concentration might be attributable to upwind seeding activities during weather regimes accompanying these short waves.

Measurements of cloud nuclei (nuclei active in the condensation process at supersaturations below 3 percent) were also taken at the Elk Mountain Observatory by using an improved thermal diffusion chamber constructed by the Natural Resources Research Institute.

Values of cloud droplet sizes and concentrations were obtained by means of the cloud droplet replicator device described in the instrumentation section. For natural (untreated) cap clouds, the average droplet concentrations is 250/cc with a medium droplet diameter of 7.8 μ and a mean droplet diameter of 8.6 μ. Assuming a cloud nuclei-to-droplet ratio of unity, the average activating supersaturation was on the order of 0.45 percent for the cap cloud.

A close scrutiny of the prevailing ice crystal climatology within the cap cloud was begun during the 1967-68 season. Ice crystal replication was accomplished through the use of a formvar-type continuous ice crystal replicator; the crystals were then classified according to Magono and Lee (1966). Ice crystals were sampled in unmodified cap clouds as well as those seeded with silver iodide. The observed ice crystal types correspond quite well with the classifications according to the formation temperature at water saturation regimes observed by Magono and Lee.

The cap cloud offers an ideal opportunity to study the ice crystal-ice nuclei concentration ratio because of the small vertical temperature variations (3°C to 6°C). Through the use of the continuous ice crystal replicator and the NCAR ice nucleus counter, comparisons were made of the ratio between the concentrations of ice nuclei and ice crystals during both seeded and nonseeded conditions. Tentative conclusions suggest that the ratio is a function of the ice crystal types (i.e., formation temperatures). Such a relationship has been recently implied by Koenig (1968) whereby the process of mechanical fracturing may be the principal mechanism of ice multiplication in clouds, so that glaciation should occur most rapidly at temperatures and supersaturations at which fragile, dendritic crystals are formed. The data obtained in the Elk Mountain experiment for formation

temperatures near -17°C indicate ice crystal concentrations exceed the ice nuclei concentrations by three orders of magnitude for the nonseeded cases; this is in general agreement with Mossop, et. al., (1967) who found ice crystal concentrations three orders of magnitude higher than would be expected from estimates of ice nuclei concentrations active near -17°C. Results from the Elk Mountain research also reveal that for the seeded cases at -17°C, only 30 times more crystals were found than ice nuclei; for -10°C during nonseeded cases, the ice crystal concentrations exceeded ice nuclei concentrations by a factor of 30.

It is interesting to note that naturally occurring crystals were found in all cap clouds without exception, even those as warm as -5°C. Because of the common frequency of cloud temperature regimes favorable for hexagonal plate ice crystals, this crystal type was most prevalent and exhibited an average size of 150 μ diameter. Assuming the observed crystals began growth at their minimum formation temperature at the leading edge of the cloud and transported by the observed wind, the observed crystal sizes were in agreement with those predicted from classical diffusional growth equations. Hexagonal crystals of maximum diameter of less than 350 μ were never observed to exhibit any rime droplets, while one millimeter hexagonal crystals (very rare) exhibited moderate to heavy riming conditions. Plain dendritic crystals ranging between 2 and 4 millimeters diameter were found to be extremely selective in the sizes of accreted water droplets. In all cases, the lower size threshold of the treated water droplets was 16 μ diameter; sizes up to 24 μ were also observed. Typically, 125 such droplets were accreted on the lightly rimed crystal. Since the cloud droplet spectra within the cap clouds is such that the droplets of diameters greater than 16 μ occur in very small concentrations, the predicted threshold of drop size for accretion growth appears to be consistent. These results are presented in Marwitz and Auer (1968).

Throughout the 1967-68 season, numerous samples of accreted rime ice were tested for their density. The results of these direct measurements taken by immersing the rime ice samples in nethanol (specific gravity 0.80) and olive oil (specific gravity 0.92) indicate that the average density of the rime ice is near 0.90 g/cm^3. This value is not in agreement with that of Macklin (1962) who calculated density values near 0.40 g/cm^3 utilizing a laboratory wind tunnel experiment which simulated cap cloud riming conditions similar to those encountered atop Elk Mountain.

D. Precipitation

The determination of the precipitation from the cap cloud is necessary to evaluate the efficiencies of both the natural and treated conditions under various meteorological conditions. Because of the severe environment encountered within the Elk Mountain Water Resources Observatory, the determination of the precipitation is very difficult.

The precipitation climatology or monthly behavior of the precipitation patterns has been observed by standard pressure snow pillows. This data, however, is not useful for evaluating the response of the cap cloud under various treatments when a relatively short experimental turn around time is used.

The natural ice forming efficiency of the cap cloud was evaluated by defining the ratio of the water content of ice (IWC) to the total adiabatic water content of the cloud (LWC_a) from the base of the cloud to the sampling altitude. The liquid water content of the cloud (LWC) was estimated from both droplet distributions and rime ice accretion rates. As previously mentioned, all cap clouds exhibited some naturally occuring ice crystals; however, the typical value of the IWC-LWC_a ratio was 0.2 for the unmodified cap cloud. Preliminary data from a limited number of cases indicates that under the proper conditions of temperature and liquid water content this ratio may be increased to 0.8 or greater during cloud treatment with known amounts of AgI nuclei.

Accretional growth appears to be the most efficient mechanism of removing large amounts of liquid water from the clouds. During periods with snowfall of moderately to heavily rimed ice crystals or graupel, the IWC-LWC_a ratio increases naturally to as high as 0.85. It would thus seem that a desirable method for optimizing the precipitation process would be to artificially initiate graupel embryos and capitalize on the accretional growth mechanisms. The mechanisms of such processes are being actively investigated.

E. Instrumentation

The design and development of instrumentation necessary to make the desired physical measurements have been an important part of the Atmospheric Resources Research program at the University of Wyoming.

Investigations by Auer and Veal (1968) suggested that the ice nucleus counter could not be operated at temperatures warmer than -10°C because of the weak cloud structure and inadequate ice crystal growth rates within the chamber during such warm temperatures. Other Elk Mountain studies indicated that a fraction of cloud droplets between 8 - 15 μ diameter within the cloud chamber were apparently freezing at temperatures colder than -32°C, following Fletcher (1962). Such droplet freezing seriously hinders the validity of the true freezing nuclei spectrum at temperatures below -30°C. Therefore, it is recommended that the NCAR ice nucleus counter be operated only between -10°C as a warm threshold and -30°C as the colder limit.

A cloud nuclei counter based on Twomey's thermal diffusion principle was developed during the 1966-67 operational season. During the 1967-68 season this unit was improved considerably by modifying the light source and the differential thermometer. In addition, the counter was compared with other similar instruments at the International

Instrumentation Workshop for Atmospheric Nuclei held in Lannemezan, France in September 1967. The results of this comparison suggested that the portable University of Wyoming cloud nuclei counter yields cloud nuclei concentrations remarkably compatible with the more sophisticated laboratory instruments.

A liquid water droplet replicating device was developed in order to monitor the droplet spectrum before, during and after treatment. The device developed uses soot-coated glass slides which are exposed to the airstream for a known period of time. In addition, the behavior of the airstream through which the slide passes is also known. This enables the experimenter to accurately determine the volume sampled. The slide exposure is measured using a light source, a field effect transistor, and associated timing electronics.

The instrumentation group of the Natural Resources Research Institute has developed a digital data acquisition system which is especially suited for airborne research. It is a versatile, high resolution system which records input data on one-half inch IBM compatible magnetic tape. The aircraft operational parameters presently being recorded are heading, indicated airspeed, pressure altitude, manifold pressure, VOR azimuth, and DME position; the presently recorded meteorological parameters are temperature; humidity, NCAR ice nucleus counter, vertical acceleration, together with time (month, day, hour, minute, second). The heading and temperature transducers were developed by the NRRI instrumentation group and were reported on by Weeks (1967a) and Weeks (1967b). In addition to the above parameters, the system is also capable of recording 10 separate coded events for the pilot, meteorologist, and operating technician.

The system uses a magnetic tape Digi-Data DRS-1420-V-200 which records at a low density of 200 bpi at a rate of 100 characters per second. The recorder generates the odd parity bit and has a parity echo check capability. The unit uses all silicon semiconductors and has +12-volt logic levels compatible with the Amelco high noise immunity logic used in the digital data acquisition system.

A complete description of the digital data acquisition system can be found in Knowlton and Veal (1968).

V. REPORTS

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LARGE SCALE DYNAMIC EFFECTS OF CLOUD SEEDING

ANNUAL REPORT

Submitted to

U. S. DEPARTMENT OF INTERIOR
BUREAU OF RECLAMATION
ATMOSPHERIC WATER RESOURCES RESEARCH

Contract No. 14-06-D-5963

September 1, 1968

AEROMETRIC RESEARCH, INC.
Santa Barbara Municipal Airport
Goleta California

LARGE SCALE DYNAMIC EFFECTS OF CLOUD SEEDING

ANNUAL REPORT

INTRODUCTION

On April 15, 1966, Aerometric Research Inc. entered into Contract Number 14-06-D-5963 with the U. S. Department of Interior, Bureau of Reclamation, Office of Atmospheric Water Resources Research, to conduct research into the large scale dynamic effects of cloud seeding. A number of investigators have reported on the possibility of large scale increases in precipitation in areas some distance downwind from the intended area of effect.

One of the earliest reports on this possibility occurred in an evaluation made by North American Weather Consultants (1956) of five years of commercial seeding operations in the Southern Cascades in Oregon. In this report an analysis of the precipitation patterns indicated an increase in precipitation over the target area and also a higher percentage of average increase some 60 to 100 miles downwind from the target.

Another case of apparent downwind effects of seeding was reported by Dr. Roscoe Braham (1965) of the University of Chicago in a paper presented at the 244th National Meeting of the American Meteorological Society on cloud physics and severe local storms in Reno on October 18-22, 1965. In this paper, Dr. Braham presented the results of a weather radar

precipitation analysis of the randomized cloud seeding project White Top in Missouri, which showed clearly that substantial positive effects occurred along the aerial seeding line and downwind therefrom up to a distance of some forty miles. Beyond this there appeared a slightly negative effect, but at a still greater distance downwind there was again a positive effect. Dr. Braham stated that he considered the overall effect to be dynamic in character; that is, that the seeding actually produced a meso-scale wave pattern as one of its essential features.

Another report on downwind effects of cloud seeding was recently released by Brier (1966). In this paper several commercial cloud seeding projects in Eastern United States were studied and statistically significant increases were detected between 125 and 145 miles downwind from the center of the target area.

A recent translation of a Russian publication by Litvinov (1967) indicated that aerial seeding in Western USSR had produced increases in precipitation in a 30 km square and also in another square of equal size some 30 km downwind.

At the First National Conference on Weather Modification held in Albany, New York from April 28 through May 1, 1968, three papers were presented which further documented the existence of downwind effects of cloud seeding operations. The first paper was presented by E. G. Bowen and covered Adderley's (1968) work showing large downwind effects in Australia. A paper by Brown and Elliott (1968) showed evidence of precipitation increases downwind from four long-duration operational

seeding projects in western United States. Hannaford and Williams (1968) found similar results by basing their evaluation on streamflow records.

The purpose of this current study is to determine what mechanism controls the occurrence of increases in precipitation in areas downwind from the intended target areas. The importance of understanding and eventually controlling this effect is evident when we consider that our preliminary findings indicate that the downwind effect appears to be larger than the primary effect and is spread over a larger area than the original target. By proper use of this tool, it may be possible to increase the water yield of a given storm by an order of magnitude over the current methods of direct nucleation over a watershed.

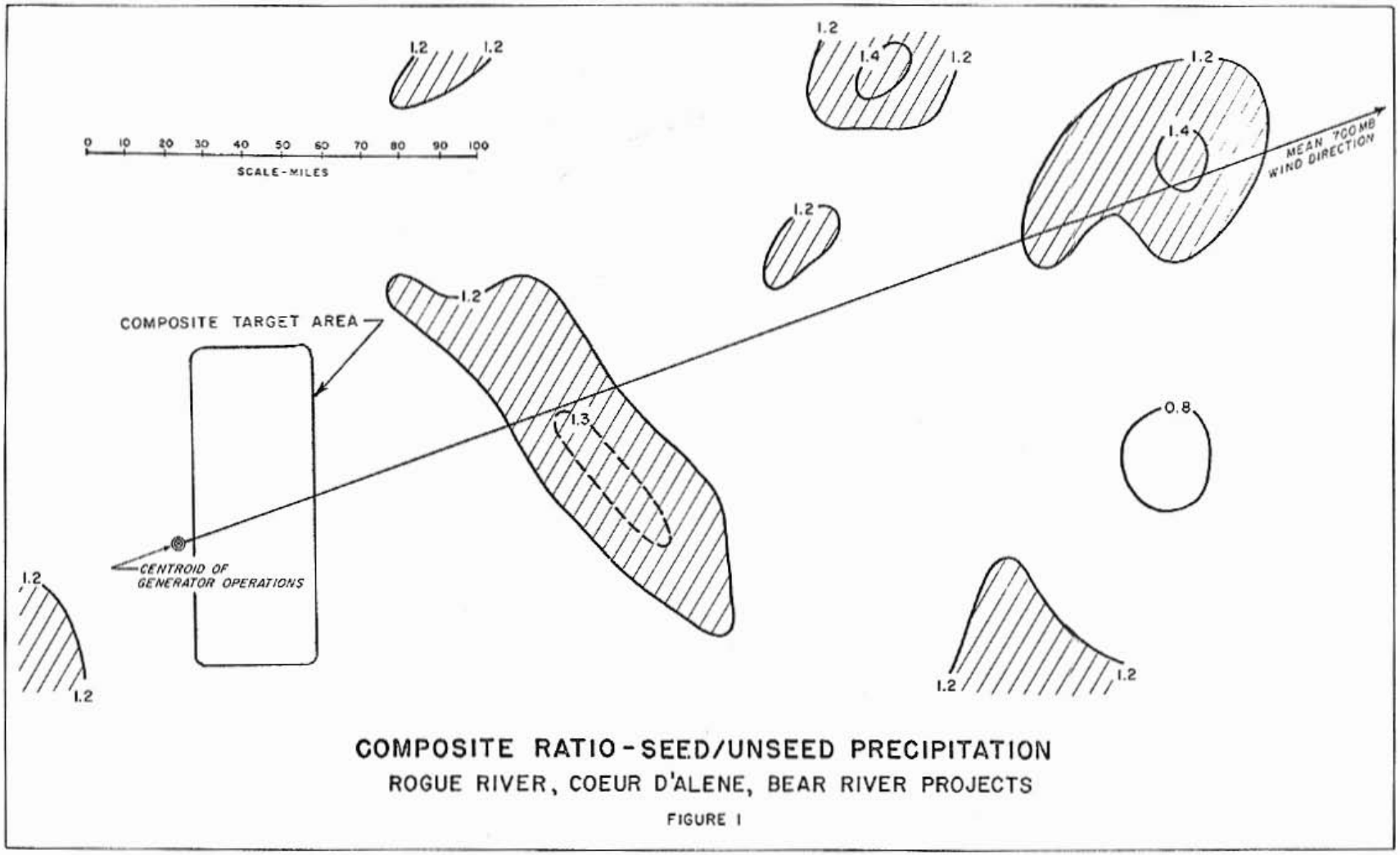
APPROACH

During the first phase of this contract we performed a statistical analysis on the precipitation patterns downwind from four long duration operational seeding projects in the western United States. The results of this analysis were reported on in the First Annual Report (1967). All four of the projects studied showed precipitation patterns suggesting a downwind effect and three of the four projects exhibited marked similarities. A composite analysis was made of the three similar projects. In order to construct a composite pattern, it was necessary to select a common point to act as a reference so that the various project areas could be superimposed. The centroid of AgI generator operations was selected as a logical common point for the three project areas. The average precipitation during seeded storms and unseeded storms at each point

on a grid was then averaged for all three projects and a composite seed/unseed ratio computed.

The pattern produced by this analysis is shown in Figure 1. Immediately downwind from the centroid of generator operations, an average target area is depicted. The absence of high seed/unseed ratios within this composite target area is due to the lack of precipitation gages within the actual targets. Independent evaluations of the individual seeding projects showed increases in snowpack and runoff during the seeding programs. Approximately 100 miles downwind from the centroid of generator operations is a well developed area of high seed/unseed ratios oriented perpendicular to the mean 700 mb wind direction. A second well marked high area occurs about 270 miles downwind and is also located on the mean 700 mb wind direction radial. The patterns seen in Figure 1 quite strongly suggest that a persistent downwind increase is occurring during operational cloud seeding programs.

With the extension of this contract for a 12-month period beginning January 1, 1968, we were able to shift our attention to a downwind analysis of past randomized cloud seeding projects in order to refine our understanding of when and how these downwind effects occur. Two well-designed randomized projects were selected for analysis. The first project was known as the Santa Barbara Weather Modification Project and was operated from 1957 through 1960. Seeding actually took place in two adjacent counties, Santa Barbara and Ventura, in Southern California. In 1957, Santa Barbara County was the only seeded area. In 1958, Santa Barbara



COMPOSITE RATIO - SEED/UNSEED PRECIPITATION

ROGUE RIVER, COEUR D'ALENE, BEAR RIVER PROJECTS

FIGURE 1

continued to be seeded on a random basis but Ventura County was seeded at every opportunity. In 1959 and 1960, the seeding in both counties was factorially randomized.

The observation unit for this project was a 12-hour period from 0900 to 2100 or 2100 to 0900. Since many storms overlapped these arbitrary time periods, only those climatological stations reporting hourly precipitation could be used in the downwind analysis. The precipitation period was then time lagged across the area of interest to insure comparable precipitation periods. A total of 82 hourly precipitation stations within the area studied were available for analysis. A control area composed of seven precip stations northwest of Santa Barbara County was selected to sensitize the statistical tests. A double ratio was then computed for each precip station on the base map. The ratio was determined by:

$$R = \frac{T_s}{T_{ns}} \quad \frac{C_{ns}}{C_s}$$ where:

R = Double ratio

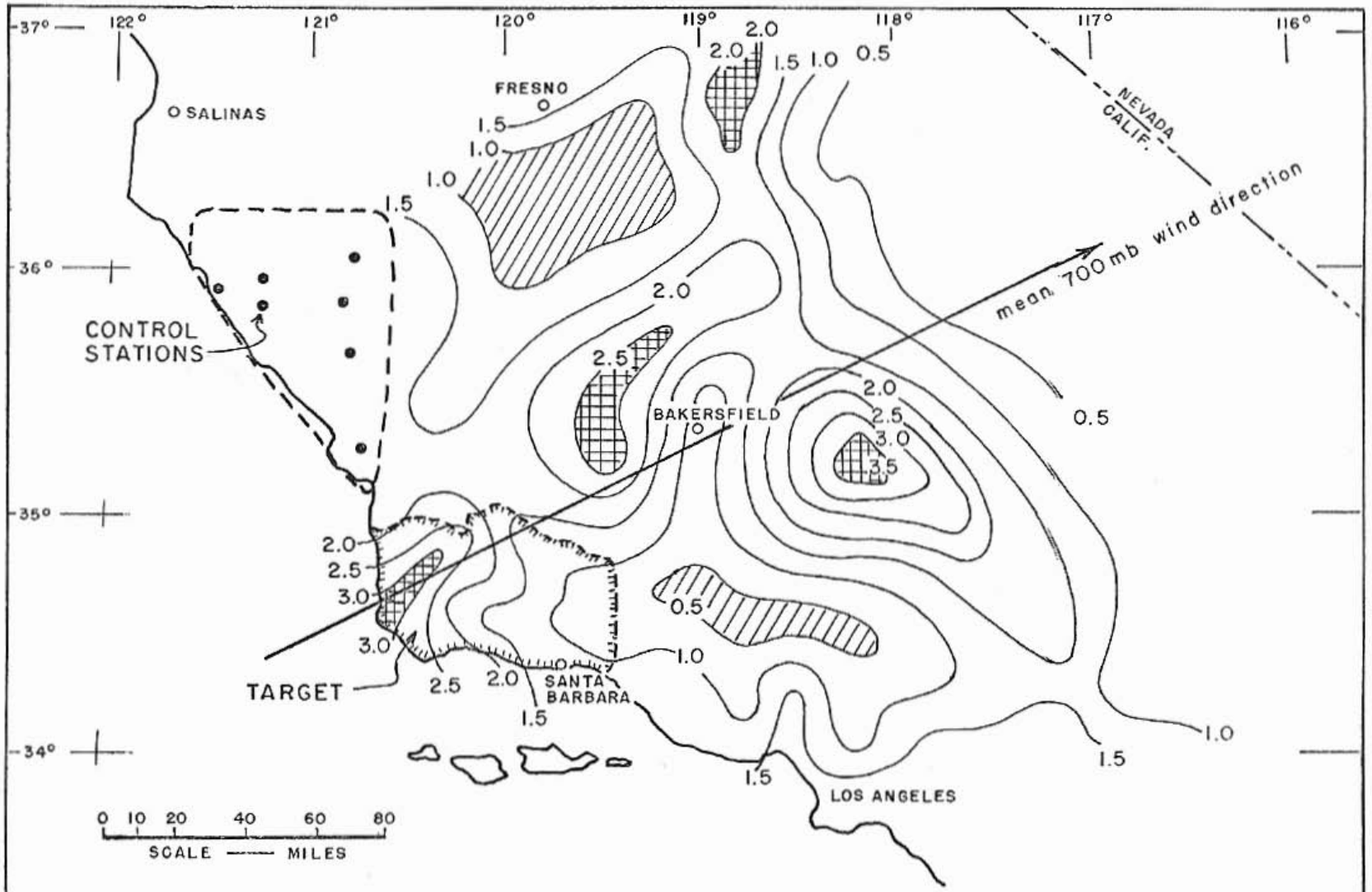
T_s = Average precip during seeded storms at an individual station

T_{ns} = Average precip during non-seeded storms at the same station

C_{ns} = Average precip during non-seeded storms in the control area

C_s = Average precip during seeded storms in the control area

If there is no effect from seeding at an individual station, the ratio should be near 1.0. The double ratio map comparing the storms when Santa Barbara County was seeded and those storms with no seeding is seen in



DOUBLE RATIO MAP - SANTA BARBARA RANDOMIZED SEEDING PROJECT

Figure 2

Figure 2. An interesting pattern is evident in this figure with high ratios in the western edge of the target area indicating there was probably a considerable low level drift of AgI from the southeast before entrainment and direct nucleation occurred. A second area of high ratios is evident in the Taft area about 80 miles downwind from the target area maximum. This second high area is located in the San Joaquin Valley to the lee of the Coast Mountain Range. Two additional high ratio areas appear on the west side of the Sierra Nevada Mountain Range. One center is near Tehachapi and one just east of Fresno. A Mann-Whitney U test was made to determine if the distribution of the seeded storms was significantly different from the unseeded storms. Only the precipitation station in the western edge of the target was significant at the 5% level. However, several stations in the San Joaquin Valley approached the 5% significance level.

Another randomized cloud seeding project analyzed for downwind effects was the Nevada Atmospheric Research Project (NARP). This project is located in northeast Nevada and has been in operation each winter season since 1961-62, however, the first year of this program was operated as a one-target randomized seeding experiment. The project design was changed at the start of the 1962-63 season to a two-target, randomized cross-over program and has continued to operate in this manner through the 1967-68 season. The storms chosen for our downwind analysis were therefore chosen from the 1963-68 period.

The design of the randomized cross-over program may be summarized as follows. Two target areas were selected and instrumented. One target was located about 50 miles north of Elko, Nevada in the Jarbidge Mountains and the other target area was about 20 miles southeast of Elko in the Ruby Mountains. Each target was 20 miles square. The operational procedure required North American Weather Consultants, the operating company, to select an 18-hour period with seeding conditions favorable in both areas. This information was relayed to the Desert Research Institute (DRI) of the University of Nevada where a random decision was made to seed either A Target or B Target. If the storm extended beyond the 18-hour period, no seeding was permitted for six hours before calling for another seeding period. A restriction on the wind flow patterns permissible during seeding operations eliminated the contamination of one target area while seeding the other target area.

The area covered in our downwind analysis of this project area extended from 112° to 117° W. longitude and from 39° to 44° N. latitude, or over 80,000 square miles. Due to the small number of hourly precipitation stations in this area, it was necessary to use all available precipitation records and eliminate those storms which were not clearly defined as to starting and ending times. A total of 133 gages were suitable for analysis. Calculations comparing the effect at each precipitation station when A target is seeded and when B target is seeded were analyzed for the NARP project area. A ratio was computed using the formula

$$R = \frac{\overline{A} - \overline{B}}{\overline{A} + \overline{B}}$$

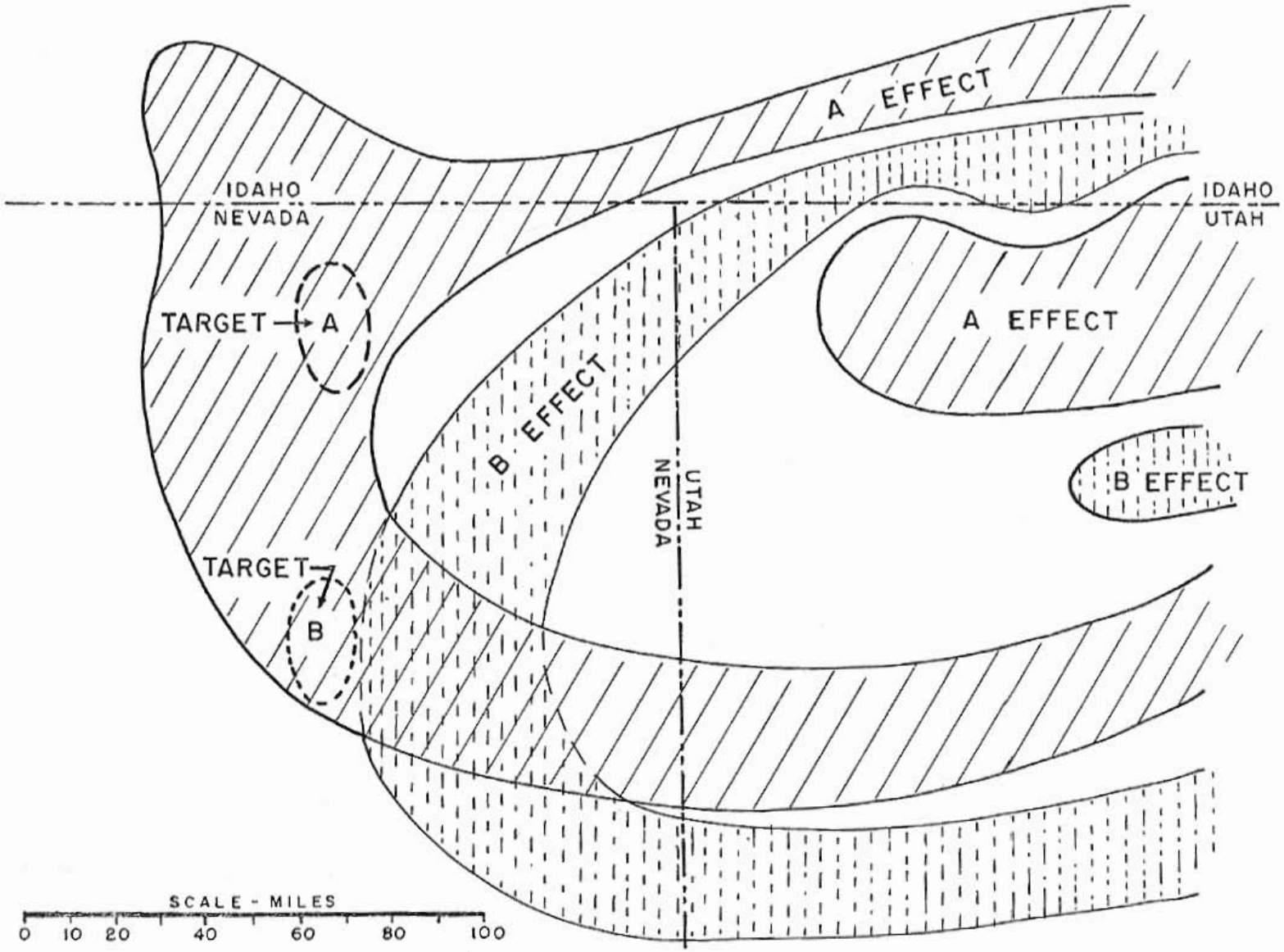
where:

$\overline{A}$ = Average station precipitation when target A is seeded

$\overline{B}$ = Average station precipitation when target B is seeded

The ratio found in this manner can be easily converted to a percentage increase with a negative sign if effected more by B target seeding and a positive sign if effected more by A target seeding. These percentage values were then plotted on a base map and analyzed. Since the anaysis of these data is still underway, the results to date are only tentative. However, the first estimate of the area of effect from each seeding area is very interesting and the patterns are shown in Figure 3. There appears to be a crescent-shaped area of effect extending from each target area to the northeast and southeast and another high area in the center of the crescent approximately 150 miles east of each target. This pattern is remarkably similar to the classic disturbed fluid flow produced when an obstruction is placed in a moving stream of water. Since one of our original hypotheses to explain the downwind effect phenomena was a dynamic response to a seeding-produced disturbance in the air flow over a barrier, this evidence lends credence to this theory.

The extension of the A area of effect to the northwest of the A target may be due to a low-level channeling of AgI on the west side of the mountains. The orographic barrier in target A is broken by several narrow valleys which could cause an extended low-level drift of AgI while the B target area is characterized by a single abrupt mountain ridge ending at the north end of the target. Any low-level AgI in this area would probably not be carried any great distance northward.



AREA OF EFFECT - NEVADA ATMOS. RESEARCH PROJ. (NARP)

Figure 3

During the 1967-68 winter season, Aerometric Research Inc.'s affiliate company, North American Weather Consultants, has been conducting a randomized seeding project in Santa Barbara County under contract to the U. S. Navy. The seeding mode used on this project was pyrotechnic devices burned at a 4000 foot ridge line location northwest of Santa Barbara. The observation unit was a convective band embedded in a synoptic-scale system as detected by weather radar and an upwind network of telemetered precipitation gages. The bands were then tracked through the target area by a dense network of recording precipitation gages. A control area was designated and double ratios were computed comparing the precipitation at each station during seeded and unseeded bands and the control precipitation during unseeded and seeded bands. In order to test whether seeding on a band basis could be used to detect downwind effects, an analysis was started on the history of the bands after they moved downwind from the target area. Since only the existing recording raingage records could be used in this study, the coverage was less than adequate but, nevertheless, some interesting patterns were suggested. The primary area of effect of the pyrotechnic seeding appeared in the form of a northwest-southeast line about 25 miles downwind from the seeding site. Beyond this line the double ratios decreased to about 1.0 (no seeding effect) and then increased again in the San Joaquin Valley about 70 miles downwind from the seeding site. This was followed by a return to ratios near 1.0 again.

While the sample size was small, ten seeded bands and eleven unseeded bands, the possibility of detecting a downwind effect on a band basis

poses some interesting questions. For example, we do not know what mechanism could cause a convective band to be amplified by seeding then return to a normal amount of activity and then regenerate into a more active band again.

CONCLUSIONS

During the course of this contract, Aerometric Research Inc. has conducted a thorough investigation into the downwind effects of cloud seeding. We have analyzed precipitation patterns and associated meteorological conditions downwind from four long-term operational seeding projects and three research projects. We believe that the results of this study, together with the work of other investigators, has shown a relationship exists between seeding operations and the precipitation patterns over extended areas downwind from the primary target areas. The importance of understanding this phenomena and being able to exploit it for the production of extra water supplies is quite evident.

We have not been able to isolate the mechanism controlling the downwind effect by making "post hoc" analyses of past seeding projects. We have been able to list various hypotheses but the supporting evidence is either lacking or contradictory. The variables which we are interested in are not available in the downwind areas since the projects studied were not designed to test for downwind effects.

In order to develop an understanding of the extended area effects of cloud seeding, it will be necessary to start a field program specifically designed to provide the inputs into our various hypotheses. The

statistical study being made under this contract is providing much information as to what must be measured and in what areas our study should be concentrated.

Reports Published:

In April, 1968, Mr. Keith Brown and Mr. Robert Elliott presented a paper covering the results of this study at the First National Conference on Weather Modification sponsored by the American Meteorological Society at the State University of New York at Albany. A summary of this work is included in the Proceedings of this conference.

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T. G. Owe Berg, Inc.

Interim Report

BUREAU OF RECLAMATION SUMMARY

INTRODUCTION

The main objective of the work under this contract is to evaluate the effect of exposure to the warm cloud base upon the seeding effectiveness of silver iodide. In terms of practical weather modification it is a comparison between seeding from the ground and seeding from aircraft with respect to effectiveness and efficiency.

This objective continues from the preceding Contract No. 14-06-D-5957. In the course of that work it became apparent that the state of the art did not provide the information required for the proper definition of the objective in terms of testing conditions and criteria of merit. Part of the effort was therefore given to the acquisition of such information. This effort has continued as a secondary objective under the present contract.

A great deal of thought and study has been given to the application of results to the weather modification program and its problems more generally than the specific scope of the contract. It is a matter of course that the work under this contract should be placed in its context within the weather modification program. A brief discussion of this subject is presented in Section 4 of this report. The testing conditions and the criteria of merit for the work under this contract are valid more generally, and a proposal has been submitted for their development for the testing of seeding agents and equipment for dissemination.

A crucial issue in laboratory work is the simulation of the partinent conditions in natural clouds during seeding. This issue has been approached along two avenues, namely the identification of pertinent conditions in the laboratory, and the checking of laboratory results by experiments in natural clouds at ground level. The latter approach has been exploratory so far, but we hope to give it extensive effort in the future.

A peculiar aspect of the simulation problem is that the concentration of seeding particles should be small enough as compared to the concentration of supersaturated (condensable) water vapor. In order to promote precipitation, as contrasted to dissipation, the concentration of seeding particles should be so small that the particles do not compete with one another for the condensable vapor. This means that the experiments should be conducted with virtually single particles. On the other hand, the actual supersaturation in clouds to be seeded, which is determined by the dynamics of the updraft and the kinetics of the cloud processes, appears as one of the most important quantities in practical cloud seeding, which needs determination in natural clouds to be seeded and simulation in laboratory experiments.

The work under this contract has been conducted under three tasks:

1. Investigation of the effect of exposure to the warm cloud base upon the seeding effectiveness of AgI.
2. Exploratory experiments in natural clouds.
3. Further experiments with AgI in the expansion chamber.

The state of the contract is that tasks 2 and 3 have been completed, and that task 1 is in progress. Task 2 was reported in a special report, a summary of which is in the process of publication. Task 3 was reported in a special report, and a summary has been prepared for publication. Task 1 is expected to reach a reasonable degree of completion by the end of the current contract period.

The personnel actively engaged in this work are Dr. T. G. Owe Berg, principal investigator, Mr. Thomas A. Gaukler and Mr. Robert L. McDonald, project engineers, and Mrs. Urte Vaughan and Miss Joyce E. Clutter, laboratory technicians.

Work Done

1. Investigation of the effect of exposure to the warm cloud base upon the seeding effectiveness of AgI.

The experience gained under the preceding contracts led to the design of an experiment, in which a charged single AgI particle is first suspended under conditions simulating those at the cloud base and then transferred to suspension under conditions simulating those at the seeding level. The apparatus contains two suspension chambers with ring-shaped electrodes. They are connected by a vertical tube, through which particles in transfer from the lower to the upper chamber are guided by the ac field from two pairs of rods in the wall of the tube. The two suspension chambers are part of a flow system, through which cooled air is flowing. The air is cooled first in a heat exchanger and then further in the flow system itself by means of cooling coils around ducts and tubing.

The main difficulty in the construction and operation of this apparatus is to simulate cloud conditions between the two suspension chambers. We have found that this cannot be achieved by means of cooling coils or by means of a cooling jacket around the intermediate tube. We have therefore made a cold box that encloses the part of the apparatus above a level at 12 inches below the lower suspension chamber. The cold box has the outer dimensions 2 x 2 x 3 feet. It is lined with 2-inch styrofoam sheet. It is cooled by 60 feet of 3/8-inch copper tubing connected to a refrigerator. A fan at the top of the box provides stirring of the air and a fairly uniform temperature distribution. Without stirring the air at the higher suspension level is 10° to 12° warmer than at the lower suspension level.

The cooling and temperature distribution problems derive basically from the fact that it is not possible to use a metal cylinder around ring-shaped electrodes for suspension. This is a matter of field distribution. But electrical insulators are also thermal insulators, and cooling of the insulating wall below and above the suspension chamber does not control the temperature in the suspension chamber. This situation is partially improved by the air current through the suspension chamber, but the outside air temperature should preferably be equal to or lower than the interior air temperature at the upper, colder, suspension chamber. Since AgI becomes effective at $-5^{o}C$ this means that the temperature in the box should be below $-5^{o}C$.

To the main purpose at hand, the observation of ice formation, it suffices that the interior air temperature at the upper suspension level is $-5^{o}C$ is slightly lower, and that there is no colder lower level. In order to study growth of an ice particle, it is desirable to have lower temperatures at the upper suspension level, but it is not necessary to prevent lower temperatures at lower levels so long as supersaturated water vapor is available at the upper suspension level.

Recent studies of strongly charged water droplets have convinced us that they retain their temperature regardless of the temperature of the surrounding air. This subject is briefly discussed in Section 4. However, weakly charged droplets containing AgI do freeze. It is therefore necessary to use weakly charged AgI particles and to support them partially by an air current, using the field essentially for their horizontal confinement. This was done successfully in the experiments at Rabbit Ears Pass.

2. Exploratory experiments in natural clouds.

The special report on this subject has been prepared ("Exploratory Experiments in Clouds at Ground Level at Rabbit Ears Pass, February 1968," T. G. Owe Berg, T. A. Gaukler and Joyce E. Clutter, March 1968). The abstract is given here.

ABSTRACT

Equipment of the type used in previous laboratory investigations was installed in a trailer and taken to Rabbit Ears Pass at Steamboat Springs for observations in natural clouds at ground level. The equipment included devices for the sampling of the cloud with respect to ice particles, and the suspension of such particles in a nonuniform ac field with or without a supporting vertical air current. The suspended particles were observed visually in scattered light and by photography in shadow illumination through the microscope at magnifications of 15 and 20, respectively. Observations were extended over periods up to 2 hours while the particle was held in its natural environment. The ice particles observed between -2^{o} and -7^{o} were all hexagonal, or agglomerates of such hexagons,

the hexagons being 15 μ along the diagonal. Some such particles were highly charged, of a charge to mass ratio of the order of 10^3 esu/gram, which is of the same order as that for the suspended droplets studied previously in the laboratory. Other such particles had smaller or much smaller charges. Both positively and negatively charged particles were observed, their relative abundances varying from one occasion, or one cloud, to another. The highly charged suspended particles collided and coalesced readily with other particles. No other mechanism of growth was observed. Occasionally, small, approximately 2 μ, ice particles were observed. They were apparently uncharged.

High-speed photography studies were made of the formation of condensate clouds in an expansion chamber at various temperatures down to -8° with air from the cloud in the expansion chamber. The condensate cloud was sparce. The droplets were of uniform size, approximately 6 μ, the same as with laboratory air.

3. Further experiments with AgI in the expansion chamber.

The special report on this subject has also been prepared ("Experiments with Silver Iodide Smoke in the Expansion Chamber," T. G. Owe Berg, T. A. Gaukler, and Urte Vaughan, July 1968). The abstract is given here.

ABSTRACT

Condensation and ice formation in an expansion chamber were studied at temperatures down to -10°C. Nucleation was effected by laboratory air with and without addition of silver iodide smoke. Plots were obtained of the number of droplets and the droplet diameter against the time after the start of the expansion.

At a high concentration of nuclei and a low concentration of condensable vapor the nuclei compete for the vapor. Some nuclei are ineffective for the lack of vapor to operate on, and the condensate droplets are small because there is not enough vapor for their growth. AgI particles form ice from the vapor by way of condensation. At a high concentration of AgI and a low concentration of condensable vapor some AgI particles appear to be ineffective merely for the lack of vapor. In nature and under normal seeding conditions the concentration of nuclei is low, and the vapor concentration is high; there is then no such interference among particles. This case is better simulated in experiments with single particles.

Work to be done

The remainder of the contract period will be devoted to the first task. The apparatus will be completed, and observations will be made with a single AgI particle under the conditions at the seeding level after exposure to the conditions at the cloud base. The

observations will include ice formation and growth. The main variables are temperature, degree of supersaturation, and abundance of condensation nuclei.

Applications to Weather Modification

Our experiments with the expansion chamber, the cold chamber, and the suspension chamber show that AgI forms ice from water vapor on the conditions that the vapor is supersaturated with respect to liquid water, and that the temperature is below -5°C. The AgI particle acts first as a condensation nucleus and then as a freezing nucleus. The same experiments show that collisions between AgI particles and water droplets are extremely rare, unless the water droplets are highly charged. The initiation of freezing of supercooled cloud droplets by AgI particles should be correspondingly rare. Thus, it may be concluded, the main direct seeding effect is the interaction of AgI particles with supersaturated water vapor.

It follows from these observations that a necessary condition for the glaciation of a cloud by seeding with AgI is that the cloud contain supersaturated water vapor. This in turn requires the supply of water vapor by way of an updraft, as in a cumulus cloud during its formation. Seeding in the dissipating stage could not be effective since the updraft is lacking. Seeding in the intermediate mature stage would be less effective than in the formative stage. Seeding through the side of a cloud would be less effective than through the base because the air entering the cloud from the side is comparatively dry. Also, the cloud must be tall enough to permit enough cooling of the water vapor in the updraft. These conclusions seem to be in fair agreement with practical cloud seeding experience.

Unfortunately, the state of the art does not permit the pursuit of these conclusions further than to qualitative generalities. There is a voluminous literature on the aerodynamics and thermodynamics of clouds, but the mathematical treatment lacks a basis of empirical knowledge of the rates of the processes involved. Reference may be made to Newton on this subject. However, a few more specific, although speculative, comments on the kinetics of the unit processes may be offered here.

It is generally believed, probably correctly, that satuation prevails at the cloud base, and that condensation nuclei are abundant enough to prevent supersaturation at the cloud base. Thus, condensate droplets and saturated vapor are carried from the cloud base by the updraft. As the air and the water vapor in the updraft proceed upward, they are cooled by expansion and by mixing with the cloud air. Their temperature is also affected by exchange with the liquid phase. The temperature of the liquid phase is determined by condensation, evaporation, and heat exchange with the adjacent air. It is thus determined by the relative rates of these three processes and also by the temperature and humidity of the air in the updraft. Little is known about these quantities.

The degree of supersaturation or, rather, the rate of production of supersaturated, i.e. condensable, vapor determines the rate of formation of ice by AgI and the rates of growth of the liquid droplets and the ice particles. A high concentration of AgI particles as compared to the concentration of condensable vapor causes overseeding and dissipation of the cloud. Thus, no, or a very slight, supersatuation in a region, where AgI is introduced, leads to no effect of the AgI or to overseeding. It appears that the seeding is most effective when the degree of supersaturation is high at the seeding level. It also appears that the rate of growth of the ice crystals is greater, and thereby that the effective mass of the seeding is greater, the greater is the rate of increase of the degree of supersaturation above the seeding level. In the study of cloud seeding one may therfore not assume that the rate processes are infinitely rapid, and that there is equilibrium between liquid water and water vapor with respect to temperature and vapor pressure at all times. Indeed, the deviation from equilibrium is essential to the seeding.

We have studied these rate processes under this contract and under other contracts. The work has revealed the complexity of the processes. Generally applicable data were not obtained because the rates depend so much upon the experimental conditions that generalization is hardly possible.

The temperature of charged water droplets was studied under our contract with National Science Foundation, and a special report on this work has been prepared. Kinser and Gunn found that a falling drop takes the temperature of the wet bulb. Alty found that a drop on a capillary takes the temperature of the dewpoint. It is a matter of course that a drop that does not evaporate or grow by condensation takes the temperature of the surrounding air. We have found that charged droplets retain the initial temperature, regardless of the temperature of the surrounding air. Thus, a 100 μ droplet of a suspension of AgI in water, corresponding to 10^{-3} moles per liter, did not freeze in 2 minutes when inserted at an initial temperature close to $0^{\circ}C$ in the suspension chamber held at $-20^{\circ}C$. Such a droplet should freeze at $-5^{\circ}C$. Recent observations have shown that cloud droplets may be as strongly charged as the ones used in these experiments.

It appears thus that charged cloud droplets may be carried up to levels of low temperatures and retain their temperature until they have evaporated. They then supply vapor to the cloud much faster then the theory of Kinzer and Gunn would suggest, and growth of cold droplets and ice particles would be correspondingly rapid.

On the other hand, it appears that small condensate droplets, say 5 to 10 μ, formed in an expansion chamber take the temperature of the vapor from which they are formed. As already pointed out a drop that does not evaporate or grow by condensation takes the

temperature of the air. Thus, with AgI smoke in the expansion chamber the condensate droplets freeze below -5°C, which is the threshold for ice formation by AgI generally accepted on the basis of observations under other circumstances. One may therefore expect new condensate droplets to form and to grow at the expense of old condensate droplets.

It follows from these speculations that condensation should suffice to cause growth, and that glaciation is not necessary. As a matter of fact, rain falls from warm clouds in the tropics. However, those clouds are generally much taller than those farther north, and it appears therefore that the growth of liquid condensate droplets is slower than that of ice particles.

Ionization of the air and electrification of the particulates in the updraft may be decisive in nucleation and growth. They may also have a role in the heat balance. Little information is available on this subject.

The discussion just presented is necessarily speculative, simply for the lack of data. It is clear, however, that nothing better than speculations can be presented until the kinetics of the pertinent processes is known. Some of the quantities are admittedly very difficult to measure in natural clouds and some, e.g. droplet temperatures, cannot be measured at all at the present state of the art. This should not deter but rather challenge research. It appears that such a task should be conducted as a combination of observations in natural clouds and in the laboratory.

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September 1968

PARK RANGE

ATMOSPHERIC WATER RESOURCES

PROGRAM

Contract No. 14-06-D-5640

Period: July 1, 1967 to June 30, 1968

INTERIM REPORT

Prepared For:

U.S. Department of the Interior

Bureau of Reclamation

Office of Chief Engineer

Denver, Colorado

E. Bollay Associates, Inc.
a subsidiary of EG & G, Inc.

BUREAU OF RECLAMATION SUMMARY

ABSTRACT

This report describes the results of the Park Range Atmospheric Water Resources Program for the period July 1, 1967 to June 30, 1968. The program is centered at Steamboat Springs, Colorado, began experimental work in November 1964, is operated for the Bureau of Reclamation by E. Bollay Associates, Inc., a subsidiary of EG&G, Inc., and has as its objective to develop the technology of weather modification for water resources augmentation by treatment of winter orographic precipitation.

Highlights of the report are:

a. A numerical model which simulates the air flow over an orographic barrier and computes the precipitation rates due to the orographic lift has been applied to the Park Range experiment. A simple but practical crystal growth-precipitation fallout nomogram has been constructed from the model calculations and has been used to indentify the optimum seeding altitude and range from the target in terms of measurable meteorological parameters.

b. Conditions favorable for cloud seeding in the Park Range target area have been identified in terms of measureable environmental parameters. Seedable, highly productive precipitation periods last only a short time during the traverse of a weather system over the area. Under these situations the optimum growth level ($T \cong -15^{\circ}$ C) is at 15-18,000 ft MSL. Analysis of past data for the area shows that the most productive precipitation periods average about 200 hours per season. The remaining precipitation falls during another 800 hours when temperatures are relatively cold and precipitation rates are low. These characteristics of the cloud conditions have significant implications in the compromises between operational complexity, reliability and the yield/cost determinations.

c. Analysis of Ag in snow samples, ice nuclei concentrations and precipitation rate have been used to understand the effects of the seeding pulse. Spectrum analysis techniques have been applied to the data but have not been able to directly identify seeding results. Detailed studies of individual cases have isolated many of the inherent problems related to detection of the periodic seeding pulse. For example, inversion conditions have limited the number of seeding hours in which the plume could be transported to the proper location in the cloud. This variability of the nuclei transport and dispersion, as well as the nonlinear precipitation reaction time, has made the pulse seeding evaluation more complex than was originally anticipated. These results clearly show that cloud seeding operations in mountainous

terrain are complicated and must be controlled carefully if proper results are to be obtained.

d. Several independent evaluations suggest possible downwind (50 miles) seeding effects caused by the Emerald Mountain seeding tests. Since the short-term pulse seeding (1 cph) is usually smeared with distance of travel, one can consider the downwind plume to be nearly continuous during the operations period. Thus small increases in precipitation downwind of Park Range appears consistent with current understanding of the plume movement.

e. Diffusuion tests have been used to develop prediction estimates of nuclei plume transport and dispersion. The seeding phases have been measured in terms of nuclei concentrations in the target area. Analysis of the diffusion studies have pointed out the complexities to be dealt with in establishing proper generator sites.

f. In view of the complexity of monitoring ground released pulses, several airborne seeding tests were performed. Preliminary results show that the seeding pulse can be identified and followed through airborne nuclei tracking. Furthermore, several cases show good correlations with snow rate in the target area. There still exists, however, considerable complexity in the determination of release patterns, seeding rates and monitoring of cloud response time. It is clear that the lag time between seeding pulses must be at least the order of 2 hours for proper experimental results.

g. Techniques have been applied, utilizing quantitative radar measurements, to identify the precipitation trajectories and to monitor changes in precipitation intensities during intervals when clouds are influenced by the seeding pulse.

INTRODUCTION

Objectives

The Park Range Atmospheric Water Resources Program, located near Steamboat Springs, Colorado, has been operated for the Bureau of Reclamation by E. Bollay Associates, Inc., for 4 years. This report describes the results of FY68 (July 1, 1967 to June 30, 1968) operations under Contract No. 14-06-D-5640.

The basic purpose of the Park Range Program is to test the effectiveness of winter-time cloud seeding and to develop the technology for optimizing precipitation in the Upper Colorado River Basin. The goal has been to obtain useful information concerning artificial cloud nucleation effects in as short a time as possible. It is inherent in

such an approach that pertinent measurements be made frequently with a relatively dense network, and be supported by detailed analyses.

Answers have been sought to the following major questions:

a. Under what meteorological conditions is artificial nucleation (seeding) of clouds effective?

b. Under what meteorological conditions will artificial nuclei be transported from a given generator location into super-cooled clouds over a given target area?

c. To what extent do artificial ice nuclei participate in ice crystal formation, and how is this participation reflected in precipitation falling on the target area?

d. What combination of operating criteria techniques and equipment will produce the maximum increase in annual precipitation for the least cost?

To answer these questions, experimental seeding tests have been conducted along with research studies which emphasize numerical modelling, ice nuclei generation, diffusion analyses, precipitation dynamics, and evaluation precedures.

Experimental Design

The underlying premise of the Park Range experiment is that winter-time precipitation (November-April), falling from storm systems moving through the area, is not totally efficient in snow production due to a lack of ice-forming nuclei. Since appropriate cloud seeding techniques are capable of increasing the number of ice-forming nuclei, it is expected that important increases in winter snow pack can be obtained in this area. However, the susceptibility of the clouds to seeding is highly variable and experimental studies are needed to derive the necessary criteria for optimizing the precipitation production.

The basic design of the experiment involves the injection of a pulse of artificial nuclei into the atmosphere and the measurement of the influence which the nuclei have on the precipitation rate across a target area. By replicating the pulsing cycle, it is possible to obtain several seed/no-seed tests for each storm period; thus increasing the number of test units available for a given season.

An instrumented network, two radars, and aircraft are used to monitor the test area. The available data are analyzed as case studies to

provide sequential information about the transport of the nuclei to the cloud level, the development and growth of ice crystals and the eventual fallout of snow on the test area. The time series of precipitation rates are also analyzed using standard power spectrum procedures.

Emphasis has been placed on the pulsed seeding technique so that a large number of experimental test periods may be obtained covering various environmental conditions.

The pulsing technique further provides information about the non-linear reaction time of the cloud systems which have been injected with seeding materials. This gives additional insight as to the delivery methods necessary to optimize winter-time precipitation.

Numerical Modelling

Application of Numerical Models

In recent years considerable success has been achieved in the simulation of cloud and precipitation processes using high-speed computers. The advantages of applying numerical studies to experimental cloud seeding projects comes from the ability to stratify the various processes and to study their sensitivities in terms of the influence on precipitation. Furthermore, it is possible to simulate the modification technique which is being tested and to estimate the magnitude of the influence. Evaluation of the experiment is facilitated by the comparison of model predictions with pertinent observations.

A simple, but practical model has been developed during FY68 for use in Park Range. The model computes the vertical component of the airflow across the orographic barrier, the condensation rate, the conversion of condensed water into ice crystals, and the precipitation rate across the mountain profile. The primary application of the model in the Park Range experiment will be to stratify the pulsed seeding periods and to compare the predicted parameters with observations. Nomograms have been constructed using the same micro-physical relations as those presented in the model. The nomograms are used in planning the seeding operations and in the concurrent analysis at the field site.

The two-dimensional mountain airflow can be represented mathematically to an acceptable level of precision, and the vertical velocities can, in turn, be used in models of the condensation process.

During the winter season, the bulk of the orographically produced condensation goes into the formation of small supercooled droplets.

Unless there are adequate numbers of ice embryos which can convert the supercooled water to crystals, large enough to descend to the mountain ridge, the condensed water will be transported across the mountain ridge and evaporate on the lee side. Thus, the cloud physics problem in mountain precipitation revolves around the problem of extracting the condensed water into hydrometeor form before the air transports the material to the region of descending motion and subsequent evaporation.

Critical Ice Nucleus Concentrations

With the assumption that ice crystals form, their growth by diffusion and accretion can be modeled and the fall velocity and advected distance can be computed. Often there are insufficient ice nuclei present to glaciate subcooled clouds. Also there is a critical ice-to-water ratio for which the cloud can become glaciated. This ratio, which varies with vertical motion, temperature and crystal type is basic to the understanding of optimum seeding of winter clouds.

The model indicates that for clouds of -15° C and 50 cm sec^{-1} updraft, about 50 crystals per liter are needed for optimum glaciation. Generally speaking, this is one to two orders greater than natural nucleus concentrations. We conclude then that the supply rate of natural systems exceeds the extraction rate in the temperature range of -5° to -25° C; hence, proper cloud seeding treatment should produce significant increases in snowfall.

A key question to be answered is, what are the proper freezing nucleus concentrations to be added by cloud seeding to optimumly glaciate the cloud system? Using a mathematical realtionship we can obtain the proper number of ice embryos. To this we must add the air flux and generator efficiency in order to obtain the seeding rate. Air flux is determined by knowing wind speed and cloud cross-sectional area. Generator production rates of nuclei are highly a function of temperature.

For typical conditions, concentration of 10-100 crystals per liter can be produced with a few grams of AgI per minute. Obviously, if the material is to be released from ground based generators, seeding amounts must be increased due to the dilution by diffusion as the plumes move from ground to cloud.

Operational Factors in Park Range

General Environmental Conditions

The climatological frequency of winter (Nov-Apr) precipitation over the Park Range by 24-hour period is about 45 percent. Precipitation

events are frequently near 12 hours in length but may range from 1 to 2 hours to as much as 48 hours and the result is approximately 1,000 hours of measurable precipitation per winter season.

Large scale upper air patterns which produce the most persistent periods of frequent snow are:

a. A low to moderate amplitude long wave ridge just off the West coast with an ill-defined long wave trough east of the Mississippi River. This gives over-extended wave length and allows short wave troughs (which arrive at 30 to 48 hour intervals) to amplify as they approach the Continental Divide.

b. A very high amplitude long wave ridge extending from the central Gulf of Alaska southward with strong moist north-northwesterly flow over the Park Range. Very fast-moving short wave troughs (arriving at 20 to 30 hour intervals) intensify and decelerate slightly as they begin to curve more easterly at the latitude of the Park Range.

These two patterns can result in very large snowfalls due to the duration of precipitation conditions.

Seedability Criteria

In order to develop seeding technology to the point where precipitation can be optimized or to stratify data for analysis from indiscriminant seeding, a set of conditions of seedability is required. For operational optimized seeding, these conditions must be predictable or at least readily recognizable in concurrent time.

The conditions of seedability (seedability criteria) established in this section are primarily theoretical and the methodology is sufficiently general to be applied to other geographical areas using synoptic scale data in order to select feasible altitudes of ground generator sites and/or to establish the most feasible mode of seeding (ground, aircraft, etc.) when planning a seeding program.

From a seeding evaluation viewpoint, seedability criteria must delineate:

a. Targeting limits (wind and stability criteria through the seeding diffusion envelope).

b. The quantity of water becoming available for potential precipitation per unit time.

c. The percentage efficiency of the natural precipitation process.

d. The conditions to which the seeding agent is exposed in its travel to the activation temperature region.

To set targeting limits (criterion 1), the geometry of the target area, the relative location of generators, and the local three-dimensional diffusion characteristics must be considered.

The amount of water becoming available for potential precipitation per unit time (criterion 2) is primarily dependent upon the temperature of the saturated air column, the vertical velocity within the column, and the airmass transport speed (horizontal) across the target area.

The percent efficiency of the natural precipitation process (criterion 3) is dependent upon the number of natural ice nuclei which become active within the super-cooled cloud column. The number of active ice nuclei, in turn, is dependent upon the coldest temperature within the cloud (usually at cloud top).

The importance of conditions to which the seeding agent is exposed in its travel to the activation temperature region (criterion 4) is pointed out by St. Amand, et. al. (1968).

According to St. Amand, et. al. (1968) dissolution of the seeding material may occur if the material is exposed to temperatures >-4° C. They have also reported that contact nucleation or condensation followed by freezing are the dominant nucleation processes from -4° C to -12.5° C, while the sublimation process takes over below -12.5° C. Thus, it would be helpful to know the climatological frequency of the occurrence of exposure temperatures >-4° C and between -4° and -12.5° C.

Figure 15 represents an overlay to be used with environmental temperature-humidity soundings on pseudo-adiabatic charts. The first step in using the chart is to overlay the chart on a pseudo-adiabatic diagram containing a vertical sounding of existing temperature-humidity curves.

Then select the mode of seeding to be employed as follows:

a. If any portion of the saturated air column (cloud layer) reaches below -24° C, DO NOT SEED.

b. If the saturated column intercepts the -15° C isotherm within either the seedable or highly seedable from Mt. Harris region, SEED FROM MT. HARRIS provided no inversion exists between 650 mb and Mt. Harris altitude.

c. If the saturated column intersects the -15° C isotherm within the airborne seedable zone, SEED FROM AIRCRAFT OR OTHER MEANS OF AIRBORNE DISPERSAL, preferably at or above the altitude of the -15° C isotherm.

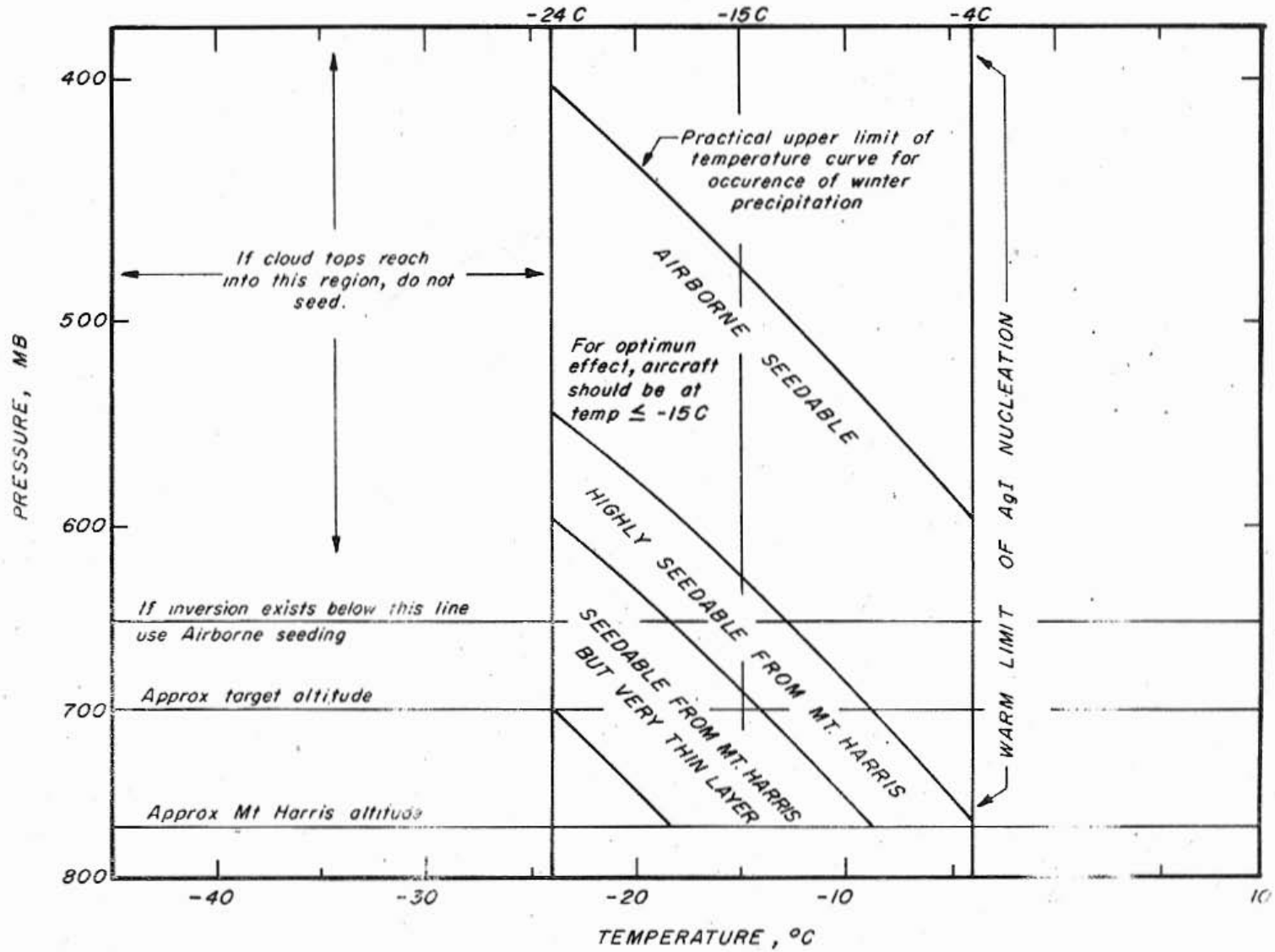


Figure 15. Theoretical Operational Envelope Based on Critical Temperature Seedability Criteria.

d. If an inversion exists between Mt. Harris altitude and 650 mb, DO AIRBORNE SEEDING.

e. Also, if the wind direction target limits for ground-based seeding are exceeded, DO AIRBORNE SEEDING regardless of temperature indications from the overlay.

Nuclei Delivery and Transport

Description of the diffusive transport of nucleating materials continues to be a major factor in evaluating the effects of artificial nucleation. A series (designated Daisy Series) of diffusion tests has been carried out during the course of the Park Range experiment. Fifty-five ground releases have been tracked in the Park Range area since the beginning of the program. A very large percentage of the tests indicated trapping or very slow vertical diffusion. This was true also of most of the Mt. Harris tests, as well as the Emerald tests.

A complicated inversion structure is often present to about half of the major ridge height above the valley floor. This stable temperature stratification severely complicates the dispersal pattern and often hampers or stops the vertical diffusion from even fairly high terrain ground releases.

Under conditions of neutral temperature stratification, vertical diffusion can be very rapid and large. In contrast, small deviations from neutral stratification tend to inhibit the vertical diffusion of an aerosol.

In summary, it is significant that the spread of a high airborne release in mountainous terrain under near neutral conditions is reasonably well predicted by standard diffusion equations. This spread is typically 7 km at 40 km from the release site. Further tests are needed to confirm the predictions of the equations during conditions of stable stratification.

Numerous tests were conducted under similar conditions using droppable vertical line releases. However, difficulty was encountered in tracking such a small release with the slow response at the nuclei counter. The data that was collected indicated that within 15-20 km from the point of release these instantaneous columns had to diffuse to about 6 km in diameter. Again, these values are in general agreement with the diffusion predicted from the standard diffusion equations for neutral conditions.

Replica Analysis

Crystal replicas were collected through the season in conjunction with each of the snow sample collections.

To correlate crystal types and cloud conditions, crystal types observed within an hour after a radiosonde launch were tabulated along with the inferred cloud top and base temperatues. From these temperatures, predicted crystal types were tabulated, the prediction being based on the following crystal type-temperature relation:

Needles	-5° to -7° C
Plates	-8° to -12° C
Dendrites	-12° to -19° C
Plates	-18° to -21° C
Columns	-19° to -26° C

The following summarizes the results of the replica analysis:

a. There is usually a greater variety of predicted crystal forms than is observed. (This excludes spatial and irregular forms for which no predictions were made.)

b. Dendritic forms occur in most sampling intervals. Quite often crystals forming at some intermediate temperature are absent while those predicted to form at temperatures both warmer and colder than the observed temperature interval are present.

c. Observed crystal types, which are included in a particular temperature range, can be excluded from the same range by another observation. For instance, in one analysis period, columns were observed to fall when cloud temperature was between -11° and -15° C. In another analysis period they did not form with cloud temperatures of -11° to -17° C.

Evaluation

Time Series Analysis

The data for the 1967-68 winter season consisted of 25 analysis periods. This section is concerned with the time series analysis of the precipitation rate data from the optical snow-rate sensor network. The data was reduced by punching instantaneous 2-1/2 min values of precipitation rate on cards for all available stations. The power spectra of these data were obtained using the NCAR computer. In addition, the ice nuclei count data measured during these analysis periods were similarly reduced to card form at 2-1/2 min intervals and analyzed with a computer program that evaluates the power spectrum and the lag cross-correlation coefficients between the time series of ice-nuclei count and the corresponding time series of precipitation-rate from each station in the network, and the coherence between these time series pairs. This analysis was done for all data for the season.

All of the available nuclei count data were run with all available precipitation rate data for all network stations for the 1967-68

season seeded analysis periods. For the most part, these cross-correlation coefficients turned out to be disappointingly low (< 0.2) with some expections.

Time series analysis of precipitation rate records using a pulsed input function from a ground generator does not yield completely unambiguous results on the effect of orographic seeding. It does under certain conditions provide useful results when interpreted in the light of measurements of other physical parameters relevant to the processes involved. The cross correlation coefficients of precipitation rate and ground measured free air nuclei counts are, as a rule, very low and useful only in special cases. The complex processes involved from the input of a ground generator to precipitation falling at a ground location severely complicate the interpretation of these correlations.

Precipitation Gage and Snow Course Data

Precipitation data from a series of weighing bucket gages in target and nearby areas were collected for the FY67 and FY68 winter seasons; these data give storm total precipitation and are useful for comparisons with snow course and snowboard data.

The target area extends from about 10 miles northeast to 10 miles southeast of the Emerald Mountain seeding site. Since there is a wide range of transport wind velocities during seeding tests, there will be times when one end of the target area is being seeded while the opposite end is unaffected. Ratios of precipitation data, from gage at either end of the target area, were plotted against prevailing wind direction for these periods. Because there is a natural variation of ratios with wind direction which acts in the same way as a positive seeding effect, it was necessary to take into account the wind speed and a model of AgI plume trajectory to obtain a potentially useful evaluation technique.

The data chosen for ratio formation were 4-hour totals from weighing buckets during the 83 periods for which Mt. Harris upper-air winds and Emerald Mountain 100 ft tower winds were available. The plume trajectory model assumed that it takes 40 minutes from release time for adequate vertical diffusion of the AgI, subsequent crystal growth, and fallout as precipitation; and that the Mt. Harris 11,000 ft MSL wind and the Emerald Mountain 100 ft tower wind exert equal influences on the trajectory of the seeding material.

The 4-hour vector averages of the respective Mt. Harris and Emerald Mountain winds were computed and averaged; the 40 minute travel from Emerald Mountain (plotted in polar coordinates) then described the probable location of greatest seeding effect. At each of these points, the ratio of Rabbit Ears to Buffalo Pass 4-hour precipitation was plotted. As expected, the ratio increased as the wind veered from SW to NW.

In an attempt to separate seeding effects from natural effects, two and three nautical mile radius circles were drawn about Rabbit Ears and Buffalo Pass, respectively, and the mean ratios within these circles were compared to the mean ratios of the remaining occurrences in the direction sector from which the circle was cut.

Statistical testing of the results for significance indicated a positive (sign) seeding effect within the Rabbit Ears circle significant at the 15 percent level and within the Buffalo Pass circle significant at the 5 percent level. Assuming that the values of $\sum \frac{R.E.}{B.P.}$ which were found for the areas outside the test circle, but still in the proper direction sector, represent the natural unseeded precipitation ratio, and computing the average precipitation rates for each sample, the average seeding-produced precipitation rates were computed as (a) Buffalo Pass circle, 0.018 in. hr^{-1} (82 percent increase over natural) and (b) Rabbit Ears circle 0.003 in. hr^{-1}, (20 percent increase over natural). Since weighing bucket data generally underestimates the amount of precipitation, computed percentage values are more apt to be realistic than absolute rate values.

The larger computed percentage increases at Buffalo Pass may be evidence of (1) a more inefficient natural precipitation process under conditions of warm southwesterly flow aloft, (2) the artificial snowfall by precipitation initiation in the warmer lower layers or (3) insufficient data to obtain a true estimate of the quantitative seeding effect. The large difference between $\sum \frac{R.E.}{B.P.}$ and $\frac{1}{N}\sum \frac{R.E.}{B.P.}$ values suggest that significant snowfall (of the order of 0.015 in. hr^{-1}) may be produced by seeding when only light snowfall (0.003 to 0.006 in. hr^{-1}) is occurring in the unseeded area. Thus, the period of significant snowfall may be prolonged by the seeding.

The analysis of the April 1 snow course data indicates slight decreases in the Park Range target area, and possible slight increases on the Medicine Bow Mountains - about 50 miles from the seeding site. The results are not statistically significant, and the only valid conclusion is that the seeding operations in the Park Range area for the past three winter seasons have not produced effects (1) consistently of the same sign and/or (2) of the order of 100 percent in the primary target area or on the next major downwind orographic barrier. This conclusion is strengthened by normalized (to Buffalo Pass) target area seasonal snowpack values, which shows a great internal consistency.

Snow Sample Silver Analysis

During the FY68 winter season, 781 snow samples were collected in the course of regular network operations. Most of them were analyzed by

an atomic absorption spectrophotometer - AAS - (for Ag mass) and by the drop freezing technique (for AgI particle detection). Samples were gathered at regular time intervals (usually 15 minutes), analyzed, and the results correlated with other data, such as seeding times, wind, and ice-nuclei concentrations.

Two factors are important in this type of work: (1) cleanliness, especially as it applies to silver, and (2) keeping the sample frozen until just before analysis. The first is self-evident when one considers that the background level of silver in snow is of the order of 10^{-10} to 10^{-11} g ml^{-1} (E. Bollay Associates, 1965, Warburton and Young, 1967). And if the snow sample melts, the AgI particles will dissolve, allowing the Ag^{+} ions to migrate to the walls of the container, where they become attached and unavailable for either type of analysis.

Snow samples were collected for AAS analysis at the ridge stations soon after each analysis period. In many storm periods, the wind veered during the period and spread seeding agent from one end of the ridge to the other. Results from the few cases in which the winds were more or less constant in direction throughout the period suggest that the silver iodide can be transported to proper clouds heights.

The range of mass concentration values found in the Park Range target area agreee with those (1×10^{-10} to 5×10^{-9} g ml^{-1}) found by Warburton and Young (1967) in other areas where seeding with silver iodide is being done.

An additional method of detecting silver is the method of drop freezing. The objective of the drop freezing technique is to determine whether AgI particles are present in snow sample. It is presumed that a higher percentage of drops formed from melt water will freeze at a given supercooled temperature than if no AgI particles were present. Immediately after the snow sample is weighed, a few grams are removed and melted in a small paper cup. As soon as the last of the snow melts, a disposable pipet is used to make fifty 4 mm drops on a sheet of clear, plastic film which is then placed on a cold stage.

The cold stage apparatus consists of a thermoelectric cooling unit resting in a circulating ice bath. Attached to the top of the cooling unit is a manifold-type copper plate which is 3/16 in. thick with 3/32 in. holes drilled on 1/4 in. centers. The holes are connected by a series of channels to a vacuum pump which is turned on when the thin plastic sheet is in place. In this way, good thermal contact is made between the cold stage and the drop's plastic support. A thermocouple is taped to the plastic to monitor the temperature which decreases quite rapidly to the plate temperature.

A cover is then placed over the unit to reduce surface temperature variations.

The drops are left supercooled (or frozen) for 3 minutes, and then the number frozen is counted. It is generally easy to tell which drops have frozen, but on occasion they must be viewed through crossed Polaroid sheets. When a record of the number is desired, the camera is used.

It was hoped that results of the drop freezing could be correlated with the mass concentration of silver in the sample, as determined by the atomic absorption spectrophotometer. A scattergram was constructed, but reveals no clear relationship between the two. The data were stratified in a number of ways, but with the same negative results.

APPENDIX

LIST OF PAPERS PRODUCED UNDER CONTRACT NO. 14-06-D-5640
July 1, 1966 - June 30, 1968

E. Bollay Associates, Inc.: Interim Report-Park Range Atmospheric Water Resources Program, November 15, 1966, submitted to the Bureau of Reclamation, Contract No. 14-06-D-5640.

E. Bollay Associates, Inc.: Interim Report - Park Range Atmospheric Water Resources Program, October 6, 1967, submitted to the Bureau of Reclamation, Contract No. 14-06-D-5640.

Davis, L. G.: "A Review of the Park Range Program", presented at the 4th Skywater Conference, Denver, Colorado, May 21-23, 1968.

Langer, G., Edwards, C. P., and Rosinski, J.: "A Continuous Ice Nuclei Counter and Its Application to Tracking in the Troposphere," Journal of Atmospheric Science, February 1967.

Marshall, R. C.: "Digital Computer Program Descriptions," September 28, 1966, submitted to the Bureau of Reclamation and other contractors of OAWR.

Morgan, G. M.: "The Detection of Zinc Sulfide in Melted Snow Samples," presented at the 46th Annual Meeting (250th National Meeting) of the American Meteorological Society, Denver, Colorado, January 24-27, 1966.

_____, and Rosinski, J.: "A Field Technique for Detecting Silver Iodide in Snow," Journal of Applied Meteorology, August 1967.

_____, and Rosinski, J.: "Technique for Detecting Lead Particles in Air," Nature, January 7, 1967.

Rhea, J. O.: "Results of the Summer Thermograph Project at Steamboat Springs, Colorado," October 14, 1966, submitted to the Bureau of Reclamation.

Rhea, J. O.: "A Storm Typing Scheme for Winter Precipitation on the Park Range in Northwestern Colorado," presented at the A.M.S. Conference on Weather Forecasting, Ft. Worth, Texas, November 6-8, 1967.

_____: "Small-Scale Spatial Variations of Summer Rainfall Totals Over and Near the Park Range, June-August, 1966," presented at the A.M.S. Conference on Fire and Forest Meteorology, Salt Lake City, Utah, March 12-14, 1968.

_____: "An Attempt to Explain Variations of Seasonal Meso-scale Target-to-Control Area Precipitation Ratios," Proceedings of the First National Conference on Weather Modification, Albany, New York, April 1968.

_____: "Mesco-Scale Patterns of Winter Precipitation as Related to Orographic Barrier Orientations," presented at the Joint Meeting of the A.M.S. and A.A.A.S., Logan, Utah, June 24-28, 1968.

Robertson, C. E.: "Ice Nuclei Measurements During Pulsed Cloud Seeding," presented at the 43rd Annual Meeting of the Southwestern and Rocky Mountain Division of the A.A.A.S., Tucson, Arizona, April 29-May 3, 1967.

_____: "Evidence of Pulsed Seeding as Measured in the Air and Snow," Proceedings of the First National Conference on Weather Modification, Albany, N. Y., April 29 - May 1, 1968, pp. 326-335.

Steele, R. L., Edwards, C. P., Grant, L. O., and Langer, G.: "Characteristics of the NCAR Acoustical Ice Nucleus Counter," presented at the Conference on Physical Processes in the Lower Atmosphere, Ann Arbor, Michigan, March 1967.

Willis, P. T.: "A Series of Diffusion Tests in an Orographic Environment," presented at the 46th Annual Meeting (250th National Meeting) of the A.M.S., January 24-27, 1966.

_____: "Diffusion in an Orographic Environment," presented at the Third Skywater Conference, Fort Collins, Colorado, February 16, 1968.

_____: "Summary of Diffusion Characteristics Near the Park Range," presented at the Meeting of the Weather Modification Association, Logan, Utah, February 26, 1968.

Zopf, D. O.: "Designing Programs Involving Orographic Clouds," presented at Skywater Conference II, Denver, Colorado, October 11-13, 1967.

A STUDY OF COMPARATIVE PRECIPITATION AMOUNTS BETWEEN MOUNTAINOUS AND PLAINS STATIONS IN COLORADO

PREPARED FOR

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF RECLAMATION

By

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BUREAU OF RECLAMATION SUMMARY

285

INTRODUCTION

The effects of weather modification can be expected to change the finite quantity of moisture which arrives in the downwind area beyond any particular primary target. This study of climatological records examines the difference between upwind and downwind precipitation amounts in and to the east of the mountainous terrain of Colorado.

Availability of precipitation data in the mountainous areas of Colorado is rather limited. A set of 12 mountainous stations, having a reasonably long record, has been used in this study. The corresponding set of 12 stations located in eastern Colorado represent the plains area and tend to be concentrated where wheat is grown.

To avoid influences of weather modification projects only historical precipitation records through 1960 were used for this comparative study.

West to East Station Pairs

As part of this study 12 pairs of stations almost directly on a west-to-east line across the state, were examined to determine whether or not they reached their extreme precipitation amounts during the same month or during the same storms. The three highest (out of approximately 30) values of monthly precipitation for each mountainous station were checked against the corresponding precipitation at a paired station in the plains. Following an examination of the highest decile of values at mountain stations, the procedure was reversed. Each plains station checked was treated as an independent variable and the corresponding precipitation amount for the paired mountainous station was examined.

Corresponding relationships between precipitation amounts at each paired set of mountainous and plains stations were considered for all 12 months. When the months were grouped into seasonal periods significant relationships appeared. During the winter months of November through March when the mountain stations received monthly precipitation amounts in the highest one-tenth percentile, the corresponding precipitation amounts received at the paired plains stations was below the long-term average. During the spring and summer months high values at mountainous stations were matched by corresponding high values at plains stations.

When the precipitation amounts for pairs of stations were compared during the winter months, starting with the highest decile of values at plains stations, the relationships were found to be quite varied. This was partially due to the leverage of very small additional

precipitation amounts causing large changes in the position of a particular month in the total historical array of monthly amounts at plains stations. When tests were made, starting with the lowest monthly precipitation amounts, a close relationship was found. When the combination of air masses over Colorado remained dry for a whole month, both the plains and the mountainous stations suffered in having low precipitation amounts.

Extreme Months in Mountains Versus Plains by Sets of Twelve Stations

Some of the most significant information obtained from studying the pairs of stations applied to winter months. It was decided that the evidence could be more conclusive if the same relationship could be shown when the pairs of stations were grouped into larger sets.

The plus abnormalities ranged from 347 percent to 131 percent of the multistation monthly normal. The largest abnormality occurred in December 1951 when the 12 mountain stations received a total precipitation amount of 78.23 inches as compared to the normal 12-station total for December of only 22.63 inches. In all cases studied the set of plains stations recorded below normal precipitation.

The analysis of historical precipitation data illustrates conclusively that instances of very high amounts of precipitation in mountainous stations are not joined with similar high abnormalities in the plains stations in the eastern part of Colorado.

When one starts with high amounts in the plains stations as the independent variable it is not conclusive that there will be a high corresponding amount of precipitation in the mountainous stations. There is some indication that if the plains stations receive a very high abnormal amount of precipitation the synoptic weather patterns will be sufficiently large scale, and the moisture content of the atmosphere will be high enough over a broad area to permit above normal amounts in the mountains also. However, when the plains stations receive only moderate plus amounts of precipitation the mechanisms which furnishes this type of precipitation do not also carry their influence into the mountainous terrain.

Significant Synoptic Patterns

The most important synoptic weather patterns capable of producing plus anomolies of precipitation in Colorado can be identified as follows:

1. West to east movement of upper level troughs.

2. West to east movement of surface low centers through mountainous Colorado followed by north to south movement of cold fronts across Colorado's eastern plains.
3. Semistationary polar fronts astride the Rocky Mountain Range.
4. Moisture surges from warm portion of the Pacific Ocean.
5. Low pressure centers originating in New Mexico and southeastern Colorado.
6. Summer showers.

The upper troughs that move from west to east tend to affect only the high mountain stations. The convergence in the trough is accompanied by topographic lift on the west slope producing precipitation only at the higher elevations. These troughs extend southward from storm centers moving from west to east across Wyoming and Montana near the surface.

When a large synoptic low-pressure center moves from west to east through Colorado in winter precipitation occurs initially at the high-level stations as convergence takes place toward the center of the low-pressure area. When the low center moves east of Colorado, deepening often takes place and cold air is brought from the north across eastern Colorado, Nebraska and Kansas with corresponding upslope motion from northeast toward southwest near the surface in eastern Colorado. The cold front lifts the modified and relatively dry marine air mass to release a limited amount of moisture at the plains stations. During the first 3 days of this storm, while the lowest pressure remains over or west of the Continental Divide, precipitation is limited to mountainous stations. When the center moves further east and the frontal boundary has been pushed from northeast Colorado toward the mountains small quantities of precipitation are released at nearly all the plains stations.

A semistationary polar front astride the Rocky Mountains is a weather pattern that occurs fairly frequently in winter. A broad frontal boundary is developed between large artic high-pressure cells over the plains and competing cells of high pressure over the Great Basin. The long zone of convergence is generally oriented along the mountain range from northwestern Montana southeastward into New Mexico. In this weather situation mountainous stations receive small amounts of precipitation at a time when most plains stations are completely cloudless. These semistationary polar fronts often die out in place and cannot be traced as moving away from the mountains.

During the fall months and more rarely in winter synoptic patterns can develop which carry large surges of moisture from the warm Pacific toward the northeast and over the Colorado Rockies. Some of these storms, particularly those which were formerly hurricanes,

are capable of releasing very large amounts of precipitation at both the mountainous and plains stations. The average frequency of these storms is less than one per year.

During the spring months of April and May there is a strong tendency for cyclogensis in the northern part of New Mexico and southern Colorado. When a low-pressure center developes in southern Colorado, Northern New Mexico or the Four Corner area, subsequent precipitation is often generated at many of the plains stations. If the center should form as far west as northeastern Arizona it may move toward the northeast and generate precipitation in both mountainous and plains areas. If it forms in New Mexico or southeastern Colorado there are two major alternate paths which it will follow. If the path taken is toward the north northeast all plains stations in eastern Colorado will be affected. However, if the newly formed storm center moves toward the east northeast, only stations in southeastern Colorado will be affected. The rapid increase in monthly precipitation amounts at the plains stations during April and May as compared with February and March are primarily due to this type of weather sequence. Summer rain showers are the rule for both mountains and plains in July and August. Greater availability of moisture over eastern Colorado in the lower levels of the atmosphere permits occasional development of very heavy thunder storms. Evaporation rates are quite high during these same months. Moisture which returns rapidly to the atmosphere through evaporation cannot contribute to runoff and be collected in the reservoirs within the Upper Colorado River Basin.

A TEST OF CERTAIN EVALUATION DESIGNS FOR CLOUD-SEEDING EXPERIMENTS

E. G. and G., Inc.

W. E. Howell Associates

An Element of System Development Division

This report was extracted by the Bureau of Reclamation from the Final Report of Contract No. 14-06-D-5962. Most of the work was performed prior to FY 1968, but is reported here for completeness.

The Problem

A striking characteristics of the science of weather modification ever since its emergence in 1946 has been the existence of vigorous disagreement over the explanations advanced for various observed phenomena and over the validity of the inferences and deductions drawn from them. While this rapidly expanding science has displayed its vitality in a multiplicity of new discoveries, investigation of the questions they pose has been seriously hampered by failure to resolve some of the oldest and most fundamental disputes regarding the effect of seeding on individual clouds and individual storms.

It now appears virtually certain that cloud seeding by certain techniques works very well in some storms, is relatively ineffective as often applied to a large proportion of storms, and may sometimes accomplish the opposite of its intended purpose. The question that exists today is: what is the response to cloud seeding by a given technique in a given weather situation? It is quite within the realm of probability that in a given weather situation one seeding technique may be appropriate for increasing precipitation and another seeding technique may be appropriate for diminishing it.

Most evaluation procedures heretofore in use lack the power to deal with these questions because they are based on lumping together "unsuccessful" seeding events with "successful" ones, as they cannot distinguish between these, and because they are based on the questionable premise that relationships developed from some historical period will apply unchanged to a current experiment.

One of the conceptual difficulties with which evaluation has had to contend is the fact that weather is basically a nonstationary process in the statistical sense; that is, when we draw successive samples (in the form of successive sets of observations) of a weather occurrence we cannot assume that these samples are all drawn from the same parent population. Further, Wallis (1965) has shown that when the functional relationships between variables are unknown, predictive equations based on one sample of data, even one exhibiting a high degree of correlation, may break down when applied to another sample drawn even from the same population. While the random alternation of seeded with unseeded occurrences has been recommended in specific recognition of this problem, this treatment is palliative and inefficient; it reduced the interference of time-trends with the application of the classical methods but does not overcome the inherent obstacle.

Most of these difficulties may be circumvented if the target precipitation estimation can be based on the same sample of data that describes the cloud-seeding experiment itself. If such a scheme could be devised, the objectionable use of historical data

would be eliminated. Further, if such a scheme could be based upon a physical unit, such as a "storm," it is possible that the duration of the experimental time necessary for performance of a reliable test of seeding hypotheses may be considerably shortened.

Wadsworth (1951) made stochastic trials of a plane-fitting method utilizing a square grid containing nine rain gages located 15 miles apart in which two of the gages were defined as target and the rest as control. It was shown that an estimate of natural precipitation arrived at in this manner has a smaller error of estimate than that yielded by the customary target-control procedure, and thus may provide the basis for a more powerful test of the seeding hypothesis. The question of the applicability of the method to actual rain gage networks consisting of increased numbers of gages and large target areas remained open.

Objective

The objective of the present research is to develop and test on a storm-by-storm basis, through realistic simulation, an evaluation idea originally proposed by Wadsworth (op cit): that if a contour map of precipitation depth from a given storm can be satisfactorily approximated by a simple geometrical surface over a limited region embracing the target, then artificial influences should show up as significant departures from this surface. In practical terms, the aim is to develop a predicting method in which estimates of storm rainfall over a target are based on the geometry of the precipitation in a nearby control during the same storm so that in essence each storm furnishes its own control. When applied to real seeded data, the technique should permit a reasonably confident distinction to be made between those storms which were susceptible to seeding influence and those which were not. In the pursuit of these objectives the investigation covers such subjects as: transformation and normalization of natural precipitation data, the development of specific test-variates, the size and shapes of applicable target and control regions, the types of storms and rain gage networks for which the technique might prove satisfactory, and a stochastic test of the power of the method in detecting real precipitation increases using various seeding-effect models.

The Model

The application of the method of target precipitation estimation proposed by Wadsworth involves the fitting of a geometrical surface by the method of least squares to the precipitation contours of a nearby control area which embraces the target. An estimate of the target precipitation is obtained by extending the surface over the target. This estimate is then compared with the actual

target precipitation and a suitable test-variate is used to estimate the probability that the observed difference could be expected by chance alone.

Before computer simulations of actual seeding could be implemented, considerable data processing and numerous preliminary studies on unseeded data were required to answer questions as to types of networks for which the method would prove feasible and optimal size of target and control regions to use in the stochastic tests. In addition, certain assumptions had to be made concerning the physical shape of the field of observations and the hypothetical seeding plume.

In determining the shapes of the target and control regions efforts were made to achieve a balance between considerations of practical application on the one hand and computational simplicity on the other. Because target rainfall estimation is based on the geometry of the precipitation in the control area, it is advantageous to have the control embrace the target as much as possible. It was originally planned to consider the field of observations in the form of a circular area of which a certain sector would be designated as the target and the rest as control. Seeding would be done from the center of the circle and the target sector would be defined by the seeding plume according to the particular wind direction of the given storm.

This model was later modified to conform more closely to actual seeding practices in which the target remains fixed and the seeding point (SP) is dependent upon wind direction. The target was selected as a circle of specified radius with the seeding done some distance directly upwind. Skilled targeting of the seeding was assumed so that the target was covered precisely each time. Thus, the hypothetical seeding plume, with a "diffusion angle" was specified to extend linearly downwind from the SP so that the plume "boundaries" were tangent to the target circle. The control zone was defined to be bounded on the inside by the plume and on the outside by a specified distance from the center of the target. Gages outside the target but beneath the plume were considered to be contaminated and therefore were not included in the plane-fitting process. For a first try the value of θ was taken to be 60 degrees and the SP was located 19 km upwind from the target.

After several tests, including the study of the optimum target and control sizes (presented later in this report), it was decided to bring the model into even further conformity with actual seeding experience and at the same time increase the proximity of the control zone to that of the target so as to gain additional accuracy in target prediction. To accomplish this, the shape of the seeding plume was modified so that it no longer spread linearly with distance downwind but became rather semielliptical in shape, being much narrower downwind than in the previous model. In addition,

gages between the SP and the target, previously considered within the plume, were now considered in the control zone. Such a configuration conforms more closely with actual measurements of effective plume shapes from point sources. Further, the new model makes some provision of the lag between time of seeding and time of any resulting precipitation increases (Leonov, 1966) since the SP is still some distance upwind from the target. As in the previous model the SP was assumed to be located 10 km directly upwind from the target.

During the course of the study under the current contract, the predictors used were simply the geographical positions (x- and y-coordinates) of the target gages and it was also assumed that as a first approximation the true predicting hypersurface could be approximated by a plane surface.

Data Used

The basic available data consisted of several years of daily precipitation amounts from three rain gage networks. In addition, daily synoptic maps and upper-level wind data presented in the Northern Hemisphere Daily Tabulations published by the Weather Bureau, ESSA, Department of Commerce was used.

The largest network covered approximately 28,500 km^2 of the mountainous portions of eastern New York State and southwestern New England. It contains 39 rain gages for an average density of one per each 73 km^2. The data comprised 21 years of winter observations, October through March, 1945-1966. The precipitation data were kindly provided by Dr. Glenn Brier of ESSA. Upper air data for this network were taken primarily from the Albany soundings, but soundings from New York City and Pittsburgh were also occasionally used.

A second network, operated in southern Illinois by the Illinois State Water Survey, was the smallest of the three networks used, covering 1,420 km^2 of fairly flat terrain. It contains 49 gages for a density of about one per each 29 km^2. The data available, provided by the Survey, consisted of 5 years of summer precipitation observations for the months of June through August, 1960-1964. Upper air data for this network were taken from the soundings at Peoria, Illinois.

The third network, operated by the Southern Plains Watershed Research Center of the Department of Agriculture, is located in the gently rolling hill country of the Washita River watershed in central Oklahoma. This network has by far the greatest gage density, comprising 185 gages in an area of approximately 2,900 km^2 for a

density of one gage per each 16 km^2. The data, provided by the Center, consisted of 4 years of both summer and winter precipitation observations from October 1961 through December 1965. Upper air data were obtained from the Oklahoma City soundings.

Normalization of Precipitation Data

The development of the most sensitive test-variate requires the use of a variate which is approximately normal. The distribution of natural rainfall is highly skewed, especially when amounts for periods of short duration are considered, and therefore it is desirable to find a function which will reduce the skewness, yet which does not entail a great deal of labor when large amounts of data have to be processed.

Such a transformation function has been found and the development was presented in Scientific Report No. 1 (Lopez and Nason, 1967). Since the development is somewhat involved, the reader is referred to that report for details. Briefly, it was found that a gamma distribution fits fairly well those rainfall series that have been truncated at some arbitrary point near the low end of the spectrum. In any series (whether truncated or not) which can be approximated by a gamma distribution, a suitable fractional power transformation will yield a new transformed series such that its cumulative normalized distribution is for all practical purposes identical with the equiprobable normal cumulative distribution of the original series. It has been found that it is sufficiently accurate to use a cube-root transformation for all shape parameters down to 1.5, that for between 1.5 and 0.5 a fourth root is satisfactory, and that a fifth root is adequate for as low as 0.3.

It may be noted that while no transformation can reduce raw rainfall data to perfect normality, a suitable fractional power transformation will reduce the data to very satisfactory approximation to the normal distribution. In addition, the removal of any definite geometric pattern from the control rainfall contributes further to the normalization of the residuals.

Operations on Unseeded Data and Selection of Target and Control Sizes

Data from all three networks were used in preliminary studies to obtain some indication of the ability of the plane-fitting method to predict natural target precipitation under various conditions in the absence of seeding. Tests were run using random selections of storms from both the Albany and Washita networks.

It soon became evident that a network with a low and irregular gage density, although not necessarily without value for routine

application of the method, would handicap the explorations for selecting acceptable target and control sizes as well as the stochastic tests of target augmentation. For this reason use of the Albany network was postponed. Since the Illinois network included only summer-type storms and is both smaller in area and lower in gage density than the Washita network, the Washita network was selected for the determination of the target and control sizes to be used in the stochastic tests and also for the tests themselves.

A random sample of storms (both summer and winter) from the Washita data was then selected and tests were continued on each storm by varying both the target and control sizes in a stepwise manner. The best normalizing transformation for the Washita network was found to be the fifth root. Target sizes were varied in steps of 5 km and from 5 to 15 km in radius, while control widths were similarly varied in steps of 5 km in width from 5 km to 30 km. At each step, a target prediction was made and its success was gaged by comparing the absolute value of the relative errors committed in making the prediction. Values of the modified test-variate were also computed at each step to gain an insight as to how such a variate would behave in natural conditions. The modified variate was used here for computational convenience.

Results of the tests on the Washita network indicated that the variability of summer rainfall is sufficiently great that a simple plane predicting surface is handicapped when the target area is of sizable dimensions. On the other hand, winter storms (here defined as storms occuring in the period from October through March) appeared, in general, to be amenable to satisfactory target prediction. Therefore, the investigation for the best target and control sizes was concentrated on the winter data since it appeared to offer the greatest potential for targets of practical size when using a first-order surface approximation.

As a result of the study on winter data of the Washita network, it was found that for all the targets used the lowest absolute error in the predictions occurred with the smallest control ring used around the target, that the distribution of the absolute errors increased as the ring was enlarged, and that a circular target of 10-km radius surrounded by a 10-km control ring afforded the highest relative accuracy in target prediction.

Modifications of the target-control geometry were made and tested. The tests indicated that the modifications do not change appreciably the results of the target-control size study. Although the differences between the 5- and the 10-km targets were small, the 10-km target together with the 10-km wide control (modified) were

chosen in preference to the smaller target to provide the field of observations for the stochastic tests as being more in consonance with a realistic operation. The target and entire control (without plume) thus defined contained 14 and 39 gages, respectively.

Stochastic Operations

In order to determine the power of a geometrical surface-fitting method in detecting real target rainfall increases and to estimate stochastically the length of time (in terms of number of storms) necessary to achieve a particular level of significance, tests were conducted in which the natural target precipitation data were augmented in a stepwise manner according to certain seeding-effect models. At each level of increase the value of the test-variate was calculated for each storm on the basis of the predicted target precipitation.

Two seeding-effect models were considered for the stochastic tests. In both models it was assumed that seeding is a scale effect so that, for a given storm and level of stochastic increase, the precipitation of each target gage is increased by the same percentage. This is different from the method used by Wadsworth in which he added the same precipitation amount to every gage. The first model is a conventional one in which it is assumed that, for a given level of augmentation, the target precipitation is increased by the same factor in all of the sample storms. In the second model it is assumed that, for a given level of augmentation, the target precipitation is increased by an amount that varies from storm to storm according to an exponential distribution, the mean and standard deviation of which equals the level of augmentation. This distribution reflects more accurately present-day concepts of the effect of cloud seeding in that an average positive effect, if present, is likely to be due to larger-than-average increases in a few favorable occasions accompanied by smaller-than-average increases in most other cases.

The levels of augmentation employed in the tests were, in terms of percent values: 1, 2, 5, 10, 20, 30, 50. For each level, precipitation predictions were made both for the mean target gage position and for each individual target gage. Values of the test-variates were then computed accordingly. Plane surfaces were fitted to the target data as well as the control so that, in the future, a comparison might be made between the two to determine, if possible, any significant lack of homogeneity.

The results of the stochastic tests as applied to the available sample, for both a constant and an exponential seeding-effect model, are presented in Fig. 1 and Fig. 2, respectively. The curves in these figures show the probabilities of rejecting the

null hypothesis (unseedable), given various seeding increases and different significance levels. The curves have been smoothed somewhat since these probabilities can only be approximated. The probability of rejecting the null hypothesis and thus labeling a given storm as seedable, at each level of "seedability," (target increase) is given by the percentage of storms for which the test-variate exceeded the critical point corresponding to the selected significance level.

To take an example, Fig. 1 indicates that if by some mechanism the precipitation of all storms were increased by 30 percent, the test-variate resulting from storm-by-storm application of the plane-fitting method will exceed 1.711 for about one-half of all such storms thus rejecting the null hypothesis (no augmentation) for these storms at the 0.05 significance level.

The values of the test-variate (Student's "t") and their combined probability of occurrence from Fisher's method have been tabulated. The results of the combinations are given in terms of strings of storms necessary to reach significance at the 0.05 level of significance when the storms are taken in order of natural occurrence. Each time significance is achieved, the string is started anew. The cumulative total combined probability of the entire sample taken as one single unbroken string is given along with the partial cumulative combined probability for each string. It is from the tabulations of the test-variate that Fig. 1 and 2 were derived.

Sorting of Seedable from Unseedable Storms

Seeding as conducted with present-day techniques is probably very effective only under especially selective conditions, so that the distribution of the seeding effect is likely to be quite skew, with large increases much more infrequent than smaller ones. Therefore, the primary aim of the present study has been to develop a tool which will permit successful seeding operations to be identified with a useful degree of reliability on a storm-by-storm basis. The identification need not be perfect in order to be useful. If it leads to recognition of the salient characteristics of storms (or portions of storms) susceptible to seeding or contributes to illuminating intuitions, it will have greatly outperformed current evaluation techniques based on target-control regressions. The aim of future field work will not be to prove beyond a reasonable doubt that a given storm was increased by seeding but to sort storms into susceptible versus unsusceptible groups for synoptic study, comparison of different seeding techniques, etc., and our concern will be for the overall correctness

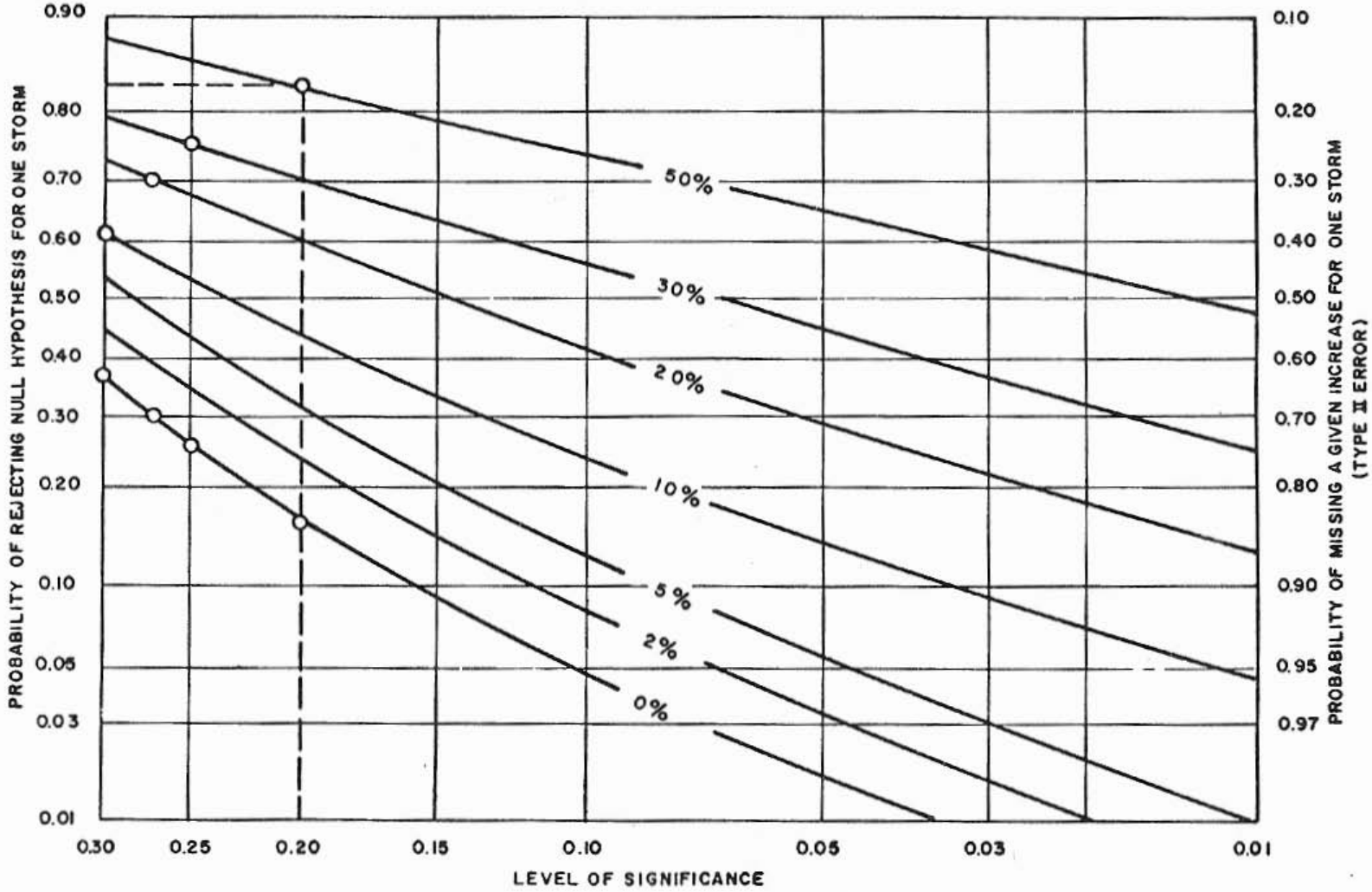


Figure 1. Probability of rejecting null hypothesis for a seeded storm (on a storm-by-storm basis): constant seeding-increase effect. Circled points on curves represent points where Type I and Type II errors are equal.

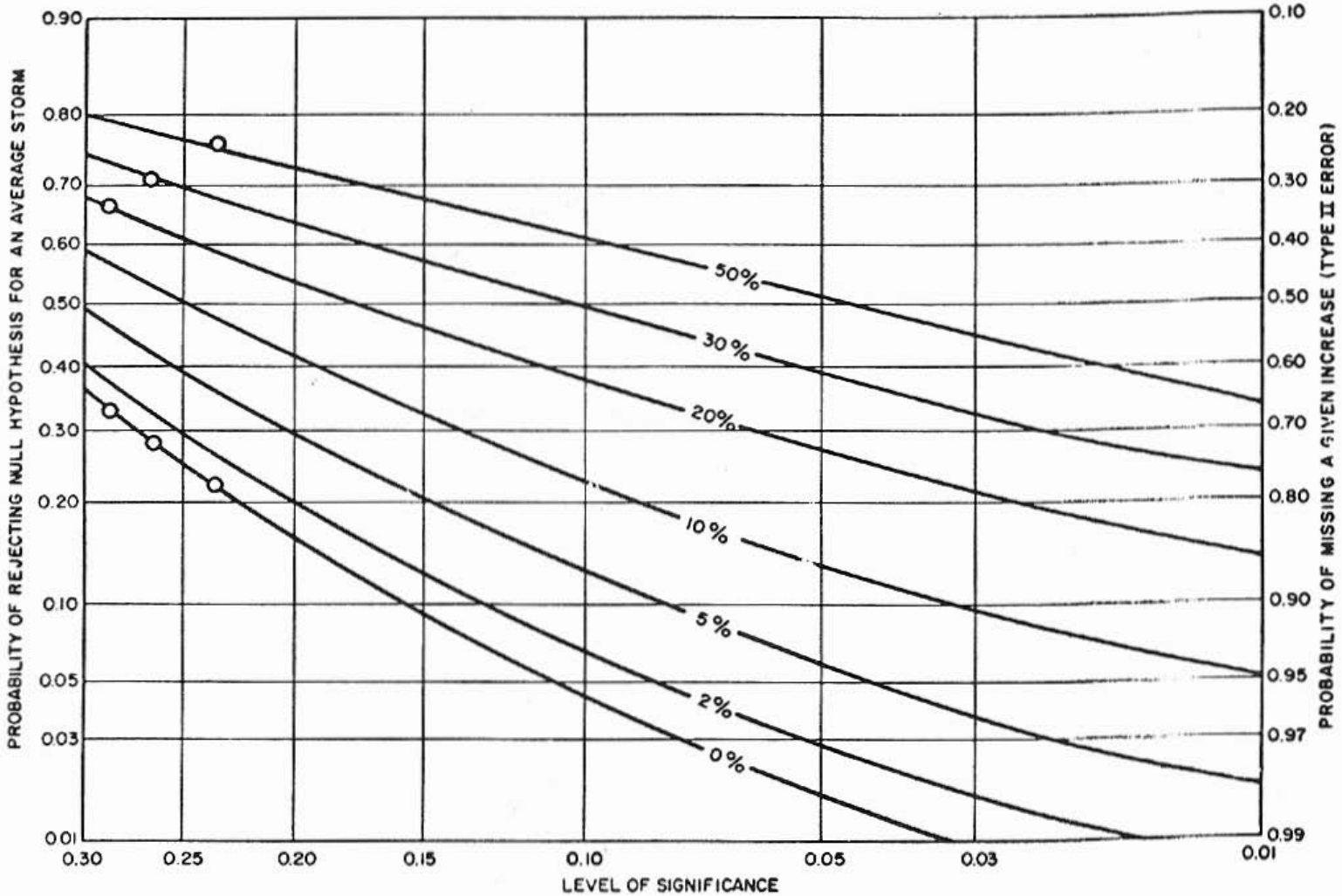


Figure 2. Probability of rejecting null hypothesis for an average seeded storm; exponential distribution. Circled points on curves represent points where Type I and Type II errors are equal.

of this sorting. The plane-fitting method provides an objective basis for such sorting.

Although the main advantage of an evaluation based on a geometrical approach lies in its ability to analyze the data on a storm-by-storm basis independent of historical data, the technique can, like any other evaulation scheme, be applied as a sequential test to replicated experiments, the results of which may be combined into one grand test. In fact, since this technique has shown a reasonable probability of detecting a real seeding effect on only one given experiment, it should prove quite powerful as a sequential test.

We have estimated the power by applying the two postulated seeding-effect models to consecutive storms in the available sample, and then computing the probability of combined simultaneous occurrence of the resulting discrepancies from the target using Fisher's method which assumes independence between successive events. This assumption was found to be justifiable in our sample.

The results show that if either seeding-effect model operates only a relatively short string of storms is needed to reach significance at the 0.05 level, even for precipitation increases averaging as little as 5 percent. The average length of the string of storms needed to reach significance ranged from a low of less than 2 for a 50-percent constant increase model to 25 for a 5-percent average increase if the seeding-effect model follows a stochastic exponential distribution. The average length of the strings needed for various levels of increases and for the two models used is presented in Table 1.

Table 1. Average length of string of storms needed to reach significance at the 0.05 level.

	Average Increase in Percent				
Seeding Increase Model Distribution	5	10	20	30	50
Constant	25	7.1	3.0	2.0	1.5
Exponential	25	7.1	3.1	2.5	2.1

No confidence bands are included with these estimates because these results are only indicative until more is known about the real shape of the seeding-effect distribution. However, the exercise was undertaken to analyze, in the light of reasonable assumptions, if the technique had a reasonable chance of success. In this respect, the answer is affirmative.

We wish again to emphasize, in view of recent experiences with cloud seeding, and especially in the light of recent numerical

simulation studies (Davis, 1966), that one of the most important needs today in evaluating cloud-seeding experiments is a reasonable power to select, on a storm-by-storm basis, cases where seeding can be considered effective. A storm-by-storm evaluation should also be capable of discriminating not only between susceptible and unsusceptible storms but between different seeding techniques, since in practice the latter is really part of the null hypothesis. For instance, it might well turn out that seeding is much more effective if conducted during certain periods of the storm. The suggested geometrical approach can easily be adapted to cope with such temporal subdivisions of the data.

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THE ARIZONA WEATHER MODIFICATION RESEARCH PROGRAM AND ASSOCIATED STUDIES

Report for FY 1968

Prepared for

Bureau of Reclamation
Office of Atmospheric Water Resources
Denver, Colorado 80225

PROJECT SKYWATER

Contracts 14-06-D-5589 and 14-06-D-6447

by the Staff of Meteorology Research, Inc.
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SUMMARY

This report describes two programs: (1) a study to identify critical areas in weather modification deserving strong emphasis in the future, and (2) the third year of the Arizona Weather Modification Research Program.

The work on identifying critical areas covered five subjects: warm cloud modification, microphysics of ice phase clouds, cloud dynamics, treatment potential, and instrumentation. Concerning the warm clouds, it is concluded that precipitation increases and decreases on an operational basis are possible now with adaptations of existing technology. Emphasis should be given to refinement of the simplified, time-dependent, numerical warm-cumulus model, use of the model with a definitive field experiment, and studies of direct methods of altering cloud dynamics. For the warm cloud modification , microphysics and cloud dynamics, the emphasis is on upgrading the numerical models which provide a quantitative tool for further research developments, and for aiding in the design and conduct of field studies and operational programs. In the instrumentation area, it is found that techniques now exist for making most of the desired measurements, and the main attention required is on a systems approach to data collection with careful attention to data handling.

The Arizona Program had four main elements: a randomized experiment in the seeding of isolated cumulus clouds, a microphysics investigation of the glaciation and hydrometeor development of seeded and unseeded clouds, a study of the numerical modeling of winter orographic storms, and an investigation of the organization of mesoscale convective systems by seeding.

The randomized seeding experiment was designed, conducted, and evaluated with the aid of a simple, steady-state numerical cloud model with parameterized microphysics and dynamic factors. Evaluation was on the basis of observations of cloud height, precipitation duration, and precipitation magnitude as ascertained by radar. There were 10 seeded and 11 control clouds. An average height increase of about 6000 feet was found by three evaluation methods: (1) from the data alone, comparing the average of all seeded cases with the average of all control cases, (2) finding that the numerical model agreed with the control cloud data and using it to estimate controls for the 10 seeded clouds, and (3) finding that the model agreed with both the control and seeded cloud height data (assuming glaciation at -25C for control and -8C for seeded), and making all calculations by the model for the cloud population studied. The first two methods permit estimation of the significance level of the average increase in height (> 96 percent by Student's t-test). Similarly, by the

first and third methods, precipitation duration was found to be increased about one-third, and the amount of precipitation doubled.

In the microphysics study, the research aircraft made repeated penetrations at the -8C level of unseeded clouds and clouds which were strongly seeded. In contrast to the unseeded clouds, the seeded clouds glaciated completely, with the glaciation appearing to help the dynamic growth of the cloud while inhibiting growth of hydrometeors after the glaciation was near 100 percent. The microphysics study supported the basis of the numerical model for cloud growth due to glaciation, but suggested (as expected) that the seeding was far from optimum for maximizing precipitation.

Numerical models of winter orographic storms were studied as a start toward applying the cloud modeling techniques to other situations. Two examples of simple models were considered in the study.

Six randomized trials of the seeding of mesoscale convective storm systems were conducted to help build the background for the development of numerical modeling and observational techniques for future quantitative experiments on modifying these large systems.

I. INTRODUCTION

For FY 1968, the main MRI work for PROJECT SKYWATER was the third and final year of the Arizona Weather Modification Research Program (Contract No. 14-06-D-5589). In June of 1968, a new three-year program (Contract No. 14-06-D-6581) was initiated to carry on this work. The other major project during FY 1968 was a study to identify critical areas in weather modification deserving added emphasis in the future (Contract No. 14-06-D-6447). The remaining work during the past year was the development of several instruments to be used at Flagstaff on Co-op II in August 1968 -- sequential collectors of rainfall samples for subsequent analysis by neutron activation, and a fast-response airborne continuous ice nuclei counter.

The study to identify critical areas in weather modification is reviewed in the next chapter. The balance of this report is devoted to a summary of the Arizona program.

II. IDENTIFYING CRITICAL AREAS IN WEATHER MODIFICATION

As the promise of weather modification grows, the field also grows in complexity. The primary components of the field -- the basic physical concepts, numerical modeling, seeding techniques and operations, field observations, evaluation -- all these are interlinked, all are involved at various phases of research and operations, and all represent increasingly complex subjects.

To aid in the orderly and efficient development of this field toward operational goals, there is the need to assess the present situation and, from this perspective, look toward the areas which will require strong emphasis in the future. Areas for emphasis include critical factors on which the technical concepts are based, special developments which might advance the field at a more rapid pace, and gaps which, if left unfilled, would slow down progress in the field.

This study, under Contract No. 14-06-D-6447, was initiated for the purpose of identifying areas for special emphasis in certain of the subjects related to weather modification. The subjects chosen were primarily those which were deemed of great importance but which had not already been treated specifically elsewhere such as in the Skywater Conference series conducted by the Bureau of Reclamation. There were five subjects discussed -- warm cloud modification, microphysics of ice phase clouds, cloud dynamics, treatment potential, and instrumentation. Each study involved a brief review of the present state-of-the-art in the field, and

an assessment of some of the critical areas on which the orderly development of the field in the next few years would depend. The overall perspective for judgment of the critical aspects assumed the objectives of weather modification to be manipulation of the precipitation process for net economic benefits.

In the treatment of warm cloud modification, microphysics, and cloud dynamics, considerable emphasis is laid on numerical modeling of the phenomena involved. These constitute the background on which the main, rapid advances in these areas must be built.

A. Warm Cloud Modification

The warm cloud modification study has shown through physical concepts, numerical modeling, and some limited field data that introduction of salt aerosols into clouds can result in significant (> 10 percent increase or decrease) precipitation alterations. There is some limited evidence from field modification experiments which supports the conclusion. A theoretical modeling experiment indicates that, in certain circumstances, far larger increases can be obtained if the diameter of the cloud could be increased by a relatively small amount.

Microphysics modeling computations show that there exists a value of droplet size -- about 40-microns diameter -- which is critical for starting the development of raindrops. In typical clouds, smaller particles grow by coalescence rather slowly, while larger ones grow rather rapidly. Precipitation modification is created by introducing salt particles into air entering the cumulus cloud base. Particles yielding droplets larger than 40 microns serve as raindrop embryos and augment precipitation. Alternatively, numerous smaller particles can distribute the water into small droplets and inhibit or delay the precipitation. Numerical techniques are shown which model each element of the precipitation development cycle, from the natural or artificial condensation nuclei distributions and hydrometeor development in the time and moisture scale of a cumulus cloud. The calculations are put into a practical perspective by attempts to estimate total rainfall modification over an area based on observed cloud size-duration statistics.

The growth of the hydrometeors to raindrops is a time-dependent process and must occur within the normal life cycle of the cloud. The steady-state cumulus model which was suitable for the Arizona Program is not appropriate to examine the time required for the raindrop-size particles to develop. The model used in the study was a time-dependent model developed by Weinstein (1968)

together with a parameterized representation of the coalescence process suggested by Berry (1968). Figure 1 is an example of the output of this model. The initial cloud drop size distributions refer to maritime cumulus clouds with relatively small numbers of drops per unit volume. For the sounding of Fig. 1 but with a smaller cloud radius (1 km instead of 1.6 km), the height reaches only 3.6 km as compared to 8.4 km, and the cloud yields only one-sixth as much rainfall. The effects of altering the initial cloud drop size distribution to represent seeding were calculated and showed the increases or decreases in precipitation of 10-15 percent.

The strong effect from increasing cloud size suggests that a direct cloud dynamic modification approach deserves attention. Calculations of the buoyancy created by carbon black in sunlight lead to the conclusion that this may be useful in augmenting cloud base size in some marine atmosphere situations.

Generating techniques for the production of salt aerosols already exist, and enough modeling has been accomplished to suggest that definitive seeding results can be obtained. The greatest needs are for (a) a definitive set of field experiments based on the time-dependent numerical model, (b) obtaining background information on naturally occurring condensation nuclei (including those inadvertently produced by pollution), and (c) getting more data on the number vs. size distributions of populations of warm clouds as a function of location and synoptic conditions. In a more exploratory vein, further examination of techniques for direct modification of cloud dynamics may subsequently prove valuable.

B. Microphysical Problems

A detailed model of the ice growth phase as it operates in natural clouds is urgently needed. The present techniques for modifying cloud systems are based on the control of the ice growth process and a quantitative model is required to explore the effects of seeding under a variety of environment conditions. It will be only through such a model that concepts for optimizing the seeding for various cloud types can be developed and appropriate seeding experiments designed.

An attempt was made in this study to formulate the framework of an ice-phase model using currently available information. The first purpose of the study has been to identify the areas where the present state of knowledge is inadequate to give the degree of understanding required. Secondly, an attempt was made to conduct sensitivity studies on the basic input parameters to determine those factors of greatest importance in controlling the mass growth rate of ice.

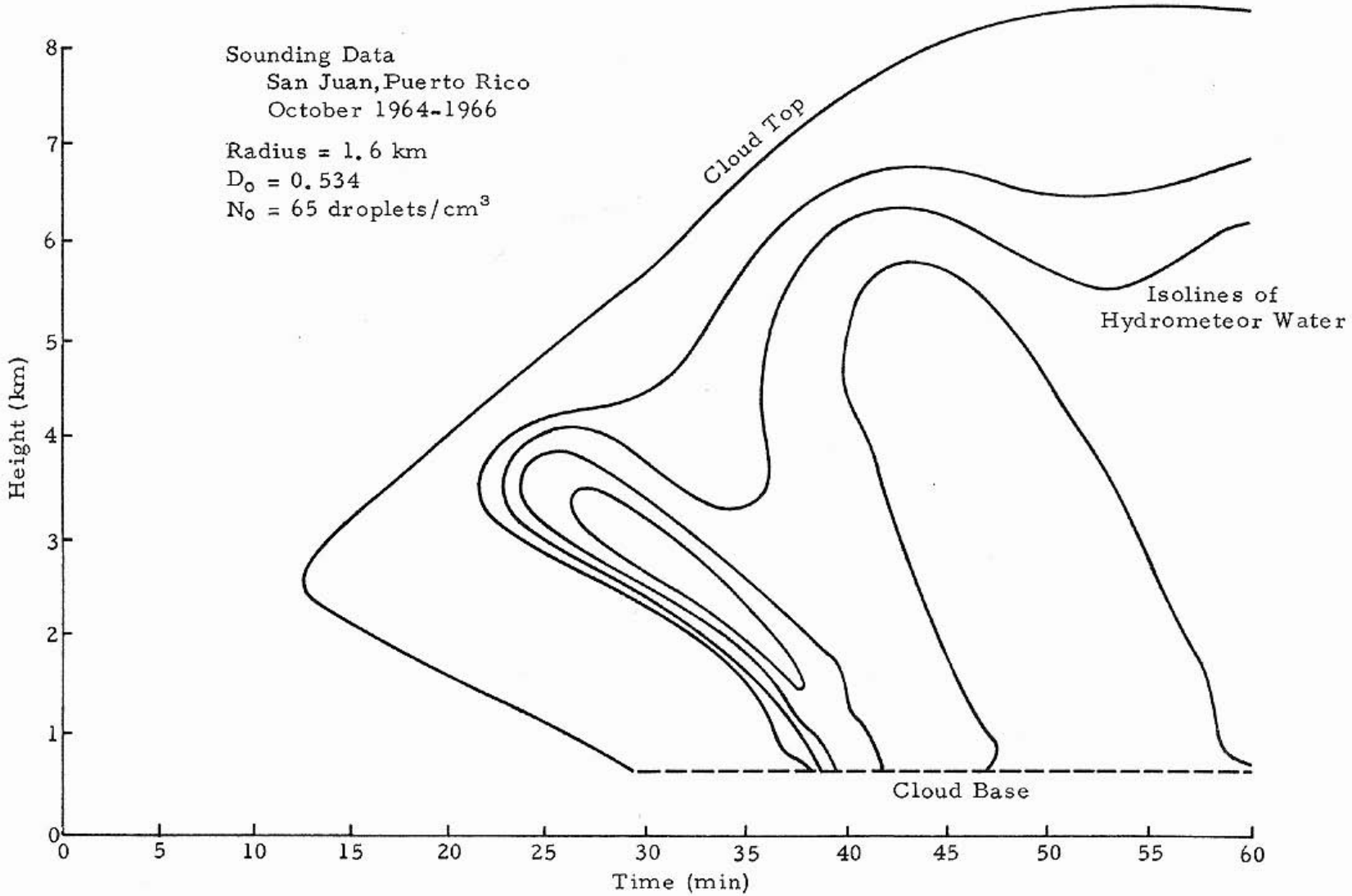


Fig. 1. TIME-HEIGHT PLOT OF TIME-DEPENDENT MODEL SOLUTION FOR 1.6 km RADIUS CLOUD IN AVERAGE PUERTO RICO SOUNDING

The principal ice growth mechanisms are recognized to be:

1. Growth by sublimation from the vapor state
2. Growth by riming or accretion with supercooled cloud droplets
3. Aggregation or clumping of ice crystals.

Primary attention in the past has been given to sublimation growth. In spite of this, there are numerous complexities such as changes in growth habit with temperature which cannot be adequately modeled on a quantitative basis. In addition, various key experimental data such as fall velocity and densities for large crystal sizes have not yet been determined. In the case of riming, further data on collection efficiencies, terminal velocities of ice particles, and experimental verifications of riming rates are needed. Observational data on aggregation of ice crystals are very limited and adequate models for describing the process do not exist. In particular, the effects of electrical charges on promoting aggregation are a large unknown area.

In spite of these limitations, a coherent ice growth model through the sublimation and riming stages was constructed. The model permits exploration of the growth rate under various conditions of liquid water and updraft velocity. It was concluded from the model calculations that riming was a significant factor in the formation of precipitation in clouds with liquid water contents of 0.3 g/m^3 or more. As the liquid water content increases above this value, growth by riming becomes increasingly important relative to sublimation growth.

An additional problem currently in the ice microphysics area is the apparent discrepancies which exist between ice nuclei counts and the occurrence of ice in clouds. In both natural and artificially seeded clouds, evidence is accumulating of larger numbers of ice crystals at warm temperatures in the cloud than can be accounted for by the nuclei observations. Explanations related to drop freezing and possible ice multiplication have been offered, but considerable work in this area is required.

C. Cloud Dynamics

A general review of cloud dynamics models was presented beginning with the steady-state versions which have been used successfully at Flagstaff. This model has evolved into a time-dependent, one-dimensional model in which it is possible to examine the time history of the cloud development. Two-dimensional cloud models, the need for mesoscale modeling, and preliminary attempts to model orographic winter storms are discussed.

The current state of dynamical modeling in weather modification is that simple, one-dimensional models have been developed and used on an operational basis to describe the response of individual clouds to seeding effects. The models are greatly simplified compared to the real atmosphere and some aspects of the process are parameterized in a crude manner. The models, even in their simple form, have proved invaluable for designing and evaluating field experiments. In addition, the computational time is short enough so that results can be obtained for a large number of environmental parameters. The two-dimensional models require much longer computational time and are not presently suited for operational use where a large number of calculations with a variety of input parameters are required. It appears that the two-dimensional models may be particularly useful as research tools to improve the parameterization which must be applied to the one-dimensional models. Orographic, winter models are in an exploratory stage and should be available for operational use in the near future. Mesoscale modeling offers the greatest developmental challenge in the area of modeling. The concepts are not yet clearly in mind and the computational problems will be complex, but the value received from the models will be great.

An important aspect of weather modification for the Bureau of Reclamation is the possible downwind effect of seeding. The microphysics effect, through transport of nuclei, is straightforward, but the possible dynamic effects of wakes and waves on a hundred-mile downwind scale is complex and not well understood. It will only be through quantitative modeling of the downwind effect that a satisfactory understanding of the phenomenon will be achieved.

D. Treatment Potential

Further growth in the field of weather modification requires a better understanding of the potential for modification treatment. Methods are required for the recognition of modification opportunities through a wide range of possible environment conditions. Temperature stability, horizontal cloud size, cloud depth, existence of supercooled water, nuclei concentrations, and the occurrence of natural precipitation are likely to exert an influence on the potential. It is desirable that the system for defining the potential involve only those parameters which are routinely measured by regular weather reporting stations so that climatological evaluations of potential can be made. It may turn out, however, that unmeasured variables such as ice nuclei counts or cloud dimensions are needed for a proper assessment.

Two significant steps toward evaluation of treatment potential have been taken with the use of cloud models to explore cumulus seeding potential and with the work of Grant, Chappell, and Mielke (1968) for winter storms. Particularly lacking, at present, is the analysis of modification potential for cloud systems larger than can be treated with one generator unit. Also required is a means for relating cloud populations to synoptic parameters. Implicit in the need for treatment potential analyses are more detailed sub-synoptic studies of storm environment conditions in areas where modification operations might be conducted.

E. Instrumentation Problems

The principal instrumentation problem required for further progress in weather modification is the acquisition and processing of increasingly large amounts of data, primarily on a real-time basis. Most of the individual variables needed can be measured by one or more methods, but the measurements characteristically require great difficulty, expense, and laborious data reduction. Techniques for solving this problem exist but have not been applied extensively in weather modification due to high, initial equipment costs.

Two major problem areas are discussed which provide the framework for instrumentation problems in weather modification:

1. Data Systems, Data Handling, and Data Display for Evaluation Purposes and for Real-Time Decision Making
2. Obtaining Dynamics and Microphysics Information in Storm Conditions.

Additional instrumentation problems of a new nature include snow measurement, use of doppler radar, remote probing, and measurement of mesoscale wind fields.

F. Reports

Reports prepared under Contract No. 14-06-D-6447 include:

1. "Areas for Emphasis in Microphysics, Cloud Dynamics, Seeding Potential, and Instrumentation" by T. B. Smith, P. B. MacCready, Jr., D. M. Takeuchi, S. Hozaki, and C.-W. Chien, June 1968,

2. "Analysis of Warm Cloud Modification Potential" by T. B. Smith, P. B. MacCready, Jr., and S. Hozaki, June 1968.

III. INTRODUCTION TO THE ARIZONA PROGRAM

The Arizona Weather Modification Program under the sponsorship of the Bureau of Reclamation was initiated by Meteorology Research, Inc., in the spring of 1965. The program was a successor to a series of studies performed at Flagstaff by MRI and the affiliated Atmospheric Research Group under AEC, NSF, U. S. Army, and U. S. Forest Service sponsorship during the past decade.

The goal of the program is to develop and demonstrate quantitative engineering techniques for cloud seeding for augmentation of precipitation on a scale that can produce economic benefit when applied to various locations. The initial phases of this goal have now been achieved in the FY 1968 program, which featured:

> Development and field use of a numerical model of cumulus cloud evolution, culminating in a randomized project which demonstrated large and useful modifications of cells by seeding.
>
> Exploratory trials of the seeding of major storm systems, which suggest that major beneficial modifications resulted.
>
> Utilization and demonstration of improved techniques for conducting quantitative field programs, in a manner aimed both at obtaining understanding of the basic physical principles involved and coping with the complexity and scope of field programs and their associated data-handling needs. Special emphasis was given to techniques in project control and real-time computing.

The main effort of the 1967 summer season was a randomized experiment on the seeding of isolated cumulus clouds. In addition, some case study investigations of microphysics factors within the clouds were carried out together with exploratory seeding and observations of mesoscale storm systems. A small part of the effort during the year was devoted to applying the Flagstaff-developed methodology to winter situations where some of the modeling and observational techniques are similar.

IV. PROGRAM APPROACH

The overall goals of the Arizona Program are:

1. To develop operational techniques for the modification of isolated cumulus clouds,
2. To explore and develop methods for the organization and modification of mesoscale cloud systems.

The FY 1968 Arizona Program has demonstrated that operational techniques are already available for the seeding of isolated cumulus clouds. It is also evident, however, that the technique is not fully optimized and continued evolvement in the technology can be expected for some time to come. The primary aims for the Arizona Program in this regard are to develop more detailed microphysics representations of the seeding effects and to use these and other data to improve the numerical cloud modeling.

The mesoscale studies are at a much earlier stage where exploratory studies, field observations, and a conceptual basis for the seeding are required. These studies will then evolve into a numerical model to provide a quantitative framework for the design and evaluation of field experiments. Although the mesoscale portion of the program is still in a developmental era, its importance is great and the potential for economic benefits far exceeds the results which can be expected from isolated cloud seeding.

V. COURSE OF EVENTS

The Arizona Program under Bureau of Reclamation sponsorship began in the spring of 1965 with preparations for a small summer field operation at Flagstaff. The aim of the first year was to explore the initial engineering of the massive seeding of large convective storms and the development of physical evaluation techniques for the seeding. During the following winter, analytical work on the summer program continued and a brief winter program was conducted at Flagstaff.

Preparations were made for an enlarged program in the summer of 1966. The Aztec aircraft was heavily instrumented, and the radar and ground network was expanded. The 1966 operation laid strong emphasis on numerical modeling, on data handling, and, as far as was feasible, on real-time evaluation. The seeding was performed in a variety of methods from the air and from the ground. The 1966 program featured use of the computer model in the field, and helped to crystallize the conceptual view of seeding effects into semi-quantitative terms and provide a basis for judging the effects compared to a calculated version of what should have happened without seeding.

The knowledge gained during the summer of 1966 was formalized into the experimental design for 1967 which involved the randomized seeding of pairs of simple cumulus clouds. The field operations were simplified to concentrate on this randomized seeding program. Only one type of seeding was used (airborne, acetone-AgI generators), and relatively little effort was devoted to the development of observational techniques. The 1967 program also carried along the exploratory investigation of the seeding of mesoscale cloud systems; the mesoscale work had comprised a part of the MRI Flagstaff studies each year of the

of the field program since 1962 when attention was first focused on the "convective wake" which sometimes organizes and helps to develop storms downwind of the isolated peaks.

VI. REPORTS AND PAPERS

It has become customary to issue the final reports in the Arizona Program in two volumes; one containing a general summary of the program and the other including detailed research reports. For FY 1968, these two volumes were entitled:

1. Arizona Weather Modification Research Program, Final Report for FY 1968 by the Staff of MRI, Dr. Paul B. MacCready, Jr., Program Director.

2. Arizona Weather Modification Research Program, Research Reports for FY 1968, by the Staff of MRI, Dr. Paul B. MacCready, Jr., Program Director.

The research reports volume contains the following individual reports where the numbering system follows in sequence from the report series published in earlier years:

Research Report

XIII. Isolated Cumulus Cloud Modification, by A. I. Weinstein and P. B. MacCready, Jr.

XIV. Aircraft Investigation of Microphysics Factors in Natural and Seeded Clouds, by D. M. Takeuchi

XV. Modeling of Orographic Storms, by C.-W. Chien

XVI. Mesoscale Convective Systems, by L. G. Davis.

Several articles related to this program have been published in journals during FY 1968:

MacCready, P. B., Jr., and R. G. Baughman, "The Glaciation of an AgI Seeded Cumulus Cloud," J. Appl. Meteor., February, 1968. This work was sponsored by the U. S. Forest Service, but was

based on the measurements with the aircraft instrumented partially with Bureau of Reclamation support.

Fukuta, N., "An Airborne Generator of Metaldehyde Smoke," J. Appl. Meteor., December 1967 (this is based on Research Reports V and XI).

MacCready, P. B., Jr., and D. M. Takeuchi, "Precipitation Initiation Mechanisms and Droplet Characteristics of Some Convective Cumulus Cloud Cores," J. Appl. Meteor., August 1968. This involved primarily Army Electronics Command support, with some help from the National Science Foundation, and was finished as part of the present program.

MRI personnel have contributed to all four of the Skywater conferences:

At Skywater I, Nucleation Conference, July 10-12, 1967, Dr. N. Fukuta presented a "Review of Physics of Ice Nucleation and Its Application to Weather Modification." The preparation of the review was sponsored by a separate Bureau of Reclamation contract with MRI.

For Skywater II, Conference on Program Design, October 12-13, 1967, Dr. P. B. MacCready, Jr., presented a paper "Designing Programs Involving Convective Clouds," which covered both the sort of supercooled clouds at Flagstaff and warm clouds which are more important at some other locations.

At Skywater III, Conference on Production and Delivery of Cloud Nucleating Materials, February 14-16, 1968, Dr. N. Fukuta presented a paper "Production of Organic Nucleants," and T. R. Mee made a presentation on "Airborne Seeding."

At Skywater IV, Conference on Optimization of Operational Weather Modification, May 21-22, 1968, Drs. P. B. MacCready, Jr., and T. B. Smith presented a paper "Role of the Arizona Weather Modification Research Program in Developing Operational Weather Modification."

VII. RANDOMIZED SEEDING OF ISOLATED CLOUDS

The simple numerical model experiments at Flagstaff in 1966 illustrated the main features of the use of such models in seeding sensitivity studies, in the selection of clouds for treatment in the field, and in evaluation. The model subsequently was improved and employed in the design of the field experiment for the 1967 program. The cloud selection procedure, the seeding procedure, and the observational program were all determined by the model. To obtain statistical significance for the

results, the experiment was randomized. Only one kind of seeding was employed so as to keep the number of variables as small as possible. The airborne seeding was designed to assure that the seeding material entered the cloud where and when desired, and to give a strong likelihood of causing as large a dynamic effect as possible. The main program emphasis was on relating cloud top height to seeding, with secondary objectives on how the seeding altered the rainfall duration and amount. In comparison to the height predictions and observations, the precipitation aspects of the model and the rainfall measurements are more complex and difficult and would be expected to show more variation between prediction and observation.

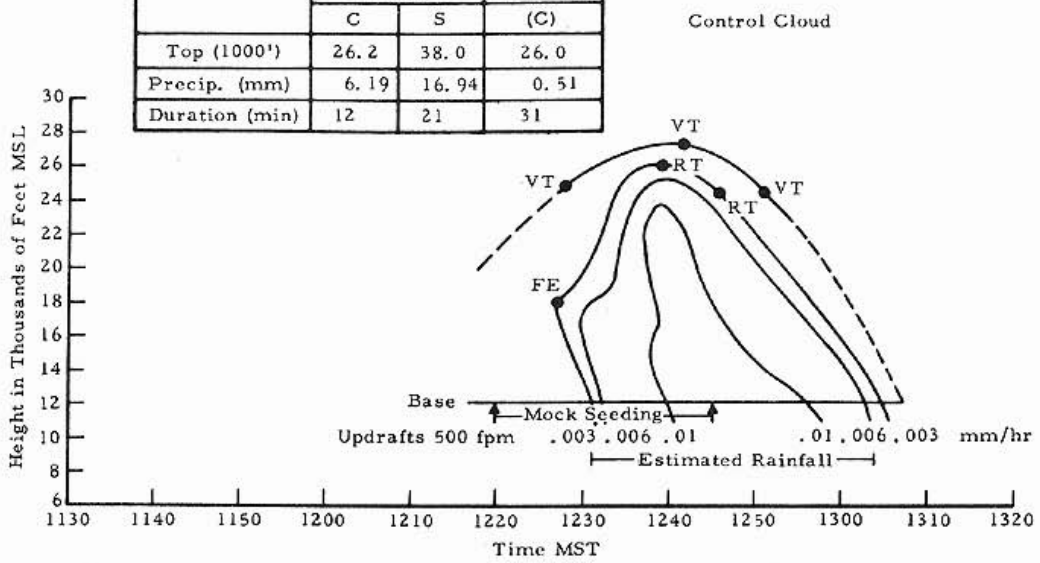
Cloud top heights of the test clouds were measured by radar and visually. Duration of rainfall from the cloud was observed by radar measurements at the cloud base. Rainfall was estimated from the radar reflectivity by assumptions of the Marshall-Palmer distribution, and the total rainfall was found by integrating the precipitation at the base throughout the duration of the rain. These three observed parameters were subsequently related to predicted values which were obtained from the computer cloud model.

Figure 2 is an example of the sort of data obtained on a typical day. Time-height plots are given for rainfall (from radar reflectivity) and visual tops. On the figure, FE denotes the first 3-cm radar echo, RT means radar top, and VT indicates visual top. The blocks listing computer predictions are seen to be in good agreement with observations. The effect of seeding on cloud growth for the seeded case is quite dramatic. At the appropriate time and location, glaciation and strong development occurred, and the precipitation grew stronger and longer lasting. In Fig. 2, it is evident that natural precipitation has started at about 1047, before the seeding could be expected to have much effect. The ability of seeding to produce effects even when there is natural rain superimposed and the ability of the model to work in such a circumstance, augurs well for eventually being able to treat a more complex cloud system in a semi-quantitative manner.

On 11 days, a total of 21 test clouds were studied, 10 seeded and 11 unseeded. On nine of the days, there was a seeded and unseeded pair. An effort was made to select the same radius cloud for both clouds in a pair on one day (and to pick a radius which would permit obvious effects from seeding), but this was generally not possible.

There were three basic treatments of the data. First, the observations were considered alone, with no involvement of the model. This was done for all cases together, then all cases on paired days (only since the seeded and unseeded populations should be in better agreement then), and finally the daily pairs were themselves examined. The second treatment

Location: 327°/7.2 km			
Radius: 1.6 km			
	Predicted		Observed
	C	S	(C)
Top (1000')	26.2	38.0	26.0
Precip. (mm)	6.19	16.94	0.51
Duration (min)	12	21	31



Location: 037°/20.3 km			
Radius: 2.0 km			
	Predicted		Observed
	C	S	(S)
Top (1000')	27.6	41.3	39.3
Precip. (mm)	7.28	19.89	4.02
Duration (min)	17	24	61

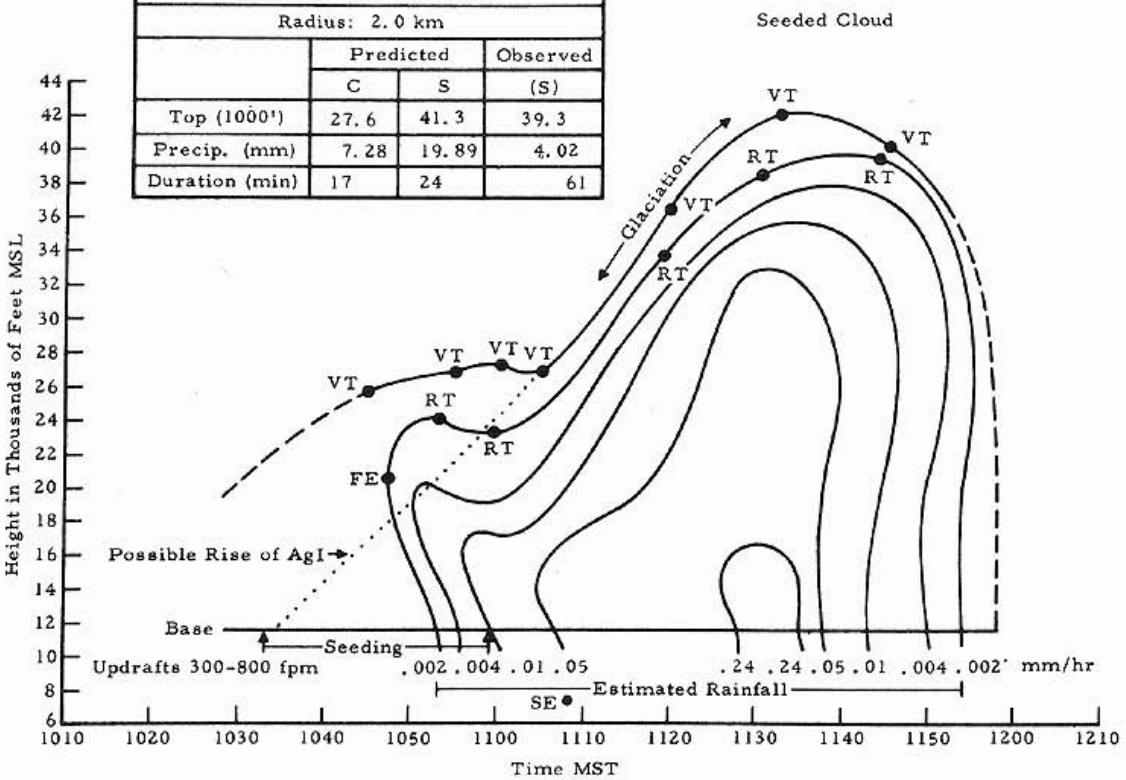


Fig. 2. 24 JULY 1967

was to adjust the numerical model for unseeded cases empirically to fit the data for the unseeded cases, and then use this model to predict for the seeded cases what the unseeded results would have been. The third treatment was to tailor the model to both the unseeded and seeded data and then use the model predictions as a guide to clarify the magnitude of seeding effects.

The first treatment, based only on observations, shows effects most simply and with fewest assumptions, but involves the lumping together of data having wide variations of conditions (radii, environments). Thus the magnitudes of effects may be unrealistic, but the validity of the existence of effects can be shown to be significant. The seeded clouds had significantly higher visual tops (7900 ft), higher radar tops (5900 ft), longer durations (10 min), and larger rainfall (2.0 mm). The respective percentage increases, assuming 13,000-ft cloud bases, were 63, 47, 39, and 76 percent. Statistical significance was determined by the t-test and found to be 99, 96, 92, and 81 percent, respectively.

The second treatment which used the model to help quantify the amount of the seeding effect for varying conditions should more accurately give magnitudes and also yield satisfying statistical validity. The third treatment used all the experimental data to derive the most accurate predictive model -- but the model validity can only be established later when the model is applied to independent data. It is interesting to note that all three treatments tend to show comparable magnitudes for the seeding effects.

The most realistic impression of the validity of the model in representing the 1967 data can be obtained by looking at the scatter diagram of predicted vs. observed cloud-top height which is represented in Fig. 3. Both seeded and unseeded clouds are shown in the figure. Note that the best-fit line fits both the seeded and control data in spite of the fact that a rather crude seeding effect assumption has been used for the seeded clouds. The best-fit line for the height prediction can be taken as the line parallel to the 45° line, and 462 ft higher (for the accuracy desired here, the 462 ft can be neglected). The correlation coefficient in Fig. 3 is $R = 0.88$, and the RMS error is 3,341 ft.

In similar plots for precipitation amounts and durations, the correlation coefficients were $R = 0.89$ and 0.76, respectively, around the linear regression lines. In the case of precipitation amounts, the slope of the best-fit line was 0.7, indicating that the model calculates approximately 44 percent more rain than is being observed.

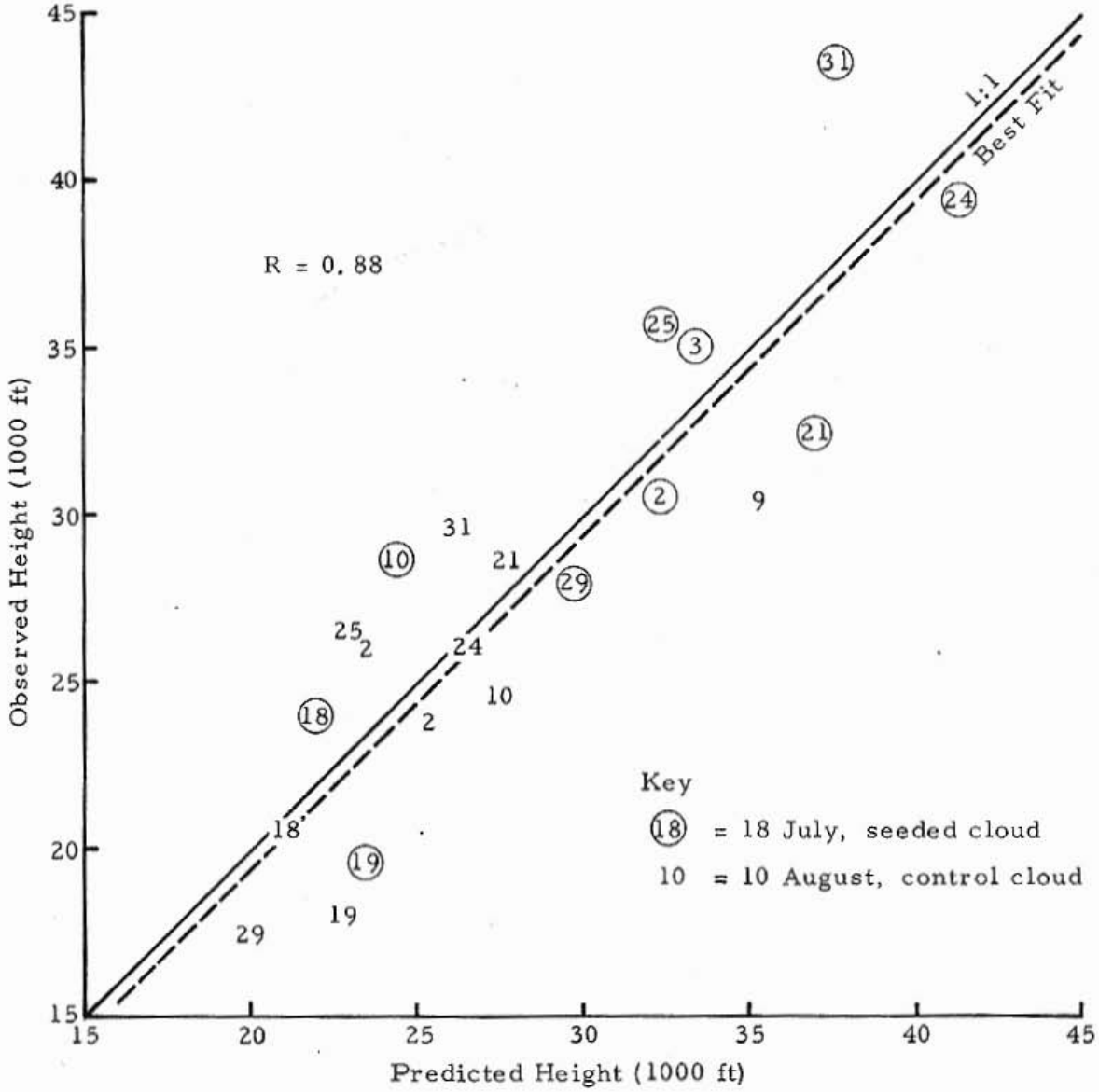


Fig. 3. SCATTER DIAGRAM OF HEIGHT

Comparing the relationship between predicted and observed duration of rainfall at cloud base, the correlation of 0.76 indicates that the model has a fair degree of skill in predictions of duration. The slope of the "eyeball" best-fit line through the origin (about 2.2) is in qualitative agreement with the slope of the regression line for total rainfall; predicting rainfall too high means predicting the hydrometeor velocity too high also, which corresponds to predicting duration too low.

In summary, the model has proved useful in describing the increase in cloud top height and increases in rainfall amount and duration in spite of a consistent bias error in amounts and duration. The results of the 1967 program indicate a promising future for the evaluation of field experiments through the use of computer models.

VIII. MICROPHYSICS INVESTIGATIONS

Physical investigations of cloud interiors have been made at Flagstaff over a period of years to obtain data on microphysical phenomena. The aim has been to learn about the growth of hydrometeors and the development of glaciation in seeded and unseeded clouds. These are vital inputs into numerical models and quantitative experiments. The basic instruments are the Continuous Particle Collector (CPC), the Continuous Hydrometeor Sampler (CHS), and the liquid water content (LWC) meter.

In FY 1968, two microphysics investigations were undertaken. One was a reevaluation of the pyrotechnic seeding event which had been reported by Takeuchi in Research Report IX, "Case Study of Vertical-Fall Pyrotechnic AgI Generators," issued in FY 1967. It was felt that a more complete analysis of the CPC record would provide more quantitative information on the glaciation effects of seeding. The other microphysics investigation was the probing of clouds at the end of the 1967 field season at Flagstaff.

The 1967 field study involved two seeded clouds and two unseeded clouds during the period August 9-11. Three clouds were probed by the Aztec at about a constant level. In one case, there were seventeen sequential penetrations. The fourth cloud was probed sequentially at decreasing height. The differences between seeded and unseeded clouds were quite evident. Figures 4 and 5 give a sample of the results for a seeded case on August 10. This cloud was not especially large or vigorous, and care must be exercised in extrapolating the observations to other situations.

Figure 4 shows selected passes at about the -7C level. Initially, before the seeding material has reached that level, there is no glaciation

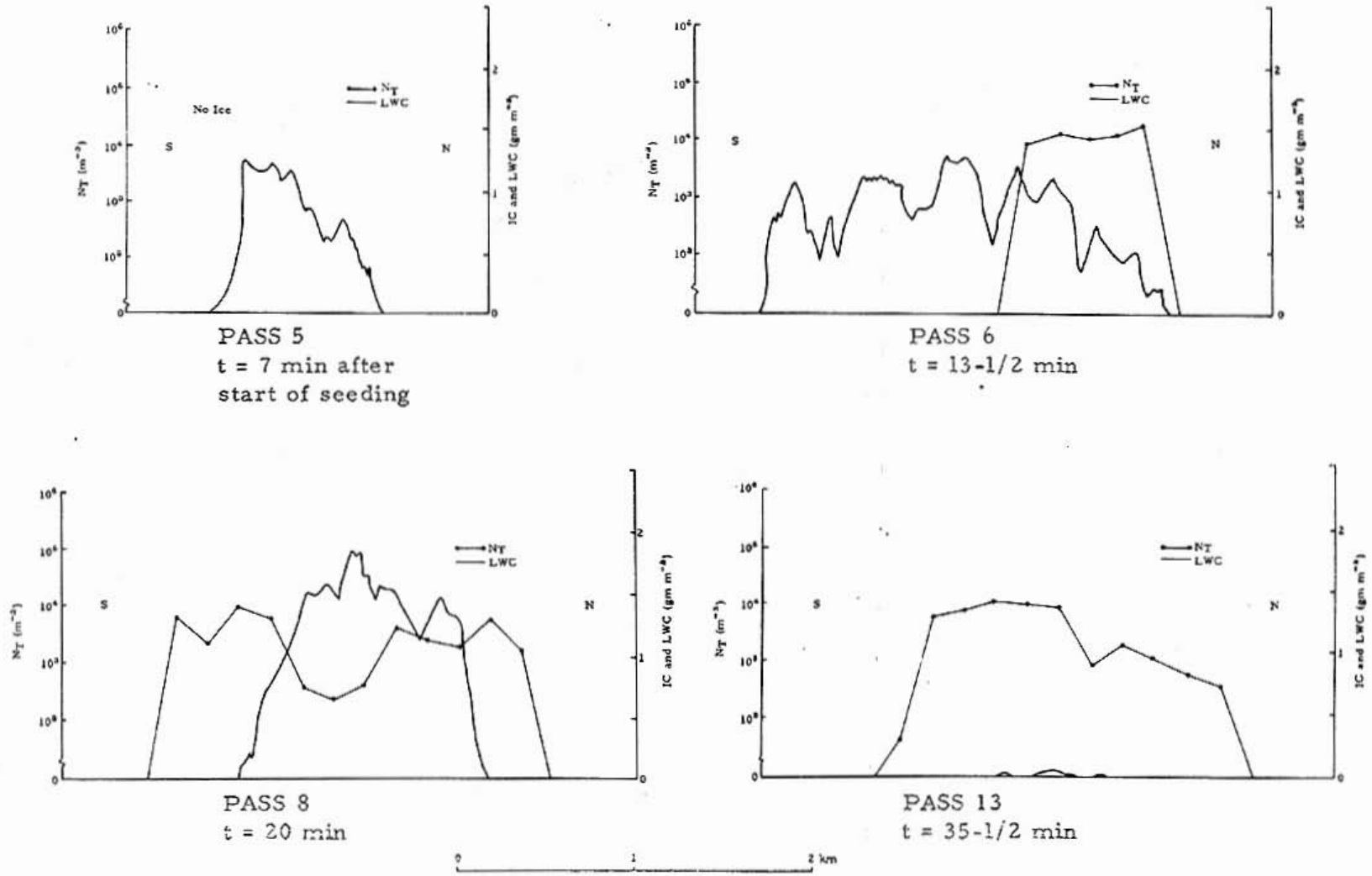


Fig. 4. SPATIAL DISTRIBUTION OF LIQUID WATER AND ICE
(Seeded cloud of August 10. N_T denotes number of ice particles larger than 0.1 mm diameter)

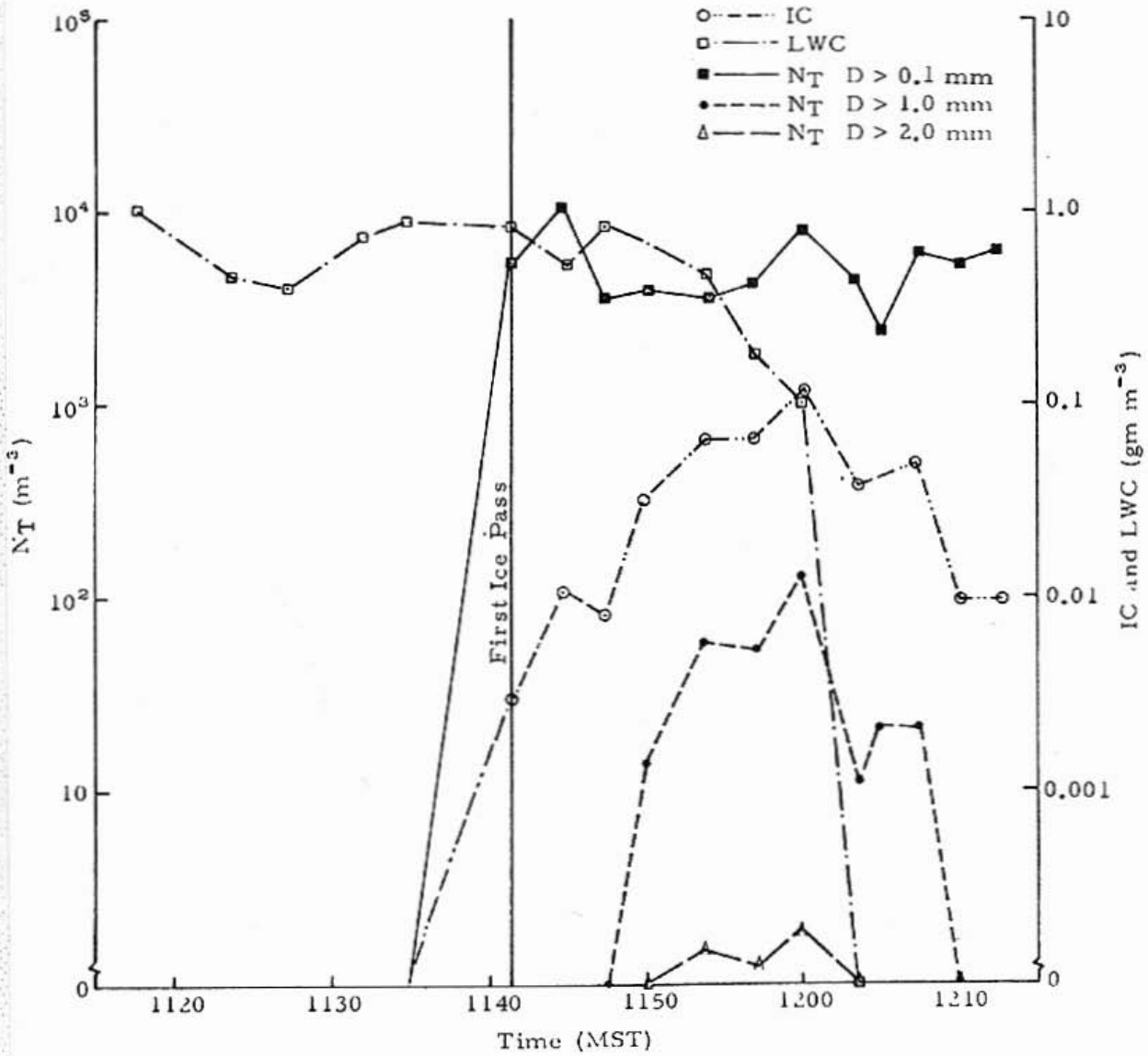


Fig. 5. DEVELOPMENT OF ICE PHASE
(Seeded cloud of August 10. IC is computed assuming the ice particles are spheres of density 0.5)

in the cloud. Subsequently, strong glaciation is noted (Pass 6), with the LWC being low where the ice count N_T is highest. On Pass 8, the glaciation is complete at both cloud edges, but simultaneously there is a stronger-than-ever core of high liquid water content. This is a time of rapid rise of the radar top. The implication is that the buoyancy from glaciation, perhaps aided by the slowing of evaporative cooling at the cloud edges from glaciation, has helped generate a new surge of upcurrent. The reservoir of glaciation at the edges and the seeding material in portions of the upcurrent subsequently glaciate this new, organized core completely, but earlier this core represented a healthy growth region for hydrometeors.

Figure 5 further examines the time history of the hydrometeor development situation. The total ice concentration quickly rises to about 10/liter (averaged across the cloud) and remains at that level. At the start of glaciation, there is about 1 g/m^3 of LWC, but after the surge of Pass 8, this rapidly is removed by glaciation until, 20 min after the glaciation starts, there is no LWC left at all. Figure 5 shows the development of hydrometeors larger than 1 mm and 2 mm. Their growth is abruptly shut off as the LWC drops.

In comparison to this seeded case, unseeded cases show that the LWC exists in fairly good amounts for much longer periods, with the growth of hydrometeors continuing all the time.

There may be important implications of such observations on the development of seeding techniques, even though the observations represent only a few cases. The glaciation of the seeded cloud apparently stimulated cloud growth (predicted by the numerical model, and evidenced in Pass 8 of Fig. 4), and quickly started hydrometeor development at a particular time, but the seeding "turned off" the hydrometeor development rather abruptly after a short time. The seeding of August 10 was perhaps optimum for maximizing the height increase but not optimum for maximizing the precipitation. The biggest dynamic effect would arise from complete glaciation but such glaciation would inhibit hydrometeor development.

The benefits of seeding would be greater if a better compromise between the conflicting microphysics and dynamic efforts were made. The best seeding technique will likely involve varying the nuclei concentrations with time, presumably using high concentrations early to get the dynamic effect started, but low concentrations later so as not to inhibit hydrometeor growth. If the environmental stability is very slight, even weak concentrations will produce large dynamics effects; greater stability will necessitate more glaciation for producing dynamic effects; very great stability negates dynamic effects and so ice concentrations should

be optimized solely for hydrometeor development. Such considerations will depend in a complex manner on cloud size and environmental considerations, and so it can be seen that numerical modeling with accurate microphysics treatment will be helpful for the development of truly efficient seeding techniques.

The microphysics study also examined the relation between the number of ice particles observed in the cloud and the number expected by calculations based on laboratory calibrations of the generators. The experiment is crude, but nevertheless is accurate enough to suggest questions which need further study. The observed crystals were equal to or fewer by two orders of magnitude than the predicted counts. The situation is confused in that other studies in different locations or with different seeding methods have sometimes given substantially different results.

An evaluation of the CPC data for the 1965 seeding case (Research Report IX) showed that 10^{10} crystals were found in a portion of the cloud compared to an expected number of nuclei of about 10^{5}. The same discrepancy has been noted and discussed by MacCready and Baughman (1968) in the seeding of small convective clouds in Montana with an acetone-type AgI generator released under the cloud. It has been noted by Mossop,et al., (1967) for natural clouds, where on occasion the observed crystal concentrations greatly exceeded the measured ice nuclei concentrations.

From the 1967 data and a more detailed analysis of the 1965 data and a summary of other available information, the situation regarding the relation of nuclei counts to ice crystals can be summarized as follows in the next two paragraphs.

There are large differences to be expected in ice crystal counts, depending on generators, application techniques, and the cloud and meteorological conditions. Knowledge is building up from theory and laboratory studies about how particular ice nuclei should act to initiate freezing in various circumstances (see Proceedings of Skywater Conferences I and III, and St. Amand, et al., 1968). The field observations referred to here are sometimes consistent with explanations of how generators should glaciate clouds, but in other cases observations apparently cannot be explained by existing concepts. To advance this subject, more systematic field observations are desirable, especially field measurements in simple conditions which can be correlated directly with laboratory observations.

The microphysics probing of 1967 can be contrasted to the assumptions of the numerical model. Although the details are very different, the overall assumptions prove to be not too bad considering the gross parameterization utilized in the model. In the unseeded cloud, a hydrometeor development mechanism is operating, and the cloud droplets are

restrictions on development and management objectives. In view of this, it was decided to shift development planning from a yearly basis to a unified 5 year basis. Funds obligated in 1 year will, under the 5 year plan, be used in part for design and construction of equipment to be placed in operation the following year. This avoids crash-type operations where system components may function inefficiently because of insufficient lead time for pretesting and installation.

It was stated in the project design study that the most accurate and efficient delivery system would be one employing high level, remote, silver iodide generators, either wholly or in part. These would be located at points on the Swan and Mission ranges upwind from the target area. The changeover to 5 year planning has made engineering and construction of three elements of the proposed system possible in the current year, and installation of these is scheduled in several months.

EVALUATION

Basic parameters available for direct evaluation of seeding effectiveness are snowpack water content and streamflow, with supplemental use of silver in snow data. Only a single precipitation gage exists within the entire target area, and its reliability is not good.

Two streamflow methods of evaluation, as developed in the report of last year, will be used when pertinent data becomes available. Data necessary for the objective forecast of January to July runoff will be acquired in August, and water year runoff data for the streamflow regression analysis will not be acquired before October. Published snowpack water content measurements made by cooperating agencies and distributed by the Soil Conservation Service are used in the following evaluation.

Snowpack Water Content

A standard regression analysis of March 1st snowpack was presented in the 1966-67 report. Four snow courses immediately west of the target area were selected as control, while target stations included two valley courses and one mountain course. The abnormal character of the 1967-68 winter has necessitated some revision in the target stations to account for an early runoff peak due to above normal temperatures in January, February, and March.

The ESSA Weather Bureau station at the Flathead County Airport reported average temperatures in the period January 13th to January 31st 5.7° F above normal, February 7.4° F above normal, and March 7.3° F above normal. There were 22 days in February in which the maximum temperature was above freezing, and on every day in March the maximum temperature was above freezing. Late in January

PERFORMANCE OF AN ATMOSPHERIC WATER RESOURCES RESEARCH PROGRAM IN THE HUNGRY HORSE AREA, MONTANA
1967-68 Season

INTERIM REPORT

INTRODUCTION

The Hungry Horse project, begun in the fall of 1966, is one of the first "operational adaptation research projects" undertaken as part of the Bureau of Reclamation's Atmospheric Water Resources Program (1967). This report covers, in preliminary form, the second year of operations.

High economic yields may be realized from small increases in precipitation over a drainage basin upstream from a large number of hydroelectric plants. Water released from Hungry Horse reservoir, for example, generates power at 18 downstream sites before finally reaching sea level. Upon consideration of typical increases expected from efficiently managed programs of precipitation augmentation, conservative estimates of benefit-cost ratios range upwards of ten to one for this region. In an exceptionally dry year, even a 1 percent increase, substantially below that expected, may result in a benefit-cost ratio of this order. The dry water year 1965-66 gave impetus for immediate development of such a program.

With support from Bonneville Power Administration (BPA), principle beneficiary of the project, the Bureau of Reclamation in 1966 issued a contract to design an optimum atmospheric water resources program in the Hungry Horse area. The final report to this study was submitted by North American Weather Consultants (NAWC) to the Bureau of Reclamation in September 1966 (1966). A contract was negotiated for the initial year by November 10, 1966, and operation status was achieved shortly thereafter.

As originally designed, the project had multiple objectives of both applied research and operational natures. These are enumerated in the Hungry Horse interim final report of 1967 as a part of the Bureau's basic philosophy of water resources development. However, funding difficulties in the initial year necessitated a major revision in research objectives to more modest ones, and in this, the second year, additional research cutbacks have been necessary.

Regardless, a major stride forward in overall planning was made. Normally, project funding for a given year cannot be expected until that season is well advanced. Although operations were begun by NAWC early in December 1967, with no contracturally assured reimbursement at that time, funds were not legally obligated until mid-January 1968. This type of situation, of course, imposes severe

PERFORMACE OF AN ATMOSPHERIC WATER RESOURCES RESEARCH PROGRAM IN THE HUNGRY HORSE AREA, MONTANA 1967-68 SEASON

INTERIM REPORT

Submitted to
U. S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
ATMOSPHERIC WATER RESOURCES RESEARCH

Contract No. 14-06-D-6039
Amendatory Agreement No. 1

August 1, 1968

NORTH AMERICAN WEATHER CONSULTANTS
Santa Barbara Municipal Airport
Goleta, California

Bureau of Reclamation Summary

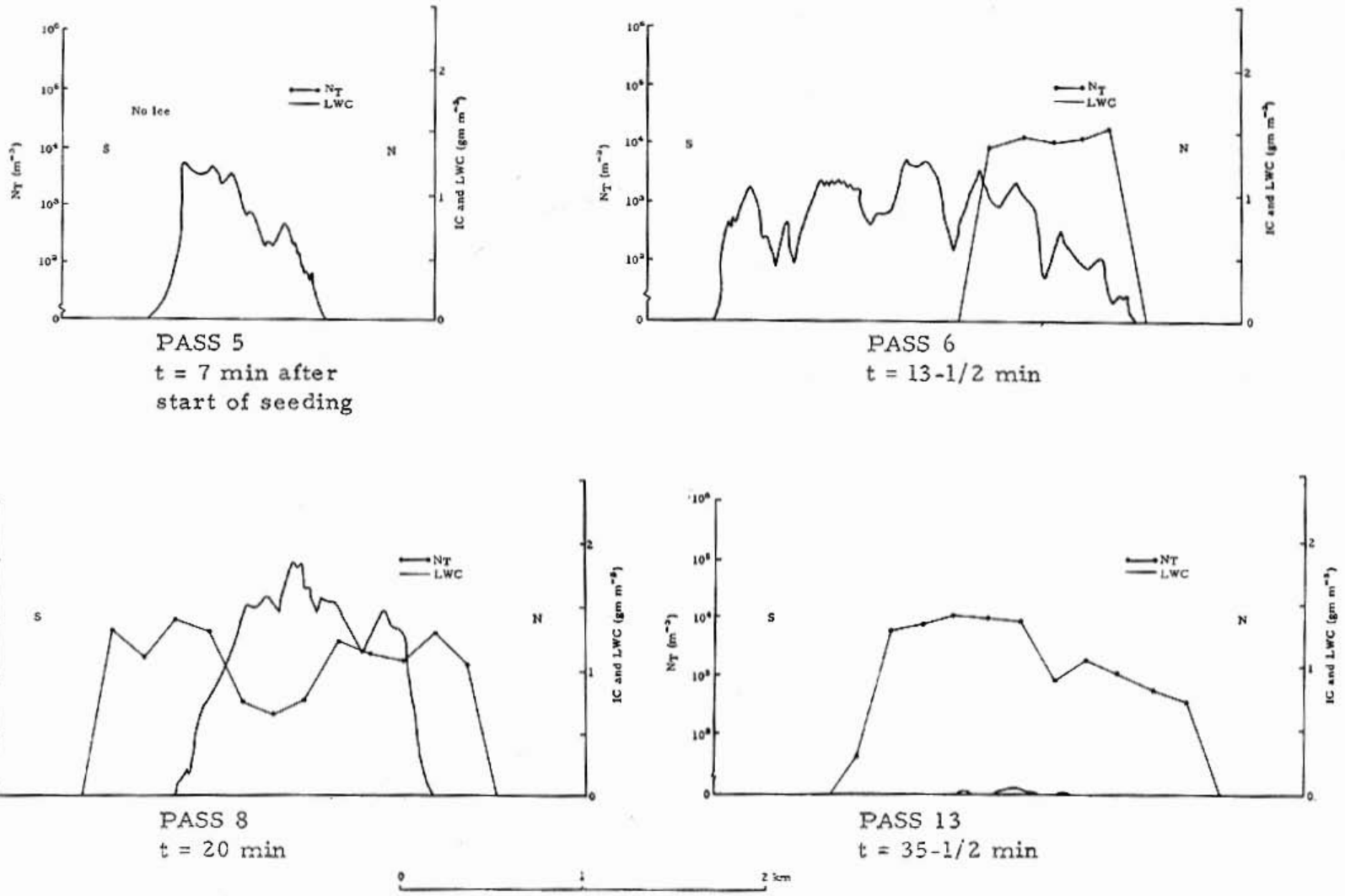


Fig. 4. SPATIAL DISTRIBUTION OF LIQUID WATER AND ICE
(Seeded cloud of August 10. N_T denotes number of ice particles larger than 0.1 mm diameter)

4. Spurious Natural Nuclei
5. Transport and Diffusion of Seeding Material
6. Warm Cloud Effects
7. Ice-Ice Coalescence.

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XI. CONCLUSIONS AND RECOMMENDATIONS

To summarize the FY 1968 Arizona Program, the randomized seeding program was successful in showing distinct seeding effects and in demonstrating the use of the simple numerical model in program design and evaluation. The microphysics investigation gave new clues as to the effects of seeding on glaciation and on hydrometeor development and provided a basis for considerations about optimizing the seeding in the future. The numerical model development for orographic storms suggests that the next stage of the model development will bring the model to a point where it can be used effectively in the design and evaluation of field experiments.

The isolated cumulus program should receive strong program emphasis in the coming year particularly in regard to maximizing precipitation, but diminishing effort will be required thereafter. Some outputs of the program seem ready for operational application in limited cases even now, and more generally applicable techniques can be foreseen in the near future. Thus the program should include some attention to the potential of such treatments in various locations so that real operational application can be made as soon as the methodology justified it.

The mesoscale seeding program should constitute the main effort at Flagstaff in the future, comprising about half of the program in FY 1969 and increasing as the isolated cumulus program diminishes. In the summer of 1968, exploratory observation and seeding of mesoscale systems should be carried out, with emphasis on initial organization of the system as well as its subsequent propagation. There are extensive data in the Flagstaff files which pertain to the mesoscale problem but which have not been analyzed with respect to the problem. The next phase of the program should make full use of these data in establishing the characteristics of the mesoscale systems. By the summer of 1969, there should be available a preliminary model around which to build a basic experimental design. The following year should see the model and the observational techniques sufficiently advanced to justify a major field experiment, drawing on the resources of various cooperative groups.

There are secondary programs which are of considerable importance in achieving the two principal objectives, as well as representing critical factors in other weather modification programs.

The following items will receive continued attention in the future:

1. Ice Phase Model
2. Nucleation Effectiveness
3. Effectiveness of Other Seeding Agents

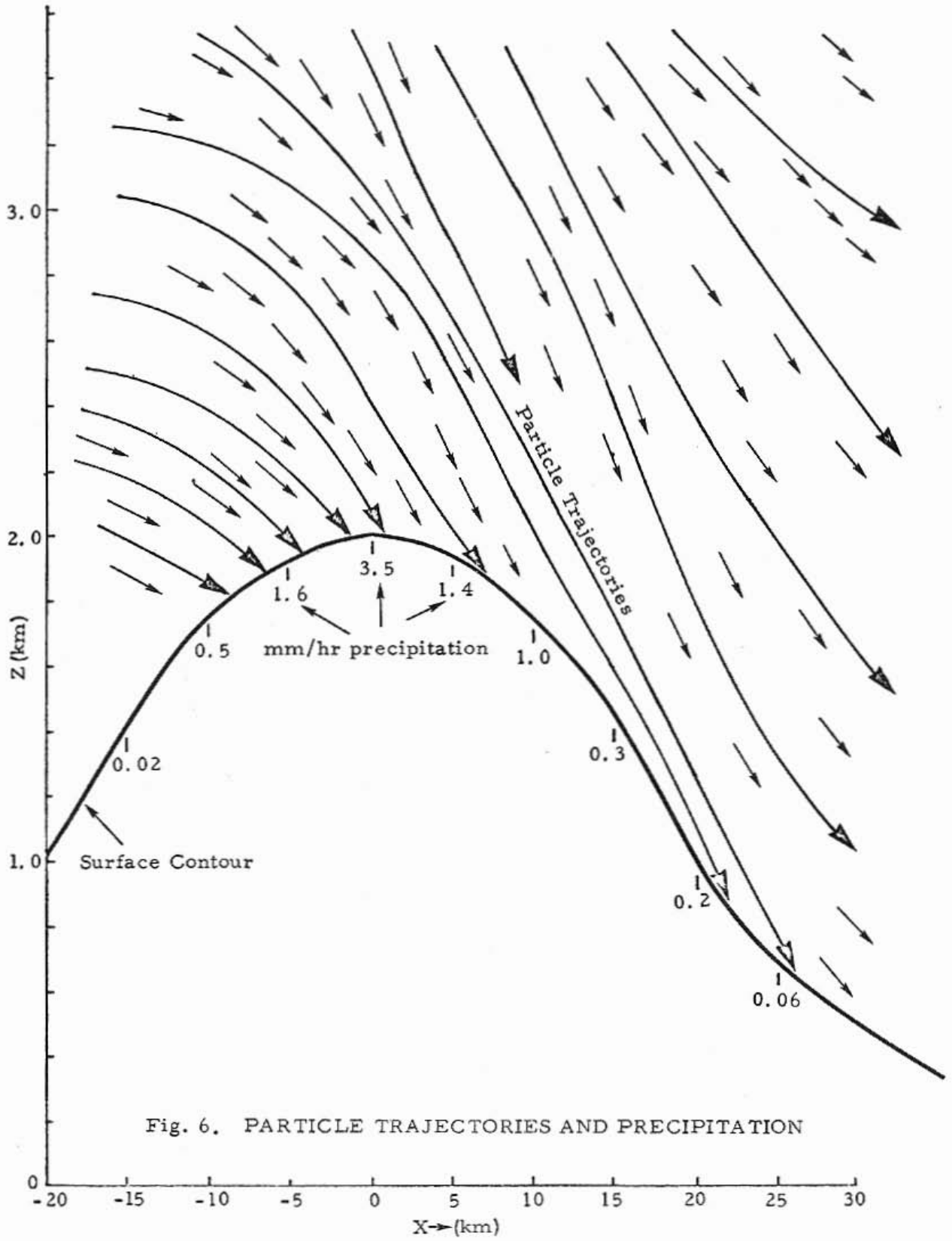


Fig. 6. PARTICLE TRAJECTORIES AND PRECIPITATION

X. WINTER STORM STUDIES

The techniques involved in studying and manipulating summer convective storms can also be applied to winter storms. This program, therefore, has included adapting techniques used at Flagstaff in the summer to winter conditions. In FY 1968, a very brief winter field investigation was carried out near the MRI Altadena offices, and the study and development of computer modeling appropriate for orographic winter storm modification was investigated.

The underlying physical concepts for orographic flow modeling are discussed: size scales, stable vs. unstable storms, upwind and downwind steady-state flows, superposition of convective effects, hydrometeor development, seeding effects, etc. Two particular, simple models are presented with sample computed results. The simpler model uses the wave flow method of Queney (1948) and superimposes parameterized microphysics but omits the feedback of thermodynamical factors onto the flow. A computational example is shown in Fig. 6. The more advanced model is based on Myers' (1962) formulation of windward slope flow and does include crude thermodynamic feedbacks into the flow pattern.

Two main points emerged from the 1968 winter field program, one operational and one meteorological. Operationally, the Altadena area (Los Angeles area) proved to be more difficult than anticipated for conducting flight operations. This was due to Air Traffic Control regulations necessitated by the heavy traffic in this region. Flights associated with storms proved to be possible, but traverses across the mountains at desired locations, altitudes, and times were not possible.

The meteorological point pertained to the large number of natural ice crystals found distributed through a great vertical depth. The research flight took place around 1600 PST on March 12, in the prefrontal stratus layer of a weak cold front. The clouds extended from 12,500 ft (-5C) to an estimated 27,000 ft (-37C), and no precipitation was observed from the bases. The airplane spiraled up 15 miles southwest of Mt. Wilson, reaching 22,000 ft. The Cloud Particle Collector showed liquid droplets through the main cloud layer from 12,500 ft to 15,000 ft in concentrations of about $10/cm^3$ with liquid water content about 0.025 g/m^3, while above that height the concentration was only of the order of $0.01/cm^3$. For the entire depth from 12,500 ft to 22,000 ft, the ice crystal situation was relatively constant, with crystal and crystal cluster concentrations averaging $0.1/cm^3$ (100/liter), and there were some large particles present at about 0.06/liter, with sizes to 1.75 mm. Such natural concentrations are high at the warm temperatures, but not unexpected at the colder temperatures. If such concentrations were naturally caused also in the more active portions of the storm, there would be little benefit to alterations which the cloud seeder could make.

In the 1967 summer program, the exploratory mesoscale investigation was conducted on six days. After the randomized seeding program was finished for the day and when there was a moderately strong thunderstorm in the area, the observer in the seeding airplane would select two regions into which he felt the storm could be grown by seeding. By flipping a coin, the project controller at the radar site would select one of these two areas, and the seeding would commence. The seeding method was to concentrate on the upcurrent and inflow parts of the storm over or leading to the specified region. The evaluation consisted of observing on the PPI radar scope how the total storm evolved, using also some radar top data from a 3-cm tracking set.

Of the six cases, in two instances the storm did seem to grow into the selected area in preference to the area which was not selected. One other case could be termed marginally successful, while the other three were inappropriate for the study. In one case the whole storm system was collapsing and continued its general collapse, in the other cases the winds had been misinterpreted 180° during the selection process. In one of the cases, the storm developed subsequently to dominate much of Arizona and could conceivably have represented a chain reaction. There were no negative cases. Because the observational data were so sparse, the selection process so un-rigorous, and the seeding technique so varied, the evaluation of these mesoscale trials cannot be quantitative. Considerable analysis effort did go into the evaluation, but the data proved inadequate to substantiate specific conclusions. The program nevertheless did serve the vital need of helping to strengthen the conceptual basis of the modification of mesoscale storms and gave experience in the seeding and observational requirements which are invaluable for planning subsequent programs.

It is a primary goal of the future work at Flagstaff to get the mesoscale seeding techniques to an acceptable operational level. The key to this is to develop a numerical model which can adequately treat the dominant factors and be used to design the quantitative experiment, to formulate seeding tactics, and to help with the evaluation of results. The successful development and application of such a model will depend upon an adequate observational network. The crude exploratory trials described here are helpful in stimulating and clarifying thoughts on observational and modeling procedures. Although it is hoped that eventually the seeding operations for such storms will prove to be simple, it is more likely that the seeding will have to be done in a careful manner, taking into account the details of convergence into specific cells, the relative location of precipitation, and the details of the wind shear. Considerable skill will probably be needed to permit the storm to extract the maximum benefit from the environment. The observational setup required may be extensive, and there would be an associated need for real-time handling and display of the data and of computer model outputs.

unglaciated (at least at the -8C level of measurement); in the seeded cloud, the supercooled water at -8C is pretty much removed in time by glaciation. The actual glaciation during seeding is obviously not a steady-state complete freezing at -8C, but rather a time-dependent glaciation which eventually goes to even much warmer temperatures. In summary, as both models and field experiments get more refined, the combined effects of nucleation, crystal growth rate, and the diffusion and transport of glaciation in the motions of a real convective cloud will all be considered in developing models and interpreting field data; for the crude approximations involved in the 1967 randomized study, the microphysics investigation showed the main concepts in the parameterized model were reasonable.

IX. MESOSCALE SEEDING

A primary aim of the Arizona Weather Modification Research Program has been to develop seeding concepts for total convective storm systems. Such systems contribute far more total water to most areas than do the small, isolated cumulus clouds, and so the seeding of these large systems can be of far more economic importance than the seeding of individual clouds. These considerations have been presented in the Final Report for FY 1965, 1966, and 1967, and in Research Report III, Traveling Mesoscale Systems, by Davis.

There are two separate aims of a mesoscale modification program which can be considered. First, the modification can aim at organizing the mesoscale system earlier than accomplished by nature or under environmental conditions when nature cannot perform the organization at all. Second, organized systems may be modified to produce larger or longer duration storms than would occur naturally. Implicit in the organizing of mesoscale systems is the concept that the storm becomes self-perpetuating to some degree. At a certain scale, the convergence pattern and interaction between cells makes the system capable of self-generation. Seeding can help with the organization, and also modify the dynamics and microphysics of an already organized storm. The dynamics effect might be accomplished, for example, by accumulating heat over a large area, due to seeding, in contrast to the localized, vigorous updrafts produced by seeding of individual cells. The key to this type of development will be learning to manipulate the heat sources produced by seeding into a configuration so that organized updraft motions will result on a broad scale. Computer models will ultimately be of great benefit in exploring the various possibilities for producing this type of organization. An alternative approach is the organization by seeding of the relative positions of updraft and downdraft areas and interactions between the cells of the system. Again, numerical modeling must be employed in these complex systems if seeding techniques and evaluation methods are to be developed to a satisfactory level.